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Thermal load mitigation and passive cooling in residential attics containing PCM-enhanced insulations

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Abstract

Residential attics has the potential to be one of the most energy efficient building components by combining thermal processes of attic floor insulation, attic air space, ventilation in attics, and solar collecting roof decks. Large amounts of solar energy collected by the roofs in cooling-dominated and mixed climates generate excess cooling loads, which need to be removed from the building by the space conditioning systems. This paper investigates potential ways to improve the thermal design of the residential home attics to minimize the cooling energy consumption in the cooling-dominated and mixed climates. Dynamic thermal characteristics of thick attic floor insulations and blends of phase change materials (PCMs) with insulations are analyzed. Both approaches can provide notable reductions of thermal loads at the attic level. In addition, a significant time shift of peak-hour loads can move a major operation time for air conditioning system from the daytime peak hours to nighttime low demand hours. A reverse heat flow direction can be observed during the day in the case of really thick layers of bulk insulation or PCM-enhanced insulations, compared to the rest of the building envelope components. This effect may provide free passive cooling to the building, and can be very useful in locations of double electrical tariffs with high daytime peak-hour electric energy rates and less-expensive off-peak energy cost. In both of the above cases, an addition of PCM to the bulk insulation brings substantial performance enhancement not available for traditional insulation applications. This paper presents a short overview of dynamic material characteristics and energy performance data necessary for future dynamic applications of different configurations of the attic floor insulation and PCM-insulation blends in residential homes. A series of whole-building scale and material scale numerical simulations were performed on a single story ranch house to analyze potential energy savings and optimize location of PCM within the attic insulation.

Keywords: Building envelopes; Attics; Thermal mass; Insulation

1. Introduction

In North America, thermal performance of the roof and attic structures is commonly based on the steady-state resistance (*R*-value). However, a day-to-day change in weather conditions causes variations in the thermal loads of the building envelope. The varying thermal loads must be accounted for in the thermal design of the envelope components to evaluate and to maximize the energy performance of the envelope. Conventional designs of the attic in residential homes often include attic floor insulation, gables, soffit, and ridge vents. These interactive components provide an example of a dynamically-working solar thermal system where significant thermal excitations are produced on the roof surfaces and transmitted to the attic

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space. The ventilation air redirects a part of the solar heat transferred to the roof deck away from the insulation on the attic floor. The attic air provides an efficient thermal break between the roof surface and the attic insulation, reducing daily temperature swings inside the attic. The attic floor insulation works against a tempered internal attic air temperature instead of the dynamic thermal excitations observed on the roof surface. For comparison, most of the cathedralized or flat roofs are directly exposed to high thermal excitations generated by the roof surfaces, making their thermal insulation system significantly less effective (Desjarlais et al., 2001; Kośny et al., 2010a). In general, benefits of the conventional attic design can be listed as follows:

- In summer, effectively reduces roof solar loads.
- In winter, reduces nocturnal cooling effects.
- Provides a conduction break between the attic floor and the roof deck.
- Causes stratification of the attic air and adds thermal resistance to the attic insulation.
- Causes a shifting of attic thermal loads.

Bulk thermal insulation is considered as one of the best-known ways of improving thermal performance of the building envelopes. In traditional simplified understanding, the thermal performance of insulation is directly proportional to the insulation thickness, when isolating the insulated area from the rest of the building. Thermal efficiency of using undisturbed attic insulation was previously analyzed by several authors (Miller and Kośny, 2007; Parker and Sherwin, 1998; Miller et al., 2007; Wilkes et al., 1991). However, earlier results of field testing, energy simulations, and cost analysis demonstrated that the conventional thermal insulations, due to relatively high cost and diminishing energy benefits, cannot be considered as the only system to achieve improved thermal performance in highly insulated assemblies (Desjarlais et al., 2001; Miller and Kośny, 2007). From the whole-system perspective, the impact of thermal insulation thickness on overall attic energy efficiency is significantly more complex. Thermal analysis becomes more difficult when adding the effects of framing (caused by structural members), local thermal bridging (caused by imperfections in insulation installation), and air leakage. In addition, in heating dominated climates, during the winter time, thermal performance of some fiber insulations used in attics is compromised by internal convection (Wilkes et al., 1991). In cooling-dominated and mixed climates attic thermal mass is notably influencing overall thermal performance as well. The effect of the thermal mass shows that taking into account only thickness and conductivity of insulation is not sufficient to analyze the overall attic thermal performance.

Several alternative attic systems have been developed during the last decades to reduce building thermal loads (Desjarlais et al., 2001; Kośny et al., 2010a; Miller and Kośny, 2007; Parker and Sherwin, 1998; Miller et al., 2007). These systems can be grouped into the following basic areas:

- Exterior radiation control technologies – cool roof coatings.
- Radiant barriers and foil-faced insulations.
- Conventional thermal mass and PCMs.
- Air spaces and naturally ventilated cavities.
- Actively ventilated attics and above deck inclined air spaces.

The addition of PCM to the attic floor insulation is considered as a promising material enhancement. PCMs are substances with a high heat of fusion and melt and solidify at a certain temperature range. The high heat of fusion gives PCMs the capability of storing and releasing large amounts of energy. In PCMs, energy is absorbed or released when the material changes from solid to liquid and vice versa. PCMs may reduce the overall heat flows across the attic insulation, and increases time shifting of the thermal peak-hour loads. In 2002, a research project sponsored by the U.S. Department of Energy was initiated to work on thermal insulations blended with microencapsulated PCMs (Kośny et al., 2006; Kośny et al., 2007; Kośny et al., 2008). These PCM-insulation mixtures function as lightweight thermal mass components. PCMs enhanced materials are expected to contribute to reduce energy consumption for space conditioning and reshape peak-hour loads.

New applications of PCMs in the design of attic components require careful selection of materials, identification of PCM location, bounding thermal resistances, and specification of the amount of PCM to be used. Concentrated PCM applications (like for example gypsum boards or arrays of PCM containers) have been tested as a thermal mass component in Northern American buildings for at least 40 years. Most of the published research data has demonstrated that PCMs can notably enhance energy performance of walls, roofs and attics. Recent studies (Feustel, 1995; Salyer and Sircar, 1989; Kissock and Kissock et al., 1998; Kissock and Limas, 2006; Zhang et al., 2005; Kośny et al., 2010b, 2012) demonstrated that the application of concentrated PCMs could generate heating and cooling energy savings of up to 25% in well insulated residential buildings in the Southern United States. In 2012, Childs and Stovall performed numerical analysis of thermal performance of different configurations of layered wall cavity insulation using microencapsulated PCM (Childs and Stovall, 2012). However, the performance of the attic insulation utilizing concentrated PCM has not been fully optimized. Similarly, most of the experimental studies on dispersed PCM applications were focused on walls (Kośny et al., 2006, 2007, 2008).

This paper proposes to replace “statically” designed conventional attic insulation with a novel dynamically working and fully-integrated envelope system. For this purpose, two major dynamic thermal effects, which can