Development of the Simple Estimating Tool to Assess the Energy Cost Savings of Attic Radiant Barrier System in Temperate Climate Regions

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ABSTRACT

Buildings are one of the US largest consumers of energy. Measures to decrease energy consumption are often overlooked during the building design process. One of the major barriers in design of buildings is the absence of tools to help architects and designers during the preliminary design stages. Therefore, the objective of this study is to develop an estimating tool to assess the energy performance and economic benefits of radiant barrier insulation in the temperate climate region in the US. The developed tool is based on transient three-dimensional finite element models that were validated based on the results of an experimental field study. The results of the three-dimensional finite element models were used to develop a set of multiple-linear regression equations to predict the thermal and energy performances of radiant barrier insulation. The simulations run hour by hour for the entire year using the Typical Meteorological Year (TMY2) weather data. Each simulation takes less than 30 seconds, allowing for very fast comparisons of different design scenarios. It is expected that the developed tool will simplify the integration of energy efficiency in residential building design and construction. Results show that attic radiant barrier can reduce building energy consumption by up to 12%. Results also indicate that cost savings in the temperate region ranges from $7 in Idaho to $41 in Connecticut in 2011.

Key words: Estimating tool, Radiant barrier, temperate climate, Heating and cooling load

INTRODUCTION

The rapidly growing world energy consumption has increased concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts such as ozone layer depletion, global warming, climate change, etc. During the last two decades, primary energy consumption has grown by 49% and CO₂ emissions by 43%, with an average annual increase of 2% and 1.8%, respectively (IE Agency, 2006). Therefore, energy conservation in residential buildings has become a key factor affecting economic development.

Solar energy has a significant effect on whole building energy consumption, but especially the roof, since this surface is the most exposed to solar radiation. Several solutions are available to reduce the energetic contribution from the roof but
the most common method is the application of thermal insulation in buildings. Heat transmission through the roof could be reduced simply by providing insulation as a radiant and conduction heat barrier. Mass insulation with low thermal conductivity (in the order of 0.05 W m⁻¹K⁻¹) is generally used, which reduces heat transfer due to conduction. Nonetheless, this type of thermal insulation does not focus on thermal radiation, which is a non-negligible form of heat transfer. To reduce thermal radiation in buildings, reflective insulation materials known under the generic name “Radiant Barrier System” are recognized as a feasible option.

A review of the literature reveals that several approaches are available for evaluating radiant barrier performance (Asadi S, 2013; Medina MA and Young, 2008; Medina MA, 1998a, 1998b; Medina., 2006; Miranville F, 2008; Miranville F, 2012). Over the last decades, different numerical simulation models have been proposed to better understand the energetic behavior of radiant barrier system. The pioneering work of Joy (1958) involved developing a single steady-state equation by assuming a flat roof and constant ventilation rate, convection and radiation heat transfer coefficients. This work forms the basis for the effective attic resistance tables recommended by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Joy, 1958). Later, several studies were carried out in the United States to assess the performance of radiant barrier system in the attic, either ventilated or not, featuring an existing nominal thermal insulation (Al-Asmar, 1996; Medina MA, 1998a, 1998b). Additional studies were carried out to examine the proper installation location of radiant barrier system in the attic. It was found that placing the radiant barrier system above the existing mass thermal insulation (Horizontal radiant barrier) provides better performance. However, it was also recognized that this position is the most susceptible to collecting dust, and to the associated deterioration in performance (Levins, 1990; Medina, 2000).

In another study by Miranville et al. (Miranville F, 2008), the thermal performance of radiant barrier system were studied based on dynamic simulations and field measurements. A test cell equipped with a standard roof was used for field measurements. Results demonstrated that the overall thermal performance of the roof was controlled by convective heat transfer in the lower air layer and that thermal bridges had little effect on roof thermal performance. The efficiency of different types of radiant barriers available in civil construction market was studied by Michaels et al. (Michels, 2008). More recently, the thermal resistance of a roof-mounted multi-reflective radiant barrier was evaluated experimentally for tropical and humid conditions. The thermal performance of multi-reflective radiant barrier was determined based on the mean energy method. Results showed that this method is able to predict the thermal performance of multi-reflective radiant barrier given the prevailing climatic conditions (Miranville, 2011). Asadi et al. (Asadi, 2013) developed a three-dimensional (3D) transient finite element (FE) model to assess the thermal performance of an attic radiant barrier system. Finite element analysis was validated the developed models using experimental data collected in a house complex in Zachary, LA. The authors also examined different design variables and their influence on the performance of the attic radiant barrier insulation system. It was
concluded that the presence of an air gap on both sides of the radiant barrier had a considerable effect – compared to other variables – on the performance of the radiant barrier insulation system.

Designers are often unable to adequately explore design alternatives and their impact on energy consumption upfront due to an array of challenges between design and energy performance domains. Typically, performance assessments are made after the initial design phase, where the analysis is performed on a very limited set of design alternatives rather than to support early stage design decisions where a broader range of possibly more optimal solutions may exist. In order to address this issue, the objective of the present study was to develop a simple estimating tool to quantify the energy performance and economic benefits of installing attic radiant barrier insulation systems in residential houses in the US temperate climate. The developed tool was based on transient three-dimensional finite element models that were validated based on the results of an experimental field study.

CLIMATIC ZONES IN THE UNITED STATES

Climate considerations are very important in building and urban design (Givoni, 1998). Buildings were considered as “climate modifiers” which could take advantage of local weather to enhance their architectural integrity and environmental quality (Torrance, 1991).

The climates of the US were categorized as cool, temperate, hot-arid, and hot-humid as shown in Figure 1. The focus of this study is on the temperate climatic region. Sacramento, California (38.5° N latitude; 121.4° W longitude) was selected to represent this climatic region. Temperate climate is characterized by a very mild climate with cool winter temperatures and frequent rain with overcast skies. However, due to varying elevations and distances from the coast, large microclimate variations of this region are expected and should be considered by designers for specific projects.

![Figure 1. US climatic regions](image)

METHODOLOGY

The objective of this study was to develop a simple estimating tool to assess the effectiveness and economic benefits of attic radiant barrier system in temperate
climate. To develop this tool, experimental and numerical studies were carried out. To conduct the experimental study, two identical houses were selected in Zachary, Louisiana. These houses were exactly identical in terms of material property, geometry, climate condition, etc. The only difference between them was the presence of radiant barrier system in one of the houses while the second one had conventional insulation. The experimental study lasted for 8 months in order to collect data in the winter and summer seasons. In the numerical study, three dimensional (3D) transient finite element models were developed to simulate the heat transfer mechanism in the attic (Figure 2). The developed models were validated based on the experimental data. After validation, a fractional factorial design was performed to assess the effect of different design and operational parameters on the performance of attic radiant barrier system. The results of the finite element simulations were used to develop a set of regression equations to predict the thermal performances of attic radiant barriers system in temperate climate. These equations were used to build the simple estimating tool to predict annual heating–cooling load and total cost savings due to the application of attic radiant barrier system in the temperate climatic region.

![Figure 2. Schematic of the heat transfer mechanisms in the roof.](image)

**Finite Element Model**

Since many parameters may affect the performance of radiant barrier in the roof, three dimensional transient Finite Element (FE) heat transfer models were developed to calculate the temperature distribution in attic, roof, and ceiling in the house with and without radiant barrier system. These models were able to assess the thermal performance of attic radiant barrier system under different design and environmental conditions in the US. The developed models considered all the heat transfer mechanisms that may occur within the space. The developed FE models were validated based on the collected experimental data. Finite element analysis results showed a good agreement with the experimental data and the error was less than 5%. A full description of the model and its validation against experimental data has been presented elsewhere (Asadi, 2013).

Depending on the radiant barrier installation method in the attic, three separate finite element models were developed to assess the effects of different air gap thicknesses on the performance of radiant barrier. A finite element model was also built to simulate the heat transfer mechanism in the similar house without attic...
radiant barrier system. The emissivity of radiant barrier, emissivity of asphalt shingle, emissivity of insulation, attic flow rate, longitude, latitude, and time zone of the locations were considered as inputs to build the finite element models. Hourly climatic data, including ambient temperature, solar radiation, wind speed, wind direction, and relative humidity, were also considered in the simulation. The local climate data was obtained from Typical Meteorological Year 2 (TMY2)(Laboratory, 1995).

Regression Equations Development

To examine the influence of different design and climate parameters on the required ceiling heating and cooling loads, a fractional factorial design was carried out. Three levels including low [0], intermediate [1], and high [2] were considered for each factor. The total number of required runs was calculated from the definition of the factorial design, \(3^{(k-p)}\), where \(k\) is the number of factors and \(p\) is one representing the half fraction. Environmental parameters such as ambient air temperature, solar radiation, wind speed, wind direction, and relative humidity were varied hourly. A typical day per month was selected for FE simulation to attain accurate data for the statistical analysis. The results of the FE models were incorporated into a set of regression equations to predict the thermal and economic performances of radiant barriers under a wide range of climatic conditions in the temperate region of the US. The multiple-linear regression analysis was used to develop the estimating equations. Multiple–linear regression modeled the relationship between two or more explanatory variables and a response variable by fitting a linear equation data. Every value of the independent variable \(x\) is associated with a value of the dependent variable \(y\). Multiple regression shares all the assumptions of correlation: linearity of relationships, the same level of relationship throughout the range of the independent variable, interval or near-interval data, absence of outliers, and data whose range is not truncated. The FE simulations were carried out based on the fractional factorial design, which provided for a large database used in the regression analysis.

To achieve the best fit between the simulated data and the model results, several statistical models were developed and tested. It was found that linear models are the most appropriate types for the problem. The regression equations were developed based on varying the different installation and type of radiant barrier as well as the presence or absence of ceiling insulation in the attic. If radiant barrier exists in the attic, three options are available: (1) radiant barrier can be attached to plywood without any air gap between them; (2) bubble radiant barrier can be installed to provide a 0.75 cm air gap; (3) radiant barrier can be installed on the rafters with a 5 cm air gap. Using multiple linear regression method, four regression equations were developed to simulate the different design scenarios. Based on the conducted regression analysis, the developed models for predicting the insulation temperature in the temperate climatic zone and for different installation methods of radiant barrier are presented. The regression equations associated with each design case are as follows:

**Attached to plywood**

\[
T_{\text{insulation}} = 45.4 + 0.87T_a + 0.07V - 0.06h + 0.012q_a e_a
\]  

(1)
Bubble Radiant Barrier

\[ T_{\text{insulation}} = 45.5 + 0.87T_a + 0.099V - 0.064h + 0.009(q_s \varepsilon_a) \]  

Installed on Rafters

\[ T_{\text{insulation}} = 45.79 + 0.87T_a + 0.13V - 0.06h + 0.006(q_s \varepsilon_a) \]  

Without Radiant Barrier

\[ T_{\text{insulation}} = 21.7 + 0.949T_a + 0.04V - 0.05h + 0.0139(q_s \varepsilon_a) \]

where

\[ T_{\text{insulation}} \] represents for insulation temperature (°C);  
\[ T_a \] represents for ambient temperature (°K);  
\[ V \] represents for wind speed (m/s);  
\[ h \] represents for relative humidity (%);  
\[ \lambda \] represents for radiant barrier coverage (full coverage = 3, east–west coverage = 2, north–south coverage = 1);  
\[ q_s \] represents for global horizontal solar radiation (W m\(^{-2}\));  
\[ \varepsilon_a \] represents for emissivity of asphalt shingle.

Coefficient of determination (R\(^2\)) and the Root Mean Square Error (RMSE) were used to assess the accuracy of the models. Table 1 shows the R\(^2\) and RMSE for each model. As shown in Table 1, the R\(^2\) of all developed models were higher than 0.98 and the RMSE was less than 1.2.

<table>
<thead>
<tr>
<th>Design Case</th>
<th>R(^2)</th>
<th>RMSE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attached to plywood</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>Bubble radiant barrier</td>
<td>0.98</td>
<td>1.1</td>
</tr>
<tr>
<td>Installed on rafters</td>
<td>0.98</td>
<td>1.2</td>
</tr>
<tr>
<td>Without radiant barrier</td>
<td>0.99</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 3 compares the predicted insulation temperatures based on the regression model (i.e., with ceiling insulation and zero air gap) with the insulation temperatures determined from the FE analysis. As shown in this figure, the results from the model are well correlated with the data from the FE simulation. The analysis of residuals was also conducted to assess the suitability of the models to fit the data. The residual results showed a random pattern indicating a good fit for a linear model.

ESTIMATING TOOL DEVELOPMENT

Although there are many software packages that perform energy analysis for buildings, many of them require comprehensive input from the user and attempt to perform very accurate calculations. When a building is in its preliminary design phase, many of these required inputs are not known by the owner, architects or building designer, rendering the software of little practical use. Even though heat transfer is a complicated process, simple models can be developed with relatively little information to produce first order estimates of building performance. The
development of a software package that requires minimal input from the user and produces meaningful output describing the energy consequences of various design decisions will be useful to building designers interested in sustainability.

Therefore, this study presents the development of a simple estimating tool to assess the effectiveness and economic benefits of radiant barrier insulation systems under different climate conditions in the temperate region of the US at the early design stage. This tool provides rough estimates of building energy use and cost savings due to the application of attic radiant barrier system and shows the energy-related consequences of certain important design decisions. This tool was designed based on the following principles: ease of application, minimum number of inputs, and simplicity and practicality of outputs. To develop this tool, Visual Basic programming language was used. The developed tool calculates annual heating-cooling loads for different building inputs by the user. The input page is designed in three parts by categorizing the inputs into logical groups related to building information, heating–cooling load information, and roof information. Several combo boxes and text boxes were defined for the users to easily enter their input parameters. A question mark was provided for a number of inputs to give more information to the users by connecting them to the related websites. The output page shows the monthly heating-cooling load in the house with radiant barrier, monthly heating-cooling load in the house without radiant barrier, annual cooling cost savings, annual heating cost savings, and the total cost savings in a year. The developed tool can be downloaded for free (http://scm.cmie.lsu.edu/home.htm).

**MODEL VALIDATION**

The validation of the developed models entails the comparison of predictions from the regression model to results from the FE model. Figures 4 and 5 compares the temperature obtained based on the regression and finite element models in a house with and without radiant barrier. It can be seen that the results of the
regression model are similar with the ones obtained by the FE model with acceptable error of 5% or less.

![Graph](image1)

Figure 4. Insulation temperature and heat flux in the house with radiant barrier.

![Graph](image2)

Figure 5. Insulation temperature and heat flux in the house without radiant barrier.

**POTENTIAL COST SAVINGS**

The potential cost savings due to the application of radiant barrier in the attic was calculated based on the fuel prices of each state in 2011 and typical HVAC system efficiencies. The standards of the Department of Energy were used for heat pump and air conditioners. According to these standards, a Seasonal Energy Efficiency Ratio (SEER) of 13 and a Heating Season Performance Factor (HSPF) of 7.7 were used to translate energy savings into electricity savings.

In order to assess the performance of attic radiant barrier in each state in the temperate region, the annual cost savings in 25 cities in each state was calculated. Table 2 shows the annual cost savings for a 148 m² (1600 ft²) single family house for
the case with zero air gap thickness (i.e., radiant barrier was attached to plywood) in 25 cities in the temperate region of the US. The ceiling of the attic was covered with insulation resistance of 3.35 m²K/W (R 19). As shown in this table, cost savings in the temperate region ranges from $7 in Idaho to $41 in Connecticut in 2011. According to this table, radiant barrier is more beneficial in the northeastern regions of the temperate climatic region. In addition, the effect of different elevations on the potential cost savings due to the application of radiant barrier system has been investigated in this study. The presence of attic radiant barrier in the house located in San Diego with elevation of 486 m can save $23 in 2011. However, this cost saving is $17 in San Francisco with elevation of 16 m.

Table 2. Potential cost savings in the temperate climatic region

<table>
<thead>
<tr>
<th>State</th>
<th>Average Cost Savings</th>
<th>State</th>
<th>Average Cost Savings</th>
<th>State</th>
<th>Average Cost Savings</th>
</tr>
</thead>
<tbody>
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<td>$26</td>
<td>VA</td>
<td>$23</td>
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<tr>
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<td>MA</td>
<td>$32</td>
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<td>$27</td>
<td>NJ</td>
<td>$31</td>
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<tr>
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<td>$20</td>
<td>DE</td>
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<td>NY</td>
<td>$38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KS</td>
<td>$22</td>
<td>PA</td>
<td>$28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS

The objective of this study was to develop a simple estimating tool that may be used by homeowners, state agencies, designers, and contractors to evaluate the effectiveness and economic benefits of radiant barrier insulation systems under different climate conditions in the temperate region of the US. A set of regression equations was developed to predict the thermal and economic performance of radiant barriers under a wide range of climate conditions in temperate region. The potential cost savings due to the application of radiant barrier was calculated separately for each state in the temperate region. Results indicated that cost savings in the temperate region range from $7 in Idaho to $41 in Connecticut in 2011. According to the results, radiant barrier is more beneficial in the northeastern regions in the temperate climatic region. It remains for future research to study the effects of radiant barrier system in other climate regions and compare the developed tool with other radiation estimator tools.
REFERENCES


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