IMPACT OF INSULATION ON BUILDING ENERGY CONSUMPTION

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ABSTRACT

The purpose of this study is to quantify the impact of insulation of various parts of building envelopes on building energy consumption. Using eQUEST, a series of parametric simulation was conducted to acquire building energy consumption data for a range of R-values of walls, roof, and windows of a typical two-story single-family home in the U.S. Two climatic zones were applied in simulation: Detroit, Michigan and Miami, Florida. Analysis was conducted for annual heat gain and loss, and benefits of insulation value of walls, roof and windows respectively. In addition, analysis of heat gain and loss components was conducted for the purpose of identifying strategies for effectively installing insulation on different parts of building envelope.

INTRODUCTION

Buildings are a major source of energy consumption and greenhouse gas (GHG) emissions, and account for 48% of energy consumption and GHG emissions annually (Mazria, 2007). Of the energy consumed by residential buildings in 2001, 53.2% was used for space heating (46.7%) and cooling (6.5%) purposes (EIA, 2001). Therefore, the conservation of heating and cooling energy presents a major target for residential building energy conservation.

Insulation of building envelopes, both opaque and transparent, is the most important strategy for building energy conservation. Insulation of walls, roof, attic, basement walls and even foundations is one of the most essential features of energy-efficient homes. In addition, as glass is a poor insulator, insulating transparent envelopes, windows and skylights, significantly reduces heat loss and gain during the winter and summer.

Diverse insulation methods have been studied in order to evaluate thermal performance and economic impact of insulation in buildings such as, thermal, economic, and environmental effects of insulation thicknesses and layer configurations (Dombayci, 2007, Dombayci et al., 2006, Karsson et al., 2006, Bakos, 2000, Erlandsson et al., 1996). Insulation thickness has proven to have a significant economic impact through the reduction of energy consumption (Karlsson et al., 2006). In these studies, insulation thickness was optimized based on insulation and fuel costs. Based on the study conducted by Ö. Altan Dombayci, as compared to conventional insulation methods, optimal insulation saves 46.6% of energy consumption, and mitigates buildings' environmental impact by reducing 41.3% of CO_2 and SO_2 emissions (Dombayci, 2007).

Previously conducted studies aimed at investigating thermal, economic, and environmental effects of insulation or at determining optimal insulation configurations. However, these studies have been conducted in laboratory settings with specific configurations for particular insulations materials. The quantitative data are not readily available on how much insulating various parts of typical American single family homes contributes to saving heating and cooling energy in different climates.

Objectives

There is no scientific question that more insulation is better for keeping heat in winter or preventing heat gain in summer. Based on this thermodynamic principle, various levels of insulation are recommended in building construction standards and regulations (MICA, 2006; ASHRAE, 2004a; ASHRAE, 2004b). However, it is still uncertain how much insulating various envelopes of a single family home will reduce energy consumption. Though the benefit of insulation is known to be less in warm climates, it is also questionable how much it will differ in a cold climate such as Michigan from hot and humid climate such as Florida.

The purpose of this study is to quantify the impact of insulation of various parts of building envelope on building energy consumption. Specifically, this study is

1. to examine how much the insulation of walls, roof and windows individually contributes to energy savings of a typical single family home in America, and
2. to compare how much the effects of insulation on energy savings differ in a cold climate from a hot-climate.

SIMULATION

Test Building

A two-story residential building was modelled, whose physical characteristics are those of typical American homes obtained from the American Housing Survey (U.S. Census Bureau, 2005). The test building is a single-family home with 185.8 m^2 (2,000 ft^2) floor area, 92.9 m^2 (1,000 ft^2) for each floor (See Figures 1 and 2).

Each floor was modelled as an independent thermal zone. Thus, the test building consists of two thermal zones. The windows were modelled with no overhangs. The window-wall ratio was 0.15. The air infiltration rate assumed to be 0.3 air change per hour. Internal loads included 4 occupants, lighting (5.38 W/m^2 for living area, 12.8 W/m^2 for storage, and 13.8 W/m^2 for laundry), and miscellaneous heat sources (3.2 W/m^2 for living area and 1.6 W/m^2 for laundry). A set of heating and cooling devices was assumed to be installed for each zone independently. The thermal control system was equipped with direct exchange coils for cooling and furnaces for heating.

The base-case R-values of opaque envelopes were assigned with standard insulation levels required for residential buildings: R-3.35 (SI) (R-19 (U.S.), U-0.30 (SI)) for walls, R-6.69 (SI) (R-38 (U.S.), U-0.15 (SI)) for the roof and R-3.70 (SI) (R-21 (U.S.) , U-0.27 (SI)) for the slab floor. The R-value of base-case windows was R-0.61 (SI) (R-3.44 (U.S.), U-1.65 (SI)) using 6.35 mm (1/4") double pane windows with a low-E coating with emissivity of 0.2, and a 12.7 mm (½") Argon-filled air space. Units of R-value in SI, R-value in U.S., and U-value in SI are °K*m^2/W, °F*ft^2*hr/Btu, and W/°K*m^2, respectively. The shading coefficient was 0.79. The visible transmittance was 0.72.

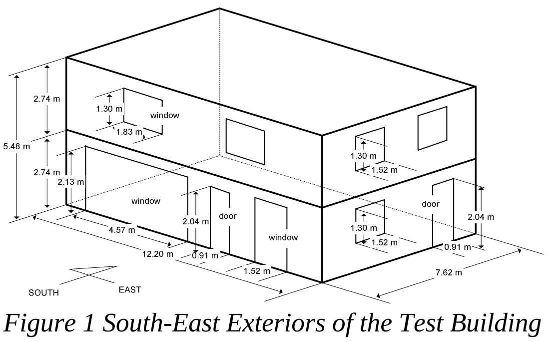

Figure 1 South-East Exteriors of the Test Building

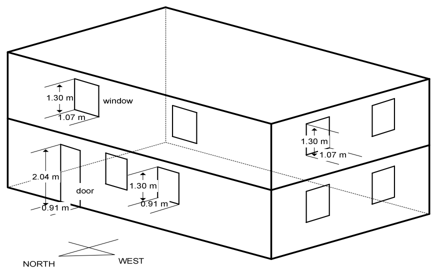

Figure 2 North-West Exteriors of the Test Building

Parametric Energy Analysis

The test building was simulated in two climatic zones: Detroit, Michigan and Miami, Florida, each representing a cold climate and a hot-humid climate, respectively. eQUEST was used for building energy analysis (eQUEST, 2007). A series of parametric studies were conducted to acquire building energy consumption for a range of R-values of walls, roof and windows. Heat gain and loss components and energy consumption by heating and cooling systems were analyzed as a function of insulation value of walls, roof and windows.

Variables for Parametric Studies

Parametric simulations were conducted for insulation of three different parts of the building envelope: walls, roof and windows.

1. Walls: The simulated R-values of the walls ranged from R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) to R-8.81 (SI) (R-50 (U.S.), U-0.11 (SI)). The R-value of the base-case walls was R-3.35 (SI) (R-19 (U.S.), U-0.30 (SI)).
2. Roof: The simulated R-values of the roof ranged from R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) to R-14.09 (SI) (R-80 (U.S.), U-0.07 (SI)). The R-value of the base-case roof was R-6.69 (SI) (R-38 (U.S.), U-0.15 (SI)).
3. Windows: The simulated R-values of the windows ranged from R-0.18 (SI) (R-1 (U.S.), U-5.68 (SI)) to R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)). The R-value of the base-case windows was R-0.61 (SI) (R-3.44 (U.S.), U-1.65 (SI)).

When parametric simulations were conducted, only one variable was varied at a time. For instance, when the impact of the R-value of walls analyzed, all other physical conditions (R-values) of the test building remained the same as those of the base-case.

DISCUSSION AND RESULT ANALYSIS

The simulation results were analyzed in terms of the impact of insulation on 1) heat loss and gain components, and 2) energy consumptions by heating and cooling systems. Analysis of heat gain and loss components is useful for identifying the major targets for energy conservation strategies.

Heat Gain and Loss Analysis

The breakdown of heat gain and loss components will reveal the sources of heat sinks in winter and heat loss in summer. Thus, heat gain and loss component analysis is instrumental for identifying energy conservation targets. With this goal in mind, components of annual heat gain and loss were analyzed.

1. Annual Heat Gain and Loss

In Michigan, the annual heat gain and loss are nearly equal (See Figure 3). What is notable is that the annual heat gain is higher than the annual heat loss. This indicates that, even in cold climate, the amount of solar radiation is a significant factor influencing a building's thermal performance. And cooling load prevention measures such as shading is as important as heat loss prevention measures. This is more evident in the breakdown of heat gain and heat loss components in the next section.

As expected, the simulation result confirms that Florida is cooling load dominated climate. The annual heat gain (40.3 MWh) is far greater than the heat loss (2.6 MWh). The annual heating load in Miami is virtually negligible (See Figure 4). This implies that in a hot and humid climate, cooling load prevention should be the primary concern for building design.

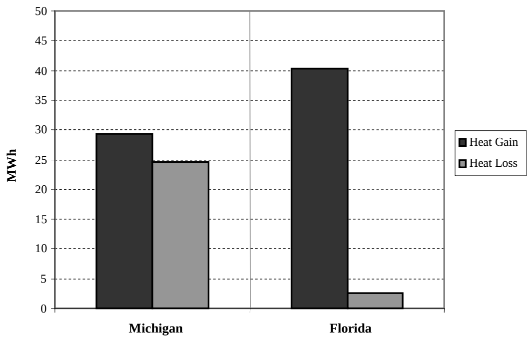

Figure 3 Annual Heat Gain and Loss

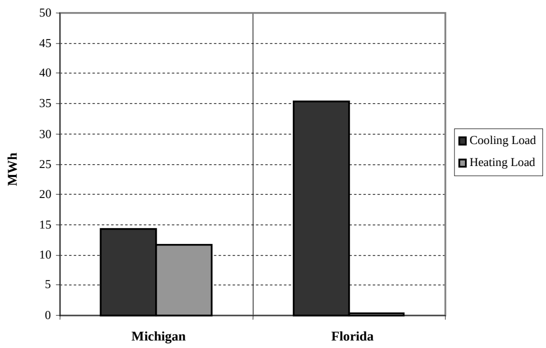

Figure 4 Annual Heating and Cooling Loads

2. Annual Heat Gain and Loss Components in Cold Climates

(1) Heat Gain

In cold climate, represented by Detroit, Michigan, the most prominent source of heat gain is solar radiation at 42.5%, followed by conduction through windows (7.4%), infiltration (2.5%). Conduction heat gain through walls (2.1%), doors (1.0%) and roof (0.8%) are insignificant. This indicates that in Michigan shading is essential for reducing the cooling energy consumption, while envelope insulation is less beneficial in summer. Internal heat gain from appliances (24.1%), occupants (10.0%) and lights (9.6%) account for over 40% of the total heat gain (See Figure 5). This indicates that reduction in heat production from home appliances and lighting will be very beneficial for conserving cooling energy consumption. Use of energy efficient home appliances is an excellent strategy for home energy conservation.

(2) Heat Loss

The test residential building loses 26.1% heat loss through windows and 25.5% through walls, while heat loss through the floor slab, doors and the roof is smaller at 13.6%, 9.3% and 7.2%, respectively. Infiltration attributes 18.3% of heat loss (See Figure 6). Accordingly the theoretical maximum heating energy saving that wall insulation can accrue is 25.5%. Considering the fact that the windows take only a small fraction, 15% of the wall area, but lose as much heat as the entire walls, one can infer that window insulation is a high priority strategy for residential energy conservation in cold climates.

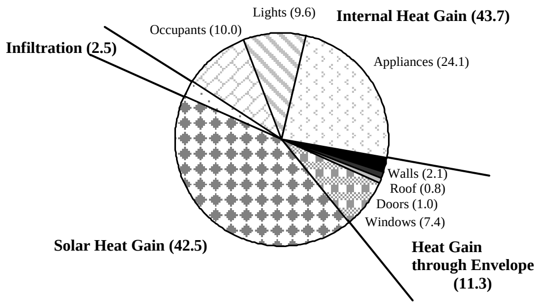

Figure 5 Heat Gain Components (%) in Detroit, Michigan

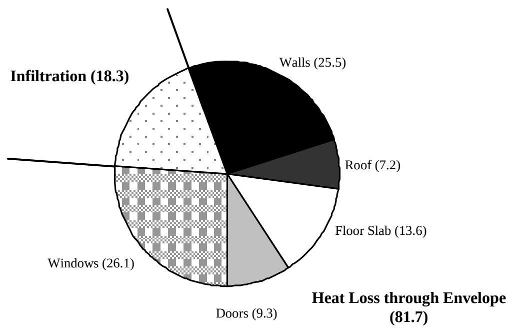

Figure 6 Heat Loss Components (%) in Detroit, Michigan

3. Heat Gain and Loss Components in Hot Climates

(1) Heat Gain

Among various heat gain components, solar radiation through windows is the highest (34.2%), followed by conduction through windows (12.3%), infiltration (11.5%) and conduction through walls (5.6%). Again this indicates that shading should be an essential strategy for home energy conservation in hot climate. The benefit of insulation in hot climate is far less significant than in cold climate.

Heat gain by conduction through doors (2.3%), roof (1.7%) and floor slab (0.5%) are small.

Compared with the case of a cold climate, the percentages of conduction heat gain through building envelopes and infiltration are higher. This is due to higher exterior temperatures in a hot climate. Internal heat gains from appliances (17.6%), occupants (7.3%) and light (7.0%) account for about 30% of the total heat gain (See Figure 7). Use of energy efficient appliances and lighting presents important strategies for cooling energy conservation in hot climates.

(2) Heat Loss

The two largest heat loss components are conduction through windows (30.4%) and conduction through walls (26.9%), followed by infiltration (18.7%), conductions through doors (10.0%), the roof (9.5%) and floor slab (4.5%) (See Figure 8). It should be noted that, because the magnitude of heat loss is insignificant in hot climates, home energy conservation strategies should be based primarily on heat gain component analysis.

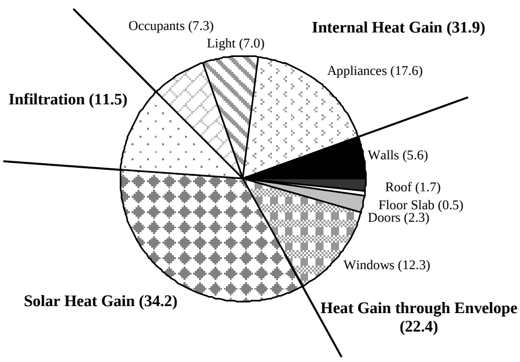

Figure 7 Heat Gain Components (%) in Miami, Florida

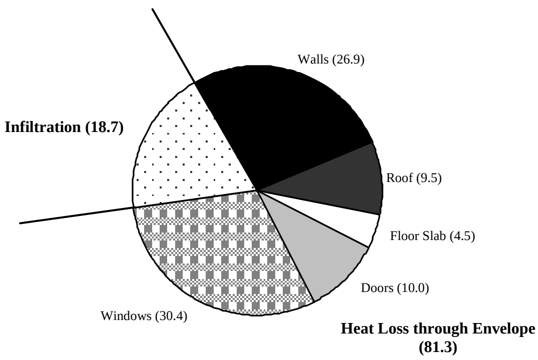

Figure 8 Heat Loss Components (%) in Miami, Florida

Benefits of Wall Insulation

1. Cold Climate

In Michigan, walls are responsible for approximately 25.5% of heat loss annually. Therefore, if walls are adiabatically insulated so that no heat is conducted through walls, wall insulation can save a maximum 25.5% of space heating energy, and 11.9 % of the annual building energy consumption (Note that space heating contributes to 46.7% of the annual home energy consumption). Because the heat gain component through wall is small (2.1%) and the cooling energy contributes a minor fraction (6.5%) of the annual home energy consumption, the benefit of wall insulation on cooling energy saving is insignificant (6.5% x 0.021 = 0.1365%). In other words, wall insulation could contribute to at most 0.1365% of the annual cooling energy consumption.

Overall, home energy consumption as a function of wall R-value shows a diminishing return. Compared with the baseline case (R-3.35 (SI), R-19 (U.S.), U-0.30 (SI) walls), when R-value of walls is R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)), the total home energy consumption increase about 24%. When the R-value of walls increases to 5.28 (SI) (R-30 (U.S.), U-0.19 (SI)), energy consumption decreases about 10%. Each additional R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) beyond R-5.28 (SI) (R-30 (U.S.), U-0.19 (SI)) reduces less than 5% of home energy consumption (See Figures 9 and 10). It could be concluded that any additional wall insulation beyond R-7.04 (SI) (R-40 (U.S.), U-0.14 (SI)) wouldn't provide significant economic benefits.

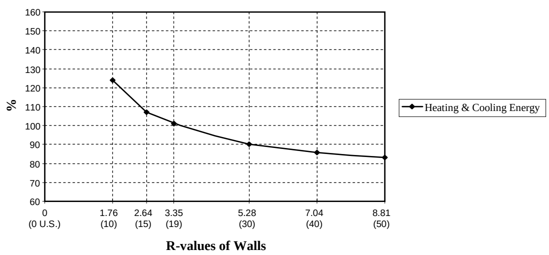

Figure 9 Energy Consumption Rate vs. R-values of Walls (Detroit, Michigan)

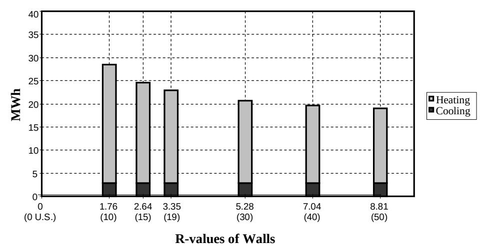

Figure 10 Heating and Cooling Energy Consumption for Various R-values of Walls (Detroit, Michigan)

2. Hot Climate

In hot climate (Miami, Florida), wall insulation does not influence home energy consumption (See Figures 11 and 12). Compare with the case when R-3.35 (SI) (R-19 (U.S.), U-0.30 (SI)) wall insulation, R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) insulation increase less than 5% of home energy consumption. When wall insulation is R-5.28 (SI) (R-30 (U.S.), U-0.19 (SI)), home energy consumption decreases less than 2%. R-7.04 (SI) (R-40 (U.S.), U-0.14 (SI)) or R-8.81 (SI) (R-50 (U.S.), U-0.11 (SI)) walls do not show any significant energy savings.

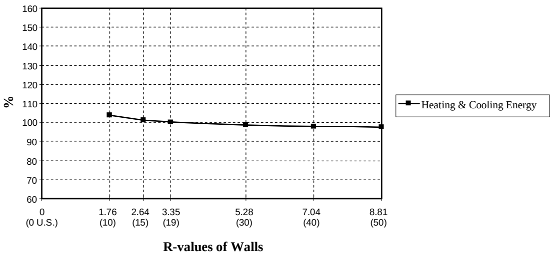

Figure 11 Energy Consumption Rate vs. R-values of Walls (Miami, Florida)

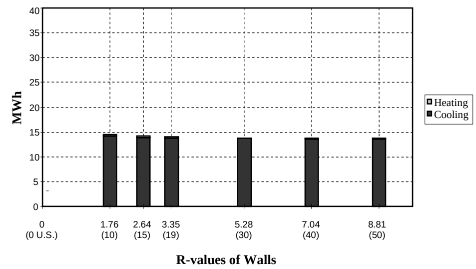

Figure 12 Heating and Cooling Energy Consumption with Diverse R-values of Walls (Miami, Florida)

Benefits of Roof Insulation

1. Cold Climate

Similarly with wall insulation, home heating and cooling energy consumption demonstrates a diminishing return with increasing R-values (See Figures 13 and 14). Compare with the base-case roof insulation R-6.69 (SI) (R-38 (U.S.), U-0.15 (SI)), R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) and R-3.52 (SI) (R-20 (U.S.), U-0.28 (SI)) roofs consume 22% and 8% more energy respectively. Roof R-values greater than the base-case result in marginal energy saving. For instance, increasing the roof R-value to R-14.09 (SI) (R-80 (U.S.), U-0.07 (SI)) reduces less than 5% of the annual heating and cooling energy. In terms of fuel type, the annual gas savings for heating is far more significant than the annual electricity savings for cooling, which indicates that insulation is mostly beneficial in winter.

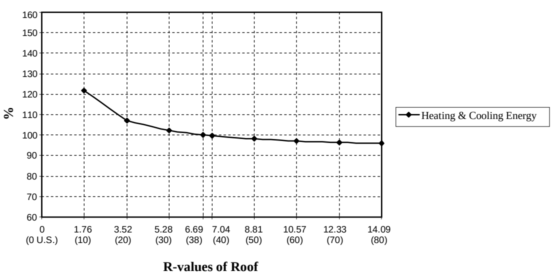

Figure 13 Energy Consumption Rate vs. R-values of Roof (Detroit, Michigan)

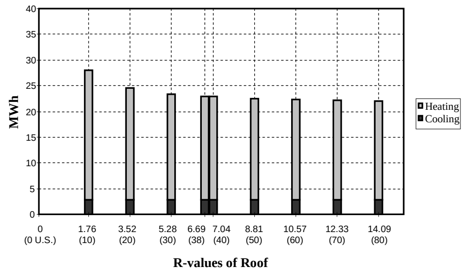

Figure 14 Heating and Cooling Energy Consumption for Various R-values of Roof (Detroit, Michigan)

2. Hot Climate

As it was the case of wall insulation, in hot climates, roof insulation in the range of R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) and R-14.09 (SI) (R-80 (U.S.), U-0.07 (SI)) does not influence home energy consumption (See Figure 15 and 16) significantly. Compare with the base-case, R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) insulation increases less than 5% of home energy consumption. When roof insulation is R-14.09 (SI) (R-80 (U.S.), U-0.07 (SI)), home energy consumption decreases less than 2% (See Figures 15 and 16). In other words, unless roof R-value is extremely low, less than R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) for instance, addition roof insulation does render significant energy benefits.

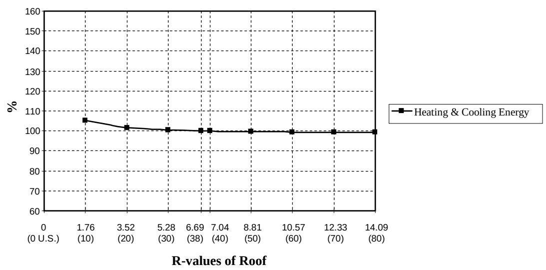

Figure 15 Energy Consumption Rate vs. Roof R-values (Miami, Florida)

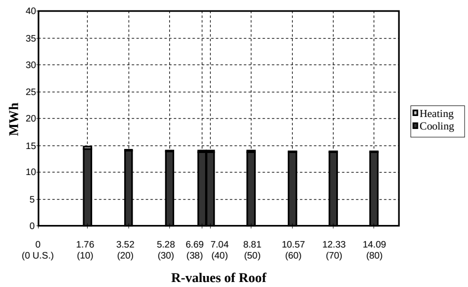

Figure 16 Heating and Cooling Energy Consumption for Various Roof R-values (Miami, Florida)

Benefits of Window Insulation

1. Cold Climate

The overall pattern of energy consumption rate vs. window insulation is similar with those of wall or roof insulation. However, the rate of diminishing is much slower in window insulation (See Figure 17).

Compare with the base-case window R-value (R-0.61 (SI), R-3.44 (U.S.), U-1.65 (SI)), R-0.18 (SI) (R-1 (U.S.), U-5.68 (SI)) and R-0.35 (SI) (R-2 (U.S.), U-2.84 (SI)) windows consume 50% and 18% more heating and cooling energy respectively. On the other hand, R-1.06 (SI) (R-6 (U.S.), U-0.95 (SI)) and R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) windows consume 10% and 17% less energy than the base-case. The energy consumption rate is sensitive to window R-values. This implies that adding more insulation should be a high priority strategy for home energy conservation in cold climates.

In cold climate, window insulation affects mostly heating energy consumption. The influence of window insulation on cooling energy is insignificant (See Figure 18).

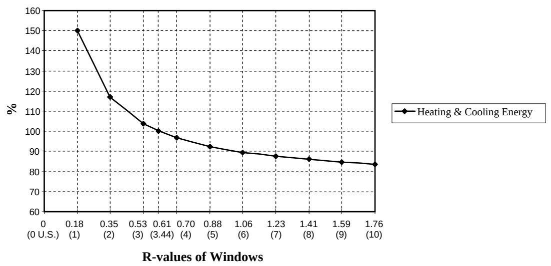

Figure 17 Energy Consumption Rate vs. Windows R-values (Detroit, Michigan)

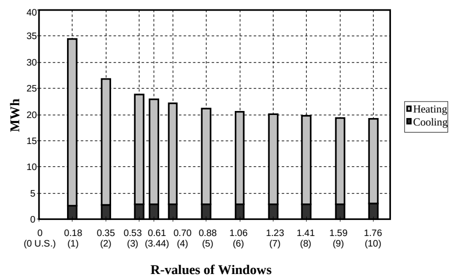

Figure 18 Heating and Cooling Energy Consumption for Various Windows R-values (Detroit, Michigan)

2. Hot Climate

In hot climates, window insulation has virtually no influence in home heating and cooling energy consumption. Window R-values in the range of R-0.18 (SI) (R-1 (U.S.), U-5.68 (SI)) and R-1.76 (SI) (R-10 (U.S.), U-0.57 (SI)) in Miami results nearly identical heating and cooling energy consumptions (See Figures 19 and 20). This result indicates that in hot climate single glazing-windows are allowed, and that multiple glazing wouldn't provide any energy benefits.

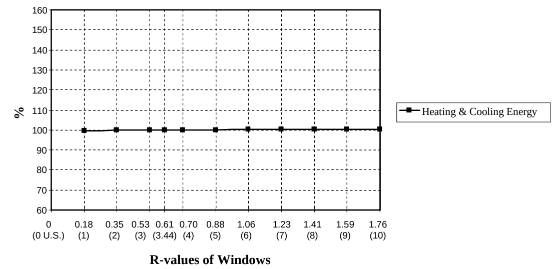

Figure 19 Energy Consumption Rate vs. Windows R-values (Miami, Florida)

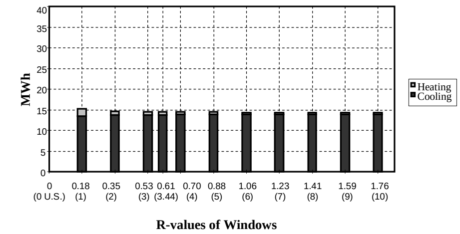

Figure 20 Heating and Cooling Energy Consumption for Various Window R-values of Windows (Miami, Florida)

CONCLUSIONS

The analysis of heat gain and loss components of a single-family home reveals that even in a cold climate like Michigan, heat gain is greater than heat loss annually. Heat gain in winter will be an asset for reducing heating load, while heat gain in summer will be a liability for additional cooling load. Although cooling energy takes a minor fraction (6.5%) of the total energy consumption in Michigan, as solar heat gain constitutes the single largest (42%) heat gain component, proper shading of walls and windows in warm seasons is an important cooling load reduction strategy for buildings in cold climates.

Another noticeable point is that internal heat gain from home appliances, lighting and occupants attributes a substantial fraction (43.7%) of the total heat gain for residential buildings. Use of energy efficient home appliances will decrease not only electricity consumption for operating them but also internal heat production from them, and thus, will reduce cooling load for air-conditioning equipment.

The parametric analyses of envelop insulation, wall, roof and windows, consistently demonstrate two phenomena. First, the energy benefit of insulation is an inverse exponential function, and reaches a point of diminishing return. In Detroit, Michigan, wall insulation over R-5.28 (SI) (R-30 (U.S.), U-0.19 (SI)), roof insulation over R-7.04 (SI) (R-40 (U.S.), U-0.14 (SI)) and window insulation over R-0.88 (SI) (R-5 (U.S.), U-1.14 (SI)) provide only marginal energy savings. Second, in cold climates, insulation is primarily beneficial for reducing heating energy in winter, and has no practical benefit for saving cooling energy consumption in summer. Similarly, envelope insulation in hot climates does provide hardly any tangible energy savings. This is due the small temperature difference between indoor and outdoor temperatures in hot climates or in warm seasons in cold climates. While a minimal level of insulation is necessary, any additional insulation would not contribute to saving heating or cooling energy. For the same reason, the results from this study clearly demonstrate that multiple glazing of windows in hot climates does not provide any significant heating and cooling energy benefits, and thus, will be unnecessary.

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