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The cooling performance of a building integrated evaporative cooling system driven by solar energy

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ABSTRACT

The solar chimney is a passive cooling technique to enhance the natural ventilation of buildings. The effect is, however, limited under hot and humid climatic conditions. In the study, the solar chimney was accompanied by a dew-point evaporative cooler. The dew-point evaporative cooler was integrated with the ceiling of a building. The air flow induced by the solar chimney was predicted by simulation, and the cooling effect of the dew-point evaporative cooler was also analyzed by heat and mass transfer simulation. The results showed that the system was capable of coping with internal heat gains of an ordinary office building. In addition, the optimal geometry of the evaporative cooling channel was revealed.

1. Introduction

Buildings are large energy consumers in urban areas. In Japanese case, for instance, approximately one-third of primary energy is consumed by residential and commercial buildings [1]. The heating of space is dominant for energy consumption in residential buildings because the traditional Japanese houses are made of wood, and kerosene or gas heaters are used in those houses. On the other hand, the cooling demand is dominant in commercial buildings, especially in office buildings, because of high-insulated and air-tight construction as well as increased office automation equipment. In the context of energy and environmental conservation, the solar heating/cooling is one of the most desirable schemes, one of technological challenges of which is the passive cooling technique in hot and humid climate.

The passive cooling can be defined as the cooling method without active mechanical devices such as pumps and fans, and the provision of cooling relies mainly on the air flow caused by the buoyancy[2]. Solar chimney, Trombe walls, and double facades are devices to induce the air flow by the stack effect, and the enhanced natural ventilation by those devices will deliver the cooling effect [3–7]. The natural ventilation may, however, harm the thermal comfort of buildings if it is implemented in hot and humid climate because the temperature and humidity of outdoor air are much higher than those of the air-conditioned room during daytime. Even at night, it is not rare in Japan that the outdoor air temperature exceeds 25 °C throughout the night during the summer season.

One way to cool the outdoor air before it is supplied to the space is the evaporative cooling. The evaporative cooling technique can be used either with active systems or with passive systems. The studies of evaporative cooling for passive systems are not many, however, and the technology to integrate it with building structure is still under development [2]. Raman et al. [8] tested passive solar systems, which provided heating, cooling and ventilation, in composite climate including hot-dry, hot-humid and cold climate. It was presented that the passive system, which consisted of a south wall collector and a roof duct with evaporative cooling surface, moderated the temperature variation of the room, and the room temperature was kept around 30 °C when the ambient temperature was 42 °C at maximum during the summer period. Chungloo and Limmeechokchai [9] conducted performance measurement of a solar chimney combined with a water sprayed roof. The results showed that the combination of the two passive measures decreased the room air temperature by 2.0–6.2 °C compared with the ambient temperature. Maerefat and Haghighi [10] investigated a system with a solar chimney and an evaporative cooling cavity by using a mathematical model. The effects of the geometrical dimensions as well as of the ambient conditions on the cooling performance were analyzed, and the results showed that the proposed system was capable of improving the indoor conditions even with low solar intensity of 200 W/m^2 and high ambient temperature of 40 °C. The room air temperature strongly depended on the relative humidity of the ambient air, however. They concluded that the system provided comfortable indoor air conditions at high ambient temperature with the relative humidity lower than 50%.

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Nomenclature

A	area (m^2)
a	channel height (m)
C_c	contraction coefficient
C_d	discharge coefficient
c_p	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
d	hydraulic diameter (m)
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
H	height (m)
h	enthalpy ($\mathrm{J\,kg^{-1}}$)
hr	hour from midnight (h)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
L	length (m)
$\dot{m}$	mass flow rate ($\mathrm{kg\,s^{-1}}$)
P	pressure (Pa)
$\dot{Q}$	heat load (W)
$\dot{q}$	heat flux ($\mathrm{W\,m^{-2}}$)
$\dot{q}_C$	convective cooling load ($\mathrm{W\,m^{-2}}$)
$\dot{q}_R$	radiative cooling load ($\mathrm{W\,m^{-2}}$)
r	latent heat of water ($\mathrm{J\,kg^{-1}}$)
S	solar radiation ($\mathrm{W\,m^{-2}}$)
T	temperature (K)
t	temperature (°C)
u	velocity ($\mathrm{m\,s^{-1}}$)
$\dot{V}$	volume flow rate ($\mathrm{m^3\,s^{-1}}$)
W	width (m)
X	humidity ratio ($\mathrm{kg\,kg^{-1}}$)
X^*	humidity ratio of saturated air ($\mathrm{kg\,kg^{-1}}$)
z	position (m)

Greek symbols

α	convective heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
α_m	mass transfer coefficient ($\mathrm{m\,s^{-1}}$)
β	radiative heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
ϵ	emissivity
λ	friction loss coefficient
ρ	density ($\mathrm{kg\,m^{-3}}$)
σ	the Stefan-Boltzmann constant ($\mathrm{W\,m^{-2}\,K^{-4}}$)
ζ	loss coefficient

Subscripts

a	air or outdoor air
C	solar chimney
c	ceiling
DA	dry air
d	dry channel
dp	dew point
f	air in the solar chimney
g	glass
i	inlet
M	the M-Cycle
o	outlet
p	heat transfer plate
r	room
rev	reverse section
s	sky
s1, s2	water absorbing sheet
w	wall or wet channel
wind	wind

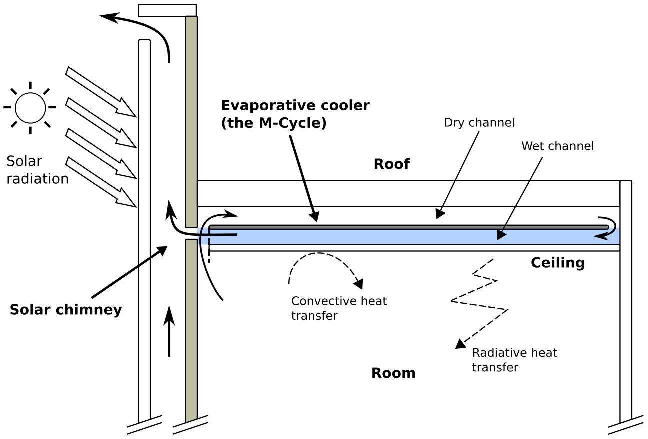

Fig. 1. The solar chimney driven evaporative cooling system integrated with the ceiling.

The purpose of the study is to develop a passive cooling device that will effectively reduce the cooling load of main air conditioners under hot and humid climatic conditions. The authors have proposed the building integration of a passive cooling system that consisted of a solar chimney and a dew point evaporative cooler [11]. This article reports the simulation of the cooling performance of the system with a modified design.

2. The system description

2.1. The building integrated solar cooling system

Our attempt is the integration of the solar cooling system into architecture. Fig. 1 depicts an overview of the building integrated evaporative cooling system and the direction of the air movement. The building is featured with a solar chimney that is attached to the south-facing wall. The evaporative cooler is integrated with the ceiling panel so that the wet channel is adjacent to the room side. The evaporative cooler is called the M-Cycle [12]. In our previous design, the dry channel of the M-Cycle was adjacent to the room to avoid problems that may arise from water leakage and penetration. The design was, however, inferior to the present design in the cooling effect.

The air inside the solar chimney is heated by the solar radiation, and the upward flow is generated due to the stack effect. The upward flow inside the chimney induces the air movement in the room. By connecting the air exit of the evaporative cooler with the inlet of the solar chimney, the air travels through the evaporative cooler before it flows the solar chimney. The inlet air duct of the evaporative cooler can be connected either to the room or to the outdoor. In hot humid climate, the inlet air of the evaporative cooler should be the conditioned room air so that the temperature of the ceiling panel is lower than the room air temperature. In this case, the cooling effect is owing to the dehumidified air by the room air conditioner, and the system assists the room air conditioner by reducing the cooling load. If the outdoor air is moderate in terms of temperature and humidity, the inlet air to the evaporative cooler can be the outdoor air. The system will provide cooling without any dehumidification work.

2.2. The dew point evaporative cooler

The evaporative cooler is a device to lower the air temperature by the latent heat of water. The water as a refrigerant evaporates by taking heat from the working air, and hence the working air is cooled and humidified. The working air has a potential to contain