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Potential energy savings by radiative cooling system for a building in tropical climate

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ABSTRACT

Nowadays, almost every building required a cooling system and most of them use active cooling, which normally operates using electricity generated from non-renewable fossil fuel. To achieve comfort, it is possible to utilize the natural environmental conditions to partially replace the active cooling energy requirements. This research attempts to investigate the correlation between the radiative cooling power and the temperature difference between the ambient and the sky. The potential of a radiative cooling system in Malaysia is evaluated as well. The radiative cooling system operates by using a flat-plate rooftop as a radiator to reject heat to the cooler nocturnal sky for cooling purposes. In addition, the radiative cooling potential is determined by using the climate data of 10 different locations in Malaysia. The study found that radiative cooling can save up to 11% of the power consumption for cooling purposes. This value is the same for all 10 locations in this country.

Contents

1. Introduction

Nowadays, a subsequent amount of energy is consumed in buildings and it leads us to concentrate on energy saving in this sector. Meanwhile, cooling and heating play a major role in energy consumption of buildings. Based on this reason, extensive research has been done to improve the efficient use of energy in buildings.

In the energy management of buildings, there are some factors discussed in the literature. These include utilizing low-energy consuming systems such as absorption cooling systems, thermal energy storage, cooling storage, off-peak cooling and ice storage [1–15], utilizing day-lighting method to reduce lighting appliances during day [16–18,19], phase change materials [20–23], heat pump

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Nomenclature

T_f	fluid temperature (°C)
T_a	ambient air temperature (°C)
T_{fi}	fluid temperature at collectors inlet (°C)
S	absorbed solar energy (W/m^2)
U_L	overall heat loss coefficient of the collector (W/m^2 °C)
n	number of pipes
W	distance between the pipe (m)
F	collector efficiency factor
y	distance from collector inlet (m)
$\dot{m}$	mass flow rate through the collector (kg/s)
C_P	specific heat of the fluid (J/kg °C)
C_b	bond conductance between the pipes and absorber plate (W/m °C)
h_{fi}	heat transfer coefficient between the fluid and the tube interior (W/m^2 °C)
D	external diameter of the pipe (m)
D_i	internal diameter of the tube (m)
F	fin efficiency factor
W	riser spacing (m)
δ	fin thickness (m)
K	thermal conductivity of the fin (W/m °C)
A	area of radiator (m^2)
εr	radiator emissivity coefficient
σ	Stephan–Boltzman constant (5.67051×10^{-8} Wm^{-2}K^{-4})
T_{rad}	radiator min temperature (K)
T_{sky}	sky temperature (K)
ε_{sky}	sky emissivity
α_W	alpha parameter for shape of weather tower
H_W	height of weather tower (m)
γ_W	gamma parameter for shape of weather tower
α_C	alpha parameter for shape of test cell
H_C	height of test cell
γ_C	gamma parameter for shape of test cell
v	wind velocity at test field (m/s)
C_{sys}	heat capacity of the cooling system (kJ K^{-1})
K_{sys}	system total heat capacity loss rate except radiator (W K^{-1})
P_{pump}	heat transfer from pump to water (75% of pump electrical usage

systems [24], optimum thermal design in buildings [25], automation systems and controlled ventilation [26–29], appliance standards [30], thermal comfort systems [31–33], and utilizing sources of renewable energy such as wind energy and solar radiation [1,34–43].

As Malaysia is located in tropical climate, energy consumption of cooling units in buildings has an essential role in energy savings. Due to this, various measures to reduce the cooling loads have been introduced. Reduction of cooling loads can be carried out in relation to windows such as smart windows [44], optimum overhang dimensions [45], optimum size of windows [46], and thermal insulation [47,48]. In addition to windows, insulation of building envelopes [49–51], high-albedo roofs [52,53], solar reflectance roofs [54–56], green roofs [57–60], shading effects [58,59,61–63], using skytherm and cooled ceiling systems [55,64–66], passive cooling systems in buildings [67–71], natural ventilation [72–74], and thermal mass [75,76] are the other factors that were analyzed previously, to reduce the cooling loads in buildings.

As mentioned above, there are various ways of reducing the cooling loads. Meanwhile, a radiative cooling system has the potential to improve enegry efficiency of cooling load in buildings.

In general, radiation is the condition where energy is transmitted in the form of an electromagnetic wave due to change in an object's atomic or molecular configuration. In the field of heat transfer, thermal radiation refers to energy transmitted by an object to the surroundings because of the temperature difference between the object and the surroundings. The object's temperature will drop resulting from loss of energy. The concept of thermal radiation has been used in cooling of a human body [77].

The radiative cooling technique is based on the principle of heat transfer by long-wave radiation emission from a high temperature object to a lower one. In this study, a building's rooftop is used as a medium to reject heat to the night sky in order to reduce the energy consumption for space cooling. The cooling object is the roof surface and the night sky is the heat sink because the temperature of the night sky is lower than most of the earth bound objects. Long-wave radiation is a continuous day and night process. In daylight, a long-wave transmitter is exposed to solar radiation and hence will absorb more heat rather than reject it. Therefore, radiative cooling can only operate at night [77].

According to the research, a night sky radiative cooling system has a great potential in reducing the energy consumption for space cooling [77]. The system consists of a transmitter or a radiator which is made of a high conductivity flat-plate rooftop where water is circulated in it and allowed heat transfer from the water to the rooftop or radiator and then radiated to the night sky [78]. Water is a good heat carrier and it will absorb the heat from the room space when cooling water from radiative cooling is circulated through the pipeline in the ceiling and wall. This system can reduce the cooling load for an air-conditioning room. In case of energy saving, this system operates under the principle of passive cooling and it is cost free. Therefore, this cooling system is an effective technology in improving the quality of indoor air and also in saving energy [79].

In this modern era, space cooling is a necessity for comfort and hence results in high energy consumption. Nowadays, almost every building required a cooling system and most of them use active cooling which normally operates using electricity derived from non-renewable fossil fuel. This non-renewable fossil fuel price is increasing and it will cost a lot for the purpose of space cooling. The increase in energy consumption will also lead to high greenhouse gas emission. Instead of investing in non-renewable energy to achieve comfort, it is possible to use the natural environmental conditions to partially replace the active cooling energy requirements [77].

Energy consumption can be reduced if some of the cooling load is replaced by passive cooling techniques. Radiative cooling is a passive cooling method, which is based on long-wave radiation emission to reject heat to the night sky. Numerous studies on radiative cooling in buildings have been conducted, and most of the systems use air [80] or water [81] as a heat carrier. The system consists of a transmitter or a radiator panel. The radiator is made of a high conductivity flat-plate in which air or water is circulated and allowed heat to transfer from the heat carrier to the rooftop and hence radiated to the sky. The air or water is circulated using a low power density pump [82]. The system's effectiveness is dependent on certain parameters such as dew point temperature, ambient air temperature, wind velocity, and relative humidity [82]. While many studies have been conducted, its commercial exploitation is still untapped [83]. This research investigates the correlation between the radiative cooling power and the temperature difference between the ambient and the sky. The parameter that influences the effectiveness of the radiative cooling system is also examined.