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Energy saving and economic analysis of a new hybrid radiative cooling system for single-family houses in the USA

Kai Zhang[a,d], Dongliang Zhao[b], Xiaobo Yin[b,c], Ronggui Yang[b], Gang Tan[a,*]

[a] Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY 82071, USA
[b] Department of Mechanical Engineering, University of Colorado, Boulder, CO 80309, USA
[c] Materials Science and Engineering Program, University of Colorado, Boulder, CO 80309, USA
[d] College of Urban Construction, Nanjing Tech University, Nanjing 210009, China

HIGHLIGHTS

- Novel hybrid Radiative cooled-Cold storage cooling ($RadiCold_{hc}$) system is proposed.
- Energy and economic analysis are investigated on a highly insulated two-story house.
- $RadiCold_{hc}$ system will save annual cooling electricity consumption by 26–46%.
- Maximum incremental costs are \$50.0/m^2–\$78.9/m^2 for an 8-year simple payback period.

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ABSTRACT

Radiative cooling has received much attention as it generates "free" cooling to buildings and helps reduce energy consumption of mechanical air conditioning systems. However, most current radiative cooling materials either work for nighttime (nocturnal) cooling only or have high cost issues. A novel scalable-manufactured randomized glass-polymer hybrid metamaterial coated with silver has recently been developed and reported a 110 W/m^2 cooling power on daily average. This metamaterial potentially provides passive cooling for both nighttime and daytime. Proposed is a hybrid diurnal radiative cooled-cold storage cooling system using this metamaterial for air conditioning purposes in single-family houses. Because single-family houses have a relatively low cooling load but high ratio of roof area to floor area, they are excellent end users of the hybrid radiative cooled-cold storage cooling system. The potential energy savings of the hybrid radiative cooled-cold storage cooling system in a typical two-floor single-family house with floor area of 204 m^2 have been modeled using EnergyPlus for four locations in the U.S., including Orlando, FL, San Diego, CA, San Francisco, CA, and Denver, CO. In comparison with the electricity consumption of a split air conditioner alone, the hybrid radiative cooled-cold storage cooling system could save annual cooling electricity by 26% to 46% for the modeled locations, under a restriction of 8-year payback period. The corresponding simple payback periods for adoption of the hybrid radiative cooled-cold storage cooling system fall in a range of 4.8–8.0 years and the maximum acceptable incremental costs are \$50.0/m^2–\$78.9/m^2. The diurnal working hybrid radiative cooled-cold storage cooling system may provide a cost-effective solution for radiative cooling technology in residential building applications.

1. Introduction

As a passive cooling technology, radiative cooling surface transfers heat to sky by infrared radiation whenever the effective sky temperature is lower than the radiative surface temperature [1–4]. Although the radiative cooling technique has been developed for many years [5–9], the application has been limited to nighttime due to solar absorption of most materials in the daytime [10–14]. With the development of micro/nanotechnologies, daytime radiative cooling has become possible, and applications of diurnal cooling to buildings could be realized [15,16]. In particular, Zhai et al. [17] has recently developed the radiative cooling film, of a randomized, glass-polymer hybrid metamaterial with silver coating, and characterized with effectively rejecting solar irradiance and strongly emitting in the infrared. This film can be scalable-manufactured at relatively low-cost. It provides high technical and economic potential for the development of diurnal radiative cooling

* Corresponding author.
E-mail address: gtan@uwyo.edu (G. Tan).

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Nomenclature

A_S	area of the radiative cooling surface (m^2)
AIC_{max}	maximum acceptable incremental cost per unit area of radiative cooling surface ($/$m^2$)
$ASPP$	Acceptable simple payback period (year)
C_{Radi}	cost of the RadiCold system ($)
C_{RSAC}	cost of the reduced-size split air conditioner in $RadiCold_{hc}$ system ($)
C_{RC}	cooling capacity for a of RadiCold module (kW)
C_{SACL}	cost of the split air conditioner lonely ($)
c_p	specific heat capacity of water (J/kg·K)
$CL_{avg\text{-}hour}$	average hourly cooling load (kW)
S_{RSAC}	size of reduced-size split air conditioner (kW)
S_{SACL}	size of split air conditioner lonely (kW)
$E_{Radi\text{-}hc}$	cooling electricity consumption of the $RadiCold_{hc}$ system (kWh)
E_{SACL}	cooling electricity consumption of the split air conditioner lonely (kWh)
h_f	forced convection component of radiative cooling surface ($W/m^2{\cdot}K$)
h_n	natural convection component of radiative cooling surface ($W/m^2{\cdot}K$)
h_{RS}	convective heat transfer coefficient over the radiative cooling surface ($W/m^2{\cdot}K$)
I_{sol}	incident solar radiation (W/m^2)
N	number of RadiCold modules employed in the residential building
P	perimeter length of radiative cooling surface (m)
P_E	price of electricity ($/kWh)
q_{conv}	convection heat transfer between radiative cooling surface and ambient air (W/m^2)
q_{RS}	net radiative cooling power (W/m^2)
q_{rad}	heat transfer between radiative cooling surface and sky (W/m^2)
q_{sol}	solar radiation absorbed by the radiative cooling surface (W/m^2)
R_f	roughness multiplier of radiative cooling surface
RSAC	reduced-size split air conditioner
SACL	split air conditioner lonely
SPP	simple payback period (year)
$t_{charging}$	total charging time (s)
T_{amb}	ambient air temperature (K)
T_d	ambient dewpoint temperature (K)
T_{sky}	effective sky temperature for longwave radiation (K)
T_{surf}	temperature of radiative cooling surface (K)
$T_{w,\tau}$	RadiCold module water temprature of current time step (K)
$T_{w,\tau+1}$	RadiCold module water temperature of next time step (K)
T_w	average water temperature in RadiCold module (K)
ΔT_{tank}	variation of the temperature in the tank (K)
V	volume of water in the RadiCold module (m^3)
V_{tank}	volume of tank (m^3)
V_z	local wind speed (m/s)
W_f	wind direction modifier

Greek letter

α	surface tile angle
ε_{sky}	average spectral and directional longwave emissivity/absorptivity of the atmospheric
ε_{surf}	radiative cooling surface emittance
η	efficiency of discharging
λ	absorption coefficient
ρ_w	density of water (kg/m^3)
ρ_{surf}	solar absorption rate of the radiative cooling surface
σ	Stefan-Boltzmann constant ($J/(m^2{\cdot}s{\cdot}K^4)$)
$\Delta\tau$	length of the time step (s)

systems for building applications. Direct thermal measurement of the radiative cooling film demonstrated approximately 110 W/m^2 cooling power on a daily average in hot weather [17].

Various strategies have been proposed utilizing the radiative cooling technology in buildings, including passive systems directly applying selective-emittance material for roofs, and active systems such as water based, air based, and hybrid systems (Fig. 1) [2,4].

The water based cooling systems can be categorized into two forms: open loop [18–22] and closed loop [23–26]. The open loop water system commonly consists of a shallow rooftop pond, where the heat is

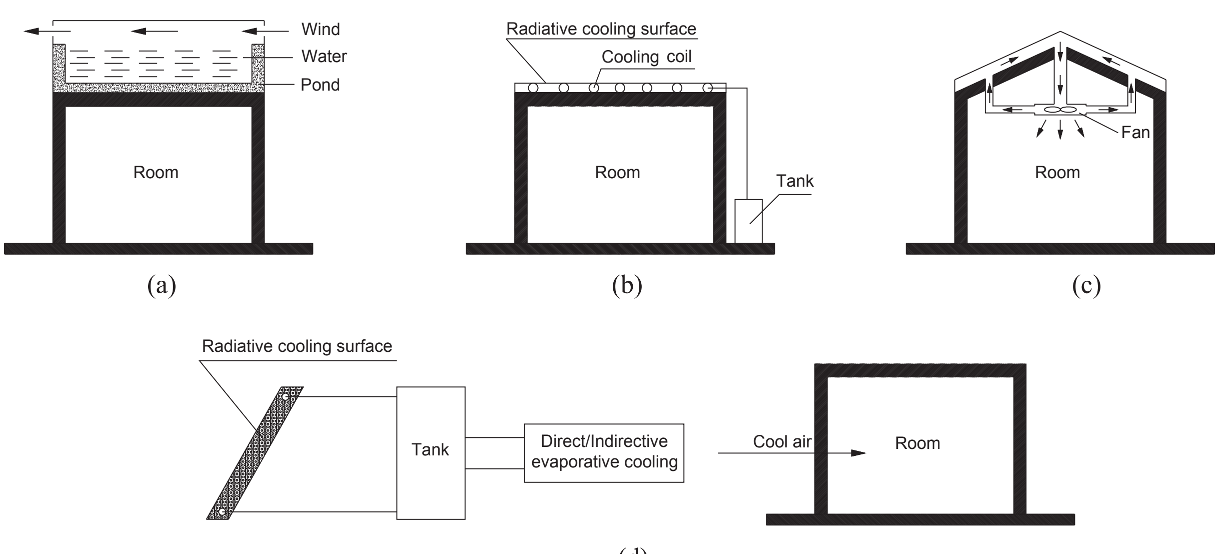

Fig. 1. Sketch of active radiative cooling systems: (a) water based system (open loop); (b) water based system (closed loop); (c) air based system; and (d) hybrid system.