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Passive cooling potential in buildings under various climatic conditions in India

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ABSTRACT

Passive cooling is a versatile technology through which energy demands to achieve the thermal comfort in a building can be minimized in places like India, where different climatic zones exist. This paper presents the outcome of various research works carried out in the field of evaporative cooling, nocturnal radiative cooling, and phase change material (PCM) based free cooling of buildings under various climatic conditions. Further, the developed empirical equations/correlations for determining the critical design parameters pertaining to the above said passive cooling technologies are summarized in order to provide a panoramic view. The achievable monthly and yearly average cooling potential through the implementation of direct evaporative cooling, nocturnal radiative cooing and PCM based free cooling system are estimated and reported for five selected cities (Chennai, Bangalore, New Delhi, Jaipur, and Jammu and Kashmir) in India, based on their corresponding weather data. It is inferred that Jaipur with hot and dry climatic zone has the highest yearly average passive cooling potential of 251 W m^{-2}, whereas Chennai with warm and humid climate zone has 127 W m^{-2}. In addition, concept of a novel hybrid passive system is presented along with the strategies required in the present scenario to promote passive building concepts. This comprehensive evaluation of cooling potential helps the researchers to select the appropriate passive cooling technologies based on the influencing parameters with respect to local climatic zones.

1. Introduction

India is the second most populous country in the world with 17.6% of world population and it is projected that by 2022 India will surpass China's population [1]. In India, energy consumption, economic growth, and increase in population rate have a strong interrelationship with each other [2]. India became the fourth biggest energy consuming nation after China, U.S.A., and Russia in 2011 [3]. Energy consumption rate has increased by 7.5% in 2014 – 2015, the highest growth rate among the developing countries [4]. India's dependency on imported fuels had increased to 38% in 2012, though it has significant domestic fossil fuel resources [5]. The energy intensive sectors in India is categorized into three main sectors namely industry, transportation, and others. Among the 'others' category, the agriculture and buildings are highly energy intensive sectors due to the agrarian nature and rapid urbanization, which leads to an unexpected hike in energy demand and consumption pattern in residential and commercial buildings. The energy consumption in the buildings is due to various appliances used for human requirement and comfort. Particularly, 45% of the total energy is spent towards maintaining the thermal comfort conditions in the residential building sector as shown in Fig. 1 [6]. Not surprisingly, the greenhouse gas (GHG) emissions associated with the building sector has also increased exponentially. The Global Buildings Performance Network (GBPN) reported that if the existing Business-As-Usual (BAU) policy for buildings is followed, India could easily experience an increase in building energy consumption and GHG emissions of around 700% by 2050 compared to 2005 levels [7]. In order to reduce the rising energy demand in buildings and its associated emissions, researchers are showing more interest towards the net zero energy/emission buildings in the recent years. The increase in number of publications in recent years regarding the energy conservation in buildings through passive cooling technologies illustrate its large energy

Abbreviations: A, Area; AFR, Air flow rate; CDD, Cooling Degree Days; CDM, Cooling Degree Months; CFC, Chlorofluorocarbons; CO_{2e}, Carbon dioxide equivalence; COP, Coefficient of performance; EC, Evaporative cooling; GHG, Greenhouse gases; GW, Gigawatt; HCFC, Hydro chlorofluorocarbons; HVAC, Heating Ventilation and Air Conditioning; IEHX, Indirect evaporative heat exchanger; kWh, Kilowatt hour; $MtCO_{2e}$, Million tonnes of Carbon-di-oxide Equivalence; NRC, Nocturnal radiative cooling; NRP, Nocturnal radiative panel; PCM, Phase change material; PF, Performance factor; RH, Relative humidity; TWh/yr, Terawatt hour per year; VCRS, Vapor compression refrigeration system

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Nomenclature

b	Width of the bond
C_b	Bond conductance between the pipes and absorber plate
$C_{p,v}$	Specific heat of air
D	Diameter
d_{mw}	Mass flow rate of evaporated water
dQ_l	Latent heat transfer caused by the evaporation of water
$E_{consumed}$	Energy consumed
E_{vm}	Monthly average evaporative cooling potential
f	Wettability
f_{cc}	Evaporative cooling channel air flow
h	Convective heat transfer coefficient
H	Enthalpy
h_m	Mass transfer coefficient
H_v	Heat of vaporization
k	Thermal conductivity
$\dot{m}$	Mass flow rate
n	Number of pipes
n_c	Total opaque cloud amount (0 for clear sky and 1 for overcast sky)
P	Pressure
Pr	Prandtl number
Q	Cooling capacity
Re	Reynolds number
S	Absorbed solar energy
T, t*	Temperature
t_c	Charging duration
V	Volumetric air flowrate
v	Velocity of air
v_{a*}	Air specific volume
V_m	Monthly average wind speed
v_w	Wind velocity
W	Distance between the pipes
W^*, x	Humidity ratio
y	Distance from the collector inlet

Subscripts

a, mean	monthly mean ambient temperature
1	Entering air dry bulb temperature
1, db	Dry bulb temperature of intake air
1, dp	Dew point temperature of intake air
1, wb	Wet bulb temperature of intake air
2	Leaving air dry bulb temperature
2, db	Dry bulb temperature of supply air
3	Entering air wet bulb temperature
4	Entering wet bulb temperature of secondary air
5	Entering dew bulb temperature of product air
a	Ambient temperature
a, in, out	Inlet & Outlet dry bulb temperature
b	base temperature
*b**	Thermal conductivity of the bond
c, inf	Convective heat transfer coefficient, lower side of the panel
c, sup	Convective heat transfer coefficient, upper side of the panel
conv	Convective heat transfer coefficient
DEC	Direct evaporative cooler
dp	Dew point temperature
DPIEC	Dew point indirect evaporative cooler
e	External diameter of the pipe
EC	Evaporative cooler
fi	Fluid temperature at radiator inlet
i	Inside heat transfer coefficient of the PCM heat exchanger
*i**	Internal diameter of the pipe
IEC	Indirect evaporative cooler
*in**	Enthalpy of inlet air
*in***	Inlet Humidity ratio
o	Outside heat transfer coefficient of the PCM heat exchanger
*o**	Outside heat transfer coefficient of the PCM heat exchanger
*pcm**	Mass of the PCM solidified in the spherical container
pw	Enthalpy of water vapor
r	Radiative panel
*r**	Radiator emissivity
r, inf	Radiative heat transfer coefficient, lower side of the panel
r, sup	Radiative heat transfer coefficient, upper side of the panel
s	Humidity ratio of the wet-bulb temperature at saturation
*s**	Surface area of the spherical capsule
s, in	Inlet wet bulb temperature of the air stream
sat	Saturation pressure

Greek letters

ΔP	Air pressure drop
$\Delta\omega$	Difference between moisture content of supply & outdoor air
α_c	Convective heat transfer coefficient
γ	Bond thickness
δ	Fin Thickness
δ^*	Time (hours)
Δt	Time required to reach the 'i'th location
ε	Emissivity
ε^*	Porosity of the PCM storage tank
μ	Viscosity of air
η	Efficiency
ϑ'_m	Monthly average air wet bulb temperature
ϑ_m	Monthly average air dry bulb temperature
λ,	Latent heat of the PCM
ρ_a	Density of air
σ	Stefan-Boltzmann constant
ω	Humidity ratio of air

saving potential in the near future. It is forecasted that it is possible to reduce the GHG emissions from buildings through the implementation of effective energy conservation measures such as adoption of passive cooling technologies/green building concepts, maximizing the renewable energy harnessing and equipping the energy efficient equipment. It is also predicted that, by implementing stringent policies and adopting the various energy conservation measures, the increase in household electricity consumption (650 kWh in 2012 to 2750 kWh in 2050) could be curtailed to 1170 kWh/household by 2050 [7].

2. Climatic zones of India – An overview

India, being a tropical country comprises of versatile climatic zones which are categorized as hot-dry, warm-humid, composite, temperate/moderate, and cold zones [8]. Continental climate with extreme summer and winter conditions prevails in the northern part of India but southern and coastal regions of the country experience the warm

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