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Solar chimney integrated with passive evaporative cooler applied on glazing surfaces

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ABSTRACT

This study investigates the performance of a hybrid system applied on glazing surfaces for reducing the space cooling load and radiation asymmetry. The proposed system combines the principles of passive evaporative cooling with the natural buoyant flow in solar chimneys to entrain outdoor air and attenuate the window surface temperature. A predictive heat and mass transport model combining the evaporative cooler, glazing section, solar chimney and an office space is developed to study the system performance in harshly hot climates. The developed model was validated through experiments conducted in a twin climatic chamber for given ambient temperature, humidity, and solar radiation conditions. Good agreement was found between the measured and the predicted window temperatures and space loads at maximum discrepancy lower than 4.3%.

The proposed system is applied to a typical office space to analyze its effectiveness in reducing the window temperature, the space load and radiation asymmetry, while maintaining the indoor comfort conditions. Results have shown that the system is reduced the space load by −19.8% and attenuated the radiation asymmetry significantly for office spaces having window-to-wall ratio of 40% in climate of Riyadh, KSA. The system performance diminished when applied in locations suffering from humid weather climates.

1. Introduction

Designing large glazing areas has become an essential feature of modern architecture and very common in office spaces. They improve the building's aesthetics, enhance the visual comfort by transmitting more natural lighting and increase the productivity of workers due to the bright working environment. This even led to the design of buildings with fully-glazed facades. However, among all the components of the building envelope, glazed surfaces are the most critical due to their weak thermo-physical properties that are easily overcome by outdoor conditions [1], and have been proven to account for 39% of the building energy performance [2].

The space load portion caused by windows is of two types; radiation transmitted through the window transparent surface and heat dissipated by solar absorption. The transmitted radiation is absorbed by the internal surfaces and causes an increase in the space air temperature and cooling load. On the other hand, the absorbed solar radiation causes a further increase in the window temperature leading to an asymmetrical radiative environment where thermal comfort requirements are sacrificed due to the exposure to high surface temperatures [3]. Reducing the space load and resulting radiation asymmetry due to windows was studied by many researchers. Antoun et al. [4] tackled this problem by changing the air distribution system to coaxial personalized ventilation. The ability of the system to localize air mitigated the thermal tension and uncomfortable sensation due to the radiative asymmetrical field and led to 36% of energy savings when compared to a mixing ventilation system. However, changing the air distribution system is not easily retrofitted in buildings and inevitably costly to implement.

Alternatively, the window performance and its effect on energy consumption has become a focal research topic. Kontoleon [5] studied different methods on reducing solar transmission through windows by considering the building orientation and facades on which windows are installed. It was found that up to 25% of the cooling energy is saved when the fully-glazed façade orientation is changed to the north direction. Nonetheless, the technique of changing the window orientation is unfeasible in existing buildings and may be practical in new buildings only. Other

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Nomenclature

c_p	Specific Heat (J/kg·K)
F	View Factor
g	Gravity (m/s^2)
f	Friction Loss Coefficient
H	Height (m)
h_c	Heat convection coefficient (W/m^2·K)
h_m	Mass convection coefficient (m/s)
h_{fg}	Latent Heat of Water (J/kg)
k	Thermal Conductivity (W/m·K)
$\dot{m}$	Mass Flow Rate (kg/s)
Q	Solar radiation (W/m^2)
q_{rad}	Radiative heat exchange with the space (W/m^2)
T	Temperature (°C)
t	Thickness (m)
u	Velocity (m/s)
W	Width (m)
w	Humidity ratio (kg/kg)
w^*	Humidity ratio of saturated air (kg/kg)
y	Height position (m)

Greek Symbols

ρ	Density (kg/m^3)
α	Surface absorptivity
τ	Surface Transmissivity
ε	Surface Emissivity
σ	Stefan Boltzmann constant (W/m^2·K^4)
β	Thermal Expansion Coefficient (K^{-1})

Subscripts

c	Convection
ch	Chimney
i	In
m	Mass
o	Out
og	Outer Glass
r	Radiation
wat	Water
win	Window

researchers have considered changing the window materials to ameliorate its performance. Some found that traditional absorptive glazing materials available in the colors of bronze and grey [6], vanadium dioxide thermochromic glass windows [7] and near-infrared electrochromic glass windows [8] managed to reduce solar radiation transmission and diminish the cooling energy consumption. In fact, windows with enhanced thermal and optical properties for reductions in heat and radiation entrance were found to reduce the cooling energy index by 40% in office spaces [9]. Moreover, heat passage through triple and quadruple pane windows has also been studied through computational fluid flow analysis and it was found that using multiple pane windows slows down the flow in the window cavities and also acts as a radiation shield resulting in large energy savings [10]. Additionally, the effect of adding phase-change materials (PCM) to windows on the dynamic heat transfer was found to reduce the heat entering the building by 18.3% for a typical summer day in China [11]. Although these alternative research methods have improved the window performance and managed to reduce the radiation and heat entrance to the space, they either do not incorporate passive systems or are expensive to adopt and unsustainable on the long run. This is why searching for alternative passive techniques for reducing the window temperature was deemed necessary.

One promising passive technique to reduce the window surface temperature was the design of single and dual airflow windows [12–14]. These windows allow air passage through their cavities and use solar heat as the driving force. During cooling seasons, indoor air driven by buoyant forces is entrained into the window cavity to reduce its surface temperature before getting exhausted. Yet, this mode imposes additional ventilation load of fresh air to the space to compensate for the air exhausted through the window. On the other hand, avoiding extra ventilation load is achieved by introducing windows with outdoor air curtain mode where moderate outdoor air is entrained into the window cavity to attenuate any increase in its surface temperature. However, this raises several limitations on the effective operation of this mode at high outdoor temperatures. In places where outdoor temperatures are very high, any heat exchange with outdoor air does not diminish the window temperature and may eventually have a counter effect in increasing the space cooling load.

Consequently, this problem highlights the need for innovative passive design strategies to enhance reductions in the temperature of glazing surfaces with no additional ventilation or energy demands. These strategies should be feasible in existing buildings and practically applicable in countries suffering from hot climates. In this study, the proposed research system is a combination of a passive evaporative cooler and a solar chimney and provides means of reducing the window temperature by cooling its surface through natural flow of outdoor air. A numerical model for the entire system is developed, validated experimentally and applied in a case study to assess its effectiveness in reducing the space cooling load and radiation asymmetry.

2. System description

The proposed system is composed of three main components; evaporative cooler, glazing section and solar chimney located consecutively above each other and applied on windows in typical office spaces as shown in Fig. 1(a). The solar chimney, which is composed of an absorptive material on the outer side and insulated on the back side, drives the airflow in the entire channel; as it is heated by solar radiation, buoyancy raises the air due to stack effect. As air is being dragged upwards, it passes through the evaporative cooler and the glazing section located respectively below and in front of the window. The evaporative cooler consists of a vertical rectangular channel with four water absorbing sheets installed along its height as well as a small reservoir and a pump that ensure continuous water supply to these sheets. This water can be provided from condensate drain of the space air-conditioning systems [15]. The evaporative cooler is assumed insulated from the outer surfaces to eliminate the effect of solar radiation. The glazing section consists of the window installed in a space and an outer glazing layer installed in front of it and closed from both sides so that air can freely move in the vertical direction only.

The whole psychrometric process of the air in the proposed system is shown in Fig. 1(b). Outdoor air at State 1 enters the evaporative cooler where it is cooled and humidified simultaneously as it exchanges heat and mass with the water sheets until it reaches State 2 at the inlet of the glazing section. As air passes through this section, it extracts heat from the outer glass and