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Thermal Comfort Analysis of Wind Tower Greenhouse Integration System using Ansys

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Abstract

Increasing urbanization, a shortage of arable land, and climate change-related weather extremes are some of the challenges facing the production of global food and agriculture due to the estimated global population of 9.6 billion by 2050. As a result, improvements in greenhouse technology and modifications pushed science-based solutions for optimal plant production in all seasons worldwide by adjusting internal climate growing factors. By using passive technology coupled with evaporation cooling from wind towers, significant amounts of energy can be saved, reducing the emissions of greenhouse gases. In this study, the effect of wind tower greenhouse integration on the micro-climatic conditions inside the greenhouse is modeled and simulated. The model is governed by the non-isothermal Navier-Stokes flow in heat, viscous and turbulent flow regimes. The effect of various parameters such as airflow velocity, relative humidity, and temperature in the greenhouse is studied as well as the effect of mist flow rate, and the position of the injector in the wind tower. The results show the optimal design of the greenhouse wind tower integrated system based on the desired temperature and relative humidity within the greenhouse. The final model selected was the flat slope geometry greenhouse with a temperature value of 29.839792°C and relative humidity of 68.34%.

Keywords: *Ansys, Evaporative Cooling, Greenhouse, Wind tower*

1. Introduction

One of the best ways to provide optimized thermal comfort for plants, especially in hot arid climates, is to develop accurate greenhouse models for the internal environment control, by adjusting internal climate factors such as temperature, humidity, light intensity, and CO_2 concentration [1]. The typical passive ventilation method for greenhouses utilizes roof vents, side vents, or a combination of these. In hot climates, wind towers, which are relatively tall and compact structures, are one of the options for passive cooling and natural ventilation in the absence of mechanical ventilation. The integration of wind towers in greenhouses has recently attracted the attention of several researchers because they lower the temperature in greenhouses, provide significant energy and water savings, and enhance the relative and appropriate humidity for the plants [2.3]. A numerical analysis was conducted by Hosseinnia, et al. [4] on the influence of various interior designs on the thermal behavior of conventional wind towers. They demonstrated how the number of partitions and how they are arranged in the wind tower significantly affect the speed of air entering the flats. A significant portion of the work done in Linden's [5] extensive models of fluid flow under passive and natural ventilation contributed to the development of CFD analysis for wind towers. Two recent studies [6,7] described the methodology for calculating airflow in wind towers, and field experiments were carried out to generate air movement in a greenhouse using a mix of natural ventilation and a fogging system. Up to 0.38 m/s of air velocity was achieved in the greenhouse with this method, which is within the average range of 0.1 to 0.5 m/s in greenhouses ventilated by side and roof vents [8].

According to Baeza et al. [9], the creation of a suitable and sufficient mix of air exchange through the roof and lateral vents to remove the surplus heat of sensible heat by the flow of air through the plants is necessary for the cooling of a greenhouse using natural ventilation. Simulation results from CFD showed that most of the exchanged air was in the upper part of the treetops, and warm, damaging areas were created inside the treetops as a result of the sluggish air circulation. Evaporative cooling is one of the most popular and efficient methods for regulating temperature in greenhouses. Bahadori [10] proposed evaporative cooling by air flowing over damp surfaces after thoroughly examining wind tower constructions and their performances for numerous places in the Middle East. Raza et al. [11] studied the microclimatic conditions in the greenhouse and showed the role of wind speed, temperature and humidity on the average temperature and humidity reached in the

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greenhouse. They investigated the impact of plant transpiration and showed that it is necessary for creating a favorable environment. The above literature insight one to investigate the integration of the evaporative cooling method to the greenhouse. One approach is the addition of cooling tower considering different greenhouse configurations.

In order to determine the amount of evaporative cooling that can be obtained by using a wind tower, a wind tower is integrated into a circular geometry greenhouse in this paper. Additionally, different slopes of the roof are studied that can also mitigate dust and rain precipitation on the greenhouse top. An assumption of axisymmetric geometry is considered to accommodate reasonable prototype greenhouse geometry. The focus of the study is to model and simulate microclimatic condition in the wind tower greenhouse integration system during the summer conditions of Abu Dhabi to assess the impact of evaporative cooling that can be obtained from the proposed incorporation when it comes to the temperature and relative humidity values within the greenhouse wind tower system.

2. Methodology

2.1. Model Setup and Governing Equations

The circular geometry of the considered greenhouse of 9.5m diameter, and 3m height is shown in Fig. 1. It is equipped with a tower at the center with 1 m diameter and 12 m height. Four slopes have been studied for the greenhouse (0^o, $0.33/9.0^o$, $0.5/9.0^o$, and $0.66/9.0^o$) for the same volume. The following medium represented by the incoming air through the tower and sources of water droplet/mist injection at the top of the tower. The greenhouse is assumed to be subjected to different temperature surrounding existing in Abu Dhabi, UAE. The flow is governed by the non-isothermal and turbulent Navier-Stokes equation in two dimensions (2-D) coupled with the energy and multiple species transport equations. A discrete particle model is also used to represent the water droplets and their mass and heat exchange coupled with the continuous flow. The 2-D continuity (Eq. 1), momentum (Eq.2), and energy (Eq. 3) equations are expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = S_{H_2o} \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla \mathrm{p} + \mu \nabla^2 \vec{u} + \rho \vec{g} + S_{H_2o} \quad (2)$$

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla \mathrm{T} - h_i \vec{J_i}) \quad (3)$$

where ρ represents the density, t is the time, $\vec{u}$ is the velocity vector, and S_{H_2o} is the additional mass and momentum source injected water droplets. The p is hydrostatic pressure, μ is the medium viscosity, p is the pressure, $\vec{g}$ is the gravitational acceleration. H is the overall sensible enthalpy, k is the thermal conductivity, and h_i is the enthalpy which is defined for the i species.

Turbulent is accounted for through the eddy viscosity model such that:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (4)$$

Where k and ε are the kinetic turbulent energy and its dissipation rate and that each represented by their transport equation.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (5)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (6)$$

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

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (7)$$

As the particles are injected, their velocity and location should be determined in every time step in order to track them. Therefore, a discrete phase equation was used (Eq. 8).

$$m_p \frac{du_p}{dt} = F_D + F_g + F_{other} \quad (8)$$

Where m_p is the mass of the particle, u_p is the velocity of the particle. On the right-hand side, the forces considered include the external forces such as gravity force, drag force and other forces like pressure gradient force and the particle-particle contact forces.

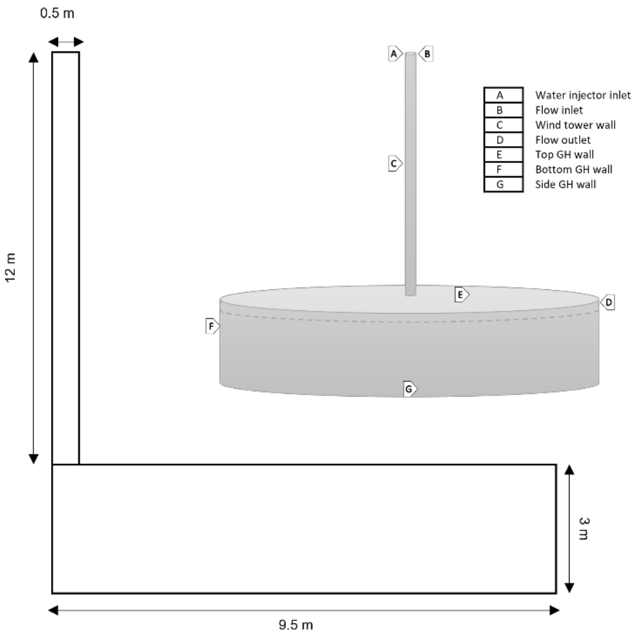


Fig. 1: Geometry of the axisymmetric greenhouse with wind tower integration (0^o slope).

2.2. Meshing and Boundary Conditions

A structured quadratic type of mesh with 387,584 total elements was used to discretize the 2-D baseline geometry (see Fig. 2). The greenhouse involves of an inlet of mass flow (temperature, velocity, and direction), an outlet (temperature, velocity and direction), wall boundaries (stationary, no slip velocity) within the flow cavity. The greenhouse ground wall and the wind tower side walls were completely insulated, while the other walls were all subjected to no-slip and convection boundary conditions with a heat transfer coefficient of 0.5 W/m^2K by natural convection. The free stream circumstances coincided with the summertime weather in Abu Dhabi taking the average temperature of 36°C. The top entrance of the wind tower's inlet was given an inlet boundary condition with assigned temperatures of 34°C, relative humidity of 49 %, and inlet velocity of 3 m/s. The baseline meshes for the 0.33/9º, 0.5/9º, and 0.66/9º slopes for the greenhouse show in figure 3.

In a greenhouse, temperature and relative humidity (RH) are connected variables that affect each other. In general, when temperatures are high, crops need more humidity, and vice versa. In Table 1 [10], ideal RH values for common greenhouse crops at various temperatures are listed. The initial condition of the temperature inside the greenhouse is assigned to be 25°C and the relative humidity is assumed to reach the ideal level.

To simulate the process of evaporative cooling in the current study, a single droplet injection was used under the inlet of the wind tower, precisely at a position (0.25 m, 11 m). Water droplets normally distributed each with diameter of 1e-4 m and injected at velocity of 4 m/s and temperature of 20 °C.

In this work, the total mist flow rate ($\dot{m}_w$) is calculated in order to reach to the desired greenhouse conditions that suited for a given greenhouse crops. The heat balance is given in Eq. 9 which is based on the equality of heat flux between the water mist and air and the vaporization of water.

$$\dot{Q}_{air-water} = \dot{Q}_{evp} \tag{9}$$

Expanding and substituting definition of these two terms gives:

$$\dot{m}_w C_{p_w}(T_1 - T_{out}) + \dot{m}_{air} C_{p_{air}}(T_{in} - T_{out}) = \dot{m}_w h_w \tag{10}$$

Where C_{p_w} and $C_{p_{air}}$ represent the specific heat of water and air which are approximately 4.2 kJ/kg °C and 1 kJ/kg °C, respectively. The heat of vaporization of water (h_w) is 2260 kJ/kg. $\dot{m}_{air}$ is calculated using equation 11.

$$\dot{m}_{air} = \rho_{air} v_{air} A \tag{11}$$

The temperatures for water droplets (T_1) and the inlet flow (T_{in}) were set to be 20°C and 34°C respectively. However, the temperature for the outlet flow (T_{out}) is assumed to be 25 °C as per table 1. At last, by solving for $\dot{m}_w$, 0.011387 kg/s is obtained and is required for the injector to achieve the optimal temperature and relative humidity level in the greenhouse.

2.2.1. Mesh Sensitivity

A mesh sensitivity analysis is studied to assess the robustness and fidelity of the analysis. Four different mesh are considered, and the average velocity is evaluated and reported for the flat roof greenhouse geometry. The flat roof of the greenhouse has been selected with four different resolutions, the fine with 1,402,368 cells, baseline with 500,000 cells, coarse I with 171,264 cells, and coarse II with 87,648 cells. The average temperature and velocity of the air of the fine mesh are obtained and used to assess the simulation accuracy. These are assessed against the results obtained by the fine mesh. Table 2 summarizes the obtained values and the percentage of error based on the fine mesh results. As shown, the baseline mesh has a relative error of 0.573% in the average temperature and 4.405% in the average velocity which is lower than coarse mesh I (0.713% and 5.687%) and coarse II (1.014% and 8.420%). Thus, we proceeded with the baseline mesh as a compromise between computational cost and accuracy.

Table 1: Ideal levels of RH for a typical greenhouse crop [10].

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

Table 2: Mesh sensitivity study for the flat roof greenhouse

	Temperature (K)	Error (%)	Velocity (m/s)	Error (%)
Fine	25.1351	-	1.0482	-
Baseline	26.8433	0.5727	1.0020	4.4048
Coarse I	27.2628	0.7133	1.1078	5.6871
Coarse II	28.1583	1.0135	1.1364	8.4199

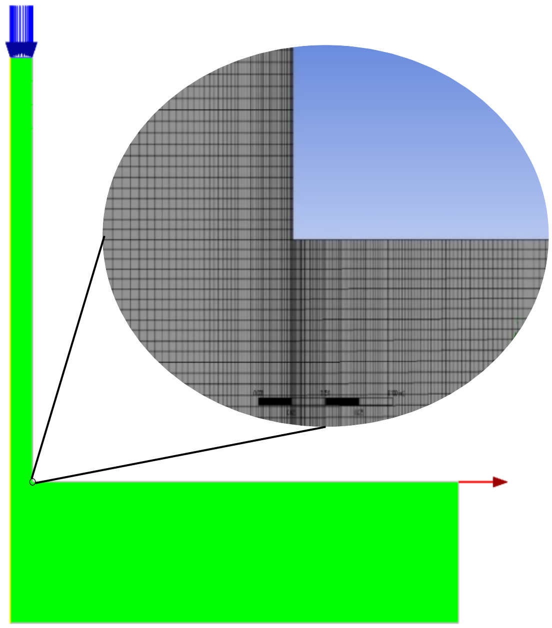


Fig. 2: Discretized mesh for the model 1 greenhouse (0º slope).

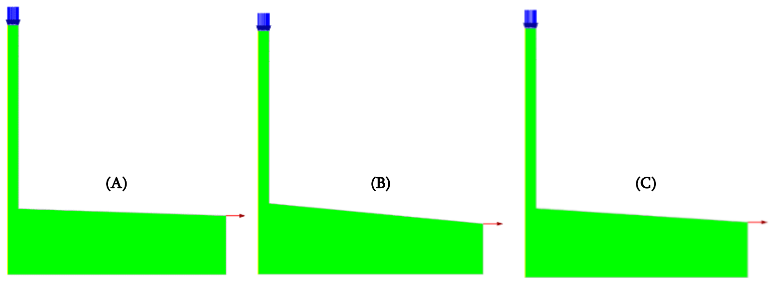


Fig. 3: Baseline mesh for the greenhouse a. 0.33/9º slope, b. 0.5/9º slope and c. 0.66/9º slope.

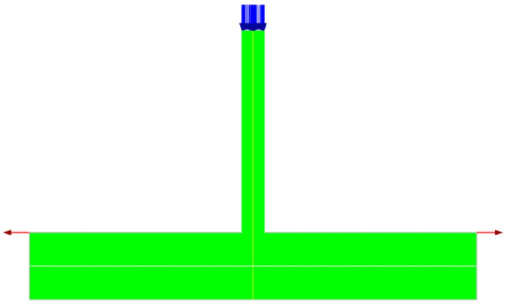


Fig. 4: The middle line along which the results are calculated.

3. Results and discussion

The steady-state flow model was solved for summer season in Abu Dhabi, UAE. A single injector was used in the current study to secure the required temperature drop. The results are discussed in further detail below.

Fig. 5 depicts the contour plots of the temperature and velocity distribution inside the flat geometry greenhouse. The temperature inside the chimney/wind tower continues to decrease due to trans evaporation occurring as the air descends and reaches a value of 28.8696°C and RH of 74.0382 %. The velocity of the air flow is maximum at the inlet, gets dispersed within the greenhouse and is close to the maximum value of 4 m/s at the exit.

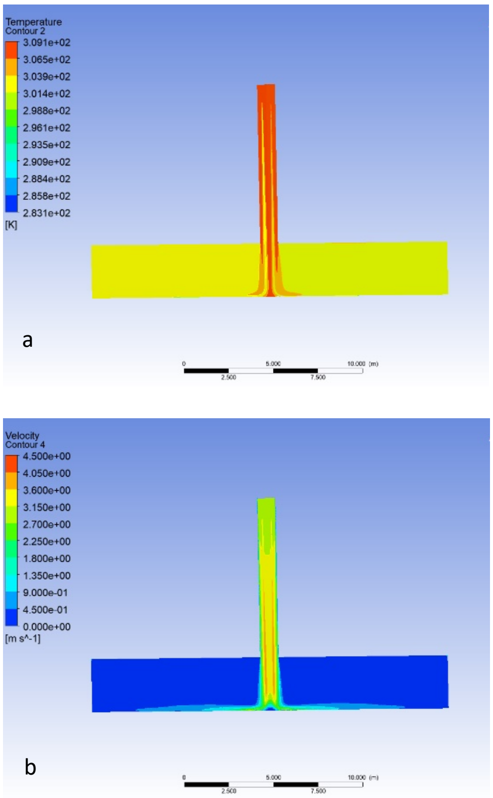


Fig. 5: The temperature (a) and velocity (b) contours of the model 1 greenhouse (0° slope).

Fig. 6 depicts the contour plots of the temperature and velocity distribution inside the 0.33° slope geometry greenhouse. The temperature behavior is the same as in the flat geometry greenhouse with a decrease being observed due to the trans-evaporative cooling process, but the distribution is different due to a change in the slope of the outer walls of the greenhouse. Obtained values for the temperature and RH in this case are 28.9131°C and 73.9844 %. The velocity of the air flow also follows a similar behavior with the maximum value of 4 m/s being observed at the inlet and exit whereas the distribution is slightly different due to a different slope.

Fig. 7 represents the contour plots of the temperature and velocity distribution inside the 0.5° slope geometry greenhouse. The behavior of the temperature and velocity is the same as for the flat and 0.33° slope geometries. The difference is the distribution of the temperature and velocity within the greenhouse and the values attained. The secured temperature and RH va

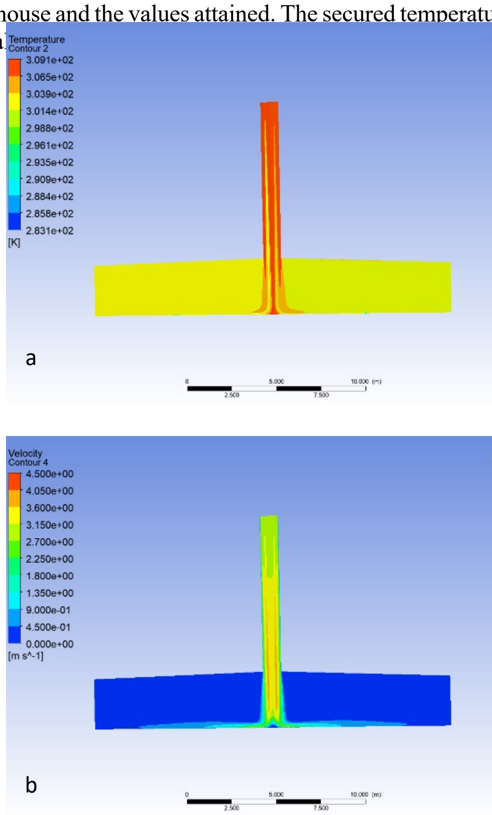


Fig. 6: The temperature (a) and velocity (b) contours of the model 2 greenhouse (0.33/9° slope).

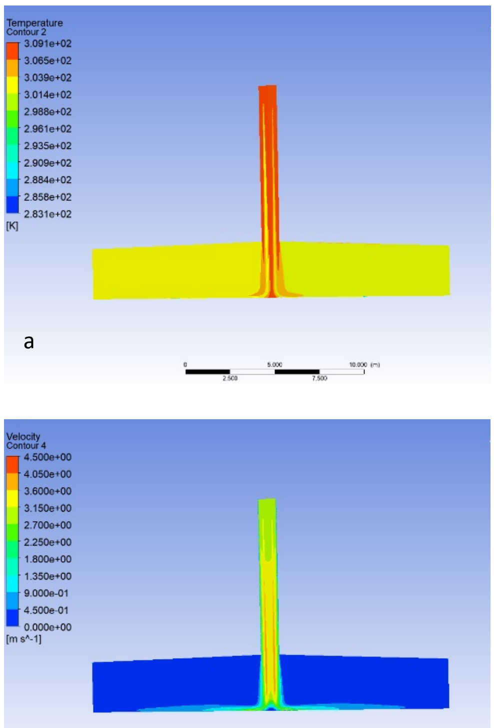


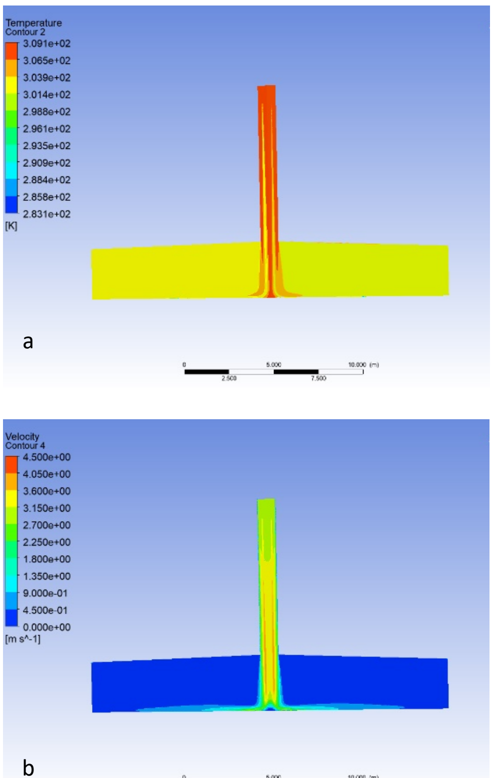
Fig. 7: The temperature (a) and velocity (b) contours of the model 3 greenhouse (0.5/9º slope).

Fig. 8: The temperature (a) and velocity (b) contours of the model 4 greenhouse (0.66/9º slope).

Table 3: Temperature and relative humidity values at selected heights of the four greenhouses studied.

	Inlet Temperature (°C)	Attained Temperature (°C)	RH (%)
1.5 m			
Baseline	34	28.869657	74.038291
Slope 0.33/9º	34	28.913101	73.984455
Slope 0.5/9º	34	27.561942	82.249754
Slope 0.66/9º	34	29.411682	70.931053
1 m			
Baseline	34	28.933431	73.628697
Slope 0.33/9º	34	28.978857	73.546343
Slope 0.5/9º	34	27.666717	81.533013
Slope 0.66/9º	34	29.445572	70.708586
0.5 m			
Baseline	34	28.874257	73.989196
Slope 0.33/9º	34	28.918165	73.92626
Slope 0.5/9º	34	27.568657	82.180244
Slope 0.66/9º	34	29.41029	70.920561

For the 0.66º slope geometry greenhouse, the behavior of the temperature and velocity is the same as for the flat, 0.33º and 0.5º slope geometries (see Fig. 8). The difference again is the distribution of the temperature and velocity within the greenhouse and the obtained values. The obtained temperature is 29.4117°C and 70.9310 %. A summary of all the attained values from the models has been plotted depicting the attained temperature vs RH values, for all 4 slopes for the greenhouse roof, is shown in Fig. 9.



From the achieved results, it can be observed that the baseline and slope 0.33º have the closest temperature and RH to the ideal values within the greenhouse. However, when it comes to the combined percentage error between the two models, it is determined that the baseline has a lower error than slope 0.33º. As a result, baseline is selected as the most optimal model for this case. Finally, the fluxes reports affirm the mass balance of the current study for each of the models. For example, for the case of the baseline model, the mass in was calculated to be 2.6714 kg/s, the mass out was calculated to be -2.6771 kg/s with the DPM mass source to be 0.008678 kg/s.

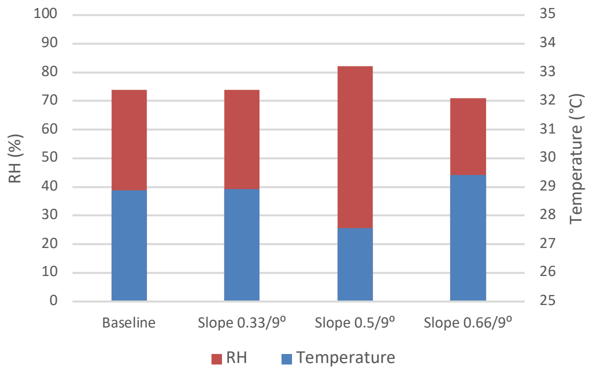


Fig. 9: Plot for the obtained temperature vs relative humidity values of all four models (1.5 m height).

In addition, to provide further validation and comparison to the current study, two additional lines were plotted within the greenhouse at 0.5 m and 1 m from the ground. The same results were calculated along these two lines as this provides important data for the greenhouse crops at early growing stages and at the later stages. Table 3 summarizes the results from taken at different heights. Plots illustrating the obtained temperature and RH values for the four greenhouses studied at different height is combined in Fig. 10.

It can be observed that the relationship between temperature and relative humidity is inversely proportional. This can be attributed to the fact that as temperature increases, air becomes drier and leads to a decrease in relative humidity whereas when the temperature decreases, air becomes wet and relative humidity increases. Finally, from the attained results for 1 m and 0.5 m height, it can be deduced that based on the combined percentage, error between the theoretical and the attained values, the baseline model, with the flat sloped geometry, is the most optimal design for the early stages of the greenhouse and at the later stage as well. Therefore, baseline is selected to be the most suitable greenhouse model for the current project.

4. Conclusion and recommendations

The current project implemented the two-dimensional Ansys model of wind tower greenhouse crops integration. The effect of Abu Dhabi summer ambient conditions on the greenhouse temperature and relative humidity was tested. Different slopes of the roof which also mitigate dust and rain precipitation on the greenhouse tops were studied. The greenhouse wind tower model with the flat slope was observed to have the most optimal values for internal temperature and relative humidity for the early stage, middle stage and matured stage of the greenhouse crops. Suggestions for future research would be to consider a 3D model of the greenhouse wind tower integrated system, along with experimental validation, and to implement the concept of VPD- Vapor Pressure Deficit into the study as well.

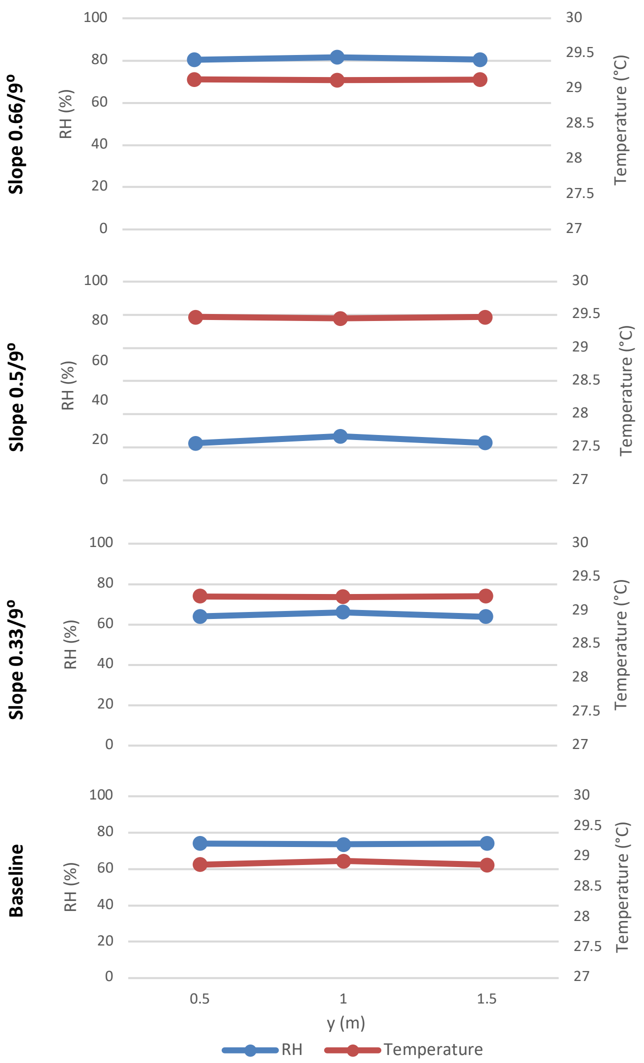


Fig. 10: Plot for the obtained temperature and relative humidity values at selected heights of the four greenhouses studied.

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