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Simulating home cooling load reductions for a novel opaque roof solar chimney configuration

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HIGHLIGHTS

- Zonal house simulation with discretized roof solar chimney and airflow network.
- High and low efficiency; single-sided, cross and stack ventilation.
- Hourly results show reliable performance of ventilated roof in all climates.
- Cooling load reductions of 49–92%.
- In three climates, passive techniques are more effective than incremental efficiency.

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ABSTRACT

The roof solar chimney (RSC) is a low cost passive ventilation technique for reducing the energy consumption for cooling buildings. This study examines the performance and level of energy savings by simulating a detached home in four climates with RSC, cross-ventilation, and standard ventilation strategies. Each case was simulated in ESP-r for baseline and high efficiency construction, detached homes with a single story, three bedrooms, a 189 m^2 floor plan and high thermal mass constructions. Photovoltaic panels were integrated into the surface of the solar chimney on the South-facing roof to improve the RSC performance with their absorptive properties, and provide cooling to the reverse of the panels with the ventilation airflow. To form the RSC, a gap under the external layer of the roof allowed airflow from the interior of the house to a plenum in the peak of the attic with vents to the outside. Cross ventilation was aided with openings in the interior walls allowing flow between rooms. The ventilation gap was modeled by discretizing the RSC into 12 sections and calibrating the air-flow and convection coefficients with corresponding computational fluid dynamics models. The results indicate that the ventilated roof provides free cooling and natural ventilation in all climates and seasons tested. Flow was caused more by the stack effect rather than through natural convection and the solar chimney effect. Cross ventilation reduced cooling load by approximately 50% percent over the baseline, and the ventilated roof by up to another 80%. Either advanced natural ventilation approach reduced cooling load by more than the green envelope and efficiency practices in three of the four climates. The natural ventilation techniques were proportionally as effective in reducing load in a high efficiency home as in the base case home.

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1. Introduction

In detached homes in the United States, electricity is the largest energy source, and the US Energy Information Administration (IEA) found that in 2009, over 100 million homes used air conditioning. The prevalence of air conditioning ranges from 98% in the warmer South to 91% in the Midwest, 86% in the Northeast and 65% in the West. The majority of houses use central air conditioning, and central air conditioning runs all summer in over one third of the homes in each region – up to 67% of homes in the South [1]. In 2005, the latest year for which data was available, homes used 25.6 quadrillion Btus (7.5×10^6 GW h), with 20% of their total electricity for air conditioning [2].

The energy consumption due to air conditioning systems can be reduced through the design or renovation of homes. Natural ventilation and free cooling are efficient ways to cool buildings and should be part of a well designed home's HVAC system, even when mechanical cooling is also required. As prescriptive energy code requirements have become stricter and homebuyers are increasingly concerned with their utility bills and carbon

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Nomenclature

ρ	density of a material layer (kg/m^3)
A	surface area (m^3)
c_p	heat capacity (J/(kg K))
f	function defining pressure flow relationship
h_c	convective heat transfer coefficient (W/(m^2 K))
$\dot{m}$	air mass flow rate (kg/s)
M	number of adjacent zones
n	number of connected air points
N	number of adjacent surfaces
ΔP	pressure differential (pa)
q''	heat flux (W/(m^2 K))
t	time (s)
T	temperature (C)
V	zone volume (m^3)

Subscripts

a	air node
$conv$	heat from internal gains
i	air node index
j	air node index
J	zone index
L	lower comfort limit, or heating setpoint
m	mean monthly
$plant$	heat injected by a plant component
S	surface index
U	upper comfort limit, or cooling setpoint

footprints, homes have become more efficient [3,4]. Advanced window, insulation and sealing technologies are used to reduce the cooling load, while high efficiency centralized air systems improve occupant control and maintain precise ventilation levels. Advances have been made in active solar thermal technologies for satisfying both for heating and cooling demand [5,6]. These trends, however, make it increasingly difficult to effectively use passive techniques to cool. With advancements in displacement ventilation efficiency and envelope improvements, the return on further incremental developments is decreasing. Passive techniques seem low tech and can be difficult to control and predict, but they have been shown to provide conditioning with no energy use and improve the occupants' perception of comfort. This paper seeks, through simulation, to explore the potential of two simple advanced natural ventilation methods for cooling. Control and comfort are addressed, and the methods are compared to, and in conjunction with, contemporary high efficiency building techniques in four US climate zones.

A ventilated roof is a double skin façade technique. It is similar to the roof solar chimney (RSC), so named because, during periods of high solar insolation, the absorptive surface of the roof heats up and air flow is induced by natural convection. RSCs often use a transparent outer layer and absorptive inner layer, while the outer layer in consideration here is comprised of photovoltaic panels applied to plywood. The roof is opaque and much of the cooling potential is found to come from buoyancy induced night ventilation, so the term 'ventilated roof' can be used. The roof was designed with an external surface of building integrated photovoltaic panels (BIPV). PV panels are highly absorptive, creating both the challenge of removing the heat that builds up during the day and an opportunity to use this heat to induce ventilation, making them ideal for a ventilated roof.

The configuration studied here draws air through inlets in the ceilings of the rooms below it. The outlets flow into a plenum in the peak of the house. The plenum is vented outside at each end of the house. This configuration is shown in more detail in Fig. 1. For the ventilation to best cool the whole house, flow between rooms must be facilitated. This is achieved with vents in the interior walls, near the floor and ceiling. These vents allow air to circulate between rooms due to temperature stratification, as well as due to pressure differentials caused by wind. In the case of typical single sided ventilation, the actual air-flow through windows is limited and difficult to predict even when there is significant wind. Simply allowing cross ventilation has been shown to greatly improve the effectiveness and predictability of natural ventilation [7,8].

Natural ventilation and solar chimneys have been studied extensively with experimental, analytical, and numerical approaches [9–11]. Aboulnaga used an analytical approach to simulate a RSC with a ventilation inlet subject to wind pressure [12]. The flow rate was predicted parametrically for different wind speeds, solar insolation values, and dimensions. Maerefat and Haghighi modeled a small house using a roof solar chimney in conjunction with an earth to air heat exchanger and evaporative cooling to preheat ventilation air [13,14]. The techniques were shown to be effective for sets of ambient conditions representative of each season. The ventilated roof was studied numerically and experimentally in a commercial building context by Susanti et al. [15]. With a simple resistive thermal model, this study showed that the use of an outer layer of sheet metal to create a double skin roof on a factory building could either significantly reduce air conditioning energy use in a conditioned space or improve comfort in an unconditioned space throughout the summer. Biwole et al. examined the heat transfer in a double skin roof, running parametric variations while holding the inlet and outlet air temperature constant [16]. In general, the operation of this passive technique in the context of a larger building has not been considered. In experimental and numerical work, inlet and outlet temperatures typically remain

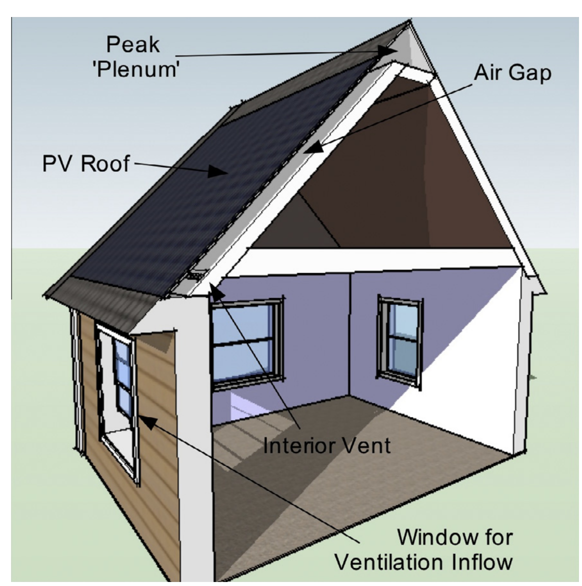

Fig. 1. Configuration of a ventilated roof.