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A Computation of U-Factor for an Entire Vented Attic Assembly using a 2D model

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Abstract

The overall *U*-factor values for an attic assembly are usually computed with the ANSI/ASHRAE/IES based *R*-value (thermal resistance) conversion. In the ANSI/ASHRAE/IES Standard 90.1 (2010), the effects of attic air resistance, roof pitch and attic width are not taken into account while calculating the *U*-Factor values. In addition, the *R*-value is estimated using a one dimensional thermal resistance model. In ventilated attics, where the insulation near the roof sheathing is tapered, it is difficult to find the correct *R*-value of the attic system as the heat transfer becomes two dimensional. In this paper, a 2-dimensional CFD model is developed for various insulation R-values and insulation taper angles near roof decks. COMSOL Multiphysics 4.4 is used to model and analyse the attic structure. Results show that a discrepancy in overall *U*-factor for entire attic assembly between the developed model and the existing standard estimation. These results are pronounced for lower slope roofs with high insulation thickness.

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Keywords: Heat flux; Insulation; R value; Taper angle; U value; Ventilation.

$R_{I,\ IF,\ GB,\ EF,\ TI,\ \text{¢}I,\ MJ}$	Thermal resistance values of insulation, inside air film, gypsum board, external film, insulation on the top of wood joist, wood joist.
$\Sigma R_{I,\ TI,\ MJ}$	R values at cross-sections through full insulation, tapered insulation and wood joists

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1. Introduction

Attic insulation separates the conditioned space from the attic to reduce cooling and heating loads during hot and cold periods, respectively. Wilkes and Rucker [1] and Wilkes and Childs [2] studied the thermal performance of residential attic insulation under different level of ceiling insulation, mean temperature and heat flow direction, and ventilation rate. The most common location of attic insulation is on the top of ceiling floor [3, 4]. The other option is moving the insulation plane from the attic floor to the underside of the roof. This practice makes the attic space a part of the conditioned space and it is commonly known as Cathedralized attic [5, 6].

Attic insulation can be characterized by its thickness, material property, and the way it is installed. Higher insulation thickness and smaller thermal conductivity provide a higher thermal resistance (*R*). Insulation with higher thermal resistance lowers the overall heat loss in the entire attic assembly. The thermal performance of the assembly is usually characterized by a term called *U*- value or thermal transmittance (*U*). Insulation thickness is not the only parameter that determines the assembly's effectiveness in energy efficiency. Reducing thermal bridging through structural members, eliminating gaps between insulation and reducing air leakage helps to improve the energy efficiency of attic roof systems.

ANSI/ASHRAE/IES Standard 90.1 (2010) requires a minimum of R-30 $h\cdot ft^2\cdot °F/Btu$ (RSI 5.28 $K\cdot m^2/W$) attic insulation for US climate zones 1 to 7 and R-49 $h\cdot ft^2\cdot °F/Btu$ (RSI 8.63 $K\cdot m^2/W$) for climate zone 8. In the Standard, wood frame vented attic are referred as attic roofs with wood joists. In such assembly, ceiling insulation fills the cavities between the wood joists and above and space above the ceiling insulation is ventilated. According to the Standard, the R-value of a ventilated attic roof is calculated from the thermal resistance values of the center and edge sections of the roof as well as that of the wood joist/truss areas. The tapered insulation near the roof edge is computed with weighing factor of 5% and thermal resistance value of half of the insulation at the roof center [7]. This half depth (average) thickness thermal resistance for tapered insulation may not give the actual *R*-value of the roof edge section. This is mainly due to the 1-dimensional conduction heat transfer model, the model used in the standard, doesn't account for the lateral heat flow shown in Figure 1. In addition, a heat loss through insulation is inversely proportional to insulation thickness and a unit change in insulation thickness doesn't ensure a constant change in heat flux value [8]. The weighting factor, other parameter that needs attention, given for the tapered part should rely on the attic floor length or the ratio between the full and tapered parts of insulation.

In this paper, a 2-dimensional CFD based attic model is used to study the heat loss through attic insulation and to better estimate the R-values of tapered insulation parts and the overall U-value of attic assembly. In the ASHRAE standard, the tapered insulation's R-value (as in Equation 2) is estimated as half depth insulation, but as mentioned above this assumption can be misleading since the lateral heat flow varies for different taper angles. The other concern, this paper want to address, is the weighting factor of the tapered insulation. Three different models are used in this study. The first one is ASHRAE based parallel conduction heat transfer model. The other two models are a 2-dimensional heat conduction model which uses a semi-exterior air layer to represent attic space and an advanced 2-dimensional conjugate heat transfer model that accounts all major constituents of an attic structure. The 2D-CFD model is developed using COMSOL 4.4 model. The turbulent model used in this paper is the k-ω turbulent model. Figure 1 shows the geometric model of the attic assembly.

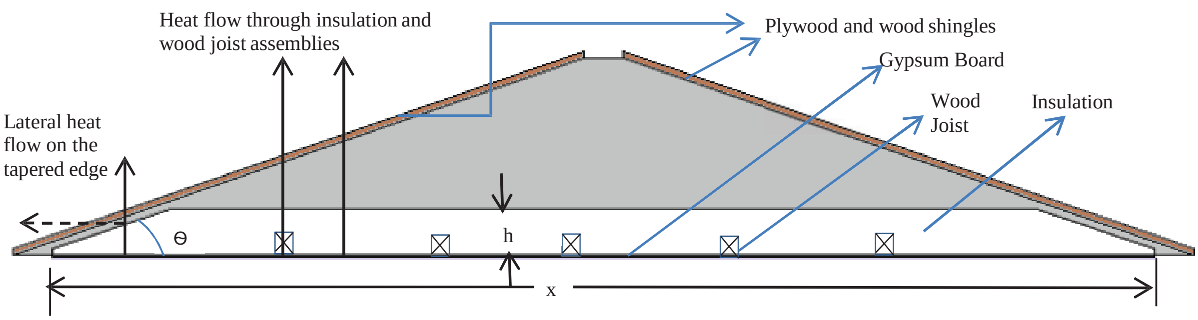

Figure 1. The attic geometric model.

2. Mathematical and Physical model

In ASHRAE 90.1-2010 Standard, the overall *U*- factor of an attic assembly is computed using the *R*-values of the insulation, wood joists, attic floor layer (gypsum board in this study), and interior and exterior surfaces air films at the full insulation, tapered insulation and wood joist roof sections. The corresponding *R* values at cross-sections through full insulation, tapered insulation and through wood joists can be calculated using Equation 1 to 3, respectively.

$$\sum R_{I} = R_{IF} + R_{GB} + R_{I} + R_{EF} \quad (1)$$

$$\sum R_{TI} = R_{IF} + R_{GB} + R_{TI} + R_{EF} \quad (2)$$

$$\sum R_{MJ} = R_{IF} + R_{GB} + R_{¢I} + R_{MJ} + R_{EF} \quad (3)$$

The effective *U*-value for the whole assembly is computed as the sum of the reciprocal of the *R*-values described in Equations 1 to 3 multiplied by weighting factors. In standard framing attic roof the weighting factors for *R*-values at the three cross-sections are 85% full depth insulation, 5% tapered insulation, and 10% joists. The overall *U*-value can be expressed as:

$$U = 0.85 \left(\frac{1}{\sum R_{I}}\right) + 0.05 \left(\frac{1}{\sum R_{TI}}\right) + 0.1 \left(\frac{1}{\sum R_{wI}}\right) \quad (4)$$

To investigate the accuracy of the assumptions made on the tapered section of the attic roof, namely half depth insulation and weighing factors assumptions, two finite element models that can capture the two-dimensional heat transfer phenomena at the roof edge are developed using COMSOL 4.4 and used in this study. The first model uses a 2-dimensional model that comprises the attic insulation in both full depth and tapered forms and the gypsum board. This problem is handled as a conduction heat transfer problem in solids and solved as a stationary heat transfer (energy balance) equation. Three different taper angles and insulation thicknesses are used to compute the *R*-values of the tapered insulation.

On the second model, a 2 dimensional attic geometry with sloped roof of 4:12 pitch and an attic floor area of 74.32 m^2 (800 ft^2) is considered for the study. Two types of ventilation scenarios are considered: sealed attic and buoyancy driven ventilation. The attic ventilation opening area is set to be 1/300 of the attic floor area. The attic is insulated with loose cellulose insulation of RSI 5.28 $K \cdot m^2/W$ (R-25h· ft^2·°F/Btu) and RSI-8.81K· m^2/W (R- 50h· ft2·°F/Btu) at full depth. Conjugate heat transfer model is used to solve the heat transfer in solids and non-isothermal flow in the fluid. The heat transfer module is tightly coupled with the turbulent fluid flow model. The radiation heat transfer inside the attic is modelled using surface to surface radiation module and considering the inner surface of the two roof sheathings and the top surface of the ceiling insulation as the three radiating surfaces. The roof sheathings are assigned a surface emissivity of 0.7. The CFD model used in this study has been verified and benchmarked in previous attic ventilation publication [9]. The result section, presents the weighting factor and R-values of a tapered insulation for different taper angles and insulation thicknesses, and the overall assembly's U-factor for various combinations of parameters including attic ventilation based on the simulation results.

3. Results

3.1. Tapered insulation weighting factor

In the ASHRAE standard, the weighting factor of a tapered insulation in standard framing attic roof is given as 5%. Equation 5 shows the geometric (volumetric) percentage of a tapered insulation.

$$\%TI = \frac{1}{\left(\frac{x}{h}\right)\tan\theta - 1} X100\% \quad (5)$$

Figure 2 shows percentage weight of the tapered insulation with respect to attic width. In this model same type of insulation of loose fill insulation of R-30 is used. The attic width runs from 7 to 15 meters. As shown in the Figure, the weight correction factor reduces as the width of the attic gets bigger. Smaller taper angles tend to have higher weighting factors. Higher slopped roofs also have a small weighting factor to the overall *U*-factor calculation. The other conclusion that can be drawn from Equation 5 is that the bigger the insulation thickness gets the higher the weighting factor of a tapered insulation part becomes.

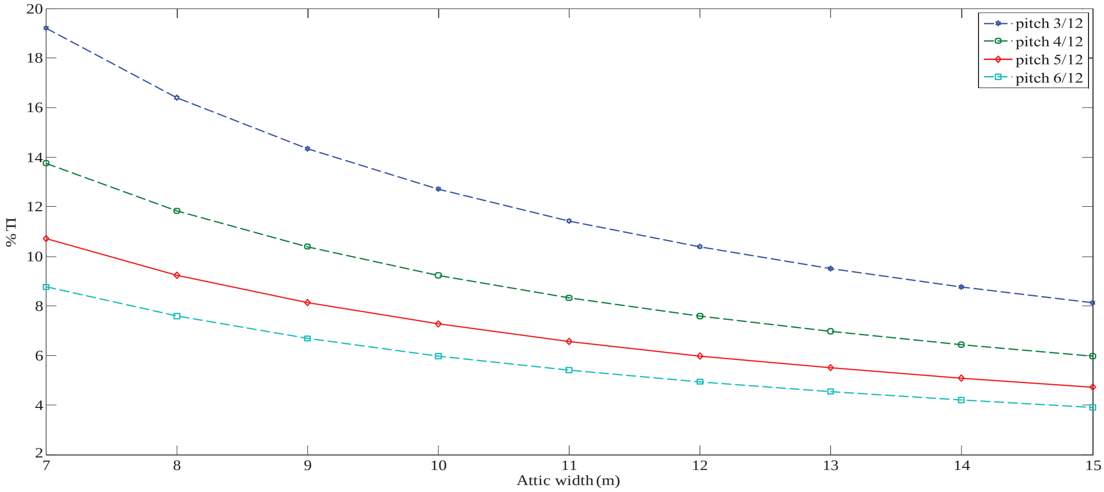

Figure 2. Measured Percentage weight of Tapered insulation vs attic width.

3.2. Comparison between ASHRAE standard and 2-dimensional Conduction heat transfer model (Model 1)

A 2 dimensional conduction heat transfer model (Model 1) is used to study the attic assembly's overall *U*-value. The resistance by the attic air space and the roof is represented by ASHRAE standard semi exterior air film value of R-0.46 (RSI-0.08). The other R-values used in the assembly are R-0.56 (RSI-0.1) for 0.625 inch gypsum board and R-0.61 (RSI-0.11) for interior air film. 2-dimensional modelling is used to accommodate the lateral heat loss at the insulation edges instead of using the rudimentary one dimensional modelling. Figure 3(a) displays a two dimensional attic model with buoyancy driven ventilation at 275K and 295K outside and inside temperatures whereas Figure 3(b) shows the temperature contour plot of an insulation assembly respectively.

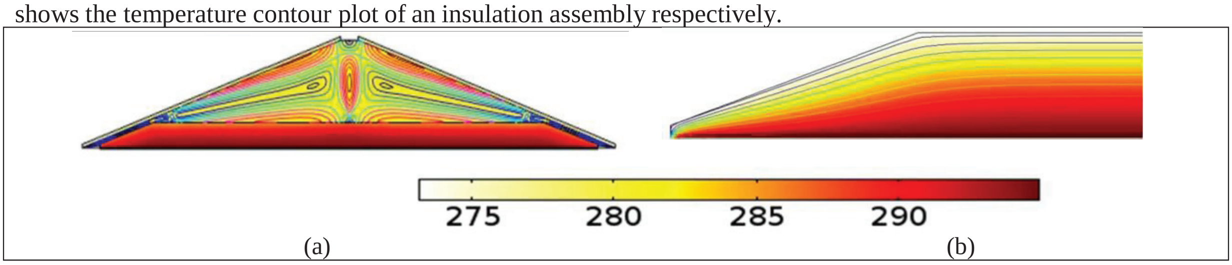

Figure 3 (a) and (b). Temperature contour plot of an attic insulation Model 1 and Model 2 respectively

The heat flux passing through the tapered edge for four different taper angles with pitches of 4/12, 5/12 and 6/12 are evaluated for R-30 insulation value. The outside and the inside temperatures are set at 273 K and 295 K respectively. The heat loss through the tapered part of the insulation is shown in Figure 4. Based on the calculated heat flux and the temperature distribution between the outside and inside temperature the overall *U*-values are computed. Low pitch roofs have got bigger tapered insulation width as a constant insulation thickness in all roof models is used. Table 2 shows the comparison of effective *U*-values between the computed result and the ASHRAE

90.1 parallel heat flow estimation method. Results show the overall U-value for 3/12 roof pitch is greater by 4.32% when compared to ASHRAE standard.

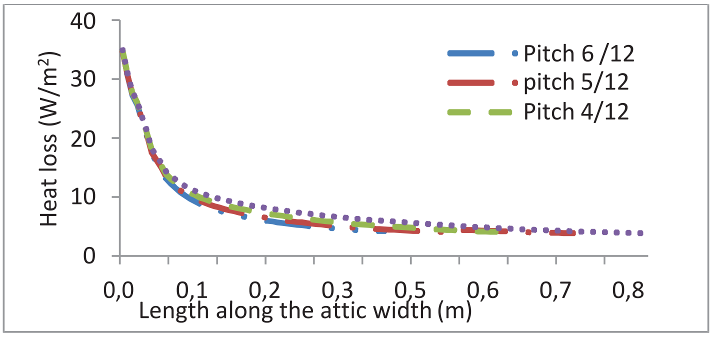

Figure 4. (a). Heat loss through tapered R-30 insulation.

Table 2. The overall *U*-value of the assembly for R-30 insulation

Roof pitch	ASHRAE	pitch 6/12	pitch 5/12	pitch 4/12	pitch 3/12
Overall U Value	0.0324	0.0328	0.0331	0.0335	0.0338
% difference from ASHRAE model		1.235	2.16	3.39	4.32

3.3. Comparison of U-value calculation between 2-D attic model (Model 2) and ASHRAE standard Estimation

A 2-dimensional attic structure with RSI 5.28 (R-25) and RSI 8.81(R-50) insulation is used to study the effects of ventilation on *U*-factor value of attic roofs. The outside and inside temperatures are set as 273 K and 295 K respectively. The coefficient of heat transfer for the outside and indoor conditions used are 33.4 W/(m^2.K) and 9.3 W/(m^2.K), respectively. These values are taken in accordance with ASHRAE's prescribed *R*-values for air films.

Sealed attic and ventilated attics due to thermal buoyancy ventilation scenarios are considered and their results are compared with ASHRAE standard. Figure 5 (a) and (b) shows the heat loss through the ceiling for RSI 5.28 (R-25) and RSI 8.81 (R50) values. As shown in the Figure, in cold outside weather the attic with buoyancy driven ventilation has got a higher heat loss when compared to the sealed attic. The inlet vents at the soffits draw cold air into the attic. This results in colder air temperature on the top of attic insulation which eventually increases the overall- *U* value of the attic space in both R-25 and R50 insulation values.

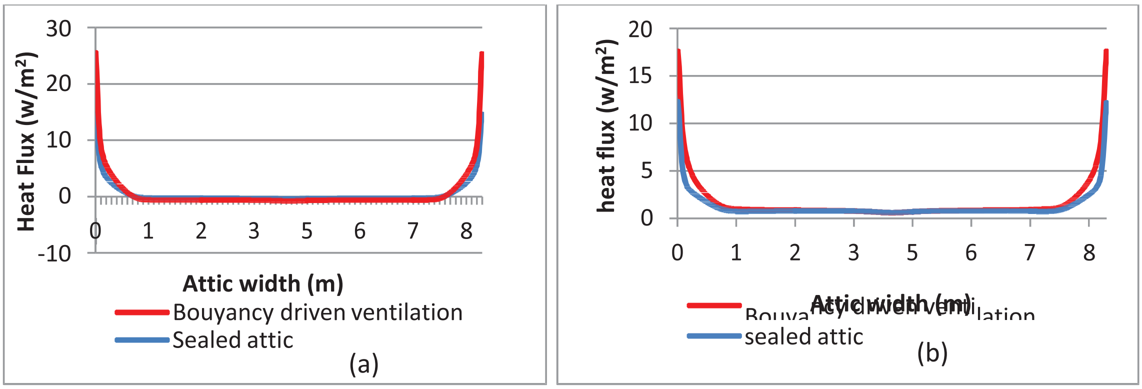

Figure 5 (a) and (b). Heat loss through the ceiling for RSI 5.28 (R-30) and RSI 8.81 (R-50) respectively.

The 2D attic model results for 4/12 roof pitch is has slightly lower overall thermal resistance/ higher thermal transmittance (as shown in Figure 6) in comparison to ASHRAE model. The maximum percentage difference between the attic model and the ASHRAE standard estimation was 6.2%.

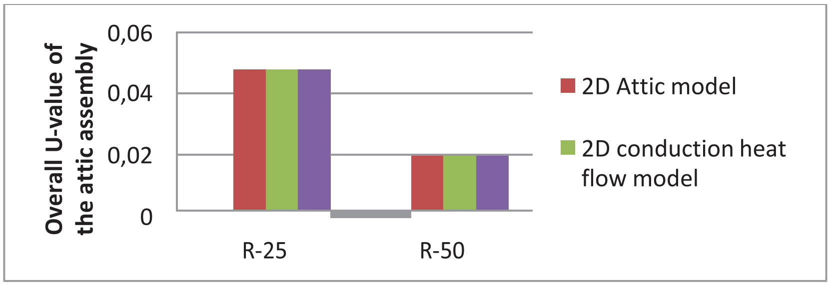

Figure 6. Overall U-factor values for different ventilation modes.

4. Conclusions

This paper shows, weighting factor for tapered insulation should be determined by insulation thickness, attic width and insulation taper angle. Small slope roofs can have lower *R*-values as the volume of a tapered insulation increases in comparison to high slope angles. Our results also show that ventilation sources decouple the attic air space and certain thermal mass components of roof (such as plywood and shingles) and increases the attic assemblies overall *U*-value. The maximum percentage difference between the two dimensional attic model and the ASHRAE standard estimation was found to be 6.2%. This difference can be pronounced in attics with lower roof pitch and smaller attic width. Results show, comprising the thermal resistance of the air space and the ventilation effects creates a higher discrepancy from the ASHRAE Attic R-value calculation procedure.

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