COMPUTATIONAL FLUID DYNAMICS ANALYSIS FOR GREENHOUSE WITH DIFFERENT VENTILATION OPENINGS AND ORIENTATIONS IN SAMSUN, TURKEY

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Abstract
Airflow and air distribution are critical factors in creating the microclimatic conditions necessary for plant growth and productivity in the greenhouse. Different greenhouse models and orientations can affect airflow and ventilation rates, resulting in greenhouse microclimate variation. The aim of this study was to evaluate the microclimatic conditions in the greenhouse in Samsun under different greenhouse models and orientations using the computational fluid dynamics method (CFD). Greenhouse microclimate conditions were simulated in two different models, M1 (45° vent) and M2 (35° vent), validated with experimental data, and airflow patterns, airspeed, temperature, and relative humidity were determined for each model in different greenhouse orientations before the winding course. The statistical parameters for evaluating model performance showed good agreement between the simulation and field test data. Since the wind was from the north, there was insufficient airflow through the greenhouse in most directions. The indoor temperature ranged from 27-28°C, and the relative humidity ranged from 42-48%. Based on the simulation, the best orientation for M1 is 45^o, while M2 is close to the wind run at 75^o. This CFD method effectively provides sufficient information to determine the appropriate greenhouse model in Samsun in less time and cost.

Key words: *numeric analysis, micro-climate, model, uniformity index.*

INTRODUCTION
Greenhouse technology is developing rapidly as it helps farmers grow crops in different regions and seasons. Greenhouse microclimate analysis, such as temperature, air velocity, and humidity, is necessary to provide adequate shading and ventilation or heat or cool the greenhouse. Determining the microclimatic conditions also allows optimizing the required environment for high-quality and quantity harvests *(Akrami et al., 2020)*.
The temperature inside a greenhouse is affected by several factors, including the temperature of the ambient air, the heat transfer coefficient of the covering material, and solar radiation. The amount of solar radiation received by the greenhouse depends on the angle of the sun at a given time based on a specific season, greenhouse type, location, and orientation. Most of the solar radiation hits the ground directly, which increases the temperature of the greenhouse *(Li et al., 2018)*.
The orientation of the greenhouse also plays an important role in determining the entry velocity of the air. *Khaoua et al. (2006)* studied the effect of air velocity and type of roof opening on the temperature distribution inside the greenhouse. This study showed that the combination of roof opening configurations and air velocity significantly affects the microclimate inside the greenhouse.
Ventilation is a critical process that significantly impacts plant performance at all stages of the process. Due to its extreme complexity, computational fluid dynamics (CFD) techniques are particularly beneficial for mapping flows and developing a better understanding of the flow fields responsible for the evolution of the microclimate, as well as conducting sensitivity studies to improve it *(Bournet & Boulard, 2010)*.
Recently, CFD has become a widely used and powerful tool for developing building plans with efficient ventilation and modeling the greenhouse under climatic conditions *(Baeza et al., 2006; Benni et al., 2016; Cemek et al., 2017; He et al., 2015; He et al., 2018; Saberian & Sajadiye, 2019; Senhaji et al., 2019)*.

Given this information, the aim of this study is to determine the effects of greenhouse vents and orientation on greenhouse microclimate. For this purpose, microclimatic conditions in greenhouses in Samsun were evaluated under different greenhouse models and orientations using the CFD method. The results were used to determine the most appropriate greenhouse model and orientation.

MATERIALS AND METHODS

Field measurement

This study was conducted in an experimental greenhouse at the Faculty of Agriculture, Ondokuz Mayıs University, Samsun, Turkey. The greenhouse is 6.20 x 20 m and has a floor area of 124 m^2. A total of 42 measurements were taken inside the greenhouse, each of which included a measurement of temperature, relative humidity, wind speed, and wind direction. The temperature and wind components outside the greenhouse, within a radius of 1 m, were also considered. The wind in Samsun was mainly from the WNW and NNW directions. The average monthly wind speed is about 3.5 m/s, with the strongest wind varying between 11 and 15 m/s.
The location of measurement points is given in Fig. 1. The internal and external wall temperatures were also measured with a Testo 875-2i thermal imaging camera. All measurement parameters were measured consecutively with two repetitions to reduce possible errors. All data were measured from 10:00 am to 3:00 pm, with a total average measurement time of 1 hour for each greenhouse condition.

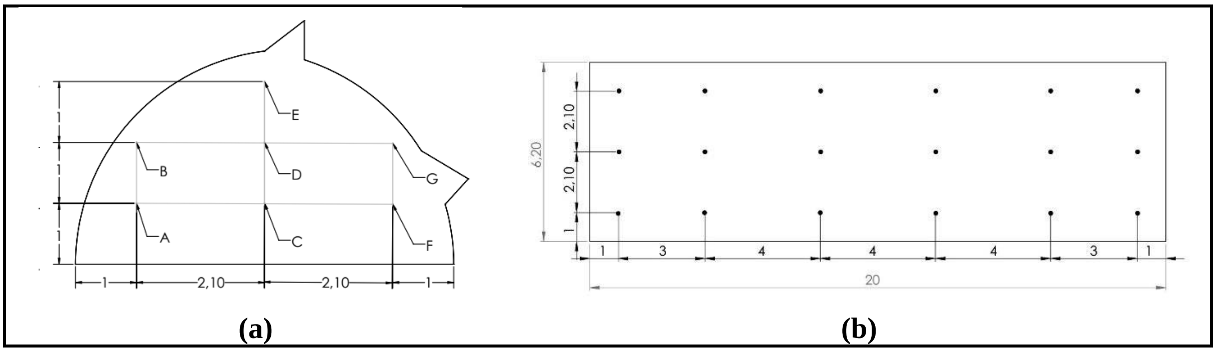


Fig. 1 Measurement points location (a) front view (b) top view

CFD Simulations

CFD is used in many disciplines worldwide *(Sørensen & Nielsen, 2003)*. With this method, a user can fully control all influencing factors for the simulation without spending much time and money. Moreover, the result of this simulation is complete and detailed information that allows the user to analyze comprehensively.
The experimental greenhouse is the same as the M1 and M2 greenhouse (Fig. 2). The models were tested in seven different directions before the wind direction (90°, 75°, 60°, 45°, 30°, 15°, 0°), as shown in Fig. 3.

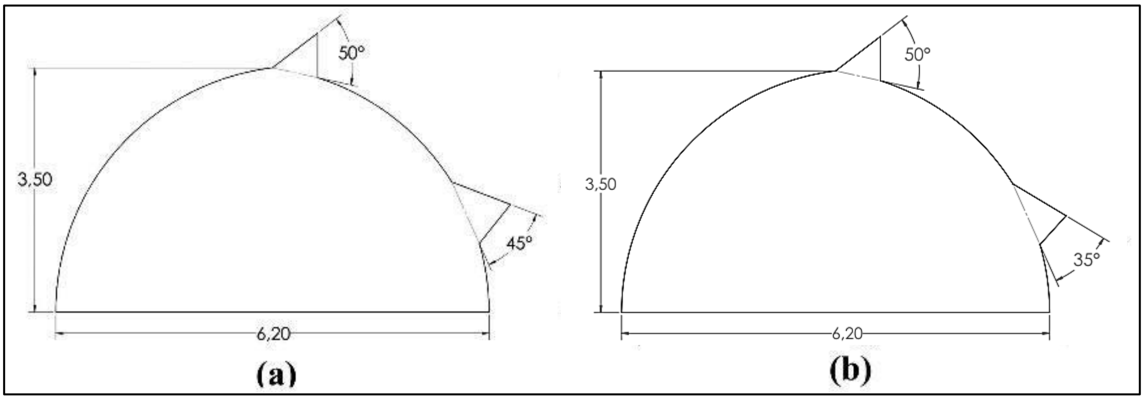


Fig. 2 Measurement points location (a) front view (b) top view

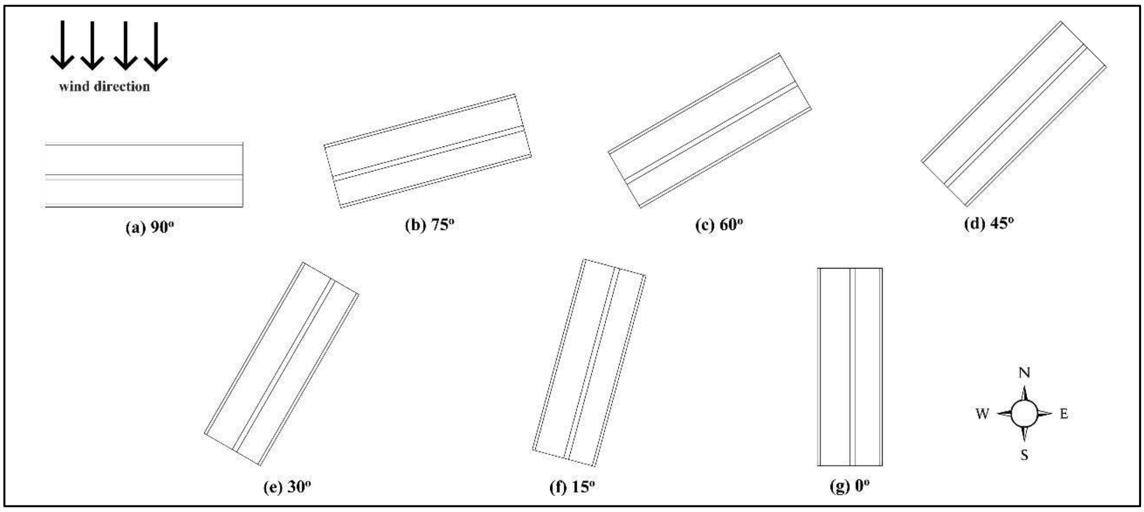


Fig. 3 Different greenhouse orientations

Solidworks was used to design the greenhouse geometry, and the simulation was performed in Ansys-Fluent. The program uses the finite volume method to numerically solve the Navier-Stokes equations, i.e., the mass, energy, and momentum balances that admit air velocity and temperature fields *(Erizal & Romdhonah, 2012)*. The geometry ratio of simulation and field experiment is 1/1. The computational domain of this CFD simulation was set to the area inside the greenhouse. The wall function used was a near-wall treatment with standard wall functions. The species transport function was used with a diffusion energy source consisting of a mixture of nitrogen, oxygen, and water vapor to simulate relative humidity.

The optimal mesh distribution and the number of cells were set in the Proximity and Curvature, Fine Relevance Center, High Smoothing, Slow Transition, and Fine Span Angle Center size functions. The minimum proximity size is 0.003 m, while the maximum area size is 0.12 m. The inlet and outlet areas have an element size of 0.05 m. The skewness of the mesh was 0.504.

There are three main methods used for fluid flow analysis: control volume or integral analysis, infinitely small element or differential analysis, and experimental study and dimensional analysis *(White, 1998)*. The second-order non-homogeneous differential solution was used for the analysis of non-compressible fluids. Some specific grid resolutions were used to maintain the accuracy of the results and reduce the calculations *(Campen & Bot, 2003)*.

Model validation

The results of the CFD model were compared with field measurements in the experimental greenhouse. Statistical parameters for model validation included fractional bias (FB), normalized mean squared error (NMSE), geometric mean bias (MG), geometric mean-variance (VG), and fraction of two (FAC2). Models were considered fit if more than half of the parameters met these criteria: |FB|<0.3, 0.7<MG<1.3, NMSE<0.25, VG<4, and 0.5<FAC2<2 *(Chang & Hanna, 2004; Küçüktopcu et al., 2022)*.

$$FB = \frac{2(\overline{C_o} - \overline{C_p})}{\overline{C_o} + \overline{C_p}} \tag{1}$$

$$NMSE = \frac{\overline{(C_o - C_p)^2}}{\overline{C_o}.\overline{C_p}} \tag{2}$$

$$MG = \exp\left[\overline{\ln\left(\frac{C_o}{C_p}\right)}\right] \tag{3}$$

$$VG = \exp\left[\overline{\ln\left(\frac{C_o}{C_p}\right)^2}\right] \tag{4}$$

$$FAC = \frac{C_p}{C_o} \tag{5}$$

where C_o is the observed value and C_p is the predicted value.

Uniformity index

The uniformity index is used to represent and evaluate the uniformity of the flow distribution. It is calculated using the statistical deviation, where the γ value is between 0-1. The larger the number, the better the uniformity *(Zhang et al., 2017)*. The uniformity index used in this study is the area-weighted uniformity index. The uniformity index can be expressed as *(Tajik et al., 2017)*.

$$\gamma_v = 1 - \frac{1}{2}\left(\frac{\sum_{i=1}^{n}\left|v_i - v_{avg}\right|A_i}{A.v_{avg}}\right) \tag{6}$$

$$\gamma_T = 1 - \frac{1}{2}\left(\frac{\sum_{i=1}^{n}\left|T_i - T_{avg}\right|A_i}{A.T_{avg}}\right) \tag{7}$$

$$\gamma_{RH} = 1 - \frac{1}{2}\left(\frac{\sum_{i=1}^{n}\left|RH_i - RH_{avg}\right|A_i}{A.RH_{avg}}\right) \tag{8}$$

Where v_i, T_i, RH_i is the local velocity magnitude, temperature, and relative humidity, respectively, A_i is the local area, and A is the area where the γ is calculated. The uniformity index is calculated using ANSYS Fluent feature on the XY, YZ and XZ surface inside the greenhouse model.

RESULTS AND DISCUSSION

Validation of CFD Model

A statistical parameter for air velocity, temperature, and relative humidity in the greenhouse was determined to evaluate model performance. From Table 1, it can be seen that all the results for air velocity, temperature, and relative humidity in NMSE, FB, MG, VG, and FAC2 are within the acceptance criteria. This proves that this greenhouse model can be used to simulate indoor environmental conditions.

Tab. 1 Statistical parameters for model performance evaluation

Parameters	Air Velocity	Temperature	Relative Humidity
NMSE (< 0.25)	0.024	0.001	0.001
|FB| (< 0.3)	0.153	0.003	0.028
MG (0.7-1.3)	1.165	1.004	1.028
VG (< 4)	1.724	1.008	1.058
FAC2 (0.5-2.0)	0.858	0.996	0.972

Evaluation of the greenhouse models

Model 1

Since there was no wall opening in the northern part of the Model 1 (M1) greenhouse, there was generally an inflow at the southern roof opening and an outflow at the southern wall opening for the 90°, 75°, 60°, 45°, 30°, and 15° greenhouse orientations. Air circulated from the roof opening to the north wall and floor and exited directly through the south wall opening. For the 0° greenhouse orientation, the south roof opening and the south wall opening were parallel to the wind flow, so air flowed into both openings. This resulted in more air circulation and rotation within the greenhouse than in the others. *Khaoua et al. (2006)* also noted that there was also a countercurrent or loop in the wind flow within the greenhouse in this direction.

The magnitude of air velocity was observed in a different orientation for greenhouse M1. For the greenhouses in the 90°, 75°, 60°, 45°, and 30° orientations, the wall region tends to have a higher air velocity than the central region, as indicated by the difference in color. However, in the 15° orientation, the air velocity in the wall and the middle of the greenhouse is slightly the same, while in the 0° orientation, the air velocity in the center area of the greenhouse is generally higher than in the wall.

The air velocity in the greenhouse with 90°, 75°, 60°, 45°, 30°, 15° and 0° orientation is 0.06-0.6 m/s, 0.02-0.45 m/s, 0.08-0.75 m/s, 0.07-0.65 m/s, 0.03-0.51 m/s, 0.07-0.35 m/s, and 0.04-0.23 m/s respectively. The greenhouse with a 60° orientation has the highest air velocity difference, 0.67 m/s, and the highest average air velocity, 0.37 m/s. This results in a relatively low uniformity index compared to the others. The greenhouse with a 0° orientation, parallel to the wind direction, has an average air velocity of 0.11 m/s and a uniformity index of 0.79. Since there is no constant inflow or outflow in this direction, the air velocity inside the greenhouse tends to be lower.

The temperature in the center of the greenhouse is constant, especially in the orientations 75° and 30°. For the greenhouses in the 90°, 60°, and 45° orientations, the wall area tends to have a lower temperature. In the 15° orientation, the temperature near the southern wall opening was slightly higher, while in the 0° orientation, the central area of the greenhouse had a higher temperature than in the other orientations. There is no difference in the uniformity index for temperature in all orientations. The temperature in the greenhouse with 90°, 75°, 60°, 45°, 30°, 15° and 0° orientation is 26.85-27.95 °C, 26.95-28.25 °C, 26.75-27.95 °C, 26.85-27.95 °C, 26.95-28.75 °C, 26.95-28.85 °C, and 26.95-29.25 °C respectively. Greenhouses with 15° and 0° orientations have a relatively higher temperature difference, 1.9 °C, and 2.3 °C, and a higher average, 28.10 °C, and 28.35 °C. This result indicates an agreement with the air velocity distribution. Since there is no constant inflow or outflow in this orientation, the air velocity inside the greenhouse tends to be lower. This results in a higher temperature. *Roy & Boulard (2004)* mentioned in their study that the temperature in the greenhouse was 5 K higher at 0° wind incidence than at 90° wind incidence. They also mentioned that the relative humidity was 20% higher at 0° incidence than at 90° incidence.

There were no significant differences in relative humidity for any of the greenhouse orientations except for the 0° orientation; the relative humidity in the western area of the greenhouse is lower than in the eastern area. The relative humidity in the greenhouse with 90°, 75°, 60°, 45°, 30°, 15° and 0° orientation is 45.15-45.77%, 44.64-45.43%, 45.37-46.2%, 45.26-45.96%, 44.87-45.48%, 42.37-45.33%, and 42.05-46.56% respectively. The greenhouse with the orientation 15° and 0° has a relative difference in relative humidity, 2.96% and 4.51%, and a lower average, 44.48%, and 43.80%. The greenhouse with orientations 15° and 0° is not as humid as the others. In all models, it was found that the lowest air temperature resulted in the highest relative humidity, mainly at the position of the air inlet *(Duong et al., 2021)*.

Overall, the highest uniformity index is seen in the greenhouse with an orientation of 0°. However, the temperature range reached in the greenhouse with this orientation is larger than the others, with a temperature difference of up to 2.3 °C. The average temperature is also higher. The same results are observed for relative humidity. The differences in relative humidity in M1 with 0° orientation are large, and the value of relative humidity is lower. Maintaining a relatively low temperature and sufficient humidity in the greenhouse to support plant growth while maintaining uniformity is essential. Therefore, the recommended values of the greenhouse can be maintained in the 45° orientation. The flow pattern, air velocity, temperature, and relative humidity for the M1 with a 45° orientation can be seen in Figures 4 and 5.

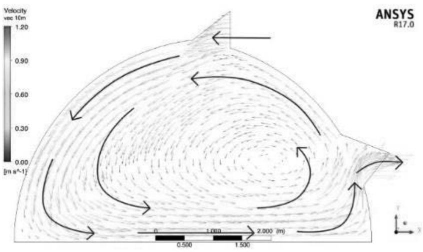
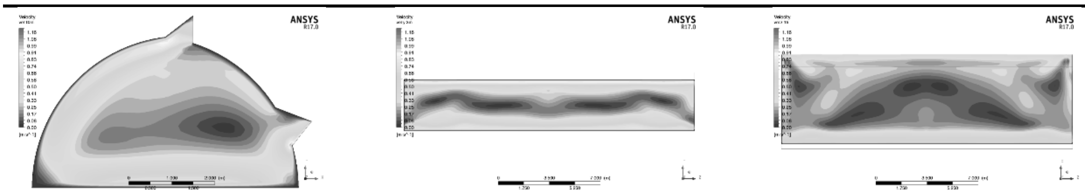
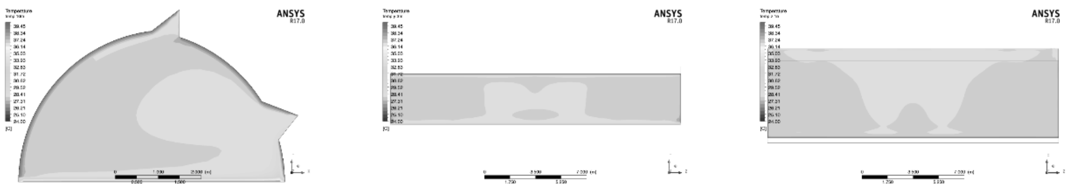


Fig. 4 Velocity flow pattern in XY and YZ plane for M1 with 45° orientation

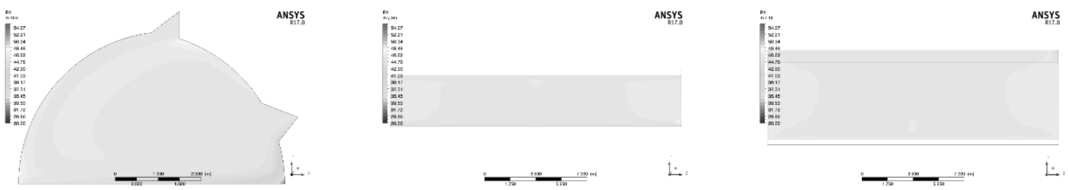
XY plane	YZ plane	XZ plane



(a) Air velocity



(b) Temperature



(c) Relative Humidity

Fig. 5 Air velocity (a), temperature (b), and relative humidity (c) distribution for M1 with 45^o orientation

Model 2

Since there is no wall opening in the northern part of the greenhouse, when the greenhouse was oriented 90^o, 75^o, 60^o, 45^o, 30^o, and 15^o, there was generally an inflow at the roof opening and an outflow at the southern wall opening, similar to the previous model. Air circulated from the roof opening to the north wall and floor and exited directly through the south wall opening. In the 0^o orientation of the greenhouse, there is an inlet at the south wall opening, and the air flows directly to the roof opening.

For the greenhouses in the 90^o, 75^o, 60^o, and 15^o orientations, the wall area tends to have a higher air velocity than the center area. However, in the 45^o and 30^o orientations, the air velocity in the greenhouse walls and the middle area are slightly equal. In the 0^o orientation, there was a large difference in velocity from the south wall opening through the roof opening compared to the other locations. This is because most of the air flows directly in this orientation. This is consistent with a study by *Shklyar & Arbel (2004)*, where a high velocity was observed near the windward corner between the sidewall and the roof. The air velocity values in the greenhouses with 90^o, 75^o, 60^o, 45^o, 30^o, 15^o and 0 ^{o} orientations are 0.03-0.41 m/s, 0.02-0.34 m/s, 0.03-0.33 m/s, 0.01-0.36 m/s, 0.04-0.28 m/s, 0.04-0.33 m/s and 0.02-0.44 m/s, respectively. The greenhouse with orientation 0 ^{o} has the highest average air velocity, 0.21 m/s, and the lowest uniformity index, 0.731.

The temperature in the central area of the greenhouse is largely constant in the 90^o, 75^o, 60^o, 45^o, 30^o, and 15^o orientations. In the greenhouse with 0^o orientation, the temperature is lower around the roof from the south wall to the south roof opening. The overall temperature inside the greenhouse with 0o orientation is also lower than the others. The uniformity index of temperature does not differ for all orientations. The temperature values inside the greenhouses with 90^o, 75^o, 60^o, 45^o, 30^o, 15^o and 0^o orientations are 26.65-28.15 ^{o}C, 26.65-28.45 ^{o}C, 26.65-29.25 ^{o}C, 26.65-29.05 ^{o}C, 26.65-29.95 ^{o}C, 26.75-30.15 ^{o}C and 25.55-28.15 ^{o}C, respectively. The greenhouse with orientation 0^o has the lowest average temperature, 26.57 ^{o}C, compared to the others. This result indicates agreement with the air velocity distribution.

There is a relatively small difference in the uniformity index in all greenhouse orientations. The relative humidity values in the greenhouse with 90^o, 75^o, 60^o, 45^o, 30^o, 15^o and 0^o orientations are 44.77-45.46%,

44.06-45.51%, 41.72-45.62%, 42.44-45.13%, 40.43-45.80%, 39.85-44.95% and 44.49-53.77%, respectively. A greenhouse with an orientation of 0° has higher relative humidity, 48.95%, and a lower uniformity index, 0.981, than the others. In contrast, a greenhouse with an orientation of 75° has the lowest average relative humidity.
The greenhouse with the 30° orientation in M2 has the highest uniformity index of 0.807. The temperature in this orientation is high, 28.23 °C, and the relative humidity is low, 43.95%. In the greenhouses with 90° and 75° orientations, the temperature was 27 °C. The uniformity index for a greenhouse with a 75° orientation is higher than the 90° orientation, so 75° was chosen as the most suitable orientation for the greenhouse with M2.

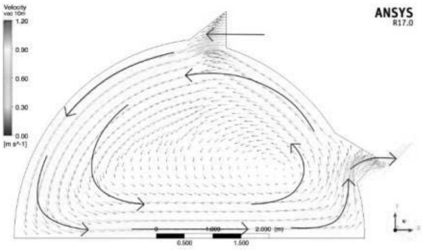
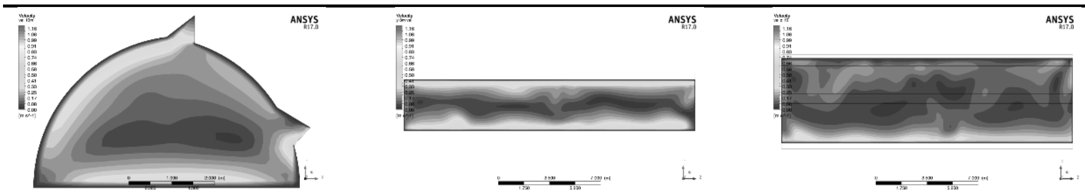
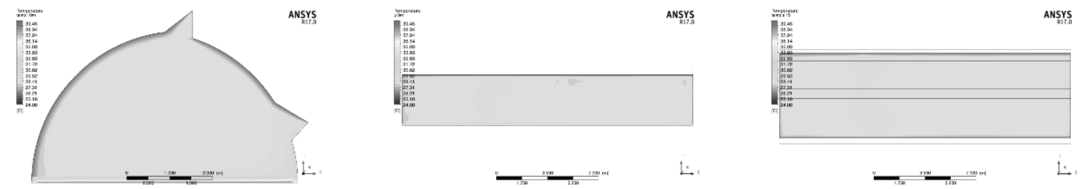


Fig. 6 Velocity flow pattern in XY and YZ plane for M2 with 75° orientation

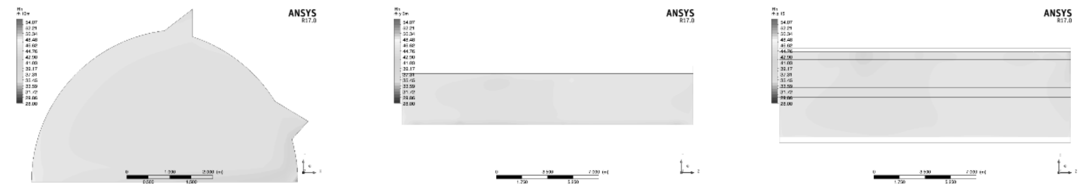
XY plane	YZ plane	XZ plane



(a) Air velocity



(b) Temperature



(c) Relative Humidity

Fig. 7 Air velocity (a), temperature (b), and relative humidity (c) distribution for M2 with 75° orientation

CONCLUSIONS

The airflow pattern, air velocity, temperature, and relative humidity in two different models, M1 (45° vent) and M2 (35° vent), each with seven orientations (90°, 75°, 60°, 45°, 30°, 15°, and 0°) were investigated in this study using CFD simulation. Validation was performed using the temperature and relative humidity data set. The statistical parameters used to evaluate the model performance showed good agreement between the simulation and the field test data. Since the wind was from the north, most orientations had insufficient airflow through the greenhouse. The indoor temperature ranged from 27-28 °C, and the relative humidity ranged from 42-48%. Based on the simulation, the best orientation for M1 is 45º and for M2 is 75º in terms of wind direction. This method effectively provides sufficient information to determine the appropriate greenhouse model in Samsun in less time and cost.

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