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Energy performance evaluation of an evaporative wind tower

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Abstract

The aim of this paper is to optimize the energy performance of cylindrical cross section evaporative wind towers as passive systems for thermal conditioning of urban spaces. Two theoretical models, a thermal model and a fluid model, have been developed to characterize the evaporative system and the tower design respectively. The thermal model evaluates the tower operation when the fan and the nozzles are working, giving as result the difference between the outlet temperature and inlet temperature. This model has been used to analyze the thermal response of the system to fluctuations in design parameters (water flow, air flow and absorption coefficient of the plastic). To that effect, three one-parametric and one multi-parametric optimization have been done. The fluid model describes the tower operation when the fan and the nozzles are not working, giving as result the wind behavior through the tower. Additional configurations of the wind tower have been evaluated: changing the number of the wind catcher openings, varying the height of the internal walls of the tower and modifying the geometry of the lower ventilation apertures.

Keywords: Evaporative wind tower; Open spaces; Energetic and fluid models; Optimization

1. Introduction

Outdoor public spaces are ecosystems where contact and interaction between people take place, and therefore play an important role in the distribution of space, energy and environment. These areas are characterized by climatic conditions such as temperature, solar radiation, humidity or wind, which affect people perception of cold and heat. However, it is unclear how these parameters influence the use of these areas since psychological adaptation or exposure time also affects this calculation (Nikolopoulou and Steemers, 2003). The improvement of the thermal conditions through the use of natural resources enhances the comfort levels of the cities (Gaitani et al., 2007), increasing their quality of life. Cities with continental climatology (warm and dry summers with high levels of solar radiation) promote the use of natural ventilation, evaporative systems and shading devices to reach higher thermal sensations in outdoor spaces.

One traditional technique to create natural ventilation inside buildings without convectional energy requirements is the wind tower (Mahmoudi, 2006; Khan et al., 2008). Its operation is based on air movements due to the pressure differences created by wind forces. In hot and dry climates, the potential of this system can be further increased by means of evaporative systems. These towers produce cooler ventilation flows due to the evaporation of the water into the dry air, which reduces the ambient temperature and increases the moisture content of the air (Givoni, 1994). Additionally, when the wind forces are too small to achieve an optimal operation of the tower, an auxiliary fan can be included in the wind tower design. However, this means an electric consumption.

Different designs have been analyzed to improve the efficiency of these systems (Bahadori, 1994). Many authors have analyzed the possibility of replacing conventional evaporative coolers with evaporative wind towers in areas

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Nomenclature

A	exchange area (m^2)
C_{pa}	specific heat capacity of dry air ($J\ kg^{-1}\ °C^{-1}$)
G	solar radiation absorbed by the plastic ($W\ m^{-2}$)
h_{ha}	enthalpy of humid air ($J\ kg^{-1}$)
$\dot{m}_{a,ap}$	air mass flow rate entering the wind tower ($kg\ h^{-1}$)
$\dot{m}_a$	air mass flow rate ($kg\ h^{-1}$)
$\dot{m}_{t,in}$	total air flow rate inside the wind tower ($kg\ h^{-1}$)
RH	relative humidity (%)
T_{amb}	inlet dry bulb temperature (°C)
T_{pl}	temperature of the plastic envelope (°C)
T_{ZONE3}	temperature in Zone 3 of the wind tower (°C)
U_{fl}	global heat transfer coefficient of the plastic envelope ($J\ °C^{-1}\ m^{-2}$)
V_v	wind velocity ($m\ s^{-1}$)
A_{ap}	wind catcher aperture area (m^2)
Cw	percentage of caught wind (%)
h_{pl}	heat transfer coefficient of the plastic envelope ($J\ m^{-2}\ °C^{-1}$)
h_w	enthalpy of water ($J\ kg^{-1}$)
$\dot{m}_w$	evaporate water rate ($kg\ h^{-1}$)
$\dot{m}_{ha}$	humid air mass flow rate ($kg\ h^{-1}$)
$\dot{m}_{v,out}$	ventilation air flow rate at the exit of the wind tower ($kg\ h^{-1}$)
$T_{AirTree}$	temperature inside the structure of the 'Air Tree' (°C)
T_{out}	outlet dry bulb temperature (°C)
T_{fl}	temperature of the moist air inside the wind tower (°C)
T_{wb}	wet bulb temperature (°C)
U_v	fluid global heat transfer coefficient ($J\ °C^{-1}\ m^{-2}$)
W	humidity ratio (kg_w/kg_{air})
Greek letters	
ρ	mass density ($kg\ m^{-3}$)
η_v	ventilation efficiency of the wind tower (%)
η	efficiency of the wind tower (%)

without an electricity grid. One of them is a residential building designed by Cunningham and Thompson (1986) and constructed in Tucson, Arizona. The prototype was composed by a solar chimney on one side and an evaporative downdraft tower on the opposite side. Few years later, Givoni (1993) completed a theoretical and experimental study on this building, and developed a model to estimate the temperatures inside lightweight residential buildings coupled to evaporative wind tower systems.

There are several published works that evaluate the use of evaporative wind towers to cool open or semi-open spaces. One of these works was carried out by the University of Seville and CIEMAT at the Universal Exposition of Seville in 1992 (Guerra et al., 1994). The pavilions and the areas connecting them were thermally conditioned by several evaporative systems: evaporative wind towers, water ponds, green areas, etc. The "shower" tower constructed to cool down the outdoor rest areas was originally developed by Givoni (1997), and consisted of an open shaft with showers at the top and a collecting pond at the bottom. All the evaporative wind towers were evaluated in real conditions of use, giving as results low temperature drops due to the rapid dispersion of the cold air stream. Another experiment was carried out at The Center for Desert Architecture and Urban Planning from the Ben-Gurion University of the Negev. The researchers constructed and analyzed an evaporative wind tower to improve the comfort levels reached in a semi-open space (Etzion et al., 1997). Continuing on this line, an evaporative wind tower was built in Negev Sde Boquer which was evaluated experimentally. The study evaluated the performance of the wind tower with and without the evaporative systems (Erell et al., 2008).

In the last years, the European Commission has been promoting projects to improve the thermal conditions of urban areas in Mediterranean countries. An example of this initiative is the 'ECO-Valle Mediterranean Verandahways' project, which is funded by the LIFE Program and is sponsored by the Empresa Municipal de la Vivienda y Suelo de Madrid (www.emvs.es). This project tries to increase the comfort levels and drive a social sustainability by the use of bioclimatic strategies, in a boulevard of Madrid during the summer months. With this objective, Ecosistema Urbano Office Architects (website Ecosistema Urbano) designed and built three cylindrical structures called 'Air Trees', which combined evaporative systems, ventilation, vegetation and shading devices. The case study of this work is one of the three 'Air Trees', more specifically the northern 'Air Tree', which was designed to improve the thermal conditions of the surrounding open areas by means of evaporative wind towers.

2. Case study

The northern 'Air Tree' was designed and constructed to improve the thermal comfort levels in the pedestrian zone of the boulevard, using three passive techniques adapted to the weather conditions of Madrid: evaporative cooling, forced ventilation and shading devices. The installation is composed of a metallic structure with a cylindrical cross section of 25 m of diameter and a total height of 18 m. Sixteen wind towers are uniformly distributed around the structure (Fig. 1). All the installation is surrounded by a plastic envelope made of polyethylene, with high resistance