



XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010



INFLUENCE OF INSECT NETS AND THERMAL SCREENS ON CLIMATE CONDITIONS OF COMMERCIAL SCALE GREENHOUSES: A CFD APPROACH

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CSBE101277 – Presented at Section II: Farm Buildings, Equipment, Structures and Livestock Environment Conference

ABSTRACT The influence of different type of insect nets and both NIR and shading screens to climatic conditions of a commercial scale greenhouse of 1 ha was analyzed using Computational Fluid dynamics (CFD). The calculations were carried out for a typical 1ha Venlo type greenhouse focusing on summer weather conditions of Western Turkey. The crop (tomato) was simulated using the equivalent porous medium approach by the addition of a momentum and energy source term. Wind characteristics, temperature and humidity of outside air and application of different type of insect nets and NIR screen specified to set up the 3D CFD model. The numerical analysis was based on the Reynolds-averaged Navier-Stokes equations in conjunction with the Realizable k- ϵ turbulence model. The ventilation rate in terms of air changes per hour for all the models was calculated by simulating the decay tracer gas method. By using insect nets the decrease of ventilation rate was ranged between 15-30%. NIR screen and shading screens influence not only the radiative heat exchange but also the air temperature distribution. Numerical techniques are proved to be a useful tool to customize the design of commercial scale greenhouses to local conditions and analyze what if scenarios for future investments.

Keywords: ventilation rate, cooling, air temperature, energy saving

INTRODUCTION Protected cultivation systems are used throughout the whole world for crop production. Areas with protected cultivation are still growing and a wide range of systems has evolved. Just like nature, the local conditions determine which designs are fitting and which are not. Obviously, the design of protected systems in fact is a multi-factorial design and optimization problem (Van Henten et al., 2006). During the design process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, energy management, light management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like climate, market, legislation and availability of resources.

Many studies have been conducted to investigate the influence of different parameters to greenhouse environment. A method to address the question of how to design a protected cultivation system that best satisfies the local conditions was presented by van Henten, (Van Henten et al., 2006). In this study the main target was to develop a generic design tool mainly focused on energy consumption using heuristic and mathematical models. The systematic design procedure was found to be a powerful instrument even if many points require attention in future research. A common characteristic of the design tools, developed as decision support

tools, is that they do not consider the spatial variability of climate parameters inside the greenhouse. To solve the problem more advanced computational tools must be used in order to customize both the design of the construction and HVAC systems to local conditions.

Insect nets and different type of screens are widely used in modern greenhouse horticulture sector. Since chemical pesticides are less and less tolerated due to their environment impact and the development of pest's resistance, the use of insect nets could be a solution (Fatnassi et al., 2003). In addition, shading screens and screens which reflect the near infrared radiation (NIR) can be used for cooling purposes in order to extend the production season and protect the crop from high temperatures (Hemming et al., 2002; Teitel 2007). Considering that a greenhouse is actually a combination of a solar collector (greenhouse construction) with biological reactor (crop) a CFD analysis of the greenhouse environment expresses the interaction between the outdoor climate and the internal crop canopy. Quantitative understanding of a microclimate can help both greenhouse constructors and growers to optimize the design of the greenhouse and the operation of climate control systems respectively. Due to the complexity of the phenomena involved in indoor production systems, the amount of information required, to fully quantify the environmental variables, is dependant both on the physics involved and the level of precision associated with the analysis tools. CFD application studies used in the advancement of greenhouse technology have been comprehensively reviewed by many authors, (Boulard and Wang 2002; Norton et al., 2007; Reichrath and Davies 2002). Aim of the present study is to investigate the influence of different types of insect nets and shading screens to the environment of 1ha commercial scale greenhouse. The calculations were performed focusing in summer weather conditions of Western Turkey.

SET UP THE CFD MODEL

Air flow through screens Analysis of the influence of shading and thermal screens on greenhouse environment requires an understanding of porous media flow and the equations governing the hydrodynamic and thermodynamic processes. The porosity, ε , of a porous media is defined by Eq. 1; where the total volume of the porous region, V_{total} (m^3), is the sum of the volume of the solid material, V_{solid} (m^3), and the volume of the void space, V_{void} (m^3). As the porosity approaches the unity, the fluid flow becomes less restricted and its physical velocity (actual velocity inside the porous media), v (m/s), is decreased relative to its superficial velocity, u (m/s), (the velocity of the fluid outside of the porous media). The superficial velocity is related to the physical velocity, by the porosity according to Eq. 2.

$$\varepsilon = \frac{V_{void}}{V_{total}} = 1 - \frac{V_{solid}}{V_{total}} \quad (1)$$

$$u = \varepsilon v \quad (2)$$

The pressure drop ΔP (Pa) of an incompressible fluid across the porous media is given by the phenomenologically derived constitutive equation know as Darcy's law (Eq. 3).

$$\frac{\Delta P}{L} = \left(\frac{\mu}{K} \right) u \quad (3)$$

where μ (Pa*s) is the fluid's dynamic viscosity, L (m) is the length the pressure drop is taking place over and K (m²) is the permeability of the porous medium which is independent of the nature of the flow. It is a statement of surface drag due to friction and is a function of the medium that can vary greatly depending on the morphology of the material used (Nield and Bejan 1999). By adding an extra term in the Darcy's equation, in order to describe the pressure drop due to inertial effects (high Reynolds numbers), we obtain the Forchheimer equation (Eq. 4). The additional term contains the permeability, K , the fluid density, ρ (kg/m³), and the dimensionless drag coefficient or Forchheimer's inertial coefficient, c_f , which is a function of the porous matrix geometry and the bounding walls of the porous medium.

$$\frac{\Delta P}{L} = \frac{\mu}{K}u + \frac{\rho c_f}{\sqrt{K}}u^2 \quad (4)$$

It has been proven that the Forchheimer equation is valid for flow through greenhouse thermal, shade and insect screens, respectively, when the Reynolds number (based on pore size) is less than 100–150, (Miguel et al., 1997). For energy-saving screens, the pore dimension is typically 0.03 mm, which under normal greenhouse conditions gives a Reynolds number of approximately 5. The pore sizes of insect screens are in the range 0.2–0.5 mm which for an air speed of 3 m/s gives Reynolds numbers between 40 and 100. Therefore, the Forchheimer equation can be used to describe the airflow through these greenhouse screens, but this requires values for the permeability K , the inertial factor Y , and the thickness of the screen (Bailey et al., 2003). The parameters K and c_f can be obtained from measurements of pressure differences across the screen and the resulting airflows by fitting the pressure difference as a quadratic function of air speed, and then identifying the coefficients with those of Eq. 4.

Ventilation rate One of the most important techniques for measuring ventilation and leakage rates is the tracer gas technique which is based on a mass balance of a tracer gas in the building air. There are three methods of measuring ventilation and leakage rates with tracer gas techniques; the decay tracer gas method, the method of constant injection and the method of constant concentration. In the most popular one, the decay tracer gas method, the building is initially enriched with a quantity of tracer gas and allowed to become well mixed to get uniform concentration (Baptista et al., 1999). Sampling is then performed over time to document the rate at which the tracer gas concentrations decreases. The ventilation rate, in air changes per hour, can then be determined from this tracer decay rate. Tracer gas techniques are used not only for ventilation rate measurements but also for identification and characterization of air movement pathways, determination of volumetric flow and determination of re-entrainment.

In this study the ventilation rate of greenhouses was calculated by simulating the method of constant injection of a tracer gas (Sapounas et al., 2009). In the simulation model the tracer gas is a virtual gas called “air-tracer” which has the same physical properties as air. The ventilation rate can be expressed as follows:

$$VR_{greenhouse} = \frac{V_{greenhouse} \phi_{m,tracer}}{A_{greenhouse} c_{tracer}} 3600 \quad (5)$$

In the present study the commercial CFD code Fluent (1998) was used. The code uses a finite volume numerical scheme to solve the equations of conservation for the different transported quantities in the flow (mass, momentum, energy and water vapour concentration). The set up of simulation model mainly consisted of the definition of boundary conditions which based on experimental data obtained the specific time period. The incoming air consisted of air and water vapour in a mass fraction corresponds to the average relative humidity obtained by the weather data. The crop was simulated using the equivalent porous medium approach, as a source term of both latent and sensible heat and as a sink momentum which dominated by viscous and inertial resistance factors, (Boulard and Wang 2002; Campen et al., 2009; Lee and Short 2001).

Greenhouse design The simulation model was designed and meshed with the geometrical processor Gambit as a 3D full scale model. The typical Venlo-type greenhouse had a span width 9.6m and a continuous roof opening width of 1.0m, a gutter height of 6.0m and a ridge height of 7.0m, (Figure 1). The covered area was 1ha (9984 m²) and the opening area was 3060m² (31% of the covered area).

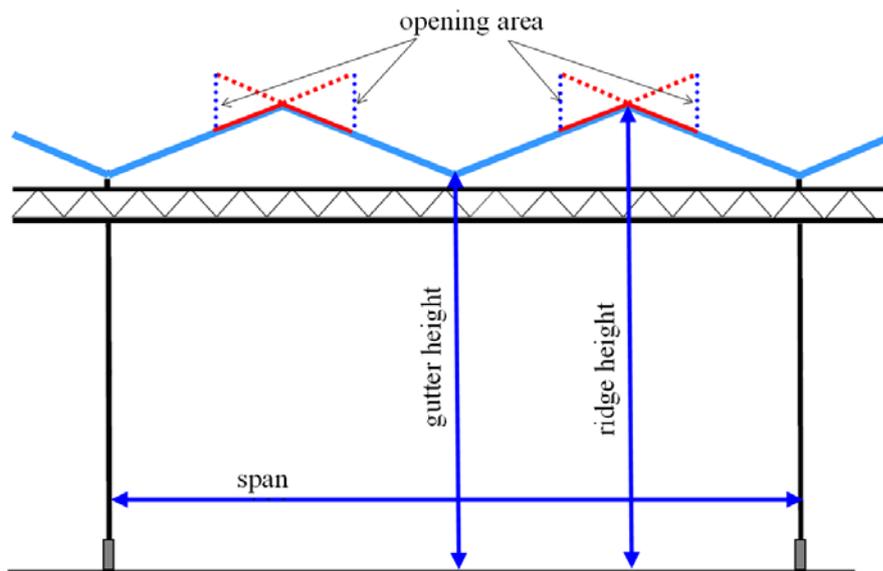


Figure 1. 2D sketch plane of a typical Venlo type greenhouse with continuous roof openings.

The main target in this stage was to combine a grid with the smallest number of cells with acceptable accuracy concerning the simulation results. Finally, a structured high quality grid consist of 944482 cells was created. The model was a 3D full scale model extended from 0-230m to x-direction, from 0-180m to z-direction and from 0-30m to y-direction (Figure 2).

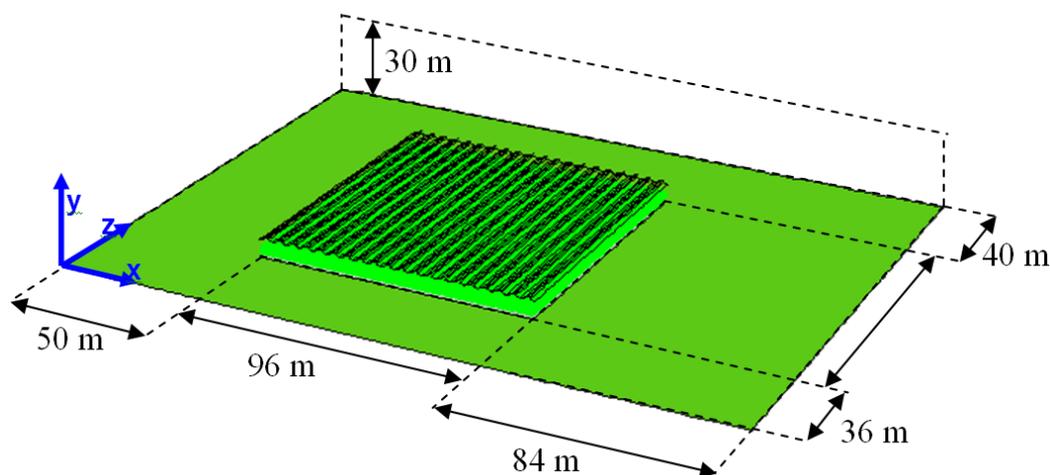


Figure 2. 3D computational domain consist of 1ha typical Venlo type greenhouse and its surrounding area.

Turbulence model One of the most important aspects in CFD modelling is the choice of the proper turbulence model (Bartzanas et al., 2007).. Several studies have focused on the effect of various turbulence models on the final numerical solution, showing that no general rules could be applied in all simulation models. The most common used turbulence model is the standard $k-\varepsilon$ which, has been tested in many cases describing the ventilation process in greenhouses. Despite it's widely usage the standard $k-\varepsilon$ model has small accuracy especially in low velocity magnitudes and should be carefully used. In addition, it contains many empirical constants that have long been known to have an adverse effect on prediction performance (Versteeg and Malalasekera 1996). In the present study, a 2D simulation model of 1ha greenhouse with its surrounding was designed and tested using different turbulence models in order to find the most appropriate one. The results shown that the best combination between physically sounds results and convergence performance was obtained by using the realizable $k-\varepsilon$ turbulence model in conduction with no-equilibrium wall functions (Fluent Inc 1998).

Boundary conditions As CFD models are totally deterministic models, next to grid quality and physical models (i.e. turbulence, wall functions, heat and mass transfer, etc), the results are depended on the boundary conditions. The boundary conditions, defined by inside and outside climatic conditions, crop behavior and use of equipments, are summarized in Table 1. For the inlet boundary condition a logarithmic wind profile was used which describes the vertical distribution of horizontal wind speeds above the ground, within the atmospheric surface layer (Sapounas et al., 2009). The model was solved for three different types of insect nets (Fatnassi et al., 2003; Fatnassi et al., 2006), for two different types of shading screens (Libeccio 30% and Libeccio 50%) and for a NIR screen (Hemming et al., 2002; Kempkes et al., 2008).

Table 1. Boundary conditions used in CFD model.

Boundary element	Value	Unit
Outside conditions		
Outside air temperature	30	°C
Outside air relative humidity	50	%
Outside global solar radiation	800	W/m ²
Wind speed (logarithmic profile)	1 / 3	m/s ¹
Material properties		
Greenhouse cover transmission	0.75	–
Glass density	2500	Kg/m ³
Glass specific heat capacity	840	J/(kg K)
Glass thermal conductivity	1	W/(m ¹ K ¹)
Wood density	700	Kg/m ³
Wood specific heat capacity	2310	J/(kg K ¹)
Wood thermal conductivity	0.173	W/(m ¹ K ¹)
Inside conditions		
Radiation reflected by canopy & construction	30	%
Crop (tomato)	porous media, power low model, C ₀ =1.7, C ₁ =1.65	
Ratio between sensible and latent heat	0.5	–
Sensible heat of plants	84 / 92.4	W/m ³
Latent heat of plants (mass flux of water vapour)	8.75 e ⁻⁵	Kg/(m ³ s)
Porosity of the plant canopy	1	–
Crop height	2.5	m
Initial mass flux of virtual gas (air-tracer)	1x10 ⁻⁶	Kg/(m ³ s)
Equipments		
Insect nets and shading screens (porous jump)	permeability / mesh size / pressure jump coefficient	
Anti-Bemisia insect net	1.89 x 10 ⁻⁹ / 0.0006 / 0.09	
Anti-aphids insect net	1.36 x 10 ⁻⁹ / 0.0004 / 0.14	
Anti-thrips insect net	2.67 x 10 ⁻¹⁰ / 0.00018 / 1.29	
Shading screen 30% (Libeccio 30)	8.50 x 10 ⁻⁰⁵ / 0.00065 / 0.372	
Shading screen 50% (Libeccio 50)	2.11 x 10 ⁻⁰⁵ / 0.00065 / 1.339	
Fogging system (heat sink)	300/-800 & 500/-200	gr/(m ² h) / W/m ³
Initial mass flux of CO ₂	0.012	kg m ² /h

COMPUTATIONAL RESULTS

Influence of insect nets on greenhouse microclimate The influence of insect nets to the ventilation performance was investigated by simulating a 1ha greenhouse with all ventilators covered with insect nets (anti-bemisia, anti-aphids and anti-thrips which is the net with the higher resistance to the air flow due to low porosity). Covering the ventilators with insect nets

for a greenhouse with area of 1ha results a decrease of ventilation rate from 14%-18%. Even if there are few research studies in the literature dealing with the influence of insect nets to the ventilation rate, no one of them has been carried out for a commercial scale Venlo-type greenhouse yet. Most of these studies concern small experimental greenhouses and this is the reason why the influence of covering the ventilators with insect nets results in a much higher decrease of ventilation rate (Katsoulas et al., 2006). Despite the obvious advantage of reducing insect pests by applying nets, the application of insect nets has positive influence to the air temperature distribution inside the greenhouse. Without insect nets the average air temperature difference between min and max values is 5.13 °C, while with insect nets is 1.77 °C, (Figures 3 and 4).

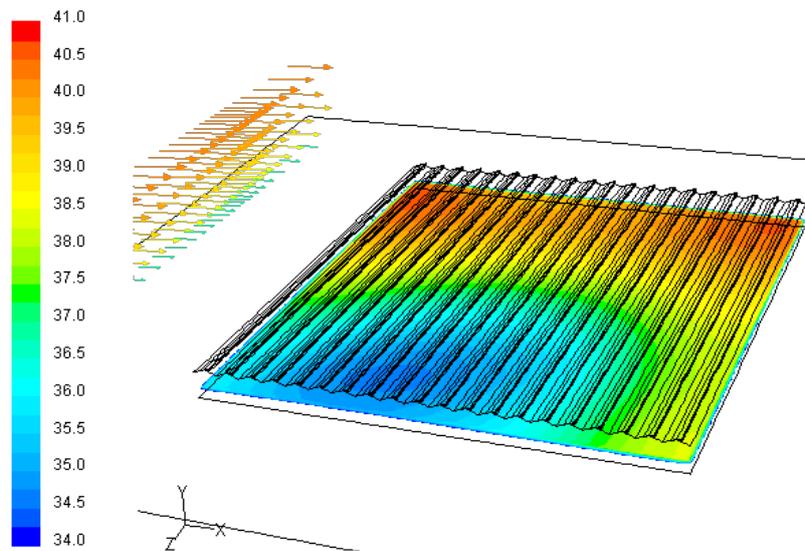


Figure 3. Air temperature distribution in 1ha greenhouse without insect nets at 2.0 m above the ground, (wind sp. 3m/s, wind dir. 10°, min air temp: 34.68°C, max air temp: 40.58°C, dif. air temp: 5.90°C, vent. rate: 69.6 m³/(m²h)).

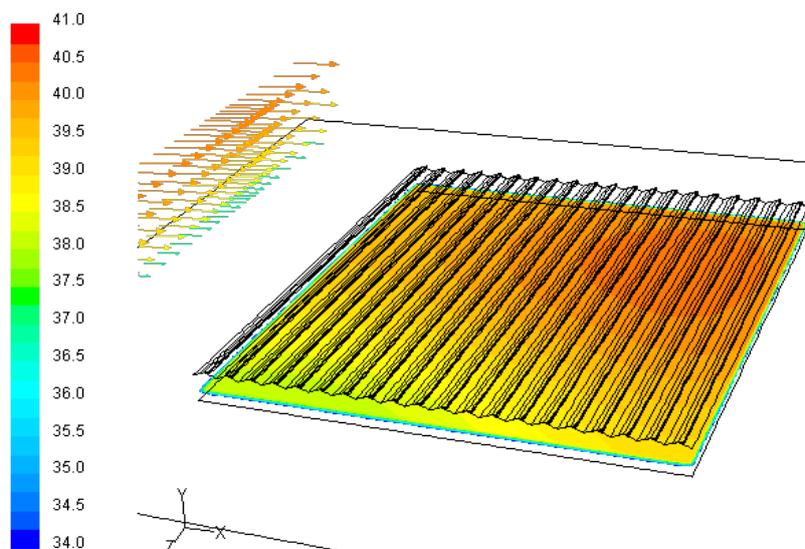


Figure 4. Air temperature distribution in 1 ha greenhouse equipped with anti-thrips insect nets at 2.0 m above the ground, (wind sp. 3m/s, wind dir. 10°, min air temp: 37.90°C, max air temp: 40.41°C, dif. air temp: 2.51°C, vent. rate: 55.1 66.6 m³/(m²h)).

In order to overcome the reduction of ventilation rate due to insect nets, calculations were carried out by simulating the same greenhouse but in this case considering roof and side openings both covered by insect nets. The results show that a greenhouse with side and roof openings has a ventilation rate higher (at the order of 30%) even from a similar greenhouse with only roof openings without insect nets. However, the main disadvantage in this case is the poor uniformity of inside climate, since the average air temperature difference is around 6-8°C.

Influence of shading nets and NIR screen on greenhouse microclimate The results regarding the ventilation performance of 1 ha Venlo type greenhouse and the air temperature inside the greenhouse indicate that there is a strong need for additional cooling next to natural ventilation. Direct evaporative cooling, applying an internal shading screen or a NIR reflecting screen are potential solutions. The principle underlying the shading screen is the reduction of solar radiation entering the greenhouse which implies a reduction air temperature while part of the radiation is converted to sensible heat. The NIR reflecting screen reacts as a normal shading screen but mainly for the infrared part of the sun radiation (700-2500nm), which means that the part of radiation that is useful for the plants (PAR, 400-700nm). The NIR screen when is combined with fogging system can provide desirable conditions by minimizing the loss of PAR light enters the greenhouse (Figure 4).

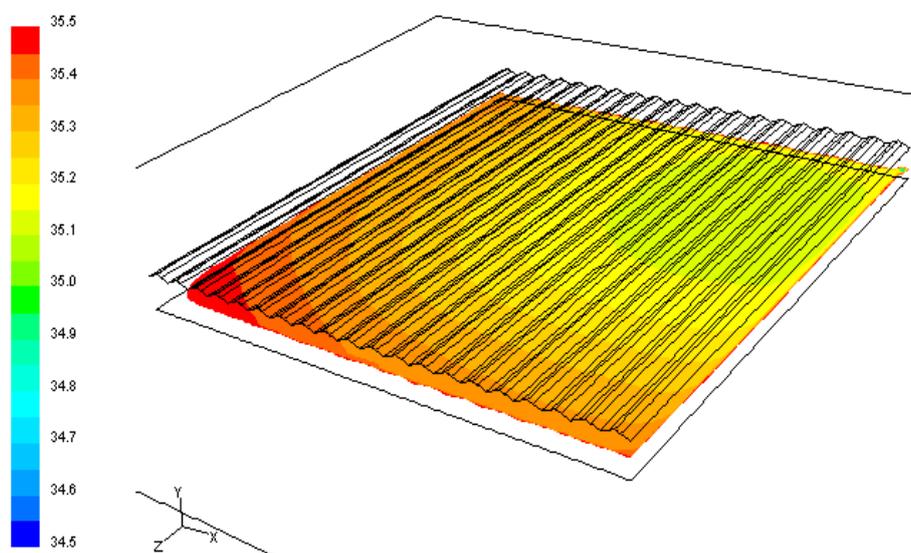


Figure 4. Air temperature distribution in a greenhouse with span width 9.6 m equipped with fogging system (capacity 300 g/(m²h) and NIR screen, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s⁻¹ and wind direction 10°, min air temp: 34.5 °C, max air temp: 35.4 °C, difference air temp: 0.9 °C).

By applying shading screen the air temperature inside the greenhouse range from 35.9-37.0 °C with almost uniform distribution. It is noticeable that by increasing the shading ratio from 30% to 50% results a small reduction to the ventilation rate from 7.04 to 6.71 air changes per hour. All the calculations results are summarized in Table 2.

Table 2. Boundary conditions used in CFD model.

Boundary conditions				Computational results		
Wind speed wind direction (m/s) / (°)	Insect nets	Shading screen	NIR screen	Ventilation rate Air changes per hour	Average air temperature inside the crop (°C)	Min Max Difference (°C)
3 / 45	Anti-thrips			7.86	39.4	37.4 40.3 2.9
3 / 45	Anti-aphids			8.86	38.9	36.9 40.7 3.8
3 / 45	Anti-bemisia			8.99	38.6	36.8 40.7 3.9
* 1 / 45	Anti-thrips			12.64	37.4	33.2 39.4 6.2
* 1 / 45	Anti-aphids			14.43	37.0	32.1 39.5 7.4
* 1 / 45	Anti-bemisia			16.30	36.9	32.0 39.6 7.6
* 3 / 10	Anti-thrips			13.28	36.9	31.0 39.6 8.6
* 3 / 10	Anti-aphids			17.92	36.3	30.9 39.7 8.8
* 3 / 10	Anti-bemisia			18.91	36.3	30.9 39.9 9.0
1 / 10	Anti-thrips	Libeccio 30%		7.04	36.75	35.9 37.0 1.1
1 / 45	Anti-thrips	Libeccio 50%		6.71	36.98	36.0 36.9 0.9
** 1 / 10	Anti-thrips		x	-	34.95	34.5 35.4 0.9

* Both roof and side ventilators are totally opened

** Combined with fogging system with capacity 300 gr/(m²h)

CONCLUSIONS CFD calculations were performed in order to investigate the performance of different insect nets and shading screens of a 1ha Venlo-type greenhouse for the Western part of Turkey. The computational results showed that the ventilation rate is mainly influenced by the temperature differences rather than wind speed. Using side openings equipped with insect nets increases the ventilation rate. The average air temperature is lower but the uniformity is worse. Using anti-insect nets has negative effect to the ventilation rate and this effect is relevant to the pore size of the net. By using insect nets with lower resistance (anti-aphids or anti-bemisia), instead of anti-thrips, the ventilation rate was increased in average terms for 12% for a greenhouse with only roof openings and for 17% for a greenhouse with both roof and side openings.

Using internal shading net of 30% or 50% decreases the average temperature level but it remains higher than applying fogging at the order of 3-4°C. A combination of NIR reflecting screen and fogging system with capacity of 300 gm⁻²h⁻¹) could provide acceptable climatic conditions even under extremely warm outside conditions.

The results show that CFD is useful tool to compare different commercial systems for specific conditions in order to optimize the design of commercial scale greenhouses.

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