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WIND TOWER INTEGRATION WITH EVAPORATIVE COOLING FOR GREENHOUSE HUMIDITY AND TEMPERATURE CONTROL

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ABSTRACT

Wind tower is well-known traditional Arabic architectural element that creates passive ventilation in buildings for human comfort in hot and arid regions. Meanwhile, greenhouse agriculture has been a profitable technology despite the large energy and water need. Integrating these technologies can result in substantial energy and water saving. Still, sensible cooling proved to be unsustainable operation with depletion in relatively short time period. This suggests utilization of very high specific heat materials or integration of trans-evaporative cooling. The latter is simulated by developing a high-fidelity 3-D computational fluid dynamics (CFD) model governed by the non-isothermal Navier-Stokes flow in conjugated heat and turbulent flow regime. Effect of mist flow rate, and seasonal ambient conditions on the greenhouse parameters, i.e. temperature, relative humidity and vapor pressure deficit, are assessed and compared. Results are favorable and show to bring the needed ideal cooling for typical greenhouse crops. It is estimated however on the average 2,102 L/m^2/year of water is needed to bring the temperature, relative humidity and vapor pressure deficit to their optimum ranges in the summer weathering of Abu Dhabi city.

Keywords: wind tower, evaporative cooling, greenhouse control, CFD, vapor pressure deficit.

1. INTRODUCTION

Wind towers (also called windcatchers) are relatively tall and small structures integrated to building in hot regions for passive cooling and natural ventilation in the absence of mechanical ventilation. Under natural conditions of wind flow, air at high temperature enters the wind tower heating of the inner walls and eventually reduces air temperature entering the building. No mechanical ventilation or electrical energy is used for cooling. Designing the wind towers depends on the on the local wind direction where single or multi openings facing the predominant areas can be used. The simplest form of windcatcher provides sensible cooling by infiltrating colder air or cooling incoming air through the lower temperature of the tower conduit. Hosseinnia, et al. [1] performed a numerical investigation on the effects of different internal designs of traditional wind towers and their thermal behavior. They showed that the number of partitions and their arrangement in the wind tower greatly influence the velocity of air entering the dwellings. Haghighi, et al. [2] studied an integrated system consisting of a windcatcher and a solar adsorption chiller for different geometric parameters under several ambient conditions including wind velocity, solar radiation, air temperature and relative humidity (RH).

Bahadori [3] extensively studied wind tower structures and their performances and suggested evaporative cooling (EC) by air flowing over moist surfaces for several locations in Middle East. The methods of calculating the air flow rate and temperature in those towers were presented by Kent and Thompson [4]. Similarly, Badran [5] developed a simple mass and energy balance model and studied the performance of windcatcher under various climatic conditions in Jordan and included evaporative cooling and determined the stipulated design for the tower for each specific regional condition. Kalantar [6] conducted numerical simulation of cooling performance of wind tower in hot and arid regions using simplified form of flow equations. Trans-evaporative cooling performance of windcatcher with mist injection was also studied by the corresponding author of this work [7, 8] who simulated a working prototype windcatcher subjected to numerous flow condition at Masdar City in UAE. While the results revealed the decreasing temperature due to mist evaporation and the role of higher incoming velocity in reaching lower dwelling's temperature, the actual high humidity conditions of UAE deemed the unimportant role of windcatcher in evaporative cooling for human comfort without pre-dehumidification integration.

Nevertheless, the cooling towers concept has neither been integrated to the cooling of greenhouse nor has it been subjected to the environmental conditions of the greenhouse. An efficient design of a greenhouse must consider the type of crops and its suitable environmental conditions manifested in the temperature, humidity, velocity, as well as species distribution (O_2, CO_2, N_2 etc). Most greenhouse crops favor RH in a range between 60-80% and stagnant but below 0.5m/s velocity, 25-35°C temperature [9]. Evaporative cooling is one of the common and effective techniques for greenhouse temperature control, i.e. greenhouse cooling, for climates with RH below 60% [9]. Raza, et al. [10] have studied the microclimate conditions of the greenhouse and demonstrated the role of each of ambient wind velocity, temperature and humidity on the average attained temperature and humidity of the greenhouse. They studied the effect of plant's transpiration and showed it plays determinate role in achieving suitable environment.

In this work, wind tower is integrated to the greenhouse in an attempt to investigate the magnitude of evaporative cooling that can be drawn from wind tower incorporation. The sensitivity of the achieved air temperature with respect to water mist flow rate (MFR) and different ambient conditions of Abu Dhabi, UAE climate are also investigated.

2. METHODOLOGY

2.1 Model Setup and Governing Equations

The 3-D geometry of the greenhouse is shown in Fig. 1 (left). It spans 10m long by 5m width by 3m height. Therefore, the flow is governed by the three-dimensional (3-D) non-isothermal and turbulent Navier-Stokes coupled with the energy equations and is associated with species transport model for the water droplets and its vapor. The discrete phase model (DPM) is used for the trans- evaporation misting process where additional mass and momentum source ($\mathrm{S_m}$) of injected water droplets is added to the 3-D continuity and momentum equations as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = \mathrm{S_m} \tag{1}$$

Where ρ is the density, t is time, $\vec{u}$ is the velocity. Additionally, the 3-D momentum equation can be described as:

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \mu \nabla^2 \vec{u} + \rho \vec{g} + \mathrm{S_m} \tag{2}$$

The right-hand side of the equation combines the hydrostatic pressure and the viscous stress as well as the gravitational body force. Where p is the pressure, μ is the molecular viscosity, and $\vec{g}$ is the gravitational acceleration activated in the negative y-axis. Energy equation is also activated to simulate the energy transfer due to conduction and species diffusion and has the following form:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot \left(k \nabla T - h_i \vec{J}_i\right) \tag{3}$$

Where H is the overall sensible enthalpy, k is the thermal conductivity, h_i is the enthalpy of the specie i, and $\vec{J}_i$ is the specie diffusion mass flux. Two additional transport equations are also solved when k-ε turbulent model is activated. The equations used for solving turbulent kinetic energy (k) and turbulent dissipation rate (ε) are stated below, respectively [11]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{4}$$

and

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \tag{5}$$

Where G_k and G_b are the generation of turbulent kinetic energy due to velocity gradient, and due to buoyancy, respectively. Y_M is the fluctuating dilatation term. Whereas S_k and S_ε are the additional turbulent source terms defined. σ_k, C_1, C_2, $C_{1\varepsilon}$ and $C_{3\varepsilon}$ are model constants. μ_t is the eddy turbulent viscosity and is computed as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

Where C_μ is a function of the mean stain and rotation rates, angular velocity, and turbulence fields [11].

2.2 *Meshing and Boundary Conditions*

The 3-D geometry was discretized using a structured quadratic mesh with total cells of 1,245,184 and perfect orthogonal quality (see Fig. 1(right)). The greenhouse walls were all subjected to no-slip and convection boundary condition with heat transfer coefficient of 0.5 W/m^2. K, i.e. natural convection environment, whereas the greenhouse ground wall and wind tower side walls were fully insulated. The free stream conditions followed the ambient conditions of the city of Abu Dhabi alternatively for both summer and winter seasons as shown in **Error! Reference source not found.**. Inlet boundary condition was assigned at the top opening of the wind tower where temperature, moisture content, i.e. RH, and inlet velocity were assigned as per **Error! Reference source not found.**.

To simulate the evaporative cooling, a droplet cone injection was set one meter below the inlet opening of the wind tower, precisely at position (0.5,9,0) (see Fig. 1). Water droplets distributed normally each with diameter of 1E-06 m and injected at velocity of 10 m/s and temperature of 20°C. In this work, a sensitivity study on the total mist flow rate (kg/s) is conducted in order to reach to the ideal control of greenhouse conditions for typical greenhouse crops.

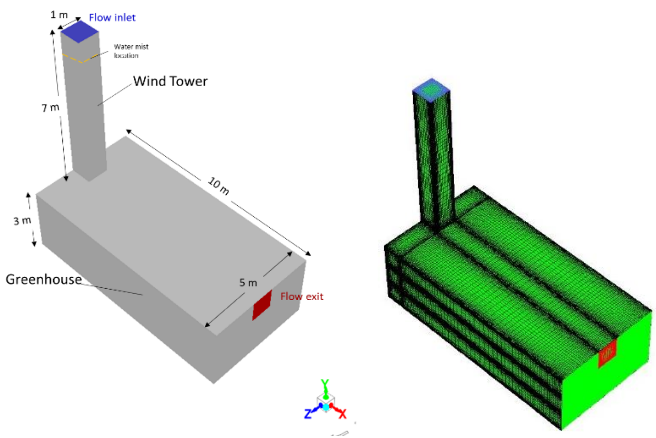

Fig. 1: Geometry of greenhouse with wind tower integration (left), and the corresponding discretized mesh (right)

2.3 Greenhouse Comfort Parameters

2.3.1 Temperature and RH

In general, the temperature and RH are the primary parameters of climate control systems. When dealing with evaporative cooling systems, two temperatures are important: (i) wet-bulb and (ii) dry-bulb temperatures. The former is the temperature at which air is fully saturated, i.e. RH=100%, therefore, it is an indication of moisture content in the air. Meanwhile, RH indicates the relative fraction of water vapor in a volume of air to that in saturated air at same STD conditions. Temperature and RH are interrelated parameters in which their control in a greenhouse is also dependent. Crops, in general, require higher humidity when temperature is high and vice versa. Ideal levels of RH for typical greenhouse crops at different temperatures are tabulated in Table *2* [9]. In this work, the EC flow rate is alternatively varied to reach to the ideal control of both parameters.

Table 1: Average ambient conditions of Abu Dhabi in winter and summer seasons [12]

Season	Temperature, (°C)	Relative Humidity, RH (%)	Wind Speed (m/s)
Winter	25	60	4
Summer	34	49	3

Table 2: Ideal levels of RH for a typical greenhouse crop [9]

Temperature (°C)	Min RH (%)	Ideal RH (%)	Max RH (%)
15	-	50	73
20	46	64	80
25	60	73	86
30	70	80	89

2.3.2 Vapor pressure deficit (VPD)

Vapor pressure deficit (VPD) is another parameter that recently popular in the greenhouse industry [13]. VPD is the difference between the saturated vapor pressure and the actual vapor pressure. VPD can be used as an indication of how close the indoor greenhouse environment is to the saturation. Moreover, VPD accounts for both temperature and RH and therefore it reflects more sensibly the crop's condition. VPD can be calculated by the following equation as per [14]:

$$\mathrm{VPD} = \exp\left(\frac{-1.044\times10^{4}}{\mathrm{T}} - 11.29 - 2.7\times10^{-2}\mathrm{T} + 1.289\times10^{-5}\mathrm{T}^{2} - 2.478\times10^{-9}\mathrm{T}^{3} + 6.456\ln\mathrm{T}\right)\left(1 - \frac{\mathrm{RH}}{100}\right) \quad (7)$$

Optimal VPD ranges between 0.45 kPa to 1.25 kPa for typical greenhouse crop [9, 13]. At higher VPDs, fogging or humidification is required, while heating and dehumidification is necessary at lower VPDs [9].

3. RESULTS AND DISCUSSION

The steady-state flow model was solved for summer season first without evaporative cooling. The computational domain was initiated using the ideal level of relative humidity and temperature for a typical greenhouse crop (T=25°C, RH=73%) as stated earlier in Table *2*. The drastic effect of summer ambient conditions on temperature rise and humidity drop inside the greenhouse leads to an average temperature and RH of 34.02°C and 48.72%, respectively. Those steady state results proved the insufficiency of sensible dry cooling for hot climate in the long-term. Wind flow and the effect of natural convection currents are seen in the 3-D velocity vectors and at the cross-sectional x-y plane displayed in Fig. 2.

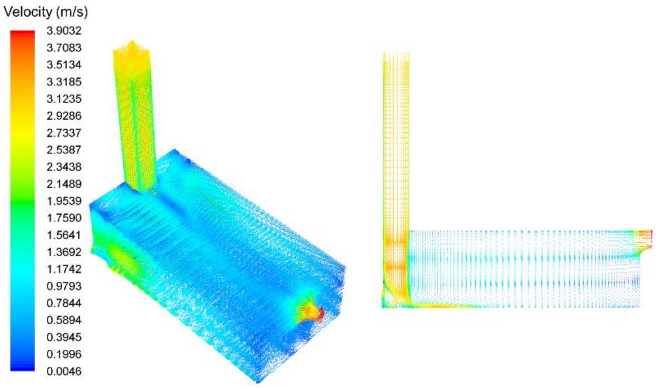

Fig. 2: Velocity vectors across the wind tower and greenhouse showing the flow distribution

Subsequently, evaporative cooling by water injection from the top of wind tower was activated. In this sensitivity study, the effect of mist flow rate varying between 5-12 L/h on the greenhouse conditions was evaluated, while mist temperature and velocity was fixed, respectively at 20°C and 10 m/s for all the cases. The goal is to reach to the comfort zone of typical crops as were stated earlier in Table *2* by Shamshiri [9].Figs. 3-6 shows the results of temperature and relative humidity distribution at a cross sectional x-y plane of the greenhouse model at different mist flow rates. It is clear from the results that increasing the evaporative cooling MFR will increase the cooling and humidity rates. Table 3 also summarizes the volume-weighted average temperature and relative humidity inside the greenhouse. Temperature and RH starts to fall into the ideal range of typical greenhouse crop at MFR of 12 L/h as per Table *2*.

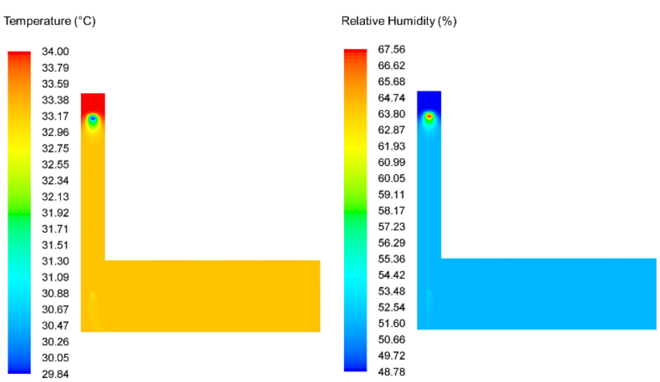

Fig. 3: Temperature and RH cross sectional contours at x-y plane of greenhouse subjected to EC at MFR of 5 L/h

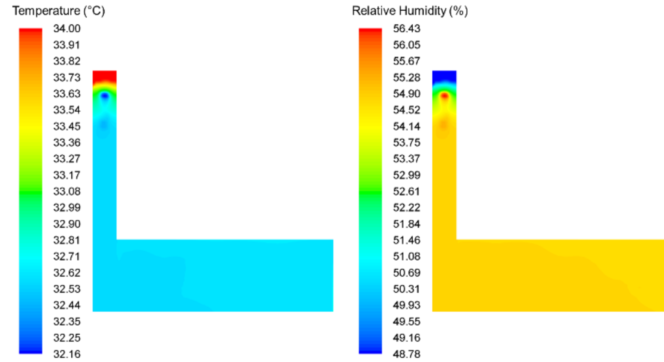

Fig. 4: Temperature and RH cross sectional contours at x-y plane of greenhouse subjected to EC at MFR of 7 L/h

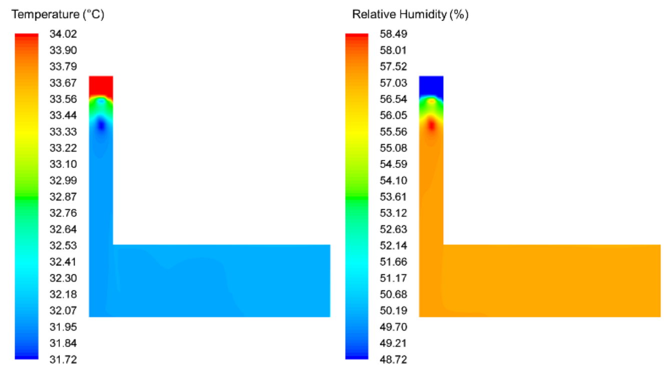

Fig. 5: Temperature and RH cross sectional contours at x-y plane of greenhouse subjected to EC at MFR of 9 L/h

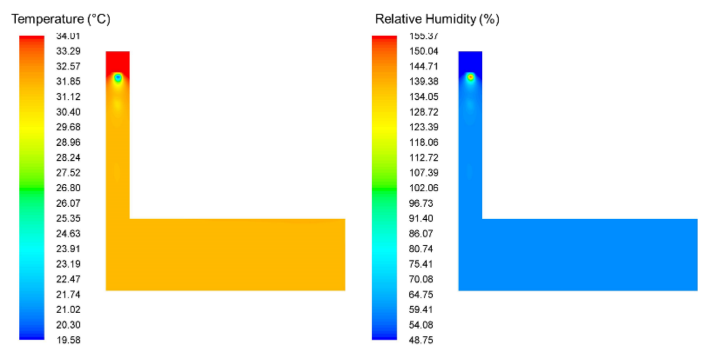

Fig. 6: Temperature and RH cross sectional contours at x-y plane of greenhouse subjected to EC at MFR of 12 L/h

Table 3: Greenhouse evaporative cooling volume-averaged temperature and relative humidity under a range of mist flow rates

Mist Flow Rate (L/h)	**Greenhouse Temperature (°C)**	**Greenhouse RH (%)**
0 (without E.C.)	34.02	48.72
5	33.03	52.77
7	32.64	54.45
9	32.18	56.51
12	31.68	58.87

VPD values were also evaluated using the volume-weighted average temperature and RH at different MFR. From the graph below one can notice the drop in VPD at higher MFR where it started falling into the ideal range of typical crops when the MRF is greater than 7 L/h.

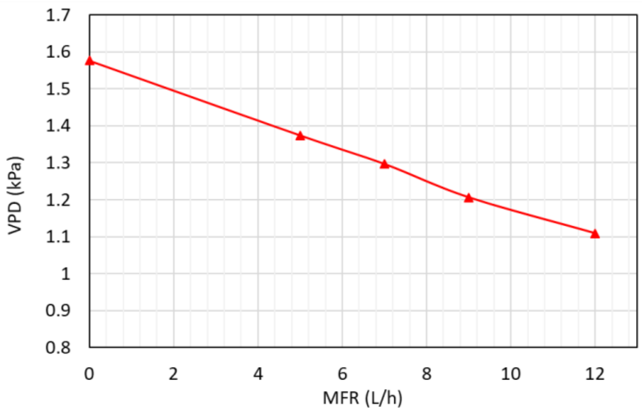

Fig. 7: Volume-averaged VPD of greenhouse subjected to EC at different MFR

Considering the total greenhouse area 50m^2 (10x5m^2) the specific water need is nearly 2102 L/year per unit area, of greenhouse that requires to bring the greenhouse temperature, RH and VPD into their ideal range of typical crops. This value found to be substantial to be added to the operational cost of greenhouse as it makes only 28% of the water need for irrigation supply, i.e. 7300 L/m^2/year [15].

4. CONCLUSION

In this work, a three-dimensional computational fluid dynamics species transport model of wind tower integration with greenhouse was implemented. The effect of Abu Dhabi summer ambient conditions on the greenhouse temperature and relative humidity was tested. Evaporative cooling of 28% of the water required for irrigation is sufficient to satisfy the ideal greenhouse conditions in summer season of Abu Dhabi. Further sensitivity studies on mist temperature and mist velocity are recommended along with experimental validation.

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