

ANALYSIS OF SINGLE PANE WINDOW REPLACEMENT

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INTRODUCTION

An engineering and economic analysis of energy loss through single paned windows in a large college building is presented. The goal of this work was to determine an economically viable solution for Marietta College to save on energy costs. Based on the model presented, the economics of double paned window installation are investigated. An alternative solution employing the addition of storm windows to the existing single paned windows has yielded very exciting results. While double paned windows are generally the first thought when it comes to energy efficient windows, this work shows that storm window addition yields a much lower investment and quicker payback period for this specific building. The engineering analysis and experimental technique presented can be used to investigate the cost benefit of single paned window upgrades for other buildings.

KEYWORDS

energy savings, single pane, windows, conduction, convection

BACKGROUND

This study was not funded, commissioned, or assigned, but was purely a result of an awareness of energy efficiency combined with an observation that led to a moment of awakening. The winter of 2013–2014 was the coldest in decades in the Midwest. It is perhaps human nature that leads us to think about energy costs and efficiency during seasons of extreme cold or heat. For homeowners or business owners, energy savings and efficiency translates directly into cost savings. As an example, a family may turn the heat down and use extra blankets in the winter to save money. They may use ceiling fans, close curtains, and wear light clothing in the summer to save on air conditioning. Many other energy saving techniques are possible concerning the homeowner; however, their concern about energy saving may not extend to their place of employment. The work presented in this paper was prompted when the thought of energy efficiency was triggered by an event at the workplace as outlined below.

The following is an account of the event that raised our awareness of the poor energy efficiency associated with the windows in our workplace. One day in January 2014, I walked into my regular classroom to deliver a lecture. Unfortunately, there were no dry erase makers to be found. After a short while they were discovered on the window sill. Grabbing a handful, I noticed they were very cold and none of them would leave a mark on the white board. After

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getting some from another room and completing the lecture, I took a moment to investigate the window. The inside of the window was extremely cold to the touch, as was the window sill. Even standing near the window, there was an area of cold air. Finally, I took notice that this was a single paned window.

The observation noted above provided the motivation to develop a model of the existing windows and study the costs associated with them. Marietta College is a beautiful campus containing many older buildings. These are all brick with single paned windows and similar geometry to the windows in the Brown building. Although this work is focused on the Brown Building, it is logical to extend these results to other buildings on campus to add to the energy savings. As with any business, cost cutting is a big deal for colleges these days as budgets get tighter. Finding a solution that requires modest investment with a rapid payback period is obviously the most attractive way to make “going green” economically viable. Based on this, the following objectives were established for this project:

1. What is a working model for the heat transfer through the existing windows?
2. How much heat is escaping and how much does this represent in dollars per year?
3. What are the economics of potential solutions, including payback periods for investment?

The Brown building at Marietta College (shown below) is 60 years old and has 100 windows that are single paned and inset approximately 6 inches from the exterior brick. There are also two single paned windows that have sealed storm windows installed nearly flush with the exterior brick. There are two floors above ground and one floor approximately 10 feet below grade. With the exception of a few smaller windows at ground level that provide light to the basement classrooms, the rest are 3 × 6 foot single paned windows.

FIGURE 1. Side view of the Brown Building.



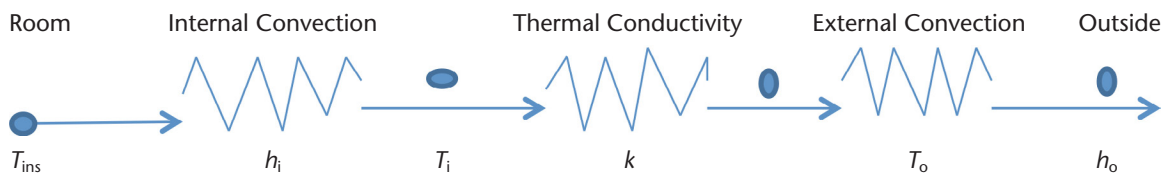
FIGURE 2. Front View of the Brown Building.



WORKING MODEL FOR WINDOWS

For heat to escape in the winter or for heat to enter in the summer, the model for a single pane window involves three resistances in series. These are inside convection, conduction through the glass, and outside convection (as shown below).

FIGURE 3. Resistance Model.



Where T_{ins} = Room temperature (F)

T_i = Inside temperature of the window surface (F)

T_o = Outside temperature of the window surface (F)

T_{out} = Outside temperature (F)

h_i = Internal convection coefficient (BTU/ft²/hr./F)

h_o = External convection coefficient (BTU/ft²/hr./F)

k = Thermal conductivity of glass (BTU/ft/hr./F)

One interesting aspect of the windows in our building is that they are inset about six inches from the brick exterior (as shown below). This causes a pocket of air on the outside that would not exist if the window was flush with the outside of the building. While this is

not anywhere close to having completely still air or a double paned window, it is clearly better than a window that is totally exposed to wind and air movement.

For resistances in series, heat flow is analogous to electric current or flow of water. The key concept is that overall flow is the same as flow through each resistance. In essence, energy is conserved and what enters one end has only one path and must be the same everywhere. Therefore, we write the following:

$$\frac{q}{A} = \frac{\Delta T}{\sum_1^n R_i}$$

Where:

$\Delta T = T_{\text{ins}} - T_{\text{out}}$ Room temperature – outside temperature (F)

q = heat transfer (BTU/hr.)

A = area of window (ft²)

R_i = individual resistance of each element (F ft² hr./BTU)

This equation relates the heat loss to the inside and outside temperatures, the area of the window, and all the elements in series that tend to resist flow. Obviously, the solution lies in increasing the denominator. This will increase the resistance and slow the flow of heat that is costing us money. This is assuming we have decreased the numerator by lowering the inside temperature to the limits of human comfort for internal heating, or raised the inside temperature for internal cooling.

The next step is to investigate all the elements that contribute the resistance. As a start, we must understand the following concept. The heat flow in each element is the same as the overall heat flow. This is analogous to a garden hose with bends and kinks in it where all of the resistance in the hose slows down the flow of water. So measuring the flow anywhere will yield the same result. For heat flow we can write:

$$q_{\text{inside convection}} = q_{\text{window conduction}} = q_{\text{outside convection}}$$

Where each term represents heat flow (BTU/hr.)

FIGURE 4. Single paned window with ledge.



EXPERIMENTAL PROCEDURE

The challenge is to somehow figure out the heat flow. The easiest way to do this is to evaluate the heat transfer by conduction through the glass, since the thermal conductivity of glass is known. An infrared temperature measuring device was used to determine the temperature on the inside and outside of the glass window. Since the area of the window was known to be

18 ft², and the thickness is 1/8 inch, the heat flow through the glass is calculated by the conduction flow equation:

$$\frac{q_{\text{conduction}}}{A} = \frac{k(T_i - T_o)}{\Delta x}$$

Where Δx = the thickness of the glass (ft).

The temperatures were measured with infrared as 41°F and 30°F on the inside and outside of the glass. To verify the accuracy of the temperature measurement, various measurements were taken inside the building and found to agree with the thermostat reading of 68°F. Likewise, measurements outdoors were close to 5°F which agreed with outdoor thermometers and the local weather. The thermal conductivity of glass is 0.55 BTU/hr./ft./F.

Therefore the heat flow per unit area (flux) is calculated as

$$\begin{aligned} \frac{q_{\text{conduction}}}{A} &= \frac{(0.55 \text{ BTU})}{(\text{hr})(\text{ft})(\text{F})} \frac{(11 \text{ F})}{(0.0104 \text{ ft})} \\ &= 580 \text{ BTU/hr./ft}^2 \end{aligned}$$

Since the conductive heat flow is equal to the convective heat flows, we can now estimate interior and exterior heat transfer coefficients. Writing the equation for exterior and interior convective heat flux:

$$\begin{aligned} \frac{q_{\text{convectiveout}}}{A} &= h_o(T_o - T_{\text{out}}) \\ \frac{q_{\text{convectivein}}}{A} &= h_i(T_{\text{ins}} - T_i) \end{aligned}$$

Now we can rearrange and solve for the convective heat transfer coefficients. The heat flow in each case will be the same as the conductive heat flow (580 BTU/hr./ft²). The temperatures were measured by infrared as:

$$T_{\text{ins}} = 68\text{F} \quad T_i = 41\text{F} \quad T_o = 30\text{F} \quad T_{\text{out}} = 5\text{F}$$

$$h_o = 23.2 \text{ BTU/ft}^2/\text{hr./F}$$

$$h_i = 21.6 \text{ BTU/ft}^2/\text{hr./F}$$

Now we can write the overall resistance as the sum of all three resistances:

$$\sum_{i=1}^3 R_i = \frac{1}{h_o A} + \frac{1}{h_i A} + \frac{\Delta x}{kA} = 0.006 \text{ F hr./BTU}$$

Looking at the magnitude of each resistance, we note that the interior and exterior convection resistance are of similar magnitudes and are higher than the glass thermal conduction resistance.

If we combine the resistances into an overall heat transfer coefficient U using the relation:

$$U = \frac{1}{\sum_{i=1}^3 R_i} = 167 \text{ BTU/hr./F}$$

We can now write the heat transfer using only the building and outside temperatures according to:

$$q = U(T_{\text{ins}} - T_{\text{out}})$$

The value of this equation is that it is not necessary to measure intermediate temperatures for each particular day to figure the heat loss. This is exactly the reason the convective heat transfer coefficients were calculated.

RESULTS

Consider a typical winter day with an inside temperature of 68°F and an outside temperature of 30°F. Using the above equation yields a heat loss of 6332 BTU/hr.

This is the heat flow through one window. Now we need to estimate the heat flow per year. The following estimates are used for the calculation:

- 100 windows, each 3 foot by 6 foot (18 ft² area)
- Energy cost \$0.11/kw/hr.
- Average temperature difference between inside and environment throughout the year shown in Table 1. These are based on historical averages¹ for Columbus, Ohio, and are assumed to be fairly representative of Marietta.

In order to estimate the economics of the heat loss, we must understand the relationship between energy lost out the window and energy input to the system. This relationship demands understanding of the heating and cooling system and associated efficiency. The question is therefore “what is the cost for each BTU lost out the window”?

Classrooms in our building have self-contained heat pumps/AC units. These were manufactured by Carrier Corporation. The nameplates on the units show the input power and associated output heating and cooling. The ratio of the output to the input is referred to as “coefficient of performance.” For operation as a heat pump and an AC unit, COP is defined as:

$$\text{COP}_{\text{hp}} = \text{Heat supplied/electrical energy consumed}$$

$$\text{COP}_{\text{ac}} = \text{Cooling supplied/electrical energy consumed}$$

Unlike traditional efficiencies, COPs can exceed a value of one. While it may seem a violation of the first law of thermodynamics to have greater output of energy than input, it is the genius of heat pumps that they supply energy to or from the environment towards their objective. For example, if 2 KW is supplied as input for heating, it is possible to have a heat supply

TABLE 1. Seasonal temperatures.

Season	Building set point (F)	Average high temp (F)	Average Low temp (F)	Mean temperature (F)	Delta Temp (F)
Winter	69	39	24	31	38
Spring	68	64	44	54	14
Summer	72	85	65	75	3
Fall	68	65	45	55	14

of 4 KW. In this case, 2 KW is transferred from the cold outside air to an even colder working fluid in the cycle. The working fluid is then compressed and heated in order to transfer heat to the inside of the building.

For the heat pumps in our building, the following data are supplied:

Heating input 1.86 KW Heating output 4.5 KW $COP_{hp} = 2.42$

Cooling input 1.86 KW Cooling output 4.0 KW $COP_{ac} = 2.15$

This data can allow us to relate lost heat or cooling to input electrical energy cost. For example, for each BTU lost in heating, we divide by 2.42 to find we only are losing 0.41 BTU in electrical energy input cost. Likewise, we assign a factor of 0.47 for cooling.

The calculation of dollars lost for the entire building for each season is shown below. The heat loss is calculated by multiplying the overall heat transfer coefficient times the Delta T listed in Table 1 for each season. The other factors below account for the heat pump/AC unit, the number of windows, hours in each season, and cost of energy.

Winter (heating)

$$\frac{6332 \text{ BTU}}{(\text{hr})(\text{window})} \frac{1 \text{ BTU}}{2.42 \text{ BTU}_{\text{supply}}} (100 \text{ windows}) \frac{24 \text{ hr}}{\text{day}} \frac{30 \text{ day}}{\text{month}} (3 \text{ month}) \frac{\$0.11}{(\text{KW})(\text{hr})} \frac{\text{KW}}{3212(\text{BTU}/\text{hr})} = \$19360$$

Fall/Spring (use average COP, assume heating and cooling 50/50)

$$\frac{2332 \text{ BTU}}{(\text{hr})(\text{window})} \frac{1 \text{ BTU}}{2.28 \text{ BTU}_{\text{supply}}} (100 \text{ windows}) \frac{24 \text{ hr}}{\text{day}} \frac{30 \text{ day}}{\text{month}} (6 \text{ month}) \frac{\$0.11}{(\text{KW})(\text{hr})} \frac{\text{KW}}{3212(\text{BTU}/\text{hr})} = \$15130 \quad \text{similarly, Summer} = \$1528, \text{ Yearly Total} = \$36,000/\text{yr.}$$

Prices vary with many factors and there is a wide variation in reported percentage savings. One study by Cornell University² claims that double pane windows should cut heat loss by roughly 50% versus single pane. This number is fairly common in the literature. It is not to be confused with total energy usage for the building. We must be careful to understand that our analysis is the loss of money as heat out the window.

So assuming our losses are cut by 50%, our savings would be roughly \$18,000 per year. This sounds fantastic, but we must look at the investment in double paned windows required to realize this savings. A conservative estimate for a new middle of the road quality double pane window is \$800. Labor costs per window are very hard to estimate since we have not requested bids. My best estimate would be \$400 per window based on conversations with our physical plant director. Using our estimates, we now have a replacement cost of \$120,000 for 100 windows, with savings of approximately \$18,000 per year. This results in a payback period of over six years.

DISCUSSION

An investment of \$120,000 with a payback period of over 6 years is not an easy sell, primarily because funds are hard to come by. It was clear that the option of replacing all the existing windows with double paned may not be received with great enthusiasm due to the large

investment up front. Nonetheless, the double paned window replacement analysis was documented and proposed for the college to consider. A list of additional positives associated with double paned windows was included in the proposal:

1. New windows can be tilted in to allow cleaning of both sides from the inside of the building.
2. They would surely be more attractive than our current windows.
3. We were doing the “green thing” which is certainly good public relations.
4. They would be zero maintenance (vinyl versus our current painted wood frames).
5. Maybe this level of investment and payback period would attract a charitable donation to the college.
6. The project may lead to tax credits for the college for an energy efficiency upgrade.

A Surprising Discovery Leads to a Better Solution

After the double paned window study was complete, the storm windows that had been installed on a couple of windows on the Brown Building were investigated. The physical plant director was not sure how long they had been there. These were situated about 6 inches out from the single paned window as shown in Figure 5.

At first glance, it seems logical that the additional exterior storm window may be doing a lot of good by trapping 6 inches of still air and greatly decreasing the heat flow. On a cold March day the temperature on the inside of the single paned window (fitted with an exterior storm window) was measured at 60°F. Interior temperatures of single paned windows without storm windows were measured at 45°F. These measurements confirmed there was a great deal of resistance added by the trapped air behind the storm window which raised the temperature on the inside surface of the single paned window. This was a very encouraging and exciting result.

Having already calculated the inside convective heat transfer coefficient from the previous work, the difference between the heat flow with and without the storm window could be evaluated. Since heat flow is directly proportional to the temperature difference through the inside convective layer, the percentage reduction in flow is simply the ratio of the temperature differences:

For the single paned window with no storm window

$$\frac{q_{\text{convective in}}}{A} = h_i(T_{\text{ins}} - T_i)$$

FIGURE 5. Storm Window.



For the storm window added

$$\frac{q_{\text{convectivein}}^{\text{storm}}}{A} = h_i(T_{\text{ins}} - T_i)^{\text{storm}}$$

The ratio of $q^{\text{storm}}/q = (T_{\text{ins}} - T_i)^{\text{storm}}/(T_{\text{ins}} - T_i)$

Since A and h_i are constant. With an inside temperature of 68°F, the ratio is 8/23 or 35%. Therefore the heat loss has been reduced by 65%.

The interesting part of this calculation is that it is not necessary to model the extra storm window, or measure intermediate temperatures. Since the inside convection resistance is unchanged, all we need to measure is the inside temperature of the single paned window to find the heat flow.

Conceptually, this can be referred to as the “igloo effect.” The addition of the storm window creates a large volume of still air, which adds a large resistance to heat flow. Heat transfer by conduction through the air trapped inside the storm window is very low since air is such a poor conductor. The analogy to an igloo refers to the fact that cold outside air cannot flow due to all of the ice particles which block it. At the same time, a large volume of air is trapped in the packed snow. This provides the huge resistance to heat flow through the snow wall.

The results of the storm window alternative were shared with the physical plant director of the college who was quite enthusiastic. The most appealing aspect of this alternative is that storm windows are much less expensive than double paned windows. Typical costs would be on the order of \$300 installed.³ This turns the payback period heavily in our favor.

With a total investment of \$30,000 and an expected savings of 65% of the total energy loss, the annual savings are expected to be roughly \$23,400.

With a payback period of just over one year, initial investment of \$30,000, and equivalent cost savings to double paned windows, this alternative is extremely attractive for the school. The final cost will be known when the price for installed storm windows is firmly quoted. At that time the possibility of grants and tax credits can be investigated.

Some final issues to consider:

1. Exterior storm windows will prevent “opening the windows.” This is sometimes an issue for a building occupant.
2. My personal opinion is that storm windows actually improve the appearance of the building by mostly hiding the old windows.
3. The Brown Building has buildings on either side with a several large trees. As a result, direct sunlight impinging on the windows only occurs for a short period during the day. As a general rule it seems logical to close the shades in the summer to minimize radiation heating. In the winter the shades should be left up to capture any sunlight. (I can attest that sunny winter days are not frequent in the Ohio Valley).

CONCLUSIONS

Storm windows are not often associated with large energy savings. Due to the geometry of our brick building and inset windows, storm windows were found to be an economically viable solution to our energy loss problems. This solution was not immediately obvious, but the lesson learned is that we need to pay attention to the details to make our dream of a greener

world converge with the reality of economics. A greener world depends on a multitude of victories where we can marry our engineering initiative with the economics of going green. When being green makes sense economically, the world will follow quickly.

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