# AN ENVIRONMENTALLY-FRIENDLY DESIGN TO REDUCE ENERGY LOSS BY HEAT TRANSFER THROUGH WINDOWS

by
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ABSTRACT

ANDREW GUANXI LI: An Environmentally-Friendly Design to Reduce Energy Loss
by Heat Transfer Through Windows
(Under the Direction of Dr. Jeffrey Roux)

With windows as main areas of energy loss in residential environments, a market exists for a product to act a removable barrier which improves heat transfer for cases of extreme temperatures in seasonal weather. Such a product would allow consumers to save money in the long run without permanently losing the use of their windows when the weather is mild and such an apparatus is not needed. This project designs such a product using an assembly of polished aluminum foil for low radiation emissivity, ABS plastic for an insulating material with low conductivity, and an aluminum glass mirror pane which lends aesthetic appeal along with good reflective and insulating properties. Thorough engineering analysis showed improvements of 89.5% to 93.5% in energy loss for varying single pane window cases and 73.1% to 87.5% improvement for double pane windows. For a residential setting with 11 windows set up using this design, this represents yearly energy savings up to $744.19, and all reasonably-constructed models experience a payback period to be profitable within 20 years. This product is to be an early entry into this particular market and aimed toward a middle-income early adopter consumer with all safety concerns both physical and mental judiciously accounted for in its design. Through careful analysis, reliable construction, and consumer-minded values, this product successfully achieves its goal of significant reduction in heat loss while keeping all other relevant concerns of machinability, reliability, safety, and socioeconomic effects at the forefront of design.

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| | |
|---|---|
| $T_n$ | Temperature of Surface n |
| $T_{\infty n}$ | Ambient temperature of fluid n |
| $k_n$ | Thermal Conductivity of material n |
| $\rho_n$ | Density of material n |
| $\mu_n$ | Dynamic Viscosity of material n |
| $\nu_n$ | Kinematic Viscosity of material n |
| $h_n$ | Heat Transfer Coefficient of fluid n |
| $u_n$ | Velocity of fluid n |
| $\epsilon_n$ | Emissivity of Surface n |
| L | Length of Window Pane |
| W | Width of Window Pane |
| A | Area of Window Pane |
| $\Delta x_n$ | Thickness of Object n |
| $\delta_n$ | Width of gap n |
| Re | Reynolds Number |
| Pr | Prandtl Number |

INTRODUCTION

As an everyday household object, the residential window has become commonplace enough to escape the attention of the general public; however, as a primary source of heat transfer between the atmosphere and a residential setting, the design of a window system can be a main source of improvement in energy efficiency in a normal home environment. Heat transfer through a window is a large source of energy loss which must then be expended to maintain temperature inside, and the cost of such inefficiency can reach thousands of dollars per year in an entire residential setting. This problem begs a solution for a window to resist such an inefficiency and save money for a consumer to eventually not only recover the implementation cost but also save on energy in the long term. Studying heat transfer theory reveals that a physically implemented solution could solve many fundamental problems with the typical window.

The design proposed in this report involves a sliding apparatus which would sit outside the window's enclosure and be easily moved to be either in use or out of use by the consumer. The basic design would include a structural sheet of ¼" polyacrylonitrile-butadiene-styrene (ABS) which is a strong plastic with very low thermal conductivity and serves as an insulating layer against conductive heat transfer. This plastic would be covered on both sides by a sheet of polished aluminum foil to create a reflective surface which would protect against radiant heat transfer. On the inward side of the aluminum sheet is a ¼" pane of glass which would create a mirror as perceived by a consumer in the house when combined with the existing structure. While from an engineering standpoint this combination of materials is not the absolute best possible for heat transfer considerations, they effectively create a functionally useful and visually appealing replacement where a

window once existed. This aesthetic appeal is important for the implementation of this product as an early entry in this particular market. The constructed window cover is designed to be set up on a standard 6 foot long sliding rail which is long enough to allow the apparatus to both completely cover the window and also sit simply on the wall to the side of the window when not in use.

In order to design this heat transfer solution, careful analysis of heat transfer was performed using various heat transfer principles applied to several java programs, and considerations for engineering, economics, aesthetics, reliability, manufacturability, social impact, ethics, and safety were made as detailed in this report. The resulting design is an economically viable, aesthetically pleasing solution which inhibits a majority of the heat transfer loss of a simple window.

ENGINEERING

In order to assess the design of this window fixture, the original condition had to be evaluated to find the heat transfer through a window 30 inches wide and 73 inches tall. Using glass panes 1/4 inch thick, the heat transfer was evaluated for cases both in single and double panes. The double pane window was modeled with a gap of 1 inch between the two glass panes for a total thickness of 1.5 inches. For the situations to be evaluated, a summer and winter case were considered. The summer temperature was assumed to be constant at 95°F and winter temperature 20°F, while an internal temperature of 70°F was used for all cases. Outside air velocity was also calculated as 15 miles per hour for every case. Calculations for these values were performed using a series of constructed java programs in which the Gauss-Seidel method was applied. In this method, the temperature at each surface was guessed for a value that makes sense (a guess at the average of the

inside and outside temperatures was used in this case) and run through the relevant

equations. These temperatures were then iteratively recalculated using the latest values for

each temperature variable until they converged upon an agreeing value accurate to within

0.001 K. Only when each temperature value converged on such an accuracy did the

program leave the loop and output the resulting heat transfer and R value results. Radiation

heat transfer is often ignored in common heat transfer evaluation, so these calculations

included one case with the assumption that radiation is negligible and one where radiation

is considered. The final program models output values to show relevant results which are

tabulated in Table 1 below.

| Table 1. Heat Transfer for Original Conditions | | | | |
|---|---|---|---|---|
| | Radiation | | No Radiation | |
| Panes | Single | Double | Single | Double |
| Summer | | | | |
| Heat Transfer (W) | 111.02 | 58.76 | 41.10 | 13.10 |
| R value ((h*F*ft$^2$)/BTU) | 1.004 | 1.896 | 2.366 | 8.507 |
| Winter | | | | |
| Heat Transfer (W) | -214.35 | -104.70 | -112.01 | -26.04 |
| R value ((h*F*ft$^2$)/BTU) | 1.040 | 2.128 | 1.989 | 8.557 |

The energy lost through the window in these cases is quite elucidating for many

reasons. Firstly, the results show clearly that an assumption that radiation is negligible

cannot readily be made without sacrificing quite a bit of heat transfer consideration. While

it makes the problem considerably easier to solve from a mathematical standpoint, the

results gleaned by the assumption are too inaccurate to be completely neglected when

considering a solution to the problem presented. Another easily apparent implication of the

results is the effectiveness of the addition of an extra pane in the window. In fact, the

change in heat transfer from single to double pane windows was a reduction of 47% in the

radiation case and 68% with no radiation for the summer conditions. For winter, the reductions for radiation and no radiation were 51% and 77%, respectively. These huge changes are due to the added gap in between the panes which facilitate convection heat transfer and reduces the heat lost over the entire system. Therefore, an effective solution would likely also benefit greatly from another layer of material separated from the window itself to create a second convection layer. These considerations were all taken into account in creating the final product design which would feature factors to inhibit radiation heat transfer as well as enabling creation of a convection layer.

For all figures and equations shown in the proceeding analysis sections, variables used are denoted as shown in Table 2 below.

| Table 2. Variables and Definitions Used | |
|---|---|
| $T_n$ | Temperature of Surface n |
| $T_{\infty n}$ | Ambient temperature of fluid n |
| $k_n$ | Thermal Conductivity of material n |
| $\rho_n$ | Density of material n |
| $\mu_n$ | Dynamic Viscosity of material n |
| $\nu_n$ | Kinematic Viscosity of material n |
| $h_n$ | Heat Transfer Coefficient of fluid n |
| $u_n$ | Velocity of fluid n |
| $\epsilon_n$ | Emissivity of Surface n |
| L | Length of Window Pane |
| W | Width of Window Pane |
| A | Area of Window Pane |
| $\Delta x_n$ | Thickness of Object n |
| $\delta_n$ | Width of gap n |
| Re | Reynolds Number |
| Pr | Prandtl Number |

All physical properties of air were found using Table A-9 of J. P. Holman's *Heat Transfer, Tenth Edition*[1].

The design created to ameliorate the detriment in heat energy included a new construction which acts as another pane for the window at an estimated 3 inches behind the window where it will sit outside the window's enclosure. This design applied to the single pane case is pictured in Figure 1 below.
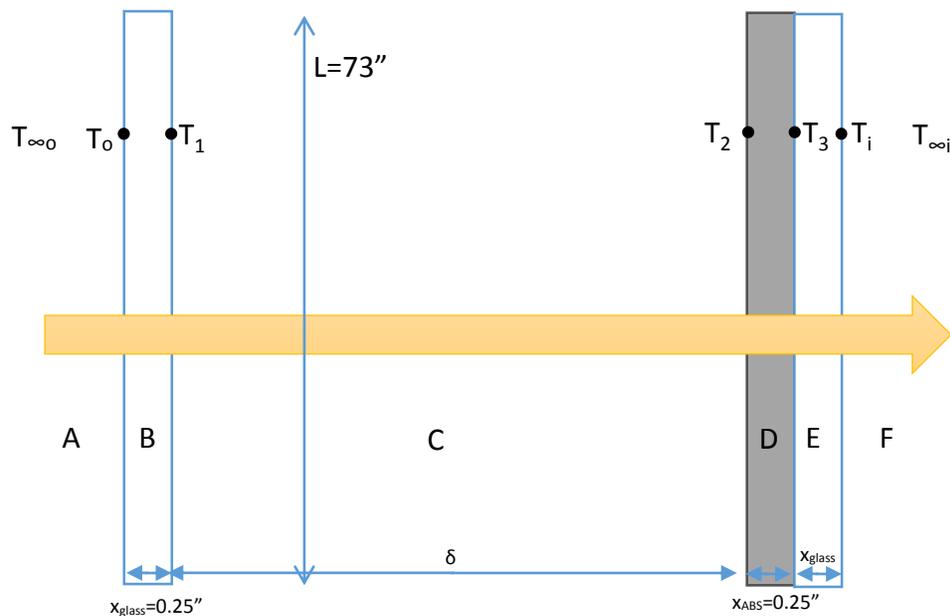


Figure 1. Design Applied to Single Pane Window (Not to Scale)

As the single pane is not as close to ideal as a double pane window for heat transfer properties, this implementation of the product design is not as optimal a situation as that of the double pane window. Sections A and F are modeled as forced convection heat transfer sections, Section C models the gap of air between the window and the apparatus, and Sections B, D, and E represent solid layers of conduction heat transfer.

The gray portion of the apparatus shown above represents a 0.25" layer of polyacrylonitrile-butadiene-styrene (ABS), a plastic widely used in household objects for its impact resistance and toughness[2]. ABS was chosen for its durability to hold together

the apparatus as well as its very low thermal conductivity at 0.17 $\frac{W}{mK}$. With such impressive

physical attributes as well as a lower thermal conductivity than similar plastics like

polycarbonate (0.21 $\frac{W}{mK}$), high density polyethylene (0.48 $\frac{W}{mK}$), and even

polyvinylchloride (0.19 $\frac{W}{mK}$)[3], it was decided that ABS would be the best plastic of choice

for an insulating material to keep conductive heat from passing through the window.

Attached to the sides of the ABS sheet are thin sheets of aluminum foil, which have a

negligible effect on conductive heat transfer at a thermal conductivity of 202 $\frac{W}{mK}$.

However, aluminum as a very reflective material has a tremendous impact on radiation

heat transfer with an incredibly low emissivity of 0.03. These sheets are located where $T_2$

and $T_3$ are modeled in Figure 1. As the thermal conductivity of aluminum is three orders

of magnitude higher than that of ABS, it can be statistically and mathematically considered

insignificant. Therefore, section D as modeled can be more accurately thought of as a

sandwiched element which has the conductive properties of ABS and the emissive

properties of aluminum. It is modeled as one structural piece and used in the relevant

equations as such.

As shown in the results collected in Table 1, the impact of radiation can very easily

be understated, and an effective method of combating heat transfer should address it as

well. For similar reasons, the sheet of glass on the inside (right) portion of the apparatus in

conjunction with the aforementioned polished aluminum sheet creates a 0.25" aluminum

glass mirror. This glass is identical to the pane of glass already used in the window itself

and carries the same properties of 0.94 emissivity and thermal conductivity of 0.78 $\frac{W}{mK}$.

The resultant apparatus lessens the problems both in conduction and radiation heat transfer associated with the problem presented.

To solve for the heat transfer through this window apparatus with the design included, a heat transfer equivalency had to be reached for sections as denoted in Figure 1 above. The heat transfer equation for the A section is shown in Equation 1 below where A represents area of the window pane, $\epsilon_o$ is the emissivity of glass, and $\sigma$ is the Stefan-Boltzmann Constant ($5.6704 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$). The denominator of the equation, as indicated, is represented as $R_1$ as used in the program to solve for the heat transfer in this case.

$$q_A = \frac{T_{\infty o} - T_o}{\left. \frac{1}{h_o A + \epsilon_o \sigma (T_{\infty o} + T_o)(T_{\infty o}^2 + T_o^2)A} \right\} R_1}$$

Eq. 1

Heat transfer coefficient $h_o$ is found as a derivation of Equation 5-46b on page 236 of Holman's *Heat Transfer Tenth Edition*[1]. This modified equation is shown in Equation 2 below where Reynolds number $Re_L$ is found using the outside velocity ($Re_L = \frac{\rho u_\infty L}{\mu}$) and Prandtl number Pr is found using the outside film temperature.

$$h_o = 0.664 Re_L^{1/2} Pr^{1/3} \left( \frac{k_g}{L} \right)$$

Eq. 2

The heat transfer $q_A$ found in equation 1 is then equivalent to the heat transfer from section B due to the First Law of Thermodynamics, and the equation to find $q_B$ is shown in Equation 3 below.

$$q_B = \frac{T_o - T_1}{\left. \frac{\Delta x_{glass}}{k_{glass} A} \right\} R_2}$$

Eq. 3

As in equation 1, equation 3's denominator can be expressed as $R_2$ when used in the program to calculate heat transfer.

$$q_C = \frac{T_1 - T_2}{\left\{ \frac{1}{\frac{k_e A}{\delta} + \frac{\sigma(T_1 + T_2)(T_1^2 + T_2^2)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}} \right\} R_3}$$  Eq. 4

Equivalent thermal conductivity $k_e$ in the above equation can be found using Equation 7-64 and Table 7-3 on pages 349-350 of *Heat Transfer Tenth Edition*[1]. The derivative of the equation used in this program is shown in Equation 5 below. Grashof and Prandtl numbers in this case are found using the film temperature of the gap itself (where $T_f = \frac{T_{left} + T_{right}}{2}$).

$$k_e = k_{air}(0.197)(GrPr_{air})^{1/4}\left(\frac{L}{\delta}\right)^{-1/9}, \ k_e = k_{air} \ when \ GrPr < 2000$$  Eq. 5

For section D of Figure 1, the heat transfer can be calculated as shown in Equation 6 below.

$$q_D = \frac{T_2 - T_3}{\frac{\Delta x_{ABS}}{k_{ABS} A} \} R_4}$$  Eq. 6

This equation shows the effect of conduction through the ABS plastic chosen as the structural element of the apparatus. Likewise, section E, the glass section of the mirror, is calculated using Equation 7 below.

$$q_E = \frac{T_3 - T_i}{\frac{\Delta x_{glass}}{k_{glass} A} \} R_5}$$  Eq. 7

Finally, the heat transfer of the inner film temperature is solved using the same method as in Equation 1 as shown in Equation 8 below.

$$q_F = \frac{T_i - T_{\infty i}}{\frac{1}{h_i A + \epsilon_i \sigma (T_i + T_{\infty i})(T_i^2 + T_{\infty i}^2)A} \Big\} R_6} \qquad \text{Eq. 8}$$

Heat transfer throughout the system should be constant; therefore, the heat transfer over the entire window and apparatus is found by equating all heat energy values using Equation 9 below.

$$q_{Total} = \frac{T_{\infty o} - T_{\infty i}}{R_1 + R_2 + R_3 + R_4 + R_5 + R_6} \qquad \text{Eq. 9}$$

As stated before, the result of all of these q equations should be a constant value, as the window apparatus is a steady-state system. After these values were all found, the R value of the system as a whole was found using Equation 10 as shown below.

$$R_v = \frac{T_{\infty o} - T_{\infty i}}{\frac{q}{A}} \qquad \text{Eq. 10}$$

These equations when solved find all relevant values for the implementation of this project's design on a standard single pane window. These equations are calculated using a Gauss-Seidel method in a java program for convergence of temperatures before outputting the values sought. This program can be found in Appendix A.3.

Similarly, a double pane window would benefit greatly from the implementation of such an apparatus. The equations involved in the calculation for a double pane are nearly identical to the single pane case, as the only difference is an added gap for convection and an extra layer of glass in between the first layer and the apparatus. The apparatus in this case is identical to the one added in the single pane case, while the window itself is simply modeled with another identical pane of glass as the original with a gap of one inch between the two panes. A model of the double pane solution is shown in Figure 2 below. Similarly

to the single pane case, the extreme sections of (A and H) model a forced convection condition with free convection gaps at sections C and E. Sections B, D, F, and G are solid sections subject to conductive heat transfer.
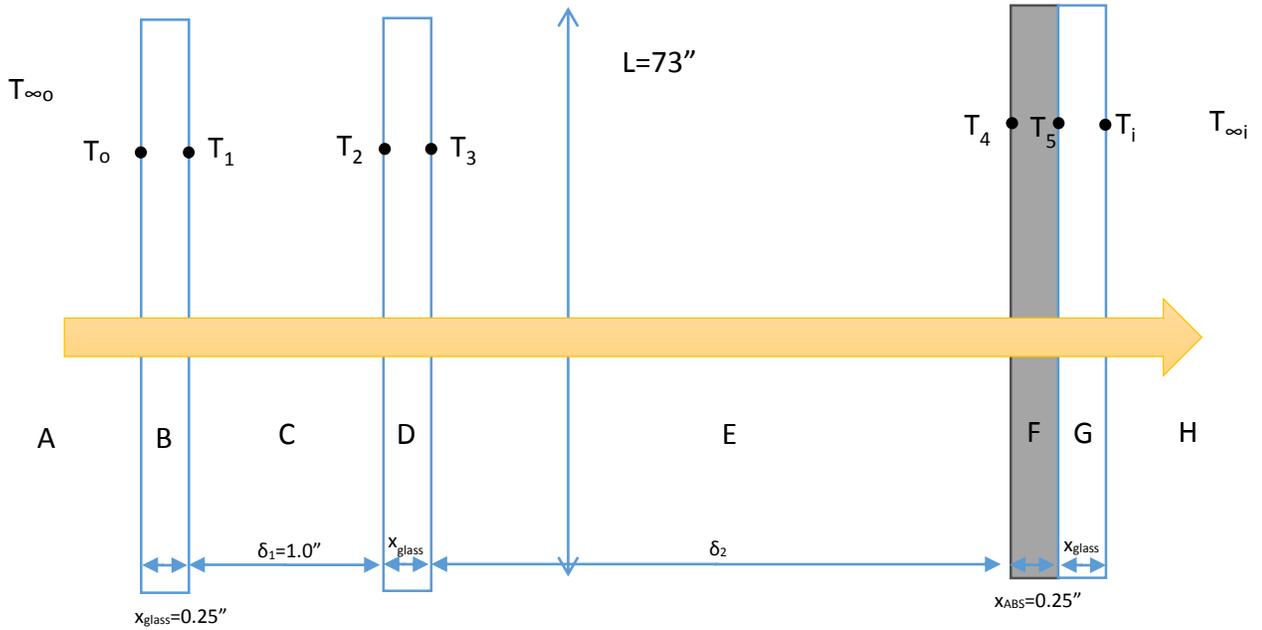


Figure 2. Design Applied to Double Pane Window (Not to Scale)

With the same physical properties as those in Figure 1 described above, the equations to find heat transfer for each section of the double pane model are quite similar to the above equations as well. First, the convective heat transfer in section A can be found using Equation 11 shown below.

$$q_A = \frac{T_{\infty o} - T_o}{\frac{1}{h_o A + \epsilon_o \sigma (T_{\infty o} + T_o)(T_{\infty o}^2 + T_o^2)A}} R_1 \qquad \text{Eq. 11}$$

This equation is identical to its counterpart in the single pane case Equation 1, and $h_o$ is likewise calculated using Equation 2. Next, the conductive heat transfer for the glass pane at section B can be found using Equation 12 below.

$$q_B = \frac{T_o - T_1}{\frac{\Delta x_{glass}}{k_{glass}A} \Big\} R_2}$$

Eq. 12

This equation is also identical to its counterpart, Equation 3 above. The convective layer in section C has heat transfer as calculated using Equation 13 below.

$$q_C = \frac{T_1 - T_2}{\frac{1}{\frac{k_e A}{\delta_1} + \frac{\sigma(T_1 + T_2)(T_1^2 + T_2^2)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}} \Big\} R_3}$$

Eq. 13

This equation is again identical to Equation 4 of the single pane case. Equivalent thermal conductivity $k_e$ is also calculated using Equation 5 as in the single pane case. The divergence from the single pane instance occurs at section D, the conductive heat transfer through the second glass pane, which is shown in Equation 14 below.

$$q_D = \frac{T_2 - T_3}{\frac{\Delta x_{glass}}{k_{glass}A} \Big\} R_4}$$

Eq. 14

This equation takes a form nearly identical to Equation 12, as it simply calculates the conductive heat transfer through the glass pane with only emissivity of air on either side. The next convective heat layer between the window and the added apparatus itself is represented by section E and calculated using Equation 15 below.

$$q_E = \frac{T_3 - T_4}{\frac{1}{\frac{k_e A}{\delta_2} + \frac{\sigma(T_3 + T_4)(T_3^2 + T_4^2)}{\frac{1}{\epsilon_3} + \frac{1}{\epsilon_4} - 1}} \Big\} R_5}$$

Eq. 15

This equation also makes use of Equation 5 to calculate equivalent thermal conductivity. Surface 4 in this equation is a thin layer of aluminum foil, so the emissivity $\epsilon_4 = 0.03$ yields a very small value and minimizes radiant energy loss. The layer of ABS which is

attached to the thin layer of aluminum foil and modeled by Section F is similarly calculated by Equation 16 below. It is important to note that the conductive heat transfer from the aluminum layer is neglected because with a thermal conductivity of $202\ \frac{W}{mK}$ the conduction from the tiny layer will do nearly nothing to insulate from heat transfer.

$$q_F = \frac{T_4 - T_5}{\frac{\Delta x_{ABS}}{k_{ABS}A}\Big\}R_6} \qquad \text{Eq. 16}$$

Section G is also calculated similarly to the ABS layer, as the very thin layer of aluminum again lends a negligible amount of insulation against conduction heat transfer. This glass layer has conduction heat transfer as calculated using Equation 17 below.

$$q_G = \frac{T_5 - T_i}{\frac{\Delta x_{glass}}{k_{glass}A}\Big\}R_7} \qquad \text{Eq. 17}$$

Finally, the last convective heat transfer section H from the apparatus into the ambient inside atmosphere is found using Equation 18 below.

$$q_H = \frac{T_i - T_{\infty i}}{\frac{1}{h_i A + \epsilon_i \sigma (T_i + T_{\infty i})(T_i^2 + T_{\infty i}^2)A}\Big\}R_8} \qquad \text{Eq. 18}$$

This equation is again identical to Equation 8 from the single pane case above, giving the final sectional heat transfer term for the entire system. Again, the window and apparatus is a steady-state heat transfer model, so all of the above equations 11 through 18 should be equal to the total heat transfer which can be calculated using Equation 19 as in Equation 9 for the single pane case.

$$q_{Total} = \frac{T_{\infty o} - T_{\infty i}}{R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7 + R_8} \qquad \text{Eq. 19}$$

Using the heat transfer calculated by the above equations, the R value of the system can be calculated using an identical equation to Equation 10 as shown in Equation 20 below.

$$R_v = \frac{T_{\infty o} - T_{\infty i}}{\frac{q}{A}} \qquad \text{Eq. 20}$$

With each equation as detailed above, the values for temperature are again solved using the Gauss-Seidel method in a java program which can be found in Appendix A.4.

One important consideration is the gap between the window and the apparatus itself, as this gap's size is the primary influencing factor of the equivalent conduction of the convection in the gap. To find the optimal gap size, a loop was created in the java program to output the heat transfer for an iteratively increasing gap size starting from zero. While the numerical values differed for each design case, the mode of each graph was the same with a shape resembling Figure 3 below.
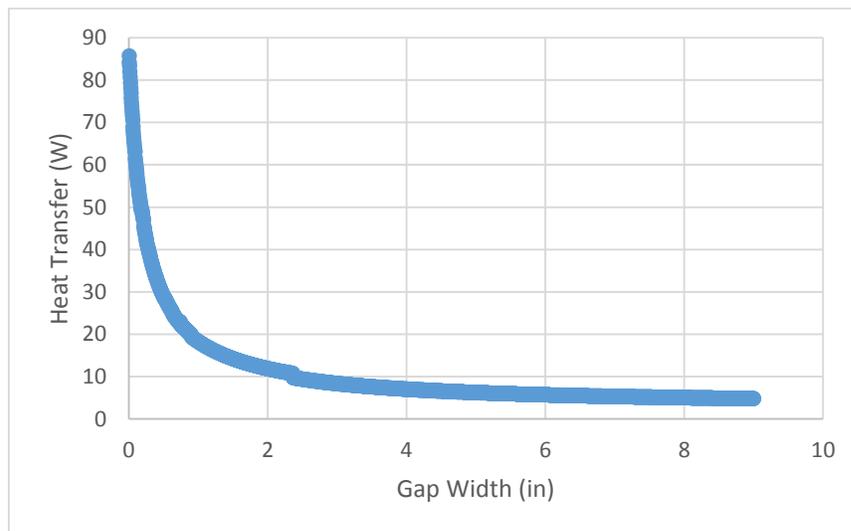


Figure 3. Heat Transfer in Relation to Gap Width

The plotted data shows some very valuable information. First, the heat transfer from the graph size very clearly decreases constantly throughout the plotted range, and even at

a maximum width of 9 inches which is far greater than any reasonable windowsill's width, the heat transfer allowed is continuing to decrease. This relationship means that for any reasonable dimension, quality of performance increases with the gap width. It is also clear that the allowed heat transfer approaches a minimum value to create drastically diminishing returns with increase in width. Therefore, while increasing width will incrementally better performance, it will not necessarily be worth the increase in cost and effort. For the design prescribed, the apparatus should be placed directly upon the wall next to the window, so a realistic number of 4 inches was chosen for the design's gap. This dimension is by no means an optimal size from an engineering standpoint, but it represents a balance of realistic design parameters and ideal solutions.

Solving for the above equations and taking into account gap considerations and assumptions of environmental values, the relevant results of heat transfer through the entire apparatus as well as the R value were calculated as shown in Table 3 below.

| Table 3. Results of Design Implementation | | | | |
|---|---|---|---|---|
| | Radiation | | No Radiation | |
| | Single | Double | Single | Double |
| Summer | | | | |
| q (W) | 7.86 | 7.43 | 4.31 | 3.53 |
| Improvement | 92.9% | 87.4% | 89.5% | 73.1% |
| rv (($h*F*ft^2$)/BTU) | 14.2 | 15.0 | 25.9 | 31.5 |
| Winter | | | | |
| q (W) | -13.98 | -13.10 | -8.25 | -6.74 |
| Improvement | 93.5% | 87.5% | 92.6% | 74.1% |
| rv (($h*F*ft^2$)/BTU) | 15.9 | 17.0 | 27.0 | 33.0 |

These numbers show incredibly successful results, reducing heat loss through each window case by more than two thirds of its original value and even as much as 93.5% in the case of heat transfer from a single pane window in the winter with radiation considerations

taken. The aluminum layers show their value by reducing heat transfer by over 85% in each radiation case. This difference is due mostly to the incredibly low emissivity of aluminum, which allows radiation emission of only 3% that of an equivalent temperature blackbody. One of the other largest factors is the added gap for free convection heat transfer between the window and the apparatus. This added distance allows the air to help as an insulator between the outside and inside conditions. As noted above, the addition of a second pane achieves similar results, and the apparatus increases the benefit in the same way. Finally, the ABS plastic used for structural support in the apparatus is a potent insulator as well with a thermal coefficient of $0.17 \frac{W}{mK}$. This design effectively utilizes the emissivity of aluminum, conductivity of ABS, and convective heat layer created by a gap in the design to enhance results. The benefits of this design are clearly apparent, and the pressing question is that of cost and whether it is worth the implementation costs for the consumer.

ECONOMICS

One of the main reasons to implement such a heat transfer solution is to save money. While the cost of implementation promises to be not insignificant, the potential long-term cost savings promise to be enormous with an improvement in energy loss of up to 93.5%. First, it is important to establish the cost condition of the window before adding this improvement. The United States Department of Energy's Energy Information Administration shows that in September 2014, the United States average cost of electricity was $0.1294/kW-hr[11]. Keeping in mind that the residential setting in question is to replace 11 windows, the total cost was calculated per household with a consideration for the coefficient of performance of the HVAC solutions it would replace as well. Because the energy moved in and out of the house would normally be dependent on the air conditioning

unit or heater for the building, they depend on the efficiencies of those machines when calculating heat energy. This inequality stems from the fact that air conditioning units utilize environmental conditions advantageously to move more heat energy than is put into the system energy-wise. The United States Environmental Protection Agency's ENERGY STAR program currently demands that single package air conditioning systems have heating seasonal performance factor (HSPF) of 8.0 in order to gain high efficiency certification[12]. The coefficient of performance COP is then related to the performance factor HSPF by Equation 21 shown below.

$$COP = HSPF \times 0.293 \hspace{4cm} \text{Eq. 21}$$

This relationship shows a calculated average coefficient of performance at 2.344. Most households do not yet have effective heat pumps, however, and the coefficient of performance of a normal furnace is conventionally very close to unity. As both summer and winter periods are both assumed to be 4 months long, these efficiencies can be averaged to find that the relevant coefficient of performance to be factored into the system is 1.672. Table 4 below shows the cost of maintaining the original window conditions.

| Table 4. Cost of Maintaining a Window Before Implementation | | | | | | | |
|---|---|---|---|---|---|---|---|
| Season | Radiation | Heat Transfer (W) | Energy Lost per Day (kW-hr) | Number of Days per Season | Energy Loss per Season (kW-hr) | Cost of Energy Loss per Season per Window | Total Cost of Energy Loss per Season |
| Single Pane | | | | | | | |
| Summer | Yes | 111.02 | 2.664 | 120 | 319.7 | $ 24.75 | $ 272.20 |
| | No | 41.10 | 0.986 | 120 | 118.4 | $ 9.16 | $ 100.76 |
| Winter | Yes | -214.35 | -5.144 | 120 | -617.3 | $ 47.78 | $ 525.54 |
| | No | -112.01 | -2.688 | 120 | -322.6 | $ 24.97 | $ 274.63 |
| Double Pane | | | | | | | |
| Summer | Yes | 58.76 | 1.410 | 120 | 169.2 | $ 13.10 | $ 144.07 |
| | No | 13.10 | 0.314 | 120 | 37.7 | $ 2.92 | $ 32.12 |
| Winter | Yes | -104.70 | -2.513 | 120 | -301.5 | $ 23.34 | $ 256.70 |
| | No | -26.04 | -0.625 | 120 | -75.0 | $ 5.80 | $ 63.84 |

As shown in the above table, the yearly cost of 11 windows in a conventional setup can cost hundreds of dollars per year in energy loss.

Next it is important to establish the implementation cost of the solution proposed. As the solution's design does not change with the type of window (single or double pane), the cost of implementation should be the same in any case given correct size. A complete bill of materials for outfitting of each windows is shown alongside other implementation costs in Table 5 below.

| Table 5. Total Customer Cost per Window | | | | |
|---|---|---|---|---|
| Material | Unit Price | Required Units | Total Cost | |
| Annealed Clear Glass 30" x 73" x 1/4" [4] | $ 297.49 | 1 | $ 297.49 | |
| ABS 48" x 98" Black; 1/4" Thick [5] | $ 143.82 | 1 | $ 143.82 | |
| CRL Brushed Nickel 72" Packaged Track Assembly D603 Upper and D602 Lower Track With Nylon Wheels [6] | $ 64.23 | 1 | $ 64.23 | |
| Aluminum Foil Roll, 0.003 th x 36 in W, 100 Ft [7] | $ 118.57 | 0.125 | $ 14.82 | |
| Single Assembly Materials Cost | | | $ 520.36 | |
| Single Assembly & Labor Cost | | | $ 5.00 | |
| Profit Margin (15%) | | | $ 78.80 | |
| Total Assembly Price- One Window | | | $ 604.17 | |

The above assembly and labor cost includes one quarter hour of manufacturing labor time and a small allowance for miscellaneous costs including industrial grade adhesive to attach the layers together. This labor cost is relatively low, as the amount of work necessary for manufacturing this product is quite small. This topic is explored more thoroughly in the manufacturability portion of this report. There is also a sizable profit margin of 15% over all costs considered in the price of each window assembly. Given that 11 window units will

be used per household, the total cost per customer would be $6,645.82. With no

maintenance or significant installation costs relevant to the operation of the apparatus, this

initial cost is the only amount that must be recovered in paying back the customer's

investment.

Adjusting the energy loss for the case after improvements have been made showed

a difference in heat loss of up to 93.5% as shown above, which should represent a

proportional decrease in cost of maintenance of the window system in general. The

resulting effect economically for the consumer is tabulated in Table 6 below.

| Table 6. Economic Effect on Customer After Implementation | | | | |
|---|---|---|---|---|
| | Radiation | Energy Loss Improvement | Total Cost of Energy Loss per Season | Total Cost of Energy Saved per Season |
| Single Pane | | | | |
| Summer | Yes | 92.9% | $ 272.20 | $ 252.93 |
| | No | 89.5% | $ 100.76 | $ 90.19 |
| Winter | Yes | 93.5% | $ 525.54 | $ 491.27 |
| | No | 92.6% | $ 274.63 | $ 254.41 |
| Double Pane | | | | |
| Summer | Yes | 87.4% | $ 144.07 | $ 125.85 |
| | No | 73.1% | $ 32.12 | $ 23.46 |
| Winter | Yes | 87.5% | $ 256.70 | $ 224.58 |
| | No | 74.1% | $ 63.84 | $ 47.32 |

These cost savings present a reduction of a huge portion and nearly all of the energy cost

for the original window conditions. The calculations show very good results in the main

focus of this design: the reduction of energy used to correct unfavorable movement of

energy for heating and cooling purposes as pertaining to the average user's home

environment. Using the information collected, it is possible to calculate payback period as

shown in Table 7 below.

| Table 7. Payback Period Calculation | | | | | | |
|---|---|---|---|---|---|---|
| | Radiation | Cost for 11 Windows | Cost Savings - Summer | Cost Savings - Winter | Total Yearly Savings | Payback Period (years) |
| Single Pane | Yes | $ 6,645.82 | $ 252.93 | $ 491.27 | $ 744.19 | **8.9** |
| | No | $ 6,645.82 | $ 90.19 | $ 254.41 | $ 344.60 | **19.3** |
| Double Pane | Yes | $ 6,645.82 | $ 125.85 | $ 224.58 | $ 350.43 | **19.0** |
| | No | $ 6,645.82 | $ 23.46 | $ 47.32 | $ 70.78 | **93.9** |

As the above table shows, the design of this solution is quite expensive and represents a long-term investment. For the single pane with radiation case, the payback period is under 9 years, while on the opposite extreme of a double pane window in the case of no radiation consideration, the payback period is over 90 years, making the option completely unviable. However, this data must be analyzed with some degree of discernment, as some of these cases are entirely unrealistic. Firstly, as seen from the calculations of every case thus far, it is quite clear that an assumption that radiation is negligible is unsound. The change in heat transfer from the radiation to a no radiation case is a heat transfer difference of nearly double in almost every case. Therefore, the only cases that should be considered as realistic are the radiation cases for both single pane payback period (8.9 years) and double pane payback period (19.0 years). The most optimal use of such a product would be in a home with single pane windows, as it represents the largest net benefit and fastest payback period.

For the sake of comparison, a similar investment in environmentally-friendly household changes is the rooftop photovoltaic solar cell. The payback period for such a system as explained by the Institute for Energy Research can range from 20 to 60 years when considering all costs associated with the investment[13]. In this comparison, the window apparatus is superior in its resistance to corrosive forces and does not require

regular maintenance or service. In this framework, the payback for a single pane is reasonable for a long-term investment, while a double pane payback period proves profitable as well after a period of roughly 22 years. If these products are installed as a design choice in building a house, they can be considered part of the cost of the house itself. If capitalized as part of the purchase of a house, the apparatus pays itself off before the length of a standard 30 year mortgage. Also important to consider is the portability of the design. One must simply remove the rails from the walls around the window to take the product to another house in the case that he moves from the original location and wishes to take his investment with him. Otherwise, the environmentally-friendly product will at the very least increase the value of the house, although statistically relevant information for this difference is not yet readily available.

Another key consideration is that this solution is a design with optimization of aesthetic appeal in mind. For a few concessions in material and appearance, a much cheaper solution could be reached for a comparable reduction in heat transfer for the entire system. For example, the sheet of ABS used as a structural support could be substituted with the much cheaper but less reliable and safe Polyurethane, a plastic with a comparable conductivity but lesser establishment as a household-safe structural element especially as a carcinogen when burned. A design with no glass pane and cheaper materials would be no less effective from an engineering standpoint and represent a fraction of the cost, and such a solution would be easy to design and feasibly sell much better for a lower-end market. The most costly aspect of the design is the glass pane which is also easily the most removable element. With all considerations taken, the reasonable cases for payback are met, and they could easily be cut down to 1-5 years with cheaper, less optimized materials.

AESTHETICS

Aesthetic appeal was a major consideration in the design of this solution. It may be tempting to design a simple foam solution with aluminum foil on either side, but from an aesthetic standpoint, a six foot tall wall of aluminum would look far from appealing for the homeowner. In this design, the solution appeals to customers by converting the window into a simple usable standard aluminum glass mirror when it is in use. The ABS structural and insulating plastic is an unassuming black background to the aluminum glass mirror and has the texture and look of a standard household item. The solution simply slides to the side when not in use as a large window along standard sliding window tracks which are 6 feet long to accommodate entirely for both an open and shut case. From the outside, the apparatus is merely a mirrored surface behind the window and does not allow for sight into the house. The resulting appearance features an effect similar to brightly colored blinds from outside and a large mirror replacing the window from the inside.

RELIABILITY

Reliability was also a principal concern in the design of this heat transfer solution. The design features no kinematic parts or hanging pieces, instead relying simply upon a design enclosed in an established window sliding track and held together using industrial grade adhesive. All materials used are well-used household materials including annealed glass, ABS plastic, and polished aluminum foil. Annealed glass, as a glass that has been cooled slowly to reduce interior strain, has good tensile strength and is already used heavily in household applications[8]. ABS plastic, commonly used in such household uses as furniture, radios, and piping, is very impact resistant and easily withstands any structural stresses from everyday use. The polished aluminum foil used to create both the outer layer

of the apparatus and the mirror is of course proven safe in everyday applications. Using only well-established materials that do not deteriorate, the reliability of this product is assured over a cheaper alternative which may prove less resistant to wear. The apparatus requires no maintenance, no servicing, and benefits merely from a routine cleaning like any other glass mirror in the house.

## MANUFACTURABILITY

Designing this product for manufacturability was an important aspect alongside all the other considerations. With so many expensive materials used in the design and a new product without the benefits of economics of scale, ease of manufacturability was an important cost control consideration. This design fortunately was able to be simplified to be incredibly easy to assemble. The glass used is purchased at exactly the 30" x 73" size of the window, making any work on the glass unnecessary. Aluminum foil is incredibly easy to machine and shape with only basic shearing tools. ABS, known as one of the easiest plastics to machine for structural use, is bought in sheets very close to the designated size, and shearing or sawing the plastic is easy using simple tools as well[8]. These plates are very simply attached using an industrial-strength adhesive and clamped into a standard design window sliding track to finish the assembly and attach to the wall of choice. The entire process would take no more than the most basic machining training and requires no large machinery or specialization.

## SOCIAL IMPACT

While an inexpensive implementation of this solution would have more mass market appeal, this design was focused on heat transfer control and the creation of a

solution which offered the greatest thermodynamic properties and not necessarily the greatest value. As a result, the product would be more focused toward mid to high-income families who are aware of environmental and economic issues like the energy cost of standard windows. As an early attempt at proliferation in this particular market, this design would be targeted at early adopters who are more aware of the potential long term savings of such a solution.

One hugely important aspect of this design's implementation is its environmental impact. By saving up to 93% of the energy lost through a normal window, this solution would allow for hundreds of dollars in energy savings yearly with very little downside environmentally. The drastic reduction in energy required for residential use would not only lessen the burden on the power grid but also increase capacity on the whole for other uses or even open up options for less powerful energy source options. The energy saved is not only financially beneficial but also beneficial for the environment, as it represents less load and therefore less electricity produced by burning fossil fuels which are the most common source of electrical energy in the United States. As opposed to other environmentally friendly commercial products such as solar panels and electric cars, this product does not require constant maintenance or unreliable weather but rather relies simply on the materials present. It promises a return on investment that would be much more reliable than other options, and while it lacks the flashy appeal of an electric car, it also provides a net return unlike an electric car which is still purchased regularly by concerned customers. The apparatus itself is also quite eco-friendly, as aluminum, glass, and ABS plastic are all recyclable and can be manufactured using recycled materials. Mass

acceptance of such a solution would undoubtedly have environmental benefits far outweighing any cost of the same category.

One aspect of this design that is cause for concern is the psychological effect of the lack of sunlight on an individual. Leaving the apparatus in effect on a window for a long duration threatens to drastically change the amount of sunlight exposure for anyone present in the room. Studies suggest that sunlight increases levels of the natural antidepressant serotonin in the human brain, and researchers increasingly find evidence that lack of sunlight and reduced serotonin is positively correlated with the development of Seasonal Affective Disorder (SAD). People exhibiting SAD often go on to develop symptoms of depression when exposed to low amounts of daylight including difficulty concentrating, low energy or fatigue, loss of interest, moodiness, and excessive sleeping[9]. For this reason, it was important to create a removable solution which allows for users to choose on their own when to apply the solution and when to allow natural sunlight into the room. Users would be able to make an informed decision given necessary facts to protect themselves from unintentional psychological harm. The solution presented would allow for the benefits presented from better heat transfer properties while keeping concessions to guarantee the mental health of individuals affected.

In terms of political impact, the introduction of such a product targeted toward early adopters at a relatively high socio-economic level allows for a small early market in which to test its effects before mass market consumption with a more affordable model. The most optimistic outcome would be immediate success which could then easily be marketed toward lower tier models and avoid any large pitfalls that may be found through implementation. A more realistic model would involve a small initial customer base to

allow for steady growth and product improvement through learned best practices which would facilitate eventual market proliferation. Any product that allows for cost savings will allow the general public to benefit and increase circulation of money throughout the general economy as a whole.

## ETHICS

The topic of ethics as presented in product design is extremely important, as the general public is not privy to the advanced knowledge of science that is institutionally provided to engineers. In designing a product that involves such advanced knowledge of physical and thermodynamic concepts of heat transfer, honesty and transparency is important in describing the effects of this product to consumers. While the benefits of such a design is impressive, it is an expensive investment to make, and money saved only comes with a long term investment. The analysis described in the engineering and economic portions of this report show the most accurate possible heat transfer information, and any savings caused are represented as conservatively as possible, giving as much information as possible that is relevant to the consumer.

## SAFETY AND HEALTH CONCERNS

As mentioned previously, all materials used in the design of this apparatus were chosen for their reliability and safety as already proven through extensive standard household usage. Unlike some cheaper plastics that could be used as a better insulating materials, the physical properties of ABS do not risk ignition or melting at temperatures possible in a residential use. Its impact resistance and high tensile strength have been proven more than adequate to handle the wear and tear of daily household use. An

aluminum glass mirror, likewise, is a standard household and workplace item with a strong annealed surface for safety and improved strength. From a physical standpoint, there should be little concern in safety of the design. With proper use and the same care given other household furniture, consumers need worry about nothing more than smudges on the mirror.

Of far greater concern is the mental health of the users of this product. As explained in the social impact portion of this report, there are some health concerns involved with limiting sunlight for extended periods of time. With a strong link between depression and darkness already established, neuroscientists found in 2008 that rats kept in the dark for six weeks not only exhibited depressive behavior but also suffered some brain damage in regions that are already known to be underactive in humans during depression. It was also found that neurons that produce norepinephrine, dopamine, and serotonin were in the process of dying under darkness. These neurotransmitters are responsible for perception of emotion, pleasure, and cognition. Furthermore, constant darkness interferes with the circadian rhythms of the human body and negatively affects the body's internal clock[10]. Given all of these concerns for mental health, it was important to design the product as a removable entity which can easily slide away from the window enclosure at will by the consumer. Feedback from customers must be carefully monitored and analyzed to document and prevent any disturbing trends in consumer health, and the product must have included in its owner's manual suggested usage adapted from thorough research.

It is important in designing any consumer product to consider health concerns in the usage of the product, and this product in particular has not only physical health but

mental health concerns. These aspects were instrumental in creating a product not only effective in its usage but also in keeping the interests of the consumer in mind.

## SUMMARY

The design proposed in this report takes advantage of the low emissivity of aluminum as well as the low conductivity of polyacrylonitrile-butadiene-styrene and glass to provide a multilayer solution for reduced heat transfer through a window. It proves through thorough heat transfer analysis to save energy loss through both a single pane and double pane standard glass window. For a single pane window, the added apparatus reduces heat transfer by 92.9% in summer and 93.5% in the winter when considering radiation and 89.5% in summer and 92.6% in winter without considering radiation. For a double pane window, the added design reduces heat transfer by 87.4% in summer and 87.5% in winter given radiation consideration and 73.1% in summer and 74.1% in winter without considering radiation. For a residential setting with 11 windows set up using this design, this represents yearly energy savings over $700 in the single pane case and over $350 when applied on a double pane window. Through payback period evaluation, it was found that both radiation cases would be profitable within 20 years, but this experimental design is too highly optimized for heat transfer to be economically viable for low-income consumers. Instead, this early product model would be marketed for middle-income early adopters and marketed for its engineering aspects and effective product specifications alongside environmental and economic benefits. The integrity of the product is ensured by using standard, proven materials and cost efficiency is somewhat sacrificed for safety and reliability. The design promises positive effects environmentally and politically with its

only downside in mental health where provisions are made by keeping the design removable at will by the customer.

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## A.1 Java Code for Single Pane Original Condition

```java
import java.io.*;
import java.util.Scanner;                    //To use Scanner class
import java.text.DecimalFormat;
import java.io.FileWriter;
import java.io.IOException;
public class SPWindow
{
public static void main(String[] args) throws IOException
{
//Single Pane
final double error=0.001;
final double x=0.00635;                      //thickness in meters
final double area=1.4129;                     //area in meters^2
final double vinf=6.7056;                     //ambient air velocity in m/s
final double sigma=0.00000005670373;          //stefan-boltzmann constant in W/m^2/k^4
final double length=1.8542;                   //length in m
final double width=0.762;                     //width in m
final double kg=0.78;                        //Thermal Conductivity of glass in W/m^2
final double tinfoutsummer=308.15;           //95 F in K
final double tinfoutwinter=266.48333;         //20 F in K
double tinfinside=294.26;                     //inside temperature in K
double tinfoutside=0;                         //outside temperature in K
double eps_o=0.98;
double eps_i=0.98;
double hToTheIzzo=0;
double hToTheIzzi=0;
double r1=0;
double r2=0;
double r3=0;
double tiold=0;
double ti=0;
double toold=0;
double to=0;
double rv=0;
double tfo=0;
double tfi=0;
double reynolds=0;
double rhoout=0;
double rhoin=0;
double cpout=0;
double cpin=0;
double muout=0;
double muin=0;
double nuout=0;
double nuin=0;
double kout=0;
double kin=0;
double prout=0;
double prin=0;
double q=0;
double qa=0;
double qb=0;
double qc=0;
double qd=0;
double tidifference=0;
double todifference=0;
double rad=0;
double season=0;
java.util.Scanner bob=new java.util.Scanner(System.in);
    //air data for varying temperature in C, rho, Cp, mu, nu, k, alpha, Pr
    double[][] airData={
      {250.0, 1.4128, 1005.3, 0.000015990, 0.00001131, 0.02227, 0.000015675,0.722},
      {300.0, 1.1774, 1005.7, 0.000018462, 0.00001569, 0.02624, 0.00002216, 0.708},
```

```
    {350.0, 0.9980, 1009.0, 0.000020750, 0.00002076, 0.03003, 0.00002983, 0.697},
    {400.0, 0.8826, 1014.0, 0.000022860, 0.00002590, 0.03365, 0.00003760, 0.683},
};

Scanner keyboard = new Scanner(System.in);
System.out.print("Enter 1 for radiation and 0 for no radiation: ");
rad = keyboard.nextDouble();
System.out.print("Enter 1 for summer and 0 for no winter: ");
season = keyboard.nextDouble();

eps_o=eps_o*rad;
eps_i=eps_i*rad;

//Guess t_o and t_i summer
if (season==1)
    {
    tinfoutside=tinfoutsummer;
    toold=303;
    tiold=298;
    }
else if (season==0)
    {
//Guess t_o and t_i winter

    tinfoutside=tinfoutwinter;
    toold=275;
    tiold=285;
    }

do{
//calculate film temperatures
tfo=(toold+tinfoutside)/2.0;
tfi=(tiold+tinfinside)/2.0;

//get outside properties
    rhoout=linearInterp(airData, tfo, 1);
    cpout=linearInterp(airData, tfo, 2);
    muout=linearInterp(airData, tfo, 3);
    nuout=linearInterp(airData, tfo, 4);
    kout=linearInterp(airData, tfo, 5);
    prout=linearInterp(airData, tfo, 7);
//get inside properties
    rhoin=linearInterp(airData, tfi, 1);
    cpin=linearInterp(airData, tfi, 2);
    muin=linearInterp(airData, tfi, 3);
    nuin=linearInterp(airData, tfi, 4);
    kin=linearInterp(airData, tfi, 5);
    prin=linearInterp(airData, tfi, 7);

//calculate reynolds number
reynolds=vinf*width/nuout;
//Compute h_o and h_i
hToTheIzzo=h_o(tfo, vinf, kout, prout, cpout, reynolds, width);
hToTheIzzi=h_i(tfi, tiold, tinfinside, kin, nuin, prin, length);

//Compute r1, r2, and r3
r1=r_1(hToTheIzzo, area, eps_o, sigma, tinfoutside, toold);
r2=r_2(x, kg, area);
r3=r_3(hToTheIzzi, area, eps_i, sigma, tiold, tinfinside);

//Compute q using qd
q=q_d(tinfinside, tinfoutside, r1, r2, r3);

//Compute to and ti
to=t_o(tinfoutside, q, r1);
ti=t_i(tinfinside, q, r3);

//find Differences
tidifference=Math.abs(ti-tiold);
todifference=Math.abs(to-toold);
```

```java
    //update t values
    toold=to;
    tiold=ti;

    } while((tidifference>error) || (todifference>error));
    qa=q_a(tinfoutside, to, r1);
    qb=q_b(to, ti, r2);
    qc=q_c(ti, tinfinside, r3);
    qd=q_d(tinfinside, tinfoutside, r1, r2, r3);
    rv=(tinfoutside-tinfinside)/(q/area);

    //SI Output
    System.out.println("SI Output");
    System.out.println("qa = " +qa);
    System.out.println("qb = " +qb);
    System.out.println("qc = " +qc);
    System.out.println("qd = " +qd);
    System.out.println("Rv = " +rv);

    //English Output
    System.out.println("English Output");
    System.out.println("qa = " +qa*3.412142);
    System.out.println("qb = " +qb*3.412142);
    System.out.println("qc = " +qc*3.412142);
    System.out.println("qd = " +qd*3.412142);
    System.out.println("Rv = " +rv*1.8*10.76319/3.412142);
}
public static double r_1(double hToTheIzzo, double area, double eps_o, double sigma, double tinfoutside, double to)
{
    double r1=1.0/(hToTheIzzo*area+eps_o*sigma*(tinfoutside+to)*(Math.pow(tinfoutside,2)+Math.pow(to,2))*area);
    return r1;
}
public static double r_2(double x, double kg, double area)
{
    double r2=x/kg/area;
    return r2;
}
public static double r_3(double hToTheIzzi, double area, double eps_i, double sigma, double ti, double tinfinside)
{
    double r3=1.0/(hToTheIzzi*area+eps_i*sigma*(ti+tinfinside)*(Math.pow(ti,2)+Math.pow(tinfinside,2))*area);
    return r3;
}
public static double q_a(double tinfoutside, double to, double r1)
{
    double q=(tinfoutside-to)/r1;
    return q;
}
public static double q_b(double to, double ti, double r2)
{
    double q=(to-ti)/r2;
    return q;
}
public static double q_c(double ti, double tinfinside, double r3)
{
    double q=(ti-tinfinside)/r3;
    return q;
}
public static double q_d(double tinfinside, double tinfoutside, double r1, double r2, double r3)
{
    double q=(tinfoutside-tinfinside)/(r1+r2+r3);
    return q;
}
public static double h_o(double tfo, double v, double k, double pr, double cp, double reynolds, double length)
{
    double nux=0.332*Math.pow(reynolds,0.5)*Math.pow(pr,(1.0/3.0));
    double hbar=2.0*nux*k/length;
    return hbar;
}
public static double h_i(double tfi, double ti, double tinfinside, double kin, double nuin, double prin, double length)
```

```java
{
    double ray=9.8/tfi*Math.abs(ti-tinfinside)*Math.pow(length,3.0)*prin/(Math.pow(nuin,2.0));
    double halfNu=0.825+(0.387*Math.pow(ray,(1.0/6.0)))/(Math.pow((1+Math.pow((0.492/0.7),(9.0/16.0))),(8.0/27.0)));
    double hbar=Math.pow(halfNu,2.0)*kin/length;
    return hbar;
}
public static double t_o(double tinfoutside, double q, double r1)
{
    double to=(tinfoutside-q*r1);
    return to;
}
public static double t_i(double tinfinside, double q, double r3)
{
    double ti=(q*r3+tinfinside);
    return ti;
}
public static double linearInterp(double[][] data, double tfi, int m)
{
    double tLow;
    double tHigh;
    int i = -1;
        do
        {
        i++;
        tLow = data[i][0];
        tHigh = data[i+1][0];
        } while (!(((tfi<tHigh)&&(tfi>=tLow)));


        double answer=(((tfi-tLow)/(tHigh-tLow)*(data[i+1][m]-data[i][m]))+data[i][m]);
        return answer;
}
}
```

## A.2 Java Code for Double Pane Original Condition

```java
import java.io.*;
import java.util.Scanner;              //To use Scanner class
import java.text.DecimalFormat;
import java.io.FileWriter;
import java.io.IOException;

public class DPWindow
{

public static void main(String[] args) throws IOException
{
//Single Pane
final double error=0.001;
final double x=0.00635;                  //thickness in meters
final double area=1.4129;                //area in meters^2
final double vinf=6.7056;                //ambient air velocity in m/s
final double sigma=0.00000005670373;     //stefan-boltzmann constant in W/m^2/k^4
final double length=1.8542;              //length in m
final double width=0.762;                //width in m
final double delta=0.0254;               //gap in m
final double kg=0.78;                    //Thermal Conductivity of glass in W/m^2
final double tinfoutsummer=308.15;       //95 F in K
final double tinfoutwinter=266.48333;    //20 F in K
double tinfinside=294.26;                //inside temperature in K
double tinfoutside=0;                    //outside temperature in K
double eps_o=0.98;
double eps_i=0.98;
double eps_1=0.98;
double eps_2=0.98;
double hToTheIzzo=0;
double hToTheIzzi=0;
double r1=0;
double r2=0;
double r3=0;
double r4=0;
double r5=0;
double tiold=0;
double ti=0;
double t1old=0;
double t1=0;
double t2old=0;
double t2=0;
double toold=0;
double to=0;
double rv=0;
double tfo=0;
double tfi=0;
double tfmid=0;
double reynolds=0;
double rhoout=0;
double rhoin=0;
double rhomid=0;
double cpout=0;
double cpin=0;
double cpmid=0;
double muout=0;
double muin=0;
double mumid=0;
double nuout=0;
double nuin=0;
double numid=0;
double kout=0;
double kin=0;
double kmid=0;
double prout=0;
double prin=0;
```

```java
double prmid=0;
double q=0;
double qa=0;
double qb=0;
double qc=0;
double qd=0;
double qe=0;
double qf=0;
double tidifference=0;
double todifference=0;
double t1difference=0;
double t2difference=0;
double ke=0;
double rad=0;
double season=0;

java.util.Scanner bob=new java.util.Scanner(System.in);

    //air data for varying temperature in C, rho, Cp, mu, nu, k, alpha, Pr
    double[][] airData={
        {250.0, 1.4128, 1005.3, 0.000015990, 0.00001131, 0.02227, 0.000015675,0.722},
        {300.0, 1.1774, 1005.7, 0.000018462, 0.00001569, 0.02624, 0.00002216, 0.708},
        {350.0, 0.9980, 1009.0, 0.000020750, 0.00002076, 0.03003, 0.00002983, 0.697},
        {400.0, 0.8826, 1014.0, 0.000022860, 0.00002590, 0.03365, 0.00003760, 0.683},
    };


    Scanner keyboard = new Scanner(System.in);
    System.out.print("Enter 1 for radiation and 0 for no radiation: ");
    rad = keyboard.nextDouble();
    System.out.print("Enter 1 for summer and 0 for no winter: ");
    season = keyboard.nextDouble();

    eps_o=eps_o*rad+.0000000000001;
    eps_i=eps_i*rad+.0000000000001;
    eps_1=eps_1*rad+.0000000000001;
    eps_2=eps_2*rad+.0000000000001;

    if (season==1)
        {
        //Guess t_o and t_i summer
        tinfoutside=tinfoutsummer;
        toold=303;
        tiold=298;
        t1old=300;
        t2old=300;
        }
    else if (season==0)
        {
        //Guess t_o and t_i winter
        tinfoutside=tinfoutwinter;
        toold=275;
        tiold=285;
        t1old=280;
        t2old=280;
        }

    do{
    //calculate film temperatures
    tfo=(toold+tinfoutside)/2.0;
    tfi=(tiold+tinfinside)/2.0;
    tfmid=(t1old+t2old)/2.0;

    //get outside properties
        rhoout=linearInterp(airData, tfo, 1);
        cpout=linearInterp(airData, tfo, 2);
        muout=linearInterp(airData, tfo, 3);
        nuout=linearInterp(airData, tfo, 4);
        kout=linearInterp(airData, tfo, 5);
        prout=linearInterp(airData, tfo, 7);
```

```java
//get inside properties
    rhoin=linearInterp(airData, tfi, 1);
    cpin=linearInterp(airData, tfi, 2);
    muin=linearInterp(airData, tfi, 3);
    nuin=linearInterp(airData, tfi, 4);
    kin=linearInterp(airData, tfi, 5);
    prin=linearInterp(airData, tfi, 7);
//get gap properties
    rhomid=linearInterp(airData, tfmid, 1);
    cpmid=linearInterp(airData, tfmid, 2);
    mumid=linearInterp(airData, tfmid, 3);
    numid=linearInterp(airData, tfmid, 4);
    kmid=linearInterp(airData, tfmid, 5);
    prmid=linearInterp(airData, tfmid, 7);

//calculate reynolds number
reynolds=vinf*width/nuout;

//Compute h_o and h_i
hToTheIzzo=h_o(tfo, vinf, kout, prout, cpout, reynolds, width);
hToTheIzzi=h_i(tfi, tiold, tinfinside, kin, nuin, prin, length);

//Compute ke
ke=k_e(tfmid, t1, t2, length, x, rhomid, mumid, numid, kmid, prmid);

//Compute r1, r2, and r3
r1=r_1(hToTheIzzo, area, eps_o, sigma, tinfoutside, toold);
r2=r_2(x, kg, area);
r3=r_3(ke, area, delta, sigma, t1old, t2old, eps_1, eps_2, rad);
r4=r_4(x, kg, area);
r5=r_5(hToTheIzzi, area, eps_i, sigma, tiold, tinfinside);

//Compute q using qd
q=q_f(tinfinside, tinfoutside, r1, r2, r3, r4, r5);

//Compute to and ti
to=t_o(tinfoutside, q, r1);
ti=t_i(tinfinside, q, r5);
t1=t_1(toold, q, r2);
t2=t_2(t1, q, r3);

//find Differences
tidifference=Math.abs(ti-tiold);
todifference=Math.abs(to-toold);
t1difference=Math.abs(t1-t1old);
t2difference=Math.abs(t2-t2old);

//update t values
toold=to;
tiold=ti;
t1old=t1;
t2old=t2;

} while((tidifference>error) || (todifference>error) || (t1difference>error) || (t2difference>error));

qa=q_a(tinfoutside, to, r1);
qb=q_b(to, t1, r2);
qc=q_c(t1, t2, r3);
qd=q_d(t2, ti, r4);
qe=q_e(tinfinside, ti, r5);
qf=q_f(tinfinside, tinfoutside, r1, r2, r3, r4, r5);

rv=(tinfoutside-tinfinside)/(q/area);

//SI Output
System.out.println("SI Output");
System.out.println("qa = " +qa);
System.out.println("qb = " +qb);
System.out.println("qc = " +qc);
System.out.println("qd = " +qd);
```

```java
		System.out.println("qe = " +qe);
		System.out.println("qf = " +qf);
		System.out.println("Rv = " +rv);

		//English Output
		System.out.println("English Output");
		System.out.println("qa = " +qa*3.412142);
		System.out.println("qb = " +qb*3.412142);
		System.out.println("qc = " +qc*3.412142);
		System.out.println("qe = " +qd*3.412142);
		System.out.println("qe = " +qe*3.412142);
		System.out.println("qf = " +qf*3.412142);
		System.out.println("Rv = " +rv*1.8*10.76319/3.412142);
	}

	public static double r_1(double hToTheIzzo, double area, double eps_o, double sigma, double tinfoutside, double to)
	{
		double r1=1.0/(hToTheIzzo*area+eps_o*sigma*(tinfoutside+to)*(Math.pow(tinfoutside,2)+Math.pow(to,2))*area);
		return r1;
	}

	public static double r_2(double x, double kg, double area)
	{
		double r2=x/kg/area;
		return r2;
	}

	public static double r_3(double ke, double area, double delta, double sigma, double t1, double t2, double eps_1, double eps_2, double
rad)
	{
		double r3=1.0/(ke*area/delta+sigma*(t1+t2)*(Math.pow(t1,2.0)+Math.pow(t2,2.0))*area/((1.0/eps_1)+(1.0/eps_2)-1.0));
		return r3;
	}

	public static double r_4(double x, double kg, double area)
	{
		double r4=x/kg/area;
		return r4;
	}

	public static double r_5(double hToTheIzzi, double area, double eps_i, double sigma, double ti, double tinfinside)
	{
		double r5=1.0/(hToTheIzzi*area+eps_i*sigma*(ti+tinfinside)*(Math.pow(ti,2)+Math.pow(tinfinside,2))*area);
		return r5;
	}

	public static double q_a(double tinfoutside, double to, double r1)
	{
		double q=(tinfoutside-to)/r1;
		return q;
	}

	public static double q_b(double to, double t1, double r2)
	{
		double q=(to-t1)/r2;
		return q;
	}

	public static double q_c(double t1, double t2, double r3)
	{
		double q=(t1-t2)/r3;
		return q;
	}

	public static double q_d(double t2, double ti, double r4)
	{
		double q=(t2-ti)/r4;
		return q;
	}
```

```java
public static double q_e(double tinfinside, double ti, double r5)
{
   double q=(ti-tinfinside)/r5;
   return q;
}

public static double q_f(double tinfinside, double tinfoutside, double r1, double r2, double r3, double r4, double r5)
{
   double q=(tinfoutside-tinfinside)/(r1+r2+r3+r4+r5);
   return q;
}

public static double h_o(double tfo, double v, double k, double pr, double cp, double reynolds, double length)
{
   double nux=0.332*Math.pow(reynolds,0.5)*Math.pow(pr,(1.0/3.0));
   double hbar=2.0*nux*k/length;
   return hbar;
}

public static double h_i(double tfi, double ti, double tinfinside, double kin, double nuin, double prin, double length)
{
   double ray=9.8/tfi*Math.abs(ti-tinfinside)*Math.pow(length,3.0)*prin/(Math.pow(nuin,2.0));
   double halfNu=0.825+(0.387*Math.pow(ray,(1.0/6.0)))/(Math.pow((1+Math.pow((0.492/0.7),(9.0/16.0))),(8.0/27.0)));
   double hbar=Math.pow(halfNu,2.0)*kin/length;
   return hbar;
}

public static double k_e(double tfmid, double t1, double t2, double length, double x, double rhomid, double mumid, double numid,
double kmid, double prmid)
{
   double ray=9.8/tfmid*Math.abs(t1-t2)*Math.pow(x,3.0)*prmid/(Math.pow(numid,2.0));
   double ratio=length/x;
   double kratio=0.197*Math.pow(ray,0.25)/Math.pow(ratio,(1.0/9.0));
   if (kratio<1)
   {
   kratio=1.0;
   }
   double ke=kratio*kmid;
   return ke;
}

public static double t_o(double tinfoutside, double q, double r1)
{
   double to=(tinfoutside-q*r1);
   return to;
}

public static double t_i(double tinfinside, double q, double r3)
{
   double ti=(q*r3+tinfinside);
   return ti;
}

public static double t_1(double toold, double q, double r2)
{
   double t1=toold-(q*r2);
   return t1;
}

public static double t_2(double t1, double q, double r3)
{
   double t2=t1-(q*r3);
   return t2;
}

public static double linearInterp(double[][] data, double tfi, int m)
{
   double tLow;
   double tHigh;
   int i = -1;
```

```
    do
    {
    i++;
    tLow = data[i][0];
    tHigh = data[i+1][0];
    } while (!(((tfi<tHigh)&&(tfi>=tLow)));


    double answer=((((tfi-tLow)/(tHigh-tLow)*(data[i+1][m]-data[i][m]))+data[i][m]);
    return answer;
}
}
```

## A.3 Java Code for Single Pane With Design

```java
import java.io.*;
import java.util.Scanner;                    //To use Scanner class
import java.text.DecimalFormat;
import java.io.FileWriter;
import java.io.IOException;

public class SPWindowDesign
{

public static void main(String[] args) throws IOException
{
//Single Pane
final double error=0.001;
final double x=0.00635;                      //thickness in meters
final double xabs=0.00635;                    //ABS thickness in meters
final double area=1.4129;                     //area in meters^2
final double vinf=6.7056;                     //ambient air velocity in m/s
final double sigma=0.00000005670373;           //stefan-boltzmann constant in W/m^2/k^4
double delta=4*.0254;                        //gap in m
final double length=1.8542;                   //length in m
final double width=0.762;                     //width in m
final double kg=0.78;                        //Thermal Conductivity of glass in W/m^2
final double kabs=0.17;                       //Thermal Conductivity of ABS in W/m^2
final double kal=205;                        //Thermal Conductivity of Aluminum in W/m^2
final double tinfoutsummer=308.15;            //95 F in K
final double tinfoutwinter=266.48333;         //20 F in K
double tinfinside=294.26;                    //inside temperature in K
double tinfoutside=0;                        //outside temperature in K
double eps_o=0.98;
double eps_i=0.98;
double eps_1=0.98;
double eps_2=0.03;
double eps_3=0.03;
double eps_air=0.0000000000000001;
double hToTheIzzo=0;
double hToTheIzzi=0;
double r1=0;
double r2=0;
double r3=0;
double r4=0;
double r5=0;
double r6=0;
double tiold=0;
double ti=0;
double toold=0;
double to=0;
double t1old=0;
double t1=0;
double t2old=0;
double t2=0;
double t3old=0;
double t3=0;
double rv=0;
double tfo=0;
double tfi=0;
double tfgap=0;
double reynolds=0;
double rhoout=0;
double rhoin=0;
double cpout=0;
double cpin=0;
double muout=0;
double muin=0;
double nuout=0;
double nuin=0;
double kout=0;
double kin=0;
double ke=0;
```

```java
double prout=0;
double prin=0;
double rhogap=0;
double cpgap=0;
double mugap=0;
double nugap=0;
double kgap=0;
double prgap=0;
double q=0;
double qa=0;
double qb=0;
double qc=0;
double qd=0;
double qe=0;
double qf=0;
double qg=0;
double tidifference=0;
double todifference=0;
double t1difference=0;
double t2difference=0;
double t3difference=0;
double rad=0;
double season=0;

java.util.Scanner bob=new java.util.Scanner(System.in);

    //air data for varying temperature in C, rho, Cp, mu, nu, k, alpha, Pr
    double[][] airData={
        {250.0, 1.4128, 1005.3, 0.000015990, 0.00001131, 0.02227, 0.000015675,0.722},
        {300.0, 1.1774, 1005.7, 0.000018462, 0.00001569, 0.02624, 0.00002216, 0.708},
        {350.0, 0.9980, 1009.0, 0.000020750, 0.00002076, 0.03003, 0.00002983, 0.697},
        {400.0, 0.8826, 1014.0, 0.000022860, 0.00002590, 0.03365, 0.00003760, 0.683},
    };

    //Choose Conditions
    Scanner keyboard = new Scanner(System.in);
    System.out.print("Enter 1 for radiation and 0 for no radiation: ");
    rad = keyboard.nextDouble();
    System.out.print("Enter 1 for summer and 0 for no winter: ");
    season = keyboard.nextDouble();

    eps_o=eps_o*rad;
    eps_i=eps_i*rad;
    eps_1=eps_1*rad;
    eps_2=eps_2*rad;
    eps_3=eps_3*rad;

    //Guess t_o and t_i summer
    if (season==1)
        {
        tinfoutside=tinfoutsummer;
        toold=303;
        tiold=298;
        t1old=300;
        t2old=300;
        t3old=300;
        }
    else if (season==0)
        {
    //Guess t_o and t_i winter

        tinfoutside=tinfoutwinter;
        toold=275;
        tiold=285;
        t1old=280;
        t2old=280;
        t3old=280;
        }

    do{
```

```
//calculate film temperatures
tfo=(toold+tinfoutside)/2.0;
tfi=(tiold+tinfinside)/2.0;
tfgap=(t1old+t2old)/2.0;

//get outside properties
    rhoout=linearInterp(airData, tfo, 1);
    cpout=linearInterp(airData, tfo, 2);
    muout=linearInterp(airData, tfo, 3);
    nuout=linearInterp(airData, tfo, 4);
    kout=linearInterp(airData, tfo, 5);
    prout=linearInterp(airData, tfo, 7);
//get inside properties
    rhoin=linearInterp(airData, tfi, 1);
    cpin=linearInterp(airData, tfi, 2);
    muin=linearInterp(airData, tfi, 3);
    nuin=linearInterp(airData, tfi, 4);
    kin=linearInterp(airData, tfi, 5);
    prin=linearInterp(airData, tfi, 7);
//get second gap properties
    rhogap=linearInterp(airData, tfgap, 1);
    cpgap=linearInterp(airData, tfgap, 2);
    mugap=linearInterp(airData, tfgap, 3);
    nugap=linearInterp(airData, tfgap, 4);
    kgap=linearInterp(airData, tfgap, 5);
    prgap=linearInterp(airData, tfgap, 7);

//calculate reynolds number
reynolds=vinf*width/nuout;

//Compute h_o and h_i
hToTheIzzo=h_o(tfo, vinf, kout, prout, cpout, reynolds, width);
hToTheIzzi=h_i(tfi, tiold, tinfinside, kin, nuin, prin, length);

ke=k_e(tfgap, t1, t2, length, x, rhogap, mugap, nugap, kgap, prgap);

//Compute rs
r1=r_1(hToTheIzzo, area, eps_o, sigma, tinfoutside, toold);
r2=r_2(x, kg, area);
r3=r_4(ke, area, delta, sigma, t1, t2, eps_1, eps_2);
r4=r_2(xabs, kabs, area);
r5=r_2(x, kg, area);
r6=r_3(hToTheIzzi, area, eps_i, sigma, tiold, tinfinside);

//Compute q using qd
q=q_g(tinfinside, tinfoutside, r1, r2, r3, r4, r5, r6);

//Compute to and ti
to=tinfoutside-q*r1;
t1=toold-q*r2;
t2=t1old-q*r3;
t3=t2old-q*r4;
ti=t3old-q*r5;

//find Differences
tidifference=Math.abs(ti-tiold);
todifference=Math.abs(to-toold);
t1difference=Math.abs(t1-t1old);
t2difference=Math.abs(t2-t2old);
t3difference=Math.abs(t3-t3old);

//update t values
toold=to;
tiold=ti;
t1old=t1;
t2old=t2;
t3old=t3;

}while((tidifference>error) || (todifference>error));
```

```java
      qa=q_a(tinfoutside, to, r1);
      qb=q_b(to, t1, r2);
      qc=(t1-t2)/r3;
      qd=(t2-t3)/r4;
      qe=(t3-ti)/r5;
      qf=q_c(ti, tinfinside, r6);
      qg=q_g(tinfinside, tinfoutside, r1, r2, r3, r4, r5, r6);
      rv=(tinfoutside-tinfinside)/(q/area);

      //SI Output
      System.out.println("SI Output");
      System.out.println("qa = " +qa);
      System.out.println("qb = " +qb);
      System.out.println("qc = " +qc);
      System.out.println("qd = " +qd);
      System.out.println("Rv = " +rv);

      //English Output
      System.out.println("English Output");
      System.out.println("qa = " +qa*3.412142);
      System.out.println("qb = " +qb*3.412142);
      System.out.println("qc = " +qc*3.412142);
      System.out.println("qd = " +qd*3.412142);
      System.out.println("Rv = " +rv*1.8*10.76319/3.412142);
}

public static double r_1(double hToTheIzzo, double area, double eps_o, double sigma, double tinfoutside, double to)
{
      double r1=1.0/(hToTheIzzo*area+eps_o*sigma*(tinfoutside+to)*(Math.pow(tinfoutside,2)+Math.pow(to,2))*area);
      return r1;
}

public static double r_2(double x, double kg, double area)
{
      double r2=x/kg/area;
      return r2;
}

public static double r_3(double hToTheIzzi, double area, double eps_i, double sigma, double ti, double tinfinside)
{
      double r3=1.0/(hToTheIzzi*area+eps_i*sigma*(ti+tinfinside)*(Math.pow(ti,2)+Math.pow(tinfinside,2))*area);
      return r3;
}

public static double r_4(double ke, double area, double delta, double sigma, double t1, double t2, double eps_1, double eps_2)
{
      double r3=1.0/(ke*area/delta+sigma*(t1+t2)*(Math.pow(t1,2.0)+Math.pow(t2,2.0))*area/((1.0/eps_1)+(1.0/eps_2)-1.0));
      return r3;
}

public static double q_a(double tinfoutside, double to, double r1)
{
      double q=(tinfoutside-to)/r1;
      return q;
}

public static double q_b(double to, double ti, double r2)
{
      double q=(to-ti)/r2;
      return q;
}

public static double q_c(double ti, double tinfinside, double r3)
{
      double q=(ti-tinfinside)/r3;
      return q;
}

public static double q_g(double tinfinside, double tinfoutside, double r1, double r2, double r3, double r4, double r5, double r6)
{
```

```java
        double q=(tinfoutside-tinfinside)/(r1+r2+r3+r4+r5+r6);
        return q;
}

public static double h_o(double tfo, double v, double k, double pr, double cp, double reynolds, double length)
{
        double nux=0.332*Math.pow(reynolds,0.5)*Math.pow(pr,(1.0/3.0));
        double hbar=2.0*nux*k/length;
        return hbar;
}

public static double h_i(double tfi, double ti, double tinfinside, double kin, double nuin, double prin, double length)
{
        double ray=9.8/tfi*Math.abs(ti-tinfinside)*Math.pow(length,3.0)*prin/(Math.pow(nuin,2.0));
        double halfNu=0.825+(0.387*Math.pow(ray,(1.0/6.0)))/(Math.pow((1+Math.pow((0.492/0.7),(9.0/16.0))),(8.0/27.0)));
        double hbar=Math.pow(halfNu,2.0)*kin/length;
        return hbar;
}

public static double k_e(double tfmid, double t1, double t2, double length, double x, double rhomid, double mumid, double numid,
double kmid, double prmid)
{
        double ray=9.8/tfmid*Math.abs(t1-t2)*Math.pow(x,3.0)*prmid/(Math.pow(numid,2.0));
        double ratio=length/x;
        double kratio=0.197*Math.pow(ray,0.25)/Math.pow(ratio,(1.0/9.0));
        if (kratio<1)
        {
        kratio=1.0;
        }
        double ke=kratio*kmid;
        return ke;
}

public static double t_o(double tinfoutside, double q, double r1)
{
        double to=(tinfoutside-q*r1);
        return to;
}
public static double t_i(double tinfinside, double q, double r3)
{
        double ti=(q*r3+tinfinside);
        return ti;
}
public static double linearInterp(double[][] data, double tfi, int m)
{
        double tLow;
        double tHigh;
        int i = -1;
            do
            {
            i++;
            tLow = data[i][0];
            tHigh = data[i+1][0];
            } while (!((tfi<tHigh)&&(tfi>=tLow)));


        double answer=(((tfi-tLow)/(tHigh-tLow)*(data[i+1][m]-data[i][m]))+data[i][m]);
        return answer;
}
}
```

## A.4 Java Code for Double Pane with Design

```java
import java.io.*;
import java.util.Scanner;                      //To use Scanner class
import java.text.DecimalFormat;
import java.io.FileWriter;
import java.io.IOException;

public class DPWindowDesign
{

public static void main(String[] args) throws IOException
{
//Single Pane
final double error=0.001;
final double x=0.00635;                     //thickness in meters
final double xabs=0.00635;                  //ABS thickness in meters
final double area=1.4129;                   //area in meters^2
final double vinf=6.7056;                   //ambient air velocity in m/s
final double sigma=0.00000005670373;        //stefan-boltzmann constant in W/m^2/k^4
final double length=1.8542;                 //length in m
final double width=0.762;                   //width in m
final double delta=0.0254;                  //gap in m
double deltagap=4*.0254;                    //added gap between window and solution in m
final double kg=0.78;                       //Thermal Conductivity of glass in W/m^2
final double kabs=0.17;                     //Thermal Conductivity of ABS in W/m^2
final double kal=205;                       //Thermal Conductivity of Aluminum in W/m^2
final double tinfoutsummer=308.15;          //95 F in K
final double tinfoutwinter=266.48333;       //20 F in K
double tinfinside=294.26;                   //inside temperature in K
double tinfoutside=0;                       //outside temperature in K
double eps_o=0.98;
double eps_i=0.98;
double eps_1=0.98;
double eps_2=0.98;
double eps_3=0.98;
double eps_4=0.03;
double eps_5=0.03;
double eps_air=0.0000000000000001;
double hToTheIzzo=0;
double hToTheIzzi=0;
double r1=0;
double r2=0;
double r3=0;
double r4=0;
double r5=0;
double r6=0;
double r7=0;
double r8=0;
double tiold=0;
double ti=0;
double t1old=0;
double t1=0;
double t2old=0;
double t2=0;
double t3=0;
double t3old=0;
double t4=0;
double t4old=0;
double t5=0;
double t5old=0;
double toold=0;
double to=0;
double rv=0;
double tfo=0;
double tfi=0;
double tfmid=0;
double tfgap=0;
double reynolds=0;
double rhoout=0;
```

```java
double rhoin=0;
double rhomid=0;
double cpout=0;
double cpin=0;
double cpmid=0;
double muout=0;
double muin=0;
double mumid=0;
double nuout=0;
double nuin=0;
double numid=0;
double kout=0;
double kin=0;
double kmid=0;
double prout=0;
double prin=0;
double prmid=0;
double rhogap=0;
double cpgap=0;
double mugap=0;
double nugap=0;
double kgap=0;
double prgap=0;
double q=0;
double qa=0;
double qb=0;
double qc=0;
double qd=0;
double qe=0;
double qf=0;
double qg=0;
double qh=0;
double qi=0;
double tidifference=0;
double todifference=0;
double t1difference=0;
double t2difference=0;
double t3difference=0;
double t4difference=0;
double t5difference=0;
double kec=0;
double kee=0;
double rad=0;
double season=0;

java.util.Scanner bob=new java.util.Scanner(System.in);

    //air data for varying temperature in C, rho, Cp, mu, nu, k, alpha, Pr
    double[][] airData={
        {250.0, 1.4128, 1005.3, 0.000015990, 0.00001131, 0.02227, 0.000015675,0.722},
        {300.0, 1.1774, 1005.7, 0.000018462, 0.00001569, 0.02624, 0.00002216, 0.708},
        {350.0, 0.9980, 1009.0, 0.000020750, 0.00002076, 0.03003, 0.00002983, 0.697},
        {400.0, 0.8826, 1014.0, 0.000022860, 0.00002590, 0.03365, 0.00003760, 0.683},
    };

    //Choose Conditions
    Scanner keyboard = new Scanner(System.in);
    System.out.print("Enter 1 for radiation and 0 for no radiation: ");
    rad = keyboard.nextDouble();
    System.out.print("Enter 1 for summer and 0 for no winter: ");
    season = keyboard.nextDouble();

    eps_o=eps_o*rad+.0000000000001;
    eps_i=eps_i*rad+.0000000000001;
    eps_1=eps_1*rad+.0000000000001;
    eps_2=eps_2*rad+.0000000000001;
    eps_3=eps_3*rad+.0000000000001;
    eps_4=eps_4*rad+.0000000000001;
    eps_5=eps_5*rad+.0000000000001;
```

```
if (season==1)
  {
  //Guess t_o and t_i summer
  tinfoutside=tinfoutsummer;
  toold=303.0;
  tiold=298.0;
  t1old=302.0;
  t2old=301.0;
  t3old=300.0;
  t4old=300.0;
  t5old=299.0;
  }
else if (season==0)
  {
  //Guess t_o and t_i winter
  tinfoutside=tinfoutwinter;
  toold=275.0;
  tiold=285.0;
  t1old=276.0;
  t2old=278.0;
  t3old=280.0;
  t4old=282.0;
  t5old=284.0;
  }

do{
//calculate film temperatures
tfo=(toold+tinfoutside)/2.0;
tfi=(tiold+tinfinside)/2.0;
tfmid=(t1old+t2old)/2.0;
tfgap=(t3old+t4old)/2.0;

//get outside properties
  rhoout=linearInterp(airData, tfo, 1);
  cpout=linearInterp(airData, tfo, 2);
  muout=linearInterp(airData, tfo, 3);
  nuout=linearInterp(airData, tfo, 4);
  kout=linearInterp(airData, tfo, 5);
  prout=linearInterp(airData, tfo, 7);
//get inside properties
  rhoin=linearInterp(airData, tfi, 1);
  cpin=linearInterp(airData, tfi, 2);
  muin=linearInterp(airData, tfi, 3);
  nuin=linearInterp(airData, tfi, 4);
  kin=linearInterp(airData, tfi, 5);
  prin=linearInterp(airData, tfi, 7);
//get gap properties
  rhomid=linearInterp(airData, tfmid, 1);
  cpmid=linearInterp(airData, tfmid, 2);
  mumid=linearInterp(airData, tfmid, 3);
  numid=linearInterp(airData, tfmid, 4);
  kmid=linearInterp(airData, tfmid, 5);
  prmid=linearInterp(airData, tfmid, 7);
//get second gap properties
  rhogap=linearInterp(airData, tfgap, 1);
  cpgap=linearInterp(airData, tfgap, 2);
  mugap=linearInterp(airData, tfgap, 3);
  nugap=linearInterp(airData, tfgap, 4);
  kgap=linearInterp(airData, tfgap, 5);
  prgap=linearInterp(airData, tfgap, 7);

//calculate reynolds number
reynolds=vinf*width/nuout;

//Compute h_o and h_i
hToTheIzzo=h_o(tfo, vinf, kout, prout, cpout, reynolds, width);
hToTheIzzi=h_i(tfi, tiold, tinfinside, kin, nuin, prin, length);

//Compute ke
kec=k_e(tfmid, t1, t2, length, x, rhomid, mumid, numid, kmid, prmid);
```

```
kee=k_e(tfgap, t3, t4, length, x, rhogap, mugap, nugap, kgap, prgap);

//Compute r1, r2, and r3
r1=r_1(hToTheIzzo, area, eps_o, sigma, tinfoutside, toold);
r2=r_2(x, kg, area);
r3=r_3(kec, area, delta, sigma, t1old, t2old, eps_1, eps_2);
r4=r_2(x, kg, area);
r5=r_3(kee, area, deltagap, sigma, t3old, t4old, eps_3, eps_4);
r6=r_2(xabs, kabs, area);
r7=r_2(x, kg, area);
r8=r_5(hToTheIzzi, area, eps_i, sigma, tiold, tinfinside);

q=q_f(tinfinside, tinfoutside, r1, r2, r3, r4, r5, r6, r7, r8);

//Compute to and ti
to=tinfoutside-q*r1;
ti=t5old-q*r7;
t1=toold-q*r2;
t2=t1old-q*r3;
t3=t2old-q*r4;
t4=t3old-q*r5;
t5=t4old-q*r6;

//find Differences
tidifference=Math.abs(ti-tiold);
todifference=Math.abs(to-toold);
t1difference=Math.abs(t1-t1old);
t2difference=Math.abs(t2-t2old);
t3difference=Math.abs(t3-t3old);
t4difference=Math.abs(t4-t4old);
t5difference=Math.abs(t5-t5old);

//update t values
toold=to;
tiold=ti;
t1old=t1;
t2old=t2;
t3old=t3;
t4old=t4;
t5old=t5;

  } while((tidifference>error) || (todifference>error) || (t1difference>error) || (t2difference>error) || (t3difference>error) ||
(t4difference>error) || (t5difference>error));

//Calculate heat transfer and r value
qa=q_a(tinfoutside, to, r1);
qb=q_a(to, t1, r2);
qc=q_a(t1, t2, r3);
qd=q_a(t2, t3, r4);
qe=q_a(t3, t4, r5);
qf=q_a(t4, t5, r6);
qg=q_a(t5, ti, r7);
qh=q_a(ti, tinfinside, r8);
qi=q_f(tinfinside, tinfoutside, r1, r2, r3, r4, r5, r6, r7, r8);
rv=(tinfoutside-tinfinside)/(q/area);

//SI Output
System.out.println("SI Output");
System.out.println("qa = " +qa);
System.out.println("qb = " +qb);
System.out.println("qc = " +qc);
System.out.println("qd = " +qd);
System.out.println("qe = " +qe);
System.out.println("qf = " +qf);
System.out.println("qg = " +qg);
System.out.println("qh = " +qh);
System.out.println("qi = " +qi);
System.out.println("Rv = " +rv);

//English Output
```

```java
        System.out.println("English Output");
        System.out.println("qa = " +qa*3.412142);
        System.out.println("qb = " +qb*3.412142);
        System.out.println("qc = " +qc*3.412142);
        System.out.println("qe = " +qd*3.412142);
        System.out.println("qe = " +qe*3.412142);
        System.out.println("qf = " +qf*3.412142);
        System.out.println("qg = " +qg*3.412142);
        System.out.println("qh = " +qh*3.412142);
        System.out.println("qi = " +qi*3.412142);
        System.out.println("Rv = " +rv*1.8*10.76319/3.412142);
    }


public static double r_1(double hToTheIzzo, double area, double eps_o, double sigma, double tinfoutside, double to)
{
    double r1=1.0/(hToTheIzzo*area+eps_o*sigma*(tinfoutside+to)*(Math.pow(tinfoutside,2)+Math.pow(to,2))*area);
    return r1;
}

public static double r_2(double x, double kg, double area)
{
    double r2=x/kg/area;
    return r2;
}

public static double r_3(double ke, double area, double delta, double sigma, double t1, double t2, double eps_1, double eps_2)
{
    double r3=1.0/(ke*area/delta+sigma*(t1+t2)*(Math.pow(t1,2.0)+Math.pow(t2,2.0))*area/((1.0/eps_1)+(1.0/eps_2)-1.0));
    return r3;
}

public static double r_4(double x, double kg, double area)
{
    double r4=x/kg/area;
    return r4;
}

public static double r_5(double hToTheIzzi, double area, double eps_i, double sigma, double ti, double tinfinside)
{
    double r5=1.0/(hToTheIzzi*area+eps_i*sigma*(ti+tinfinside)*(Math.pow(ti,2)+Math.pow(tinfinside,2))*area);
    return r5;
}

public static double q_a(double tinfoutside, double to, double r1)
{
    double q=(tinfoutside-to)/r1;
    return q;
}

public static double q_f(double tinfinside, double tinfoutside, double r1, double r2, double r3, double r4, double r5, double r6, double r7, double r8)
{
    double q=(tinfoutside-tinfinside)/(r1+r2+r3+r4+r5+r6+r7+r8);
    return q;
}

public static double h_o(double tfo, double v, double k, double pr, double cp, double reynolds, double length)
{
    double nux=0.332*Math.pow(reynolds,0.5)*Math.pow(pr,(1.0/3.0));
    double hbar=2.0*nux*k/length;
    return hbar;
}

public static double h_i(double tfi, double ti, double tinfinside, double kin, double nuin, double prin, double length)
{
    double ray=9.8/tfi*Math.abs(ti-tinfinside)*Math.pow(length,3.0)*prin/(Math.pow(nuin,2.0));
    double halfNu=0.825+(0.387*Math.pow(ray,(1.0/6.0)))/(Math.pow((1+Math.pow((0.492/0.7),(9.0/16.0))),(8.0/27.0)));
    double hbar=Math.pow(halfNu,2.0)*kin/length;
    return hbar;
```

```java
}

public static double k_e(double tfmid, double t1, double t2, double length, double x, double rhomid, double mumid, double numid,
double kmid, double prmid)
{
   double ray=9.8/tfmid*Math.abs(t1-t2)*Math.pow(x,3.0)*prmid/(Math.pow(numid,2.0));
   double ratio=length/x;
   double kratio=0.197*Math.pow(ray,0.25)/Math.pow(ratio,(1.0/9.0));
   if (kratio<1)
   {
   kratio=1.0;
   }
   double ke=kratio*kmid;
   return ke;
}

public static double t_o(double tinfoutside, double q, double r1)
{
   double to=(tinfoutside-q*r1);
   return to;
}

public static double t_i(double tinfinside, double q, double r3)
{
   double ti=(q*r3+tinfinside);
   return ti;
}

public static double t_1(double toold, double q, double r2)
{
   double t1=toold-(q*r2);
   return t1;
}

public static double t_2(double t1, double q, double r3)
{
   double t2=t1-(q*r3);
   return t2;
}

public static double linearInterp(double[][] data, double tfi, int m)
{
   double tLow;
   double tHigh;
   int i = -1;
      do
      {
      i++;
      tLow = data[i][0];
      tHigh = data[i+1][0];
      } while (!((tfi<tHigh)&&(tfi>=tLow)));

      double answer=(((tfi-tLow)/(tHigh-tLow)*(data[i+1][m]-data[i][m]))+data[i][m]);
      return answer;
}
}
```