Solar Energy 169 (2018) 187–195

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Performance assessment of evaporatively-cooled window driven by solar chimney in hot and humid climates

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ARTICLE INFO

Keywords:
Evaporatively-cooled window
Solar chimney
Solar radiation
Window temperature
Space load and energy savings

ABSTRACT

This study investigates the application of the evaporatively-cooled window system in hot and humid climates and assesses its seasonal performance and benefits in terms of energy savings. The validated system is a hybrid combination of solar chimney, window and evaporative cooler that induces a natural buoyant flow originated by direct solar radiation application.

As proper solar radiation data is critical in applying solar-driven technologies, an on-site weather station was established in Qatar for the measurement of several meteorological parameters for the entire year of 2016. The measurements represent actual validated data recordings in the city of Doha, mimicking harshly hot and humid weather conditions. The simple application of the evaporatively-cooled window on a typical office space subjected to such driving weather conditions was found to save 8.8% of the space total annual energy demand. During the summer, the performance of the system was enhanced by saving 11.3% of the space total daily heat gain. However, the benefits of the system diminished and were sometimes unfavorable during the winter due to its limited cooling performance caused by high humidity.

1. Introduction

A large portion of the energy produced worldwide is consumed in residential and commercial buildings (Al Touma et al., 2016a). For this reason, more awareness on the adoption of energy-reduction practices, including the usage of solar-driven technologies, are raised to mitigate this increasing consumption especially in hot climates (BP, 2012). In Qatar, the country currently ranked third in the Middle East in terms of electrical energy consumption (US Department of Energy, 2016), residential and commercial building alone account for over 60% of the total annual energy demand (Ayoub et al., 2014). This highlights the urgent necessity to incorporate mitigation strategies in the country to trim down the energy costs and abide by the National Vision 2030.

As windows are commonly known as the weakest component of the building thermal envelope and consequently the most contributive towards the space load (Al Touma et al., 2016a), traditional energy conservation strategies have focused on the reduction of either solar transmission or solar absorption through these glazed surfaces. In the purpose of reducing radiation transmission into spaces, the selection of the proper orientation of the fully-glazed façade in new buildings was studied and found to save up to 25% of its cooling energy demand (Kontoleon, 2012). Similarly, the appropriate selection of the window material depending on the outdoor climatic conditions managed to moderate radiation transmission into the space and consequently decreased its cooling energy consumption (Tsikaloudaki et al., 2012a, 2012b; Li et al., 2015; DeForest et al., 2013; Ye et al., 2014). However, the first suggested mitigation method is found to be unfeasible in existing buildings whereas the latter is expensive to adopt.

On the other hand, means of decreasing the effect of the windows solar absorption included the design of multiple-pane windows (Arici et al., 2015), the addition of phase-change materials (PCM) to window gaps (Zhong et al., 2015), and the installation of single and dual airflow windows (Chow et al., 2009; Gosselin and Chen, 2008). More importantly, the addition of shading devices (blinds, shutters, screens) on the window external or internal surfaces was found to simultaneously diminish radiation transmission and solar absorption significantly (Al Touma et al., 2016a; Li et al., 2015, 2004, 2008; Lee et al., 2013; Tzempelikos and Athienitis, 2005). Although of these systems were variably successful in achieving their goals, the PCM-filled windows and the shading devices may over-obscure the outside view, which is the primary function of windows, whereas the airflow windows may perform adversely in harshly hot and humid conditions. In addition, none of these devices composes a controlled technology driven by a renewable source of energy. This sheds lights on the necessity of having alternative passive applicable techniques, one of which is the installation of solar chimney integrated with passive evaporative cooler on the

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https://doi.org/10.1016/j.solener.2018.04.046
Received 5 October 2017; Received in revised form 5 February 2018; Accepted 22 April 2018

window external surface, or the so-called evaporatively-cooled window (Al Touma et al., 2016b; Hweij et al., 2017). This system, which could be easily installed on existing buildings, is driven by the solar radiation intensity hitting the window surface and reduces the radiation transmission and absorption into the space simultaneously.

Nonetheless, technologies driven by solar energy are highly dependent on the radiation intensity hitting their surfaces as well as on other meteorological parameters such as outdoor temperature, humidity, wind speed, wind direction and dust. In fact, the performance of the evaporatively-cooled window was found to diminish with reduced radiation intensity and increased humidity conditions (Al Touma et al., 2016b). Hence, for the proper implementation of these mitigation methods, accurate data for all relevant outdoor parameters is crucial.

Ground measurements of the Global Horizontal Irradiance (GHI), diffuse horizontal irradiance or direct normal irradiance across many cities in the Arabian Gulf peninsula have been the scope of many research projects (Al-Hinai and Al-Alawi, 1995; Islam et al., 2009; El-Sebaii et al., 2010; Zell et al., 2015). In Qatar, old data of direct and diffuse radiations were measured and correlated to empirical equations, but results seem very outdated (Abdalla and Baghdady, 1985). More recently, the spatial and temporal variations in GHI in Qatar have been investigated (Bachour and Perez-Astudillo, 2014; Perez-Astudillo and Bachour, 2015). However, none of the aforementioned studies has ever dealt with radiation intensities on vertical surfaces with different orientations, which are the driving force of solar-driven technologies applied on these surfaces, such as in the case of the evaporatively-cooled window. Therefore, the measurement of GHI only becomes unhelpful as it does not reflect the percentage share of direct and diffuse solar radiations that are necessary in calculating the radiation hitting vertical surfaces.

In the present study, ground measurements of the GHI, the global solar radiation hitting vertical surfaces (GVI) oriented towards the south, temperature and relative humidity are measured over a period of one year in Qatar and validated with data available in literature. Then, the hourly recorded data is applied on the evaporatively-cooled window driven by a solar chimney of a typical office space to assess its performance in hot and humid climates. This system, which was previously developed, modeled and validated, was found to reduce the window surface temperature in hot climates, with more reductions in representative dry conditions than in humid conditions (Al Touma et al., 2016). In addition, the effect of installing this window on human thermal comfort has been also studied and quantified (Hweij et al., 2017). The study investigates the annual performance of evaporatively-cooled window subjected to hourly driving conditions as actually recorded in the State of Qatar.

2. Methodology

2.1. Description of evaporatively-cooled window

A schematic of the evaporatively-cooled window is shown in Fig. 1. This system is applied on windows of typical office spaces and is composed of three main components: the solar chimney section above the window height level, the glazing section on the window level and the evaporative cooler placed below the window. All three components are located consecutively above each other and are closed on the sides so that air can move from one component to the other in the vertical direction only.

The solar chimney is made of an absorptive material from the outer side and an insulative material from the back side. The back insulation prevents any heat exchange occurring in the channel from dissipating into the space. Similarly, the glazing section is made of the window, originally installed on the office space, and an outer glazing layer installed in front of it. On the other hand, the evaporative cooler consists of water absorbing sheets all along its inner surface and is insulated from the outer side so that solar radiation does not interfere in any heat

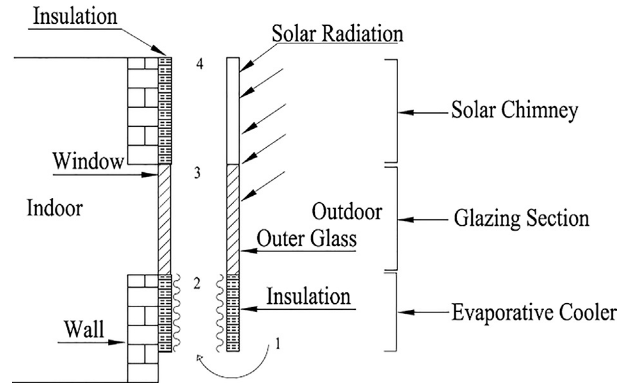

Fig. 1. Schematic of the evaporatively-cooled window.

transfer occurring in this section of the channel.

As for the movement of air inside the system, once solar radiation strikes the solar chimney outer surface, a difference in air temperature initiates a buoyancy-driven upward airflow in the entire channel. As air is being dragged out, outdoor air (State 1) is entrained at the bottom of the system to enter the evaporative cooler where it exchanges sensible and latent heats. Then, the cooled air (State 2) passes through the glazing section where it extracts heat from the window and outer glass and reduces their surface temperatures (State 3). Later, the air repasses through the solar chimney where it is exhausted out of the entire system (State 4).

2.2. Modeling and validation of evaporatively-cooled window

The evaporatively-cooled window has been previously assessed through a simplified one-dimensional steady-state heat and mass transfer model along the vertical direction of the channel (Al Touma et al., 2016b). This model uses the differential form of the equations to describe the air temperature and humidity distribution states at different heights. In addition, it assumes constant window, outer glass and solar chimney surface temperature along their heights resulting in the use of energy balance equations in the integral form. Schematics explaining the modeling of the evaporative cooler and glazing section are shown in Fig. 2.

The developed model assumes forced convection in the evaporative cooler and glazing section of the channel by ensuring values of Grashof number to Reynolds number squared smaller than 0.1 in both of these two sections. Hence, the model does not consider any downward circulative air in the evaporative cooler or upward heated air in the glazing section. Furthermore, the model also considers a channel gap that is much smaller than its width, which allows the system to be

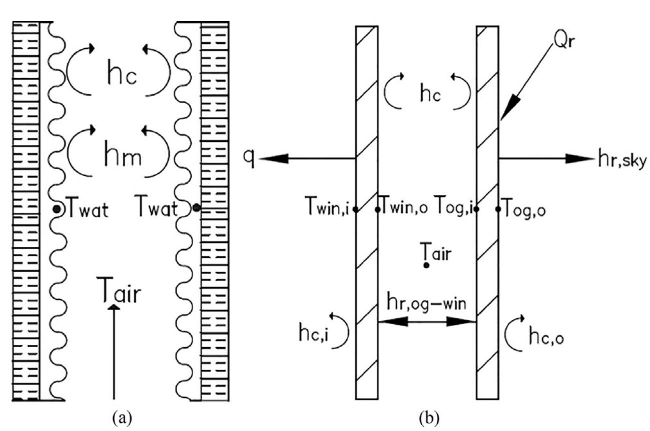

Fig. 2. Schematics explaining the modeling of the (a) evaporative cooler and (b) glazing section.