Energy and Buildings 66 (2013) 211–221

Contents lists available at ScienceDirect

Energy and Buildings

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

A study of air flow and heat transfer in building-wind tower passive cooling systems applied to arid and semi-arid regions of Mexico

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ARTICLE INFO

Article history:
Received 14 December 2012
Received in revised form 23 May 2013
Accepted 9 July 2013

Keywords:
Wind tower
Passive cooling
Thermal comfort
Conjugate CFD solution
Heat transfer

ABSTRACT

Wind towers have been traditionally used as passive climate solution in Middle East countries. They are massive structures that capture local wind mainstream in order to force fresh air to circulate inside the building promoting thermal comfort to occupants. This work analyzes air flow distribution in five different configurations of coupled systems building-wind tower. The objective is demonstrating this concept is technically feasible for producing thermal comfort in popular houses built in arid and semi-arid climate conditions in Northern Mexico. The study is based on numerical simulations, conducted with RANS method on a commercial program Fluent. Simulations of conjugate coupled solutions between air flow and heat conduction through ceiling, floor and walls were carried out in steady state and turbulent regime with appropriate boundary conditions. Analysis of results focused on air flow circulation inside the building lead to selecting the best configuration, which was tested by conjugated flow distribution and heat transfer in buildings located in Monterrey, Nuevo Leon. Contours of velocity and temperature for the selected configuration demonstrate an environment of comfort for the specific site climate conditions. The remainder is devoted to emphasize that wind-tower as passive cooling method enables electricity savings, otherwise spent in conventional air conditioned systems in Monterrey.

1. Introduction

Historically, societies in Central and Middle East have developed creative and traditional architectural solutions for facing high temperature habitat conditions. Extreme climate conditions in arid and semi-arid regions lead to concepts like the wind tower [1–5]. This is a passive cooling system typically used in places like Yazd in Iran, among other cities.

The wind tower is a massive structure made of materials of high specific heat with the purpose of minimizing heat transfer toward building interior environment. It has opened windows oriented upstream in order to capturing local predominant wind streams. Once air stream crossed the windows it passes into one or more channels designed with reduced cross section area to promote an increment of its velocity. This effect makes it easy for air to circulate naturally through the building keeping fresh and comfortable the environment, like a passive climate system [6,7]. Wind tower produces thermal comfort without any electric or mechanical air conditioned device [1,2]. It is a concept that leads to sustainable development by saving large amounts of electrical energy during hot seasons [7–17]. A wind tower located at a country of Middle-East, is shown in Fig. 1.

Monitoring studies of buildings that incorporate wind towers to provide thermal comfort were conducted by Karakatsanis et al. [18], Coles and Jackson [19], Ahmadreza and Nicol [20], Bahadori et al. [21]. Most of them have concluded favorably toward proposing wind towers as effective natural cooling systems, Kalantar [22]. In addition, Bahadori [21] besides Shorbagy [23] and Bansal et al. [24] have proposed new designs of wind tower incorporating combined solar and geothermal technologies in order to produce more efficient prototypes.

However, despite these examples of demonstrated feasibility of this concept, it is still needed to provide answer to basic questions like how wind tower performs in other climate conditions, including extreme weather, which presents low and high temperature diurnal oscillations.

One alternative to respond is making use of powerful computers and theoretical algorithms to simulate the operation of air distribution in wind towers coupled to different building designs. Numerical solutions can be obtained by resolving coupled mass, momentum and energy equations. This methodology belongs to a modern technique called computational fluid dynamics, CFD.

CFD has been used in studies carried out by Moya et al. [25], Sami [26], Badran [3], Narayan [27], Kalantar [22], Mahmoudi [28] and

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http://dx.doi.org/10.1016/j.enbuild.2013.07.032

Fig. 1. Wind-tower photograph in the Middle East.

Reyes [29], which have proved that CFD represents one affordable option for predicting air flow behavior associated to heat transfer in buildings. Following this trend, the present work makes use of a commercial program Fluent [30] for resolving the conservation equations of mass, momentum and energy that govern air flow distribution and heat transfer in different wind tower-building configurations. By analyzing simulations results the best configuration was chosen considering as a dependent variable the air stream distribution within the building, assuming this is a necessary condition to ensure thermal comfort to occupants. The selected configuration produced the best distribution of air inside the building.

Furthermore, simulations of selected configuration were extended to conduct a thermal performance study of wind tower employing measured weather data of Monterrey, Nuevo Leon, Mexico as boundary conditions.

The literature survey described above leads to realize that none of these studies included an analysis of several configurations, with emphasis on the selection of the best design of the building based on flow distribution, because these were orientated to simulate only one existing configuration. Furthermore, the present study proposes an enhanced design of wind tower based in the modification of the inlet section, which is demonstrated that improved the air velocity that impacts on the comfort zone size inside the main room.

The remainder is focused to emphasize the importance of using wind towers in a city characterized by traditional high consumption of electricity through conventional air conditioning during summer season, such as Monterrey. The results in this paper are considered the technical feasibility of employing wind towers for thermal comfort in arid and semi-arid regions of Northern Mexico.

2. Methodology

This work is divided into two sections: a first part addresses predictions of air flow distribution through five different wind tower-building configurations (it is called flow dynamics problem). In a second part, it conducts conjugate flow dynamics-thermal transport solutions (called thermal-dynamic problem) of one selected configuration from the five cases mentioned before.

All simulations assumed incompressible steady state turbulent flow, as well as bi-dimensional. Thermo physical properties of building materials were taken into account in the conjugate conduction-convection solution, which provided a more realistic approximation. The option of a QUICK scheme was adopted in combination with SIMPLEC algorithm for coupling velocity and pressure. The simulations were obtained by numerical solution of discretized equations in Reynolds averaged Navier–Stokes, RANS, form. The governing equations mass, momentum and energy considered are given below by Eqs. (1), (2)–(3) and (4), respectively:

$$\nabla \cdot (\rho \bar{\vec{V}}) = 0 \tag{1}$$

$$\nabla \cdot (\rho \overline{u_i \vec{V}}) = -\frac{\partial \bar{P}}{\partial x} + \nabla \cdot [(\mu \nabla \overline{u_i}) + \rho \overline{u_i' u_j'}] \tag{2}$$

$$\nabla \cdot (\rho \overline{u_j \vec{V}}) = -\frac{\partial \bar{P}}{\partial y} + \nabla \cdot [(\mu \nabla \overline{u_j}) + \rho \overline{u_i' u_j'}] - \rho g \beta (\bar{T} - \overline{T_o}) \tag{3}$$

$$\nabla \cdot (\rho C_p \overline{T \vec{V}}) = \nabla \cdot (\lambda \nabla \bar{T}) + \rho \overline{u_i' T'} \tag{4}$$

$\vec{V}$ is the velocity vector, components (u_i, u_j), ρ is density, P accounts for pressure, while g, μ and β are gravity, molecular viscosity and volumetric thermal expansion coefficient of air, respectively. In RANS approach the stress tensor included in Eqs. (2) and (3) leads to a closure problem given that the whole equation is formulated in terms of an average velocity plus a fluctuating one, such as $V = \bar{u} + u'$ [31]. New terms called the Reynolds stress tensor, $\tau'_{ij} = \rho \overline{u_i'} \cdot \overline{u_j'}$ appear. The method RANS has been widely used since it represents one of the few affordable ways to resolve the problem of turbulence in engineering applications [30,31]. One approach in this method is based on the Boussinesq assumption, which means that the Reynolds stresses are proportional to the average gradients of the velocity:

$$\rho \overline{u_i'} \cdot \overline{u_j'} \equiv \mu_T \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \tag{5}$$

where μ_T is a turbulent viscosity. In the present study the Reynolds stresses $\rho \overline{u_i'} \cdot \overline{u_j'}$ were modeled using the specific dissipation κ–ω model. It has been demonstrated that this model performs better compared against the standard model κ–ε. The κ–ω model rendered very good results in previous computations of incompressible flow involving two rectangular cavities with ventilation [32]. The relation between the turbulent kinetic energy, k, and its specific dissipation, ω, is such that:

$$\mu_T = \alpha^* \rho \frac{k}{\omega} \tag{6}$$

These two variables are solved through a couple of transport equations listed below:

$$\nabla \cdot (\rho k) + \nabla \cdot (\rho k u_i) = \nabla \cdot [\Gamma_k \nabla k] + G_k - Y_k + S_k \tag{7}$$

$$\nabla \cdot (\rho \omega) + \nabla \cdot (\rho \omega u_i) = \nabla \cdot [\Gamma_\omega \nabla \omega] + G_\omega - Y_\omega + S_\omega \tag{8}$$

The reader is referred to the specialized literature for more details about the κ–ω model, which are out of the scope of the present study [30,31].

The validation of the numerical methodology in the present study was supported by direct comparisons to reproduced conditions of results reported in the literature, with acceptable