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Controlling Heat Transfer Through Existing Windows

A Major Qualifying Project Report:

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Abstract

The Major Qualifying Project “Controlling Heat Transfer Through Existing Windows” focused on the research and analysis of how heat transfer occurs through windows, and how and why modern technologies seek to lessen this heat transfer. From the literature review, new methods to limit heat transfer through existing windows were created. Additionally, a manufacturing process and testing procedure was outlined for a window pane gas replacement.

Objective

The objective of this project is to research and analyze the methods inside and outside of windows in order to develop a method to reduce heat transfer through existing windows. Following the development of a method to reduce heat transfer through existing windows, a comprehensive guide for the design, manufacturing, and testing of the method will be outlined.

Rationale

Windows are essential to the aesthetic of nearly every building, residential and commercial. Windows are responsible for allowing natural light to enter a building, and allow residents to see inside and outside of the building. However, windows are not adequate insulators when compared to walls, as they are susceptible to an average of 30 percent of the total heat transfer in and outside of a residential house (Engineering Educators, 2016), (Arıcı & Kan, 2015).

Depending on the location and climate of the building, extreme outdoor temperatures can cause uncomfortable interior temperatures in residential and commercial buildings. In cooler climates, heat can very quickly leave the interior of a home causing temperatures to drop. Conversely, in warmer climates, solar radiation can quickly transfer through windows and increase the temperature of the interior of a home. This can cause uncomfortable home temperatures in the Winter and Summer months for many home-owners.

Not only does this large percentage of total heat transfer contribute to the potential for uncomfortability in the home, in order to keep the building climate comfortable, air conditioning and heating systems are run. A poorly insulated building would cause HVAC systems to run for an extended period of time to maintain a comfortable interior temperature. A reduction in heat transfer through the windows would be able to lessen the amount of time heating or cooling systems need to run inside the building. While the fuel for heating systems can vary, lowering the need to run any system will decrease the amount of fuel needed. Additionally in the summer months, reducing the time needed to run an electric air conditioning system even fractionally would help to lower the electricity usage and bill for the customer.

While more modern and expensive windows seek to minimize heat transfer through them, purchasing and replacing windows for an entire household is both time consuming and expensive. This gives motive to the objective of designing a system that can be applied in existing windows, and still limit the heat transfer through them. If an efficient, automatic system that limits heat transfer could be installed in existing windows, consumers could benefit from not having to invest in replacement windows, and experience lower electric and heating bills while experiencing comfortable temperatures inside their home.

State-of-the-Art

There are several recently marketed solutions that aim to reduce the heat transfer through windows. These solutions range from cheap and easily manufacturable to expensive. There are both interior and exterior solutions, changing the specifications of the window or the frame itself, or altering the exterior surroundings in order to reduce the solar radiative heat transfer through the window.

The effectiveness of a window to limit heat transfer through is measured by its U-value. A U-value is a measurement of the rate of the heat loss through the window, measured in Watts per square meter Kelvin (*What Are Typical U-Values on Windows and Doors?*, 2018). The lower the U-value of the object, in this case a window, the less heat transfer will occur through it. The oldest single pane windows typically have a U-value of around 5. According to the Guide to Energy-Efficient Windows, the most advanced modern windows have tested U-values below $0.3W/m^2K$ (*Guide to Energy-Efficient Windows*, 2010). There are many different factors and new technologies that have significantly reduced this U-value in recent years. This section will detail all of the current and potential solutions for heat transfer mitigation through new and existing windows.

Low-Emissivity Glazed Windows

Many advancements have been made to the composition of the glass in the windows themselves. In order to reduce the emissivity of the glass, the material is coated with a thin reflective glaze that reflects solar energy (Vitro Architectural, n.d.). Low emissivity (low-ε) glass is generally composed of extremely thin layers of silver, or other low emissivity materials. When coated on both the interior and exterior pane, the glaze limits the heat transfer through the window from both the outside into the building and vice versa. Some of the solar radiation from the exterior is reflected away from the window and back outside. Conversely, heat energy from the interior of the building can be reflected back into the building, allowing the building to more easily be able to remain at a consistent temperature.

Gas Fills

The gap between the majority of older double pane windows is filled with air. Air has a very low density at $1.225kg/m^3$ (Czernia, 2022). This low density does not provide much thermal insulation in between windows. Therefore, modern windows are often filled with argon. Argon is a colorless, orderless, and harmless gas, and it is nearly one and a half times more dense than air at atmospheric pressure. Krypton, with a density of 3.733kg/m^3 is also used in many windows. Krypton however, is significantly more expensive, and therefore less commonly used.

To analyze the effect of the U-value on the gas fill, a parametric study in the Renewable Energy journal was conducted that investigated how different parameters, including gas fills, affected heat transfer through windows. The figure below shows the direct comparison of the U-value of air and argon-filled double pane windows for windows with different emissivities with different lengths between the window panes.

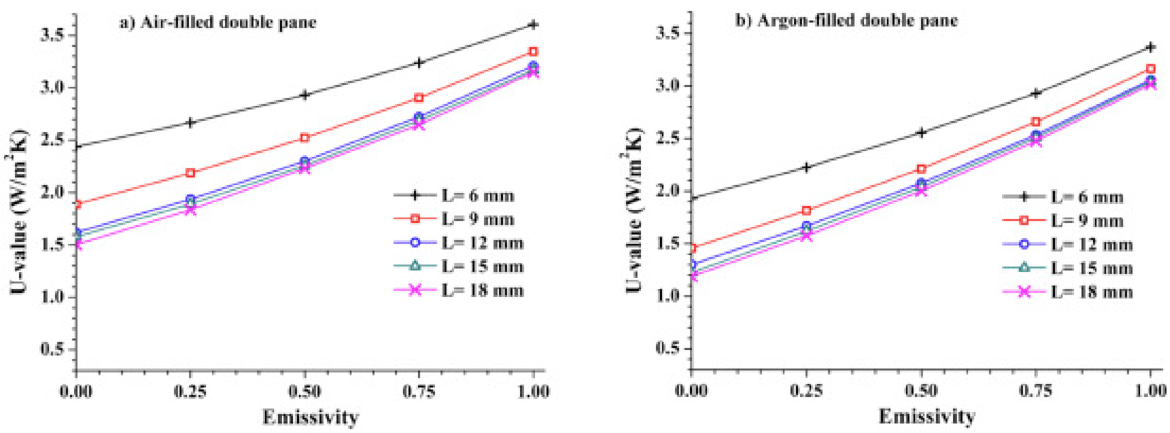

Figure 1, Comparative Analysis Results for Air and Argon-Filled Windows, from Sciencedirect.com

As shown in the figure above and explained further in the scientific journal article, depending on the emissivity of the window, the U-value can be reduced around 5-20% when the window is filled with argon (Arıcı & Kan, 2015). A reduction up to 20% is significant, as this drastically lowers the heat loss into and out of the building. Another important factor to note is that argon gas fills decrease the U-value more as the emissivity of the window is decreased. This means that as other factors, such as low emissivity glass glazes, reduce the emissivity of the window, the argon gas fill is more efficient at further reducing the U-value of the window. Also seen from the figure is a decreasing U-value as the gap between the panes increases from 6mm to 18mm, although decreasing returns on increasing length are seen. This gives cause to the normality of 12mm gaps between modern windows.

Overall, it has been shown that argon gas fills in new windows drastically reduces the U-value, or heat transfer, through windows, especially those with low emissivity. This is because of its high density when compared to atmospheric air, which insulates the window, helping to maintain a more consistent temperature in buildings.

Triple and Quadruple Pane Windows

The first windows were single pane, and not very good insulators. The majority of modern windows are double paned and coated with a low emissivity glaze, and the gas in between the panes acts as an insulator. This had led several manufacturers to create and analyze triple and even quadruple pane windows. While more expensive to manufacture, these windows aim to drastically decrease the heat transfer through windows.

In the same journal article cited above, a comparative analysis for U-value evaluation was completed to directly compare double, triple, and quadruple pane windows at varying emissivities. The figure below shares the results of the analysis for argon filled windows at varying window gap lengths for double, triple, and quadruple pane windows.

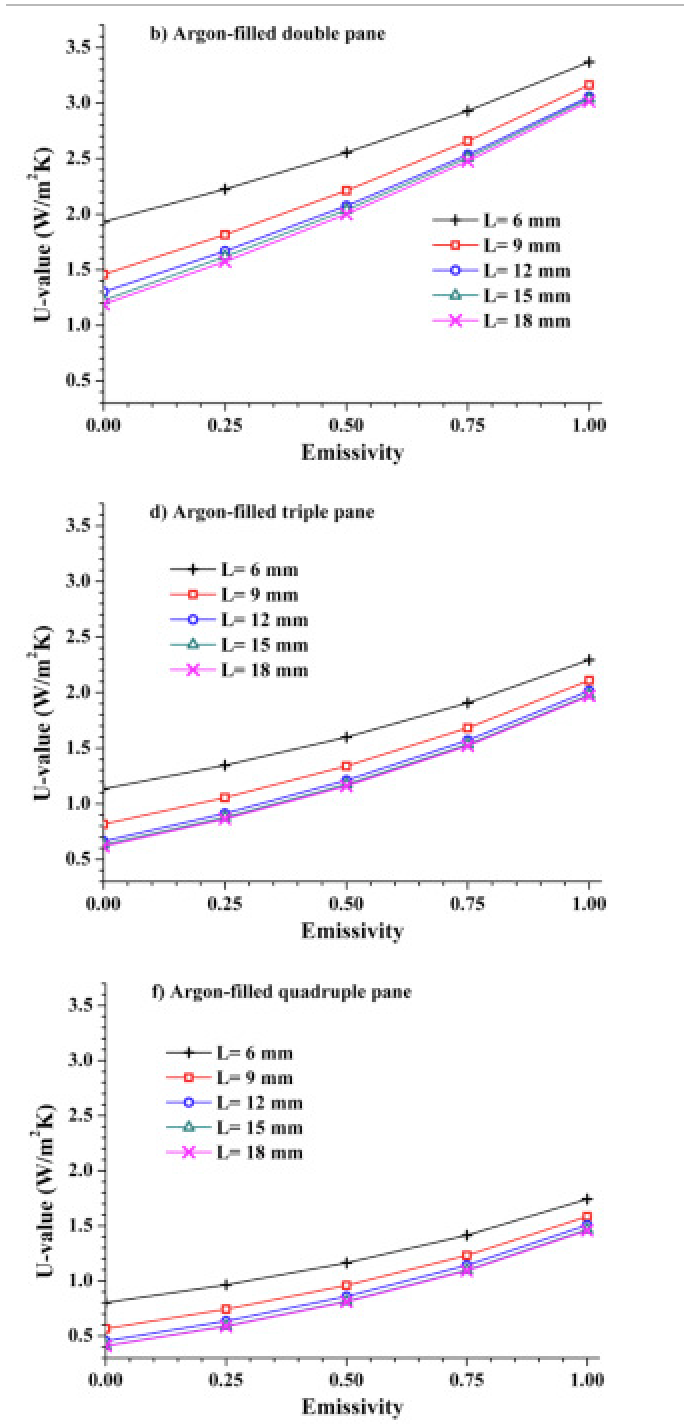

Figure 2, Comparison of Double, Triple, and Quadruple Paned Argon-Filled Windows, from Sciencedirect.com

As shown in the figure, a triple pane window has more effective insulating factors than a double pane window, A quadruple pane window additionally has an even lower U-value when directly compared to windows of the same emissivity with lower panes. The benefit of the addition of another pane to a window greatly decreases the U-value in higher emissivity windows. This does not demean the fact that low emissivity argon-filled triple pane windows still greatly benefit from being triple paned, reducing the U-value from a double to triple pane by 50-100%.

Frame Material and Composition

While much of the heat transfer through windows occurs through the glass itself, a lot of the heat loss through windows occurs through the frame itself. Over the last several years, improvements have been made to the material composition and style of window frames in order to increase the overall U-value for the window apparatus. Generally, window frames are either made from aluminum, vinyl, or wood; and each material has different thermal properties (Van Den Bossche et al., 2015). A study was conducted with Belgian window manufacturers to determine how much and where heat transfer took place in three windows. In this study, the main differences between the window composition was their materials; wooden, vinyl, and aluminum.

Results of this study concluded that convection and radiation was the most prominent heat transfer method in vinyl and aluminum frames, while conduction is most prevalent in wooden frames. The U-values of the different material window frames from the study are shown below.

U_f-values	double glazing 24mm (W/m²K)	triple glazing 42mm (W/m²K)	difference (W/m²K)	difference (%)
aluminum	2.773	2.618	0.155	5.59
wood	1.707	1.640	0.067	3.93
vinyl	1.503	1.451	0.052	3.46

Figure 3, U-Values of Windows of Different Frame Composition, from Van Den Bossche et al., 2015

As shown from this analysis, the material composition of the window can greatly contribute to the U-value, or the heat transfer and heat transfer rate, through the window. Aluminum windows are shown as the least effective insulators, and vinyl window frames are shown to be the most effective at preventing heat transfer.

While the three materials above have long been the three most common material compositions for window frames, new incentives to reduce the thermal conductivity of windows has led to the development of new insulating materials for frames. For example, composite and fiberglass frames have been developed to combat heat transfer and longevity limitations. Composite frames consist of wood products mixed with polymers in order to have slightly increased thermal properties to wood, but increase their resistance to environmental conditions. Fiberglass frames have also been developed to be strong and stable, while also having air or insulation cavities in order to significantly decrease heat transfer through the frame (*Window Types and Technologies*, n.d.).

It has been shown that the frame material of the window has a significant effect on the thermal conductivity of the window. Overall, frame material for windows is an ongoing researching topic, with methods developing to increase the longevity and insulating properties of the window.

Reflective and Tinted Window Coatings

While most modern windows are glazed with a thin low-emissivity coating, tinted and reflective low-emissivity postmarket window films have been developed in order to both reduce glare through windows, and also radiative heat transfer through them. Similar to window glazing, these films can be applied to both the exterior pane and interior pane in order to keep radiative heat transfer out, while keeping interior temperatures regulated. Window film producing companies advertise this solution as a low cost, highly effective solution that may be able to reduce “up to 78% of the sun’s heat coming through…windows” (*Home Window Films for Temperature Control | 3M United States*, n.d.).

Low emissivity window films are generally made from thin, bonded layers of polyester. Typically, they range from 2mm-7mm depending on the level of solar reflectivity and cost desired. To analyze the effectiveness of low emissivity films, a study was conducted during the summer at a hotel in China. This study aimed to analyze how effective the window films were on limiting outside heat transfer, and how economically viable the solution is.

This study, completed by some dude, analyzed the changes in electricity bills between two south facing hotel rooms. With the same windows, one set of windows was coated with solar radiation films. With the air conditioner set to a consistent temperature, the energy consumption and electricity bills of the two rooms were compared. The energy usage over the course of the day saw a 28% reduction for the room with the window films. Furthermore, given the increasing costs of electricity in China, it is projected that a singular window film has a payback period of around 4 years (Chan et al., 2008).

Overall, it can be seen that window films are a low cost, simple, yet effective step towards limiting the heat transfer through windows. While not quite as effective as the addition of another pane to the windows, or using technologically advanced engineering materials for the window frame, window films can significantly reduce energy bills especially during the Summer months in warmer climates. There are many window films currently on the market, and while some will cause shading and a reduction of natural light into a building, there are also several clear products that block much of the incoming solar radiative heat transfer (*Home Window Films for Temperature Control | 3M United States*, n.d.).

Shading on Windows

While much can be done to the windows and their frames in order to limit heat transfer through them, much can be done to the exterior of homes that can help to reduce solar radiation through windows. With over one-sixth of the total energy use in the United States being used for building air conditioning, there is a push to plant trees, specially in urban locations in order to induce shading on buildings and their windows (Akbari, 2002).

While planting trees is certainly an extremely long term solution without an immediate benefit, urban tree planting for shading can have both economical and environmental benefits. A study was completed in California cities on environmental pollution analyzing the effect of shade on buildings by planted trees focuses on their relevant potential benefits. The planting of trees increases the shading on windows, can shield high wind speeds, which can reduce energy consumption needs. South facing windows recieve an excess of solar radiation throughout the day, especially in the Summer months. Shading on residential and commercial buildings, especially on the windows, would drastically help to reduce heat transfer through the panes of the windows and into the building. Furthermore, wind shielding helps to lower the convection heat transfer through the windows throughout the day as the air closer to the building becomes more stagnant.

Not only does shading on the southern facing windows decrease the electric bill and heat transfer through windows, it is also passive and relatively inexpensive. While planting trees for shading is an indirect and long term solution to reduce heat transfer through windows, it is a successful external approach to the solution of limiting heat transfer through windows.

Approaches

The extensive literature review was able to provide a comprehensive background on all of the design considerations made in order to lower the U-value of windows. While most of the advances in window heat transfer limitation technology researched above were applied to new windows, a lot of the information and similar concepts can be used in the development of a heat transfer limitation method for existing windows. In this section, the literature review will be used in order to develop methods to limit heat transfer through existing windows.

Gas Fills

Modern windows are typically double or triple paned. A large difference that sets them apart from older windows is the gas between the panes. While older windows are typically filled with air between the panes, modern windows are generally filled with argon gas. The higher density of the argon gas helps to limit the radiative and convective heat transfer through the windows.

While argon gas filled windows are a technology used in modern windows, this technology could be applied to existing windows. Existing windows could have the air between their panes replaced with an alternative gas in order to limit the heat transfer through the panes. From the literature review, it was shown that the density of the gas in the pane directly correlates to the heat transfer through the windows.

Knowing this, there are a few different gas fill methods that could be used in order to limit heat transfer. Because pressure has a direct and linear correlation with density, increasing the pressure of a gas in between the window panes would increase its density, and therefore limit the heat transfer. This leads to the development of three different gas replacements, all with similar design, manufacturing, and testing procedures and environments.

The first concept would be to add in and compress the air inside the panes. Having compressed air inside the panes of the window would increase the density of the space between the panes, and therefore reduce the heat transfer through the window. The second approach would be to replace the gas between the windows with argon at atmospheric pressure. This, like most modern windows, would also aid to lower the heat transfer through existing windows. The third option, which if manufactured ideally, would have the greatest decrease in radiative and convective heat transfer, would be to replace the air between the panes of the window with argon, then add additional argon gas to compress the gas, further increasing its density.

While each of these methods would require slightly different manufacturing procedures, all three would require the window to be very well sealed. This would ensure the compressed air would not lose pressure, or the argon would not leak out. Overall, this method and its flexibility has the potential to provide a relatively inexpensive yet effective way to limit heat transfer. Additionally, once all of the required manufacturing and testing materials are ordered, many windows would be able to be gas filled for a minimal cost.

Low-Emissivity Window Film

As shown in the literature review, post market manufactured low-emissivity window films are a proven method to reduce heat transfer through windows. These films are typically very thin and transparent, and can significantly reduce the radiation through the windows. Window films are inexpensive, easy to install, and have a superior cost to benefit ratio. The problem with this is that window films are already heavily patented and marketed. Because of this, creating an original yet effective low-emissivity film to limit radiative heat transfer through windows would be difficult.

Window Shading Awnings

From the literature review, it was shown that shading windows with trees has multiple benefits. One of these benefits include that shading drastically reduces the solar radiative heat transfer through walls and windows. In order to increase shading on windows in a more short term and less obstructing manner than growing trees, constructing window awnings would be a viable method.

While several awnings currently exist and are marketed, developing a new, smarter shading awning to reduce or allow more or less solar radiation into a building depending on season and temperature could be developed. In the summer for example, windows could be shaded throughout the day, depending on the direction of the sun (Eastern facing windows in the morning, then Southern, with Western facing windows in the evening). These would help to reflect some of the incoming solar radiation from the high summer sun out of a building, while also reducing solar glare. Conversely in the Winter, these awnings could have segments that tilt towards the window in order to reflect more solar radiation into the building, increasing the heat of the building in the Winter. The awnings could also have levels of transparency, where in the winter or on colder days. A transparent awning would reflect a larger area of solar radiation into a building, which on a hot day, the radiation would be reflected elsewhere. Alternatively, the awnings could be retracted in order to not shade or reflect any solar radiation if unwanted.

Window awnings could be a more expensive solution and could also affect the aesthetic of the building. In order to design and manufacture an awning that would sell, it would have to be original, effective in reducing heat transfer through windows, low maintenance, and aesthetically pleasing for the customer and the building.

Methods

Requirements Review

Below lists the requirements and objectives of the design. These criteria are used to define the scope and expectations of the device. A **Must** denotes that the device must meet the requirement listed, while a ***May*** denotes the device should meet the requirement listed, if feasible within budget and manufacturability. The requirements are listed below in order of importance.

Table 1: Requirements

The device must limit the overall heat transfer through an existing window

- The device must be able to be installed into many standard existing windows
- The device should significantly limit the heat transfer through a window to justify product purchase and installation.

The device must be worth the investment

- The cost of the improvement to the window should pay for itself during its lifetime with lowered energy bills
- The device should cost significantly lower than an improved window replacement

The device must be automatic

- After installation, the device must be passive, and require no manual input in order to limit the heat transfer through the window

The device must be safe to install and use

- No harmful fluids or chemicals shall be exposed to the customer, manufacturer, or installation team during and after manufacturing
- The window improvement mechanism must not cause the panes or frame to wear excessively or break over time

The device may not significantly alter the view from the interior to the exterior. Additionally, the view from the exterior should not be significantly altered in a way that could be deemed “aesthetically unpleasing”

The device must be original, and may not impede on any current patents

Project Scope

After reviewing the design requirements review above and analyzing the literature review, the project scope can be narrowed down to achieve a more focused design. Reviewing the low-emissivity window films, it is clear to see that they are a proven marketed way to reduce incoming solar radiation in the Summer and reduce heat loss. However, the new design has to be original and not impede on any current patented and marketed ideas, while being more efficient than the mass marketed films. For these reasons, the design of an original low-emissivity window film would prove to be a monumental challenge to be taken on by an individual when other design options may be easier to manufacture and are original. Therefore the main focus for the remainder of the project will not focus on the design of a low-emissivity window film.

The development of an original smart window awning is possible and would be beneficial to the limitation of heat transfer through the windows. However, again there is a struggle to develop a product that is completely original, not overly expensive, and significantly reduces heat transfer through windows. It is certainly possible and should be investigated further, but for this current project, focusing on window gas replacement fills is an original and nearly definitive way to be able to successfully manufacture and test a heat transfer limitation method for existing windows. In the following section, a detailed guide to the overview, manufacturing and testing methods will be presented.

Gas Replacement Fill

The gas replacement fill will focus on the change of air in between existing window panes to compressed air, argon, or compressed argon gas. While the design and manufacturing for the three are slightly different, they are all the same concept and can be tested the same way.

Manufacturing

In order to ensure that the desired gas can enter and stay in the window panes for a justifiable lifetime, a sealant is required to make sure gas cannot enter or exit the window panes. In order to feed both the liquid sealant and the gas, whether it is compressed air, argon, or compressed argon, a small hole must be scored and cut into the bottom corner of the window. From there, the liquid sealant can be poured into the gap between the panes and rotated around in order to more properly create a new seal in the window pane gap.

Once the seal is created, for the argon gasses, it is necessary to score another hole in near the top of the glass, which will enable the air that was previously inside of the window to exit as argon gas is pumped in. For the compressed air, which is the easiest to manufacture, an air compressor is needed to further compress the air in the window pane gap up to the desired pressure. Once the pressure is reached, the glass must be quickly sealed back up. In order to do this, a sealant can go in the small area where the glass was. A sticker with the specifications of the changes done to the window can then be placed over this area, so as to not greatly impede on the aesthetic of the window. For the argon and compressed argon, the gas, which generally can be ordered from a large industrial producer in a highly compressed form, will have to be hooked up to a pressure gauge and thin tube in order to pump the proper pressure and amount of gas into the bottom hole in the window pane. While this is occurring, air will be flowing out the top window until the argon has completely replaced the air. The top hole then can be sealed. From here, if able, the argon can continue to be pumped into the window with a compressor compatible with the gas in order to pressurize the gas in the window pane.

The higher the pressure is within the window, the lower the heat transfer through the window would be. There is however, a safety limit on how pressurized the gas inside of the window can be, without risk of putting excess strain on the glass. In order to properly ensure the safety of the manufacturer and customer, the glass used for the window has to be inspected for its yield stress values, and using a proper engineering safety factor, an appropriate maximum pressure for the air and argon gas can be calculated.

Design for Testing Environment

The design of the system focuses on improving existing windows. Ideally for a testing environment, two identical and adjacent rooms facing the same direction (ideally south for maximum solar radiation) would be used. One of these rooms would have windows that would be retrofitted with one of the above methods, while the other room would have the control windows. Note here that the windows used in both of these rooms would have to be the same model and installation time period, in order to ensure other variables do not interfere with the test. Additionally, the rooms would have to be empty, with all appliances that would generate heat and use electricity either consistent or off. From here, there would be two different testing methods in order to test if heat transfer through the windows is limited.

The first is to set the HVAC system to a set temperature (68 degrees fahrenheit in the Summer) in both rooms. Then, over the course of a specified period of time, ideally multiple days in order to collect the most data, energy usage in the room could be measured to determine the usage of the air conditioning systems in the rooms. If the heat transfer through the windows is reduced with compressed air or argon windows, a lower energy usage would be expected. The difference in energy usage could be easily converted to a monetary savings amount depending on electricity costs in the area. From there, savings and return on investment periods can be calculated.

However, it is not likely that for a project of this scale, the testing environment above could be replicated. This would involve the total occupation of two identical rooms in a building, such as a hotel, with a major alteration to one of their windows. In this case, a testing environment would have to be created. An accurate testing environment could be designed to successfully determine the effectiveness of limiting the heat transfer through the window.

For this an existing window with its wooden border, not the whole frame, could be used as part of the testing environment. Two model “buildings” could be made around the window from where the temperature can be monitored throughout a day. One model would be for the control window, and one would be for the improved window. The model could be as simple as the construction of a wooden box surrounding the window. The box may be double layered and insulated in order to more accurately reflect the interior of modern buildings. Alternatively for simplicity, the box could be single layered plywood. The single layered would allow much more heat inside of the model, but that should not significantly affect the testing of the radiative heat transfer through the window as long as both models are built identically. Computer Aided

Designs of the two different model options, single layered and double layered insulated, are shown below. Window dimensions were received from existing double paned extra windows.

Single Layer Uninsulated Testing Environment Design

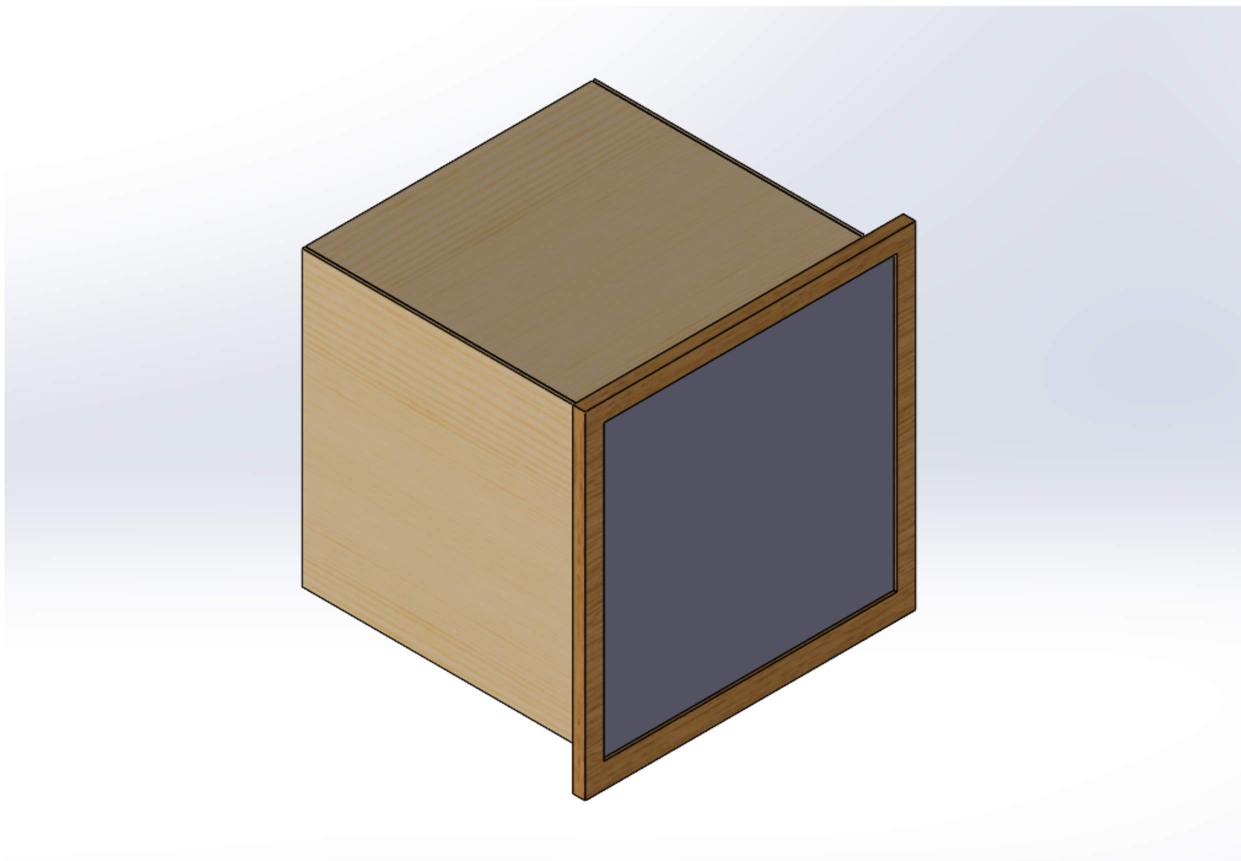

Figure 4, Computer Aided Design of Single Layered (Uninsulated) Model Testing Environment Featuring an Existing Window and Plywood Boards

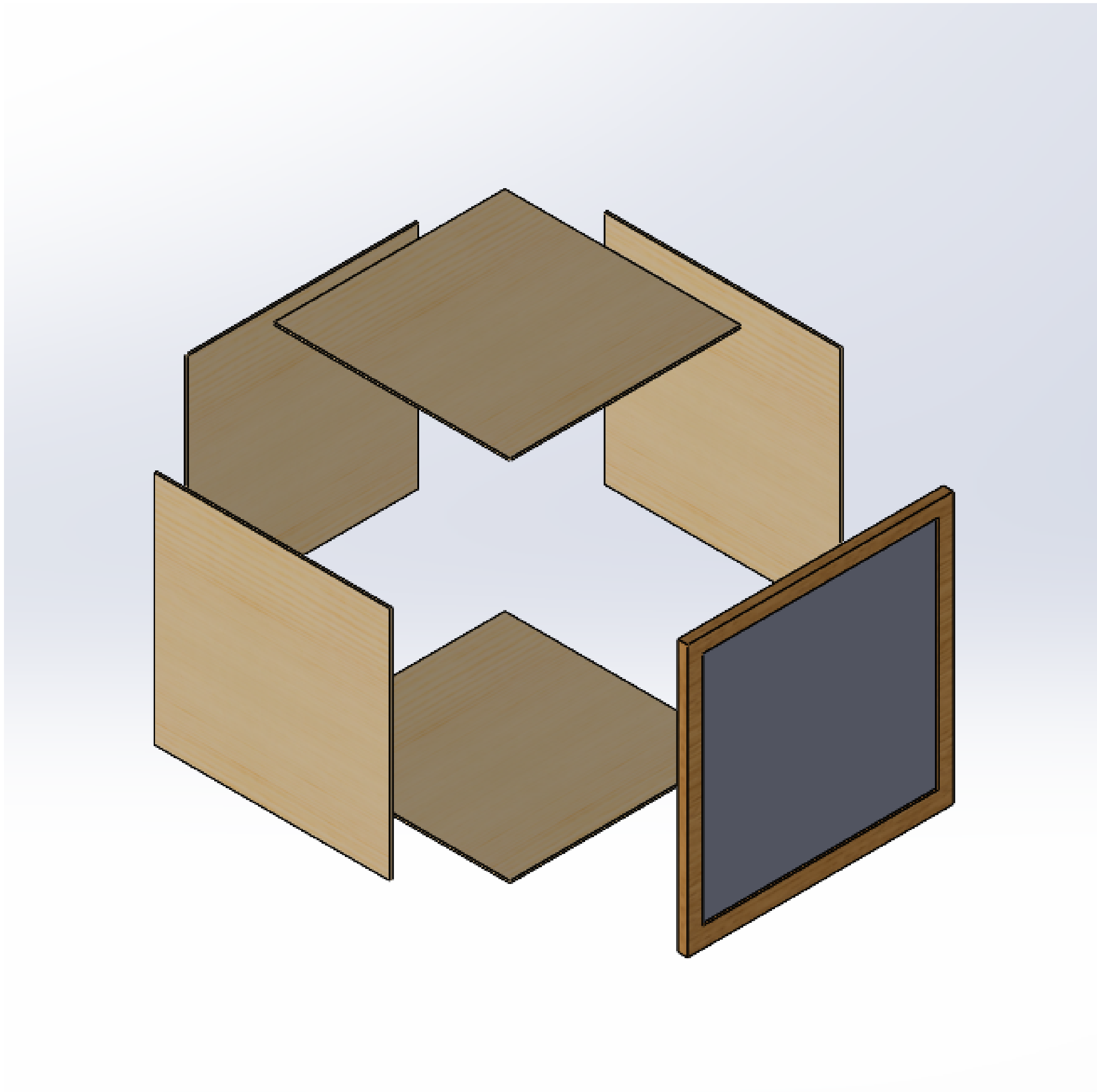

Figure 5, Exploded View of Single Layered (Uninsulated) Model Testing Environment

Table 2, Bill of Materials for Single Layered (Uninsulated) Model Testing Environment

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Window Frame With Panes	Existing Window Frame with Outside Dimensions of 27" x 26.5" Glass Pane Dimensions 23.5" x 23.5"	1
2	23.5" x 23.5" x .25" Wooden Board	Plywood Boards Used for Sides of Box	2
3	23" x 23.5" x .25" Wooden Board	Plywood Boards Used for Top and Bottom of Box	2
4	23" x 23" x .25" Wooden Board	Plywood Board Used for Back of Box	1

The single layered model can be constructed from an existing window and a singular 4’ x 8’ x ¼” plywood board. This board can be cut into the five smaller boards represented in the computer design. These boards then can be fastened to each other and the window frame with wood screws. Keeping in mind that two testing environments need to be created, two wooden boards need to be purchased, along with a box of 30-50 screws. Alternative to screws, wood glue can be used to attach the boards to the frame and to each other. Overall, being unable to buy in bulk, budgeting $70 for the plywood and $15 for either screws or glue, the two models can be constructed for around $85. This also assumes that there is access to a saw and drill.

Double Layered Insulated Testing Environment Design

The single layered uninsulated testing environment will provide accurate data on how the heat transfer is limited through the windows. However, as the plywood boards are thin, they will not limit much radiative heat transfer through the plywood. This could, in turn, drastically increase the temperature inside of the environment on a hot Summer day. This could cause an interior temperature greater than the exterior, which could skew the data on the limitation of heat transfer through the window itself.

Because of this, a second testing environment was created. This environment features a double walled system, allowing for air or insulation to act as a barrier for heat transfer into and out of the system. This would allow for temperature data inside of the environment to be more influenced by the window and less by the plywood boards. This would lead to a larger difference in temperature variation with the two systems of different windows. Below shows the computer aided designs of the double walled system and the bill of materials from the design.

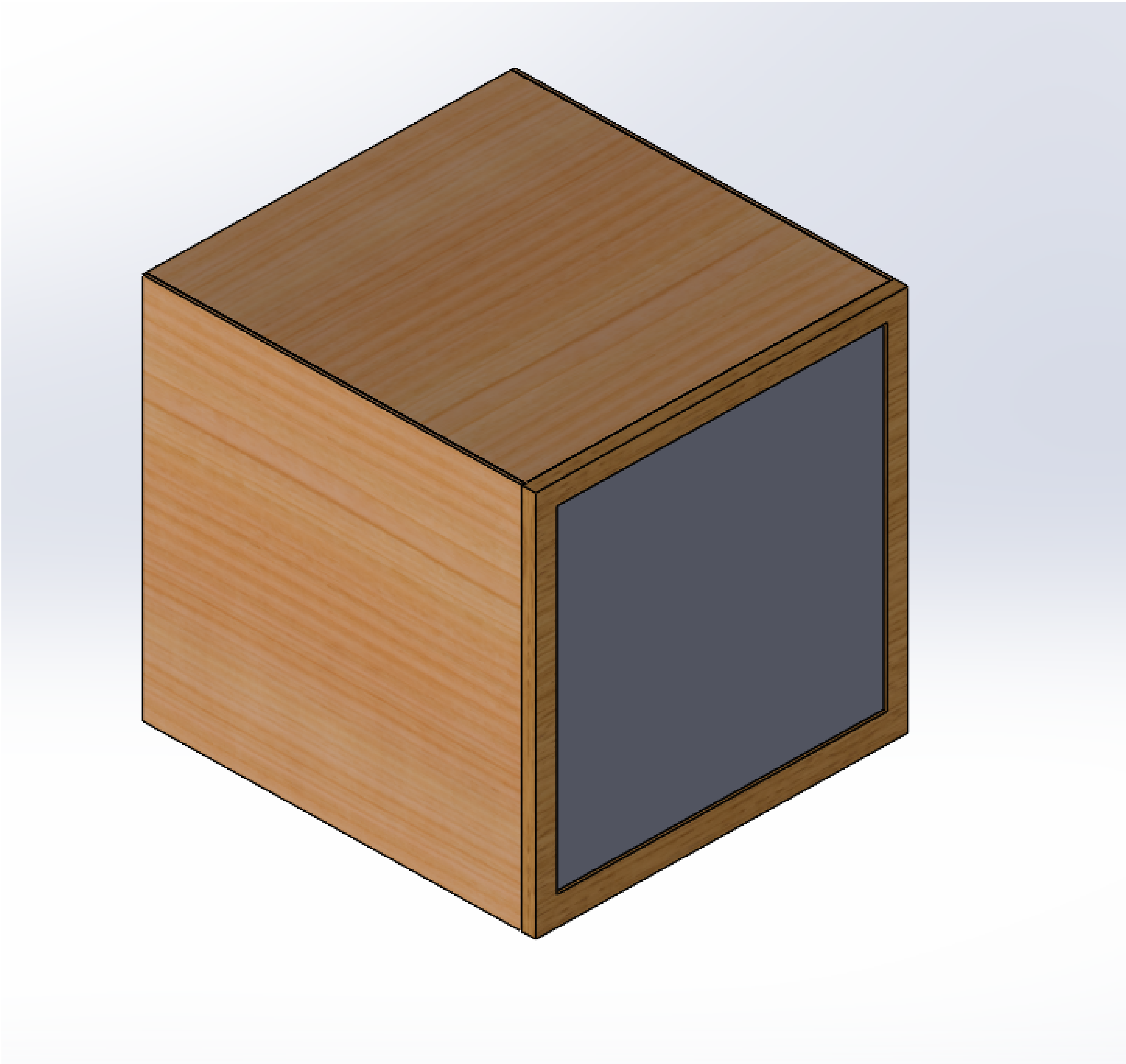

Figure 6, Computer Aided Design of Double Walled Insulated Testing Environment System

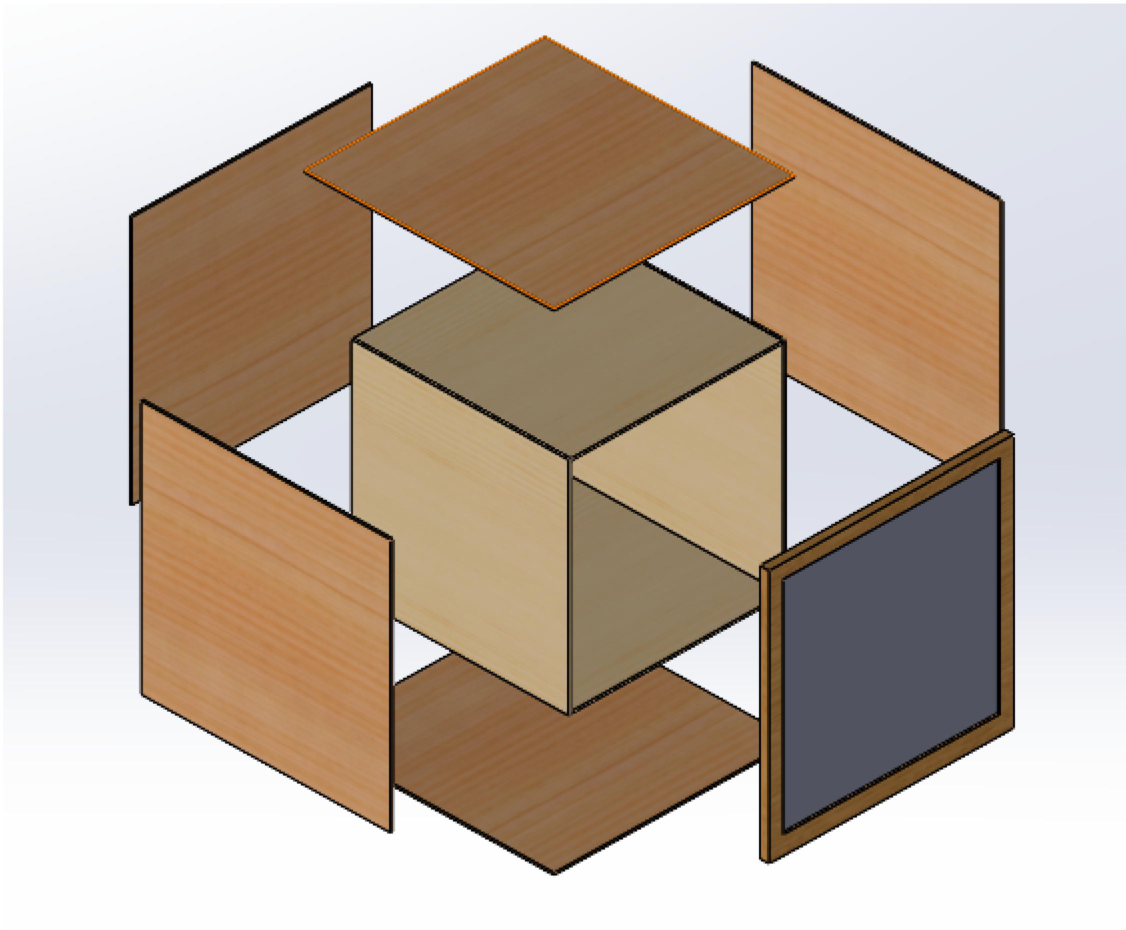

Figure 7, Exploded View of Double Walled Insulated Testing Environment System. Exterior Walls are Shown in the Darker Wood, and Interior Shown in Lighter Wood

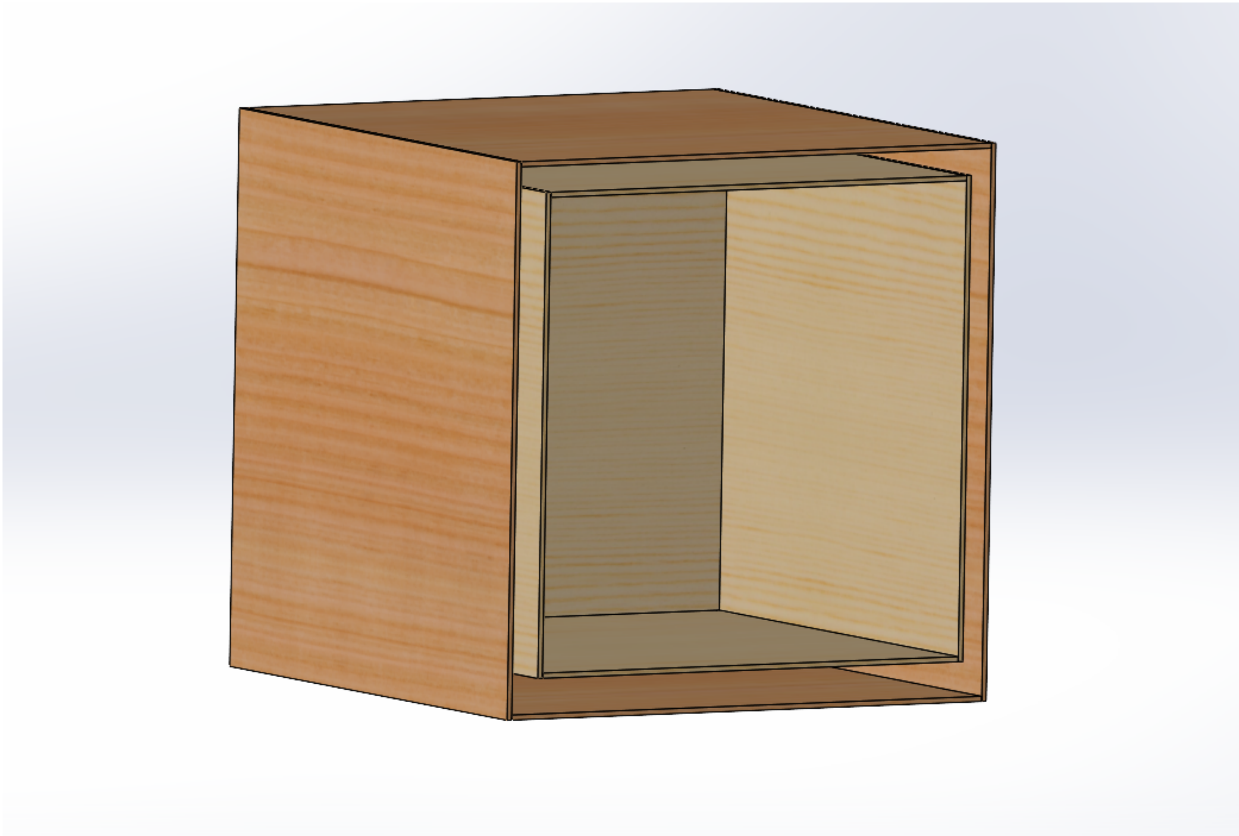

Figure 8, Computer Aided Design of Double Walled Insulated Testing Environment System with the Window Frame and Pane Hidden for View Clarity

Table 3, Bill of Materials for Double Walled Insulated Testing Environment

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Window Frame With Panes	Existing Window Frame with Outside Dimensions of 27" x 26.5" Glass Pane Dimensions 23.5" x 23.5"	1
2	23.5" x 23.5" x .25" Wooden Board	Plywood Boards Used for Inside Sides of Box	2
3	23" x 23.5" x .25" Wooden Board	Plywood Boards Used for Inside Top and Bottom of Box	2
4	23" x 23" x .25" Wooden Board	Plywood Board Used for Inside Back of Box	1
5	26" x 27" x .25" Wooden Board	Plywood Board Used for Outside Top and Bottom of Box	2
6	27" x 27" x .25" Wooden Board	Plywood Board Used for Outside Sides of Box	2
7	26" x 26.5" x.25" Wooden Board	Plywood Board Used for Outside Back of Box	1

As shown in the table above, the double walled system requires significantly more materials. This includes five more larger plywood boards in addition to the single layered system. All of this wood can be cut from a 7’x7’ or larger plywood board. Because that large board is difficult to source and purchase, four 4’x8’ wooden boards could be used instead. This would price out to around $140 for plywood per testing environment. This, combined with a larger package of wooden screws or glue could be priced at $20 for use in both systems. Overall, for the construction of two double walled existing window testing environments, given that the windows are sourced for free, the total cost would be $300. In the case that this is out of budget with the gas and the method of replacement, one singular testing environment can be created and the two windows can be tested on separate occasions. This would reduce the price down to approximately $160 for the double walled environment.

Either of the computer aided designs shown above can be assembled to test the heat transfer through windows. The plywood boards can be fastened to the window and each other with screws. Alternatively with the double walled design, one of the plywood boards will be fastened to both the inside and outside of the window frames, allowing for a small gap around the sides of the plywood boards. Here, if desired, insulation can be placed into this gap. Two plywood layers can also be inserted onto the rear side of the board, and also the bottom and top, enclosing the ‘buildings’ and providing some insulation. Once the building is closed, it can become ready for testing.

Testing Procedures

In order to optimally test the windows for heat transfer limitations, a few preliminary procedures are necessary. Firstly, the window testing buildings should be faced south in order to maximize the solar radiation into and through the window. This will allow for the change between the control and experimental window to be most significant. In order to maximize the data and to see how the gas fills prevent heat transfer through windows throughout the course of the day, it is necessary to take several consistent temperature measurements in multiple places throughout the day.

Thermometers should be used to measure the outside temperature throughout the day. One thermometer should also be placed against the interior of the glass on each window in order to measure the radiative and convective heat transfer through the window. Lastly, thermometers should also be placed in the middle of the chambers in order to monitor their temperature throughout the day. From an hour before sunrise to two hours after sundown (or as long as possible in order to provide a comprehensive data set), temperature data should be taken every 15 or 30 minutes.

With this data taken through the day, line graphs can be made comparing the temperatures of the two windows. With more data, direct comparisons can be made between the control and the gas filled window. Additionally, a comparison on the percentage of heat transfer limitations can be drawn, with accommodations for a conversion to a traditional building. This can correlate to calculating average reductions in electricity bills, which can also provide an estimate on return on investment given the overall cost of manufacturing.

With more data collected from multiple days in both Summer and in Winter months, where the interior of the building is both hotter and colder than the exterior, the specific benefits for the gas filled windows can be clearly seen. If the concept can be successfully manufactured and tested, the manufacturing process for gas replacement fills could be further streamlined, leading to more efficiency and cost reduction.

Further Research

This paper focused on a literature review on the limitation of heat transfer through windows in order to develop a method for application to existing windows. The scope was narrowed down to a singular method, being a gas fill replacement for existing windows. This would focus on either compressing air in between gas panes, or replacing the air inside of them with argon or compressed argon gas. A method in order to replace the gas and test the new window was outlined.

For the next portion of the project, the manufacturing and testing should be completed. This would start with the product ordering. Once completed, the windows can be scored, cut, and sealed in order to prepare them for gas replacement. Once the gas replacement is completed, the windows can be compared and tested. Following this, data analysis can be done in order to detail the significance of gas window replacements.

Conclusion

This section of the project largely focused on a comprehensive literature review analyzing the methods of limiting heat transfer through windows. With windows being an essential element to the aesthetic of nearly every building while contributing to over a third of the heat transfer through the walls of the house, it is necessary to develop methods to increase the insulation properties of windows. From decreasing the U-value of the glass and window frame itself, to coatings and shading on the windows, there are several developing methods for limiting heat transfer through windows. This will aid in lower electricity bills, an increase in the lifetime of windows, and lower strain on building HVAC units.

Following the literature review, three methods that have the potential to limit heat transfer through existing windows were reviewed. These methods included low-emissivity, solar radiation reflecting window films to be applied to the exterior and interior of window panes. While a proven concept, this idea is currently mass marketed, leading to a struggle to design and manufacture an original design. Similarly, many window awnings are currently marketed, but further research should be done in the development of a smart awning that can actively limit or allow solar radiation through a window based on the temperature differences between the building and exterior.

Overall, the development of a manufacturing and testing environment of a window gas replacement method seemed to be the most straightforward, original, yet effective way to significantly reduce heat transfer through a window. Throughout this project, a manufacturing method was developed in order to streamline the process of gas replacements for windows. Furthermore, an accurate yet easily manufacturable testing environment was designed and a bill of materials for it was created. Moving forward, this gas fill manufacturing process should be carried out and tested in order to accurately depict the significance of the gas fill.

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