

Passive Cooling of Glazing Surfaces Using Solar Chimneys

A. Al Touma¹, K. Ghali¹ and N. Ghaddar¹

¹ Department of Mechanical Engineering

American University of Beirut, P.O. Box 11-0236, Beirut 1107-202, Lebanon

Phone number: +961 1 340340, Ext: 3438, e-mail: aga32@mail.aub.edu, ka04@aub.edu.lb, farah@aub.edu.lb

Abstract

The aim of this project is to reduce the cooling loads in spaces by decreasing the window temperature and solar radiation entrance through the use of a passive evaporative cooler combined with a solar chimney and with no additional energy consumption. The cooler provides heat and mass exchange that render the air capable of cooling the space in front of the window. On the other hand, the solar chimney works based on principles of buoyancy-driven natural flows. Mathematical models of the evaporative cooler, glazing section, solar chimney are developed and integrated with a space model in an algorithm where the entire system is tested under different outdoor temperature and solar radiation conditions. As the outer glass temperature typically represents the temperature of the window without the installation of this system, reductions of 8% to 12% in the window temperatures were seen for an outdoor temperature of 30°C and a solar radiation of 300Wm² and for small chimney sizes.

Key words

Key words: Solar Chimney, Evaporative Cooler, Integrated System, Window Temperature

1. Introduction

All spaces are now equipped with Heating, Ventilation and Air-Conditioning (HVAC) systems that allow proper control of the heating and cooling set-point temperatures. The building envelope is what surrounds the space from the outer environment. It consists of walls, roof, ceiling, windows, materials, insulation and so on. Extreme care has to be taken when designing the building envelope due to its importance on the lifecycle of the building. Windows are known to be the weakest components of the building envelope due to their thermo-physical properties that are vulnerable to outdoor climatic conditions [1]. Significant amount of solar radiation and heat enter the building through windows during the summer and a considerable amount of heat leaks out during the winter, which causes an increase in the cooling and heating loads, respectively. For instance, the windows' contribution in the building energy performance was around 39% of the space total cooling load in the hot climate of Texas for a space that had a Window-to-Wall Ratio (WWR) of 18% only [2].

The space load that is caused by windows could be divided into two: direct solar radiation transmitted into the space and radiation absorbed by the envelope materials. Extensive researches have been conducted in the purpose

of improving window physical and optical properties. Tsikaloudaki et al studied the effect of window thermal heat transfer coefficient, solar transmittance, frame fraction and pane gap width on the reduction in energy consumption [3]. Vanhoutteghem et al considered the possibility of changing the building orientation and the facades on which windows are installed in a manner that reduces the amount of solar radiation entering the space [4]. Arici et al considered the heat passage through multiple pane windows and their effect during the summer in Turkey [5]. It was found that increasing the number of window panes slows down the flow of heat in the cavities and acts as a radiation shield yielding energy savings of 50% and 67% when double pane windows are replaced by triple-pane and quadruple pane windows.

Although designing high-performance windows turned out to be successful, yet they were unable to deteriorate the window temperature to reduce its effect on space loads. One mitigation was the design of single and dual airflow windows that work based on free and forced convection between layers of glass that capture solar heat. Single airflow windows have been designed to work on four modes: supply, exhaust, indoor air curtain and outdoor air curtain [6]. In both the supply and the indoor air curtain modes, the solar heat is used to preheat the air passing through the window to reduce the heating load in cold seasons. In contrary, the solar heat is used to extract the excess of heat around windows in the exhaust and outdoor air curtain modes during the hot seasons. Similarly, dual airflow windows consisting of triple-glazed units were subject to many studies [6, 7].

Although all of the aforementioned methods have caused some decreases in the buildings' energy consumption, they are often either unpractical in existing buildings or expensive to adopt. Hence, this study considers means of reducing the window temperature passively through the natural flows without any additional energy consumption and without sacrificing the thermal comfort of the occupants of the indoor air quality inside the space.

2. Design of Proposed System

The combined system of passive evaporative cooler and solar chimney is shown in Fig. 1. What drives the flow of the entire system is the solar chimney; as solar

radiation hits its outer surface, it induces a difference in temperature between the outdoor air and the air inside the chimney, which rises due to buoyancy forces. As it moves upwards, air passes through the evaporative cooler where it exchanges heat and mass with the water absorbing sheets installed along its height. Then, air reaches the glazing section, which is composed of a window and an outer glass layer, and extracts the heat accumulated within this small space until it reaches the solar chimney where it is once again dragged out of the system.

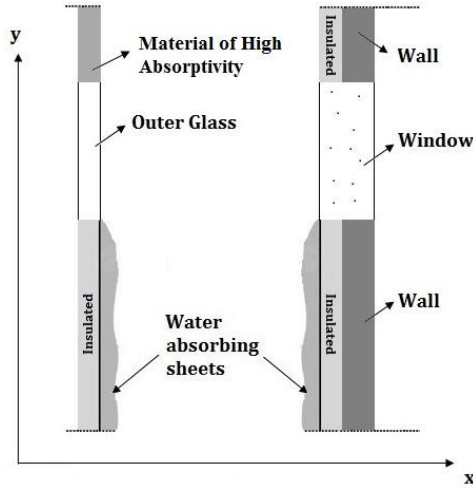


Figure 1: Passive evaporative cooler and solar chimney of the designed system.

Note that the system includes insulation layers on both sides of the evaporative cooler and on the space side of the solar chimney so that any heat transfer in these directions is neglected.

3. Mathematical Formulation

This section describes the mathematical models adopted for the suggested system.

A. Evaporative Cooler

A schematic of the evaporative cooler is shown in Fig. 2.

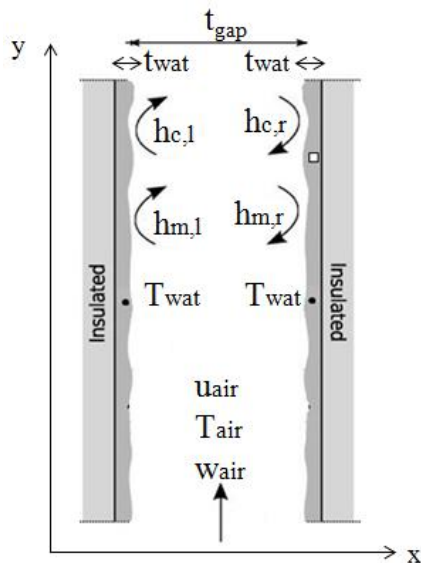


Figure 2: Passive evaporative cooler of the designed system.

Assuming that the air gap is much smaller than the width of the channel, the energy balance equations describing the temperature and humidity changes are:

$$\rho_{air} c_{p,air} u_{air} t_{gap} \frac{dT_{air}}{dy} = 2 \times h_c (T_{wat} - T_{air}) \quad (1)$$

$$u_{air} t_{gap} \frac{dW_{air}}{dy} = 2 \times h_m (w^* - W_{air}) \quad (2)$$

As for the water absorbing sheets, their energy balance equation is:

$$h_c (T_{air} - T_{wat}) + \rho_{air} h_m h_{fg} (w_{air} - w^*) = 0 \quad (3)$$

In Equations 1, 2 and 3, ρ is the density, c_p is the specific heat, u is the velocity, t is the channel gap, h_c and h_m are the heat and mass convection coefficient, h_{fg} is the latent heat of water and w^* is the humidity of saturated air.

B. Glazing Section

A schematic of the glazing section is shown in Figure 3.

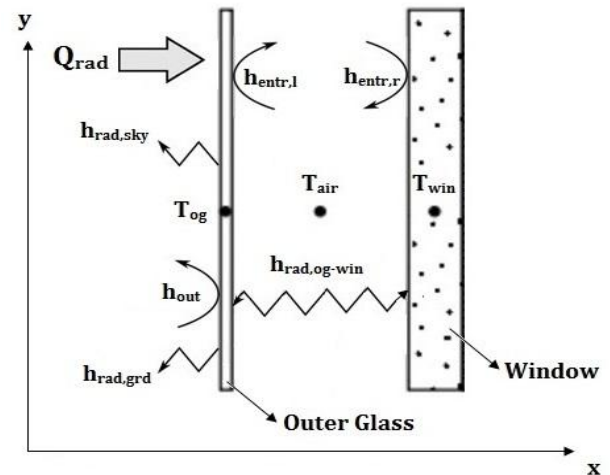


Figure 3: Schematic of the glazing section.

According to the stated assumptions, the glazing section is divided into three main sub-components: outer glass, air and window. The outer glass is subjected to direct solar radiation hitting its outer surface, convection with outdoor air, radiation exchange with the sky and ground from the outer environment, convection with the induced air and radiation exchange with the window. On the other hand, the induced air is subjected to convection heat exchange with the outer glass and the window simultaneously. Lastly, the window is subjected to solar radiation that has been transmitted through the outer glass, convection with the induced air, radiation exchange with the outer glass, convection with the room air and radiation exchange with the space surfaces. Their three energy balance equations are:

$$\alpha_{og} Q_r + h_{c,out} (T_{out} - T_{og}) + h_{r,sky} (T_{sky} - T_{og}) + h_{r,grd} (T_{grd} - T_{og}) + h_{c,air} (T_{air} - T_{og}) + h_{r,og-win} (T_{win} - T_{og}) = 0 \quad (4)$$

$$\rho_{air} c_{p,air} u_{air} t_{gap} \frac{dT_{air}}{dy} = h_c (T_{og} - T_{air}) + h_c (T_{win} - T_{air}) \quad (5)$$

$$\tau_{og} \alpha_{win} Q_r + h_{c,air} (T_{air} - T_{win}) + h_{r,og-win} (T_{og} - T_{win}) + h_{c,r} (T_r - T_{win}) + q_{rad} = 0 \quad (6)$$

In Equations 4, 5 and 6, α is the absorptivity, τ is the transmissivity, $h_{r,og-sky}$, $h_{r,og-grd}$ and $h_{r,og-win}$ are the radiation heat transfer coefficients of the outer glass layer with the sky, ground and the window respectively, and q_{rad} is the radiation exchange between the window and different surfaces in the space including walls, floor, ceiling, furniture, and so on.

The sky temperature model of Duffie and Beckman [8] has been adopted in this study and the ground temperature is assumed to be equal to the outdoor temperature. Nusselt number has been calculated using correlations of free convective flow and the heat and mass convection coefficients have been found accordingly assuming a Lewis number of unity [9]. Lastly, the radiation heat transfer coefficients were calculated in their simplified forms using the view factors between different surfaces [9].

C. Solar Chimney

Similar to the glazing section, energy equations were carried out for the solar chimney material and the air passing through its channel. Note that a reduction of one energy equation is noticed due to the installation of the insulation layer in the original model.

$$\alpha_{og} Q_r + h_{out} (T_{out} - T_{ch}) + h_{r,sky} (T_{sky} - T_{ch}) + h_{r,grd} (T_{r,grd} - T_{ch}) + h_{c,air} (T_{air} - T_{ch}) = 0 \quad (7)$$

$$\rho_{air} c_{p,air} u_{air} t_{gap} \frac{dT_{air}}{dy} = h_c (T_{ch} - T_{air}) \quad (8)$$

C. Flow Model

The solar chimneys flow model of Chen et al [10, 11] is adopted. The model assumes unidirectional upward flow of a vertical chimney with small gap-to-height ratio (less than 0.2). The volume flow rate is calculated by assuming a balance between stack pressure and pressure loss throughout the chimney. The model for the average flow rate depends of the buoyancy flux “B”, which is a function of the solar radiation intensity hitting the chimney surface area and the outdoor conditions, and a correlation for the pressure loss coefficients assuming a constant cross-sectional area.

$$\dot{V} = A \left(\frac{B}{2\psi} \right)^{1/3} \quad (9)$$

$$B = \frac{g Q_r H W}{\rho_{air} c_{p,air} T_{amb}} \quad (10)$$

$$\psi = \frac{A}{H} \left[f \frac{H}{2D_h} + \frac{1}{2} (c_{in} + c_{out}) \right] \quad (11)$$

In Equations 9, 10 and 11, A is the chimney cross-sectional area, g is the gravity, D_h is the hydraulic diameter of the channel and c_{in} , c_{out} and f are the pressure loss coefficient at the inlet, outlet and throughout the chimney.

C. Models Implementation

A MATLAB-based algorithm has been implemented to perform the energy calculations and find the temperature distributions over the system components. The algorithm starts with the required outdoor conditions to estimate the flow rate using the described model. It then uses the energy equations in the evaporative cooler to solve for the air temperature and humidity distribution along its height. At the end, it uses these values as boundary conditions for the glazing section that has outer glass, air and window temperatures initialized. This section undergoes an iterative process until the error between two iterations at any node is less than 0.1°C. Upon convergence, the solar chimney section similarly initializes the temperatures and undergoes a similar iterative process until the same temperature criteria is met.

Upon the implementation of the algorithm, it has been tested for the conditions described in Table 1.

Table 1: Simulation Parameter.

Parameter	Value
Outdoor Temperature	30 °C
Outdoor Relative Humidity	33%
Outdoor Global Solar Radiation	400 W/m ²
Evaporative Cooler Dimensions	0.6m x 0.8m
Glazing Section Dimensions	0.8m x 0.8m
Solar Chimney Dimensions	0.5m x 0.8m
Entire System Air Gap	7cm

4. Results and Discussion

The result of the simulation is shown in Fig. 4.

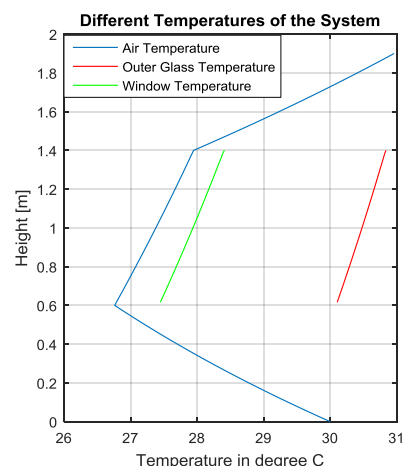


Figure 4: Temperature change in the entire system.

In the 0.6m high evaporative cooler, air gets cooled from a temperature of 30°C to 26.8°C by exchanging heat with the water sheets until it reaches the glazing section. In this 0.8m high section, air extracts the heat in between the outer glass and the window and its temperature increases back. In the solar chimney, air extracts much more heat due to the installation of the insulation layer and its temperature reaches around 31°C at the outlet. Note that the system has managed to render the window at a temperature relatively lower than that of the outer glass by around 2°C.

Parametric Study

Based on the conducted analysis, the effect of the channel gap has been studied for outdoor temperatures of 35 °C and 40 °C and for different solar radiation intensities ranging between 300W/m² and 700W/m². Results of the window temperature at a height of 0.4m (in the middle) are shown in Fig. 5. Note that the same system dimensions as in Table 1 were used.

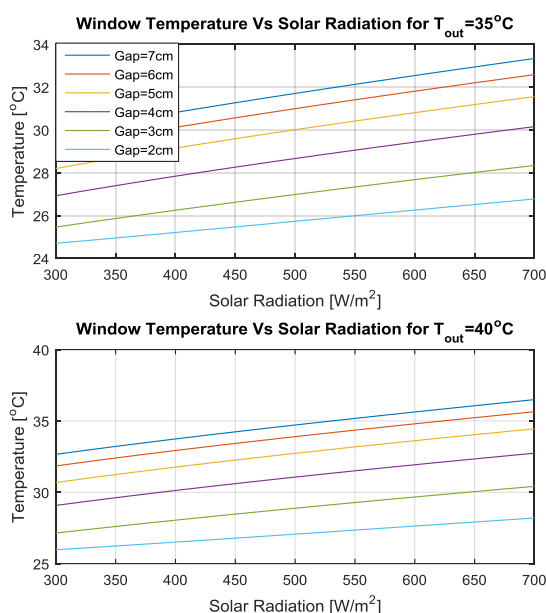


Figure 5: Window temperature Vs Solar radiation for different channel gaps.

As seen in Fig. 5, the window temperature decreases as the gap of the channel is smaller. This could be attributed to the fact that as the gap is smaller, the airflow in the entire channel is faster, and so becomes the heat extraction process. However, to better understand the effect of gap, the change in the window temperature with and without the installation of the suggested system should be analyzed. Since the outer glass temperature is relatively an estimation of how much the temperature of the window would be if the system has not been installed, the percentage reductions in temperatures between the window and the outer glass have been found and results are shown in Fig. 6. As it could be seen, the percentage reduction decreases as the channel gap decreases. In fact, having a smaller gap has a counter-effect in decreasing the flow of air and the effect of the solar chimney, which renders the two layers at temperatures relatively closer to each other. Regarding the outdoor conditions, it was noted that the

percentage reduction decreased as the solar radiation intensity increased, which reduced the system efficiency in serving its purpose. Lastly, the percentage reduction increased at a higher outdoor dry-bulb temperature. This is attributed to the enhancement of the evaporative cooler effect at higher outdoor temperatures that render the air more capable of extracting heat and reducing the window temperature.

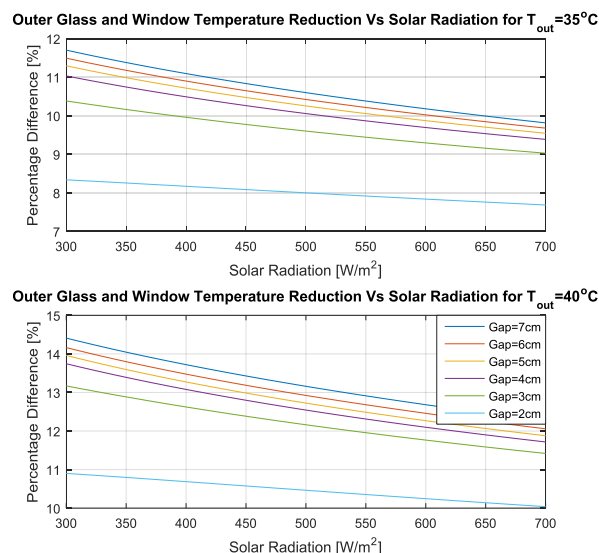


Figure 6: Percentage different in window and outer glass temperatures for different temperatures and solar radiations.

5. Conclusion

This study considered new means of reducing window temperatures passively and with no additional energy consumption. The system consisted of a passive evaporative cooler combined with a solar chimney and applied above and below glazing surfaces. Numerical models for each component of the system have been developed and integrated together. Simulations have proved the capability of the system to reduce the window temperature when compared to the outer glass layer. A parametric study has been conducted on the channel gap; it was shown that smaller gaps tend to increase the airflow velocity in the channel and reduce more the window temperature. When compared to the outer glass, smaller reductions in temperatures were seen as the gap is decreased. Higher reductions could be achieved by enlarging the evaporative cooler and solar chimney sizes.

6. References

- [1] E. M. Alawadhi, "Effect of an incompletely closed window shutter on indoor illuminance level and heat gain", in *Energy and Buildings*, 2015, 110, 112-119.
- [2] D. Chasar, N. Moyer, A. Rudd, D. Parker, S. Chandra, "Measured and simulated cooling performance comparison; insulated concrete form versus frame construction", in: *Proceeding in ACEEE 2002 Summer Study*, American Council for an Energy Efficiency Economy, Washington, DC, August, 2002.
- [3] Tsikaloudaki, K., Laskos, K., Theodosiou, T., & Bikas, D., "The Energy Performance of Windows in the Mediterranean Regions. *Energy and Buildings*", 2015, 92, 180-187.

- [4] L. Vanhoutteghem, G. Skarning, C. Hviid, S. Svendsen, "Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses", in *Energy and Buildings*, 2015.
- [5] M. Arıcı, H. Karabay, M. Kan, "Flow and heat transfer in double, triple and quadruple pane windows", in *Energy and Buildings*, 2015, 86, 394-402.
- [6] J.R Gosselin, & Q. Chen, "A dual airflow window for indoor air quality improvement and energy conservation in buildings", in *HVAC&R Research*, 2008, 14(3), 359-372.
- [7] J. Wei, J. Zhao, Q. Chen, "Energy performance of a dual airflow window under different climates", in *Energy and Buildings*, 2010, 42(1), 111-122.
- [8] Duffie, J. A., & Beckman, W. A. (1980). *Solar engineering of thermal processes* (Vol. 3). New York etc.: Wiley.
- [9] T. Miyazaki, A. Akisawa and I. Nikai, "The cooling performance of a building integrated evaporative cooling system driven by solar energy", in *Energy and Buildings*, September 2011, Vol. 43, Issue 9, Pages 2211-2218.
- [10] H. Jing, Z. Chen, A. Li, "Experimental study of the prediction of the ventilation flow rate through solar chimney with large gap-to-height ratios", In *Building and Environment*, 2015, 89, 150-159.
- [11] Z. Chen, P. Bandopadhyay, J. Halldorsson, C. Byrjalsen, P. Heiselberg, Y. Li, "An experimental investigation of a solar chimney model with uniform wall heat flux", *Building and Environment*, 2003, 38 (7), 893-906.