Evaluating Energy Loss through Recessed Lighting Fixtures (RLF) in Residential Buildings through a Case Study

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ABSTRACT

Unintended air leakage through building envelope is a major source of energy loss of residential buildings. Air leakage through improperly installed recessed lighting fixtures (RLF) has been identified as one source of unintended air leakage. However, little quantitative study was found on the energy loss through improperly-installed RLF. In this paper, the authors conducted preliminary evaluation of the magnitude of such energy loss by numerical simulations using 3D transient CFD model. One case was studied using boundary conditions of four seasons, which were obtained from historical experimental data from Mississippi. The results of the simulations indicate RLF can be a very significant source of energy loss in both summer and winter conditions. The study suggests that systematic approach is needed to improve the RLF design and construction practice to reduce or remove the RLF's negative impact on energy loss of residential buildings.

INTRODUCTION

Unintended air leakage through buildings' envelopes is one of the common issues which affect energy performance of single-family residential buildings in the U.S. Air leakage through improperly installed recessed lighting fixtures (RLF) has been identified as one source of unintended air leakage. In response to its impacts, Washington State revised its codes and started to require all recessed lighting to be strictly air tight. The code demand that air leakage rate of RLF could not exceed 2 cfm (cubic feet per minute) at 75 Pascals pressure difference, which firstly provided the manufacturers with valuable references (Meer, 2002). Later on, IECC also enacted a series of corresponding provisions to regulate the industry standards.

However, even under the above guidance when the lighting trim is properly sealed, the perforations on the recessed lighting cans are still found to be a cause of air leakage (McCarthy, 2000). Though employing the physical methods, such as the blower door test and infrared camera techniques, the leaking areas can be easily detected, it is still difficult to quantify the energy loss. Little quantitative study was found on the energy loss through improperly installed RLF. Thus, the goal of the research is to quantitatively investigate the impact of the air leakage through RLF on the energy performance of residential buildings through a case study. The case study only considers the situation when the light bulbs are not on. The light-bulb-on cases are going to be studied in the further research.

The goal of the paper is to utilize numerical models to simulate the air leakage under different weather conditions, and to provide a rough estimate of the energy loss caused by air leakage in RLFs in terms of magnitude in four seasons in the Mixed-Humid zone in the U.S.

METHODOLOGY

Numerical Model. A 3D transient Computational Fluid Dynamics (CFD) model using the commercial software Fluent 13.0 was built with different boundary conditions. An attic with RLFs is simulated in this case. Due to the buoyancy stableness of the attic ventilation as well as the symmetry in both geometry and boundary conditions, only a quarter of attic with 9 RLFs is employed as the computational domain to achieve computational efficiency. The schematic of heat transfer mechanisms in ventilation attic is shown in Figure 1. Both the convection and radiation are considered in the simulation. To simplify the simulation, the computational domain is only occupied by air, which is assumed to be a Boussinesq fluid with a reference temperature, T_o (specified as the outdoor ambient air temperature to adjust the buoyancy effects in the simulation). The pressures at the soffit and ridge vents are specified to be zero gauge. Therefore, the obtained air flow is purely driven by the thermally induced buoyancy forces, i.e., the stack effect. At the soffit vent, the inlet air is assumed to be ambient air and a turbulent intensity of 1%.

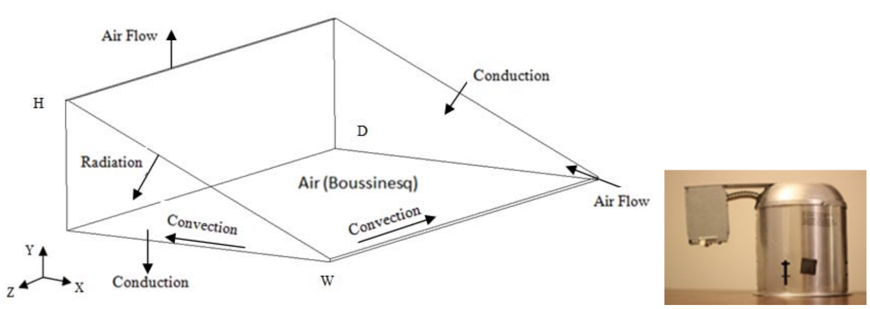

Figure 1. Schematic of the Heat Transfer Mechanisms in the Ventilated Attic

The detailed schematic diagram of the RLFs is shown in Figure 2. The length, width, and height of the attic simulated in the model are 6 meters, 4 meters, 1.677 meters respectively, corresponding to a roof pitch value of 5/12. Each recessed light is supposed to be non-IC rated, and have four 0.5 cm x 2 cm openings of air leak surround the recessed lighting can (Figure 1). The diameter of each lighting can is 15cm. The ratio of canister areas V.S. total ceiling area is 0.68: 100. The roof and vertical wall are assumed to be made of 3cm thick ply wood while the ceiling is assumed to be made of 15cm thick glass fiber.

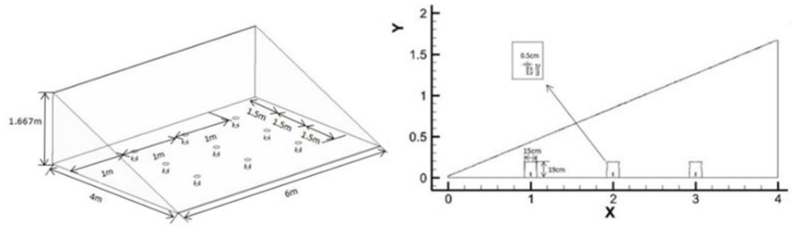

Figure 2. Geometry of an attic with recessed lighting

Natural ventilation through the attic is considered in this case. Ventilation ratio refers to the net free area, such as soffit and ridge vent regions, divided by the deck area of the attic (Shiming wang, 2012). In this case, the ventilation ratio is supposed to be 1/200. The insulation level represented by R-value as well as emissivity is also considered in this model as shown in Table 1. All the bounding surfaces in the attics are subjected to the conduction heat transfer. Besides, convection-type boundary conditions are applied to ceiling, roof and vertical wall. In addition, surface-to-surface type radiation boundary conditions are applied to both roof and vertical wall.

Table 1. Boundary Conditions

	Thermal Conductivity	Emissivity
Roof	R-1.2 (4.733W/m^{2}K)	0.85
Vertical Wall	R-1.2 (4.733W/m^{2}K)	0.85
Ceiling	R-20 (0.284W/m^{2}K)	/

Roof Temperature Data Collection and Processing. The roof temperatures employed in the case study refer to the temperature data recorded by Mississippi Forest Products Laboratory in Starkville, Mississippi, in 1999 (Winandy, Barnes, & Hatfield, 2000). According to Building America climate zone divisions, Starkville is located in the Mixed-Humid zone and has relatively moderate weather conditions in winter and hot weather conditions in summer. Five identical wood-framed black shingle roofed attic structures were built and instrumented with type-T thermocouples placed at different locations. In this case study, the rooftop and ambient temperature data are applied as the boundary conditions in the 3D model. After validation, they are identified as applicable data for the following reasons: the ambient temperature is not affected by the configuration of the exposure roof structures; the roof temperature is mainly determined by the ambient temperature and solar radiation other than the roof structure. Two of the five structures which were not artificially humidified are selected as the boundary conditions in the simulation, due to the fact that their higher temperature gradient with the ambient temperature can provide a better understanding of alternation of the energy loss in different weather conditions.

To reduce the computational cost, only one day for each season is selected from the temperature observation period. According to the climate statistics, the coldest and hottest days of the year usually appear in January and July. These data represent the winter and summer seasons in this study. Meanwhile, April and October, which have more mild temperatures, represent the spring and fall. The variances of temperature data in each hour of the four months are calculated and summarized. The smallest daily total variances are identified for each month. The days which had the closest daily temperatures to their monthly average were January 7th, April 28th, July 10th, and October 29th in 1999. Thus these four days are selected to be employed as the boundary conditions in the 3D model.

Then the roof and outdoor ambient air temperatures in the four selected days are fitted into a four series Gaussian function respectively as listed in (1) using nonlinear least square fit method in Matlab. The R-squares are all above 0.99 which indicate a good match between the experimental data and the fitted data.

$$f(x) = a_1 e^{-\left[\frac{(x-b_1)}{c_1}\right]^2} + a_2 e^{-\left[\frac{(x-b_2)}{c_2}\right]^2} + a_3 e^{-\left[\frac{(x-b_3)}{c_3}\right]^2} + a_4 e^{-\left[\frac{(x-b_4)}{c_4}\right]^2} \quad (1)$$

Where x is time (s) and starts from 14400 s for each, because four hours before each day are taken account in the function fitting so as to improve the effectiveness of the results; f(x) is in terms of "K"; a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2, c_3 are constants.

The data of the mass flow rates in the recessed lighting and the heat transfer rates in the ceiling are exported from the simulation results. Then by using the following equations (2, 3), the energy loss from RLFs and ceilings can be estimated.

$$Q = cm\Delta T = q\Delta t \quad (2)$$

$$m = V_m \times \Delta t \quad (3)$$

where Q is the energy loss (J); c is the specific heat capacity constant (J/kg•K) which equals to 1006 for the air; m is mass (kg); and ΔT is the indoor and outdoor air temperature difference (K); Indoor air temperature equals to 293k in winter, 297K in summer and 295K in spring and fall; Δt is the duration of the energy loss(s); in (7) V_m is the mass flow rate of air (kg/s); q is the heat transfer rate (W);

The convection heat transfer rate of ceiling can be calculated by the following equation:

$$q = h_c A \Delta T \quad (4)$$

Where q is heat transfer rate (W); A is heat transfer area of the surface (m^2); h_c is convective heat transfer coefficient of the process which equals to 0.284 (W/m^2K); ΔT is temperature difference between the surface and the bulk fluid (K).

RESULTS AND DISCUSSION

Winter Condition. The 24 hour attic energy loss shows various characteristics in each season. In winter, the energy consumption for maintaining the indoor air temperature all comes from the heating load. Much of the heating load is due to the substantial energy loss from ceiling and recessed lighting. As listed in equation (4), the energy loss rate of ceiling in this case study is determined by the temperature gradient at two sides of ceiling multiplied by two constant values for this case study. The temperature of the lower side of the ceiling is a constant value (293K), while the temperature of the upper side of the ceiling is determined by both radiation and air convection. In the nighttime, as shown in Figure 4-A, the roof temperature has very small discrepancy with the outdoor temperature which results in a very low radiation effect. Thus, the temperature of upper side of the ceiling is mainly dominated by air convection. Since the difference between the outdoor and indoor air temperature is bigger in the nighttime, the energy loss from the ceiling exhibits a relatively high value (Figure 4-C). In the daytime, as the roof temperature becomes higher than the outdoor temperature (Figure 4-A), the radiation from the roof gradually increases. In the meantime, the difference between the indoor air and outdoor air temperature decreases. As a result, the energy loss from the ceiling decreases to a relatively low value in the daytime.

However, as shown in Figure 4-C, the energy loss rate of recessed lighting has an adverse tendency. As listed in equation (2, 3), the energy loss from the recess lighting is determined by the mass flow rate of the air leakage and the indoor and outdoor air temperature difference. Although the temperature difference is smaller in the daytime, the energy loss rate of recess lighting is larger than that in the nighttime. This is due to the fact that the rise of the roof temperature intensifies the soffit-ridge ventilation which results in the increase of the mass flow rate of the leakage air in the recess lighting, as shown in Figure 4-B. The streamlines and contour of temperature of the recessed lighting are shown in Figure 5.

Spring Condition. In spring, the energy consumption for maintaining the indoor air temperature is from both heating the load and the cooling load (Figure 6-C). Other than the mass flow rate in January, which is positive anytime, the mass flow rate in April appears negative in the nighttime, as shown in Figure 6-B. This

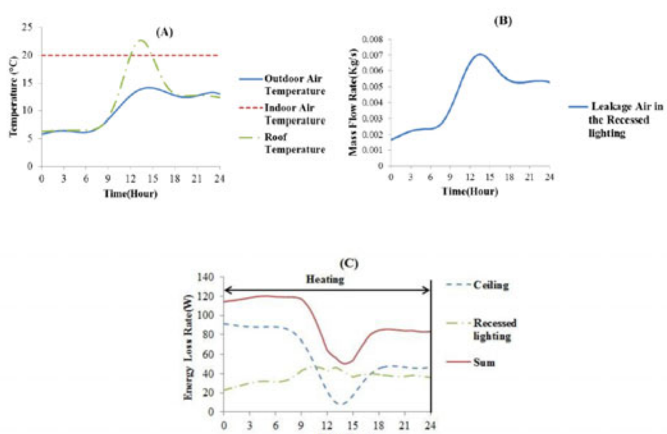

Figure 4. Temperature data (A), Mass Flow Rate of the Leakage Air in Recessed Lighting (B), and 24 Hour Attic Energy Loss (C) on 1/7/1999

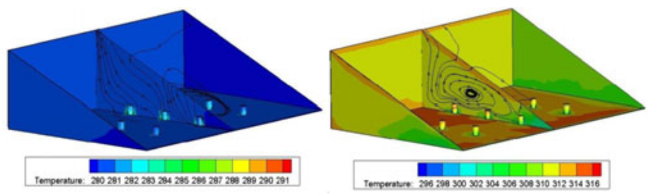

Figure 5. Streamlines and Contour of Temperature in the Nighttime (Left) and in the Daytime (Right) on 1/7/1999

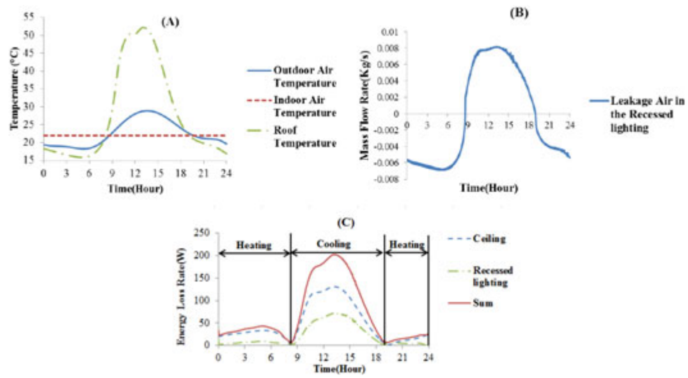

Figure 6. Temperature data (A), Mass Flow Rate of the Leakage Air in Recessed Lighting (B), and 24 Hour Attic Energy Loss (C) on 4/28/1999

means that rather than in January when the indoor air enters through the bottom of the canister, rises up and goes out from the ridge vent (Figure 5), the air flow is in completely opposite directions during the nighttime in spring (Figure 6-A). The primary cause of the phenomena is that the roof temperature becomes lower than the outdoor temperature. Compared with the heating effect of the celling, the cooling effect of the roof is more intense. As a cold source, the roof reduces the outdoor ambient air temperature, and increases the density of the air, which makes the outdoor air flow into the attic and then leaks into the home from recessed lighting. However, the outdoor air and roof temperature difference is relatively small, thus the energy loss from the recessed lighting is slight during this time.

In the daytime, as the roof temperature rises higher than the outdoor temperature, the roof becomes a heating source which increases the temperature of the air in the attic and decreases the air density. This makes the indoor air rise, and leak into the attic and form a convection cell. In addition, other than in January, the energy loss from the ceiling becomes more significant in the daytime in April (Figure 6-C), which is due to the bigger indoor and outdoor temperature difference (Figure 6-A).

Summer Condition. Due to the warm climate in the Mixed-Humid zone, the characteristic of the energy loss in summer is generally similar to that in spring. However, the energy loss rate for both ceiling and recessed lighting becomes bigger. In addition, the duration of the heating time is shorter. Even though the indoor air temperature set in the case study is only a little higher than the outdoor air temperature from 12 a.m. to 6 a.m. as shown in Figure 7-A, this temperature difference can result in the emergence of the heating load (Figure 7-C). As the outdoor air and roof temperatures gradually fall down after 1 p.m., the cooling load also begins to reduce. When close to 12 p.m., as the outdoor and roof temperature approach the indoor temperature, the energy loss rate of both ceiling and recessed lighting, becomes close to zero. Thus, the heating load appears when the outdoor air and roof temperatures are lower than the indoor temperature even though it is in summer.

Fall Condition. As shown in Figure 8-C, the curve of the energy loss rate of the recessed lighting shows more fluctuations than that in the other seasons. This is due to the fact that the outdoor air and the roof temperatures reach the value of the indoor air temperature at different times respectively. As the mass flow rate of the leakage air in the recess lighting approaches zero, the energy loss from the recessed lighting tends to be zero at the first time. In addition, when the other energy loss determinant, the indoor and outdoor air temperature difference, as listed in Equation (2), reaches zero around 10:30 a.m., the energy loss from the recessed lighting falls to zero at the second time.

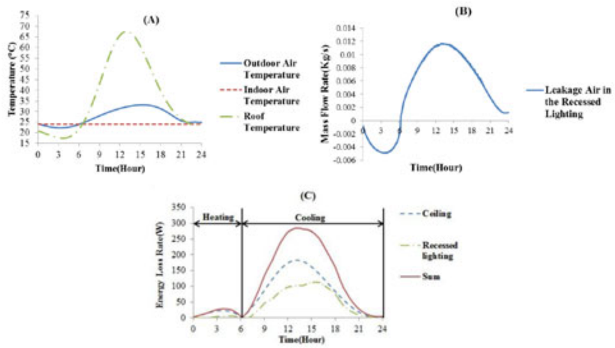

Figure 7. Temperature data (A), Mass Flow Rate of the Leakage Air in Recessed Lighting (B), and 24 Hour Attic Energy Loss (C) on 7/10/1999

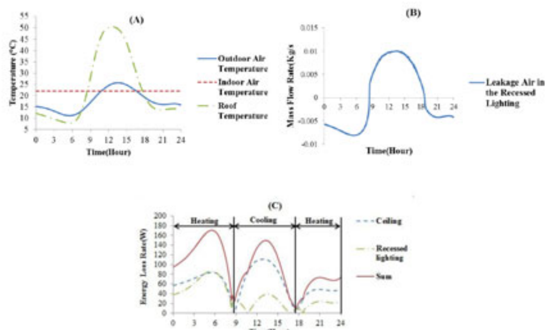

Figure 8. Temperature data (A), Mass Flow Rate of the Leakage Air in Recessed Lighting (B), and 24 Hour Attic Energy Loss (C) on 10/29/1999

Estimate of the Energy loss from Recessed Lighting in the Mixed-Humid Zone. Due to the various factors mentioned in the introduction of this chapter, the energy loss in the Mixed-Humid zone is just a rough estimate in terms of magnitude. Twenty-eight RLFs per household are assumed in the estimate, according to the related literature (Meer, 2002). Moreover, the temperature differences between the other regions in the Mixed-Humid zone and Starkville, where the data are collected from, is ignored. The number of the homes that have unfinished attics without air conditioning in the Mixed-Humid climate zone is 10.2 million (U.S EIA 2009). As shown in Table 2, the monthly energy loss from the recessed lighting in the Mixed-Humid zone is quite considerable and is in terms of million MMBTU.

Table 2. The Energy Loss from Recessed Lighting in the Mixed-Humid Zone

	24 Hour				Monthly
	The Nine Recessed Lights (BTU)	Per Recessed Light (BTU)	Per Home (BTU)	The Mixed-Humid Zone (MMBTU)	The Mixed-Humid Zone (MMBTU)
January	3026.19	336.24	9,414.81	96,031.11	2,976,964.273
April	1677.86	186.43	5,220.00	53,244.04	1,597,321.275
July	3427.93	380.88	10,664.69	108,779.79	3,372,173.498
October	2784.76	309.42	8,663.71	88,369.84	2,739,465.019

CONCLUSIONS

This paper quantitatively investigates the energy impact due to the air leakage phenomenon through the RLFs. Even though the climate is relatively moderate in the Mixed-Humid zone, the results of the simulations indicate RLF still can be a very significant source of energy loss all over the year. The percentages of the energy loss from recessed lighting versus the total energy loss from the attic are all above thirty percent all over the year. Excessive energy is consumed due to the leakage through RLFs to maintain the indoor air temperature. The magnitude of the monthly energy loss from the recessed lighting in the Mixed-Humid zone could be inferred as million MMBTU per month.

Though there are a lot of limitations which makes it only a rough estimate, the results of the case study are already enough to give reasonable evidence of the energy impact of the air leakage in the recessed lighting. The study suggests that systematic approach is needed to improve the RLF design and construction practice to reduce or remove the RLF's negative impact on energy loss of residential buildings.

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