Greenhouse Design Applying CFD for Indonesian Conditions

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Abstract

In the design phase of a test site in Indonesia computational fluid dynamics has been used to design the construction of the plastic greenhouse. Greenhouses in Indonesia are built to protect the crop from heavy rain and insects. The climate in four different greenhouse designs is calculated without insect gauze and with two types of insect gauze in the openings. Two designs consist of greenhouses with a top opening at one side of the ridge, with different dimensions of the top opening. The third design has no top opening, and the fourth design is the conventional Indonesian design consisting of three spans with an opening on one side of the ridges. The walls of the greenhouses are open or covered by insect gaze. The ground area in the greenhouse is equal for all designs.

The ventilation rate and the maximum temperature in the greenhouse have been used to evaluate the designs. The influence of the wind speed and direction has been investigated.

The design without an opening in the top has the highest ventilation rate and the lowest maximum temperature in case of wind due to aerodynamics. In case of no wind the climate in the design without top ventilation is slightly worse than in the other designs. Increasing the length of the greenhouse reduces the ventilation for this design. The insect gauze reduces the ventilation by more than 50%.

Based on these results a new design has been developed with an aerodynamic top opening. This design proved to function with and without wind. This design is currently being tested in Indonesia.

INTRODUCTION

In tropical lowland of Indonesia heavy rainfalls, wind and various plant pests and diseases often damage the open field grown vegetables (von Zabeltitz, 1999). The use of pesticides needs to be restricted, while it often leads to unacceptably high levels of residues in the products, heavy pollution of the environment, and high levels of resistance of insects to these pesticides. In Indonesian highland farmers also use simple protected structures for the production of vegetables. In these protected structures they often have problems with the inside temperature and humidity. The bamboo greenhouse construction often used is not durable, plastic films cannot be fixed properly; a lot of maintenance is needed. The greenhouses cannot be made tight for insects; plant pests and diseases affect crop production. An introduction of protected cultivation in tropical lowland of Indonesia can contribute to reach a higher yield and better quality of the crops using less water, fertilisers and pesticides. The agricultural production can be improved, leading to an increasing social welfare of the farmers.

For the greenhouse design with proper indoor climate for crop production the local outdoor climate conditions are boundary conditions. The experience with protected cultivation in Indonesia, the used greenhouse structures, the used materials and the occurring diseases, insects etc. have to be integrated in the design. To do so computational fluid dynamics (CFD) is a powerful tool. CFD modelling for greenhouse design is already reported extensively (e.g. Boulard et al., 1995; Mistriotis et al., 1997; Fatnassi et al., 2002; Campen and Bot, 2003).

Also the insect nets have to be optimised for local conditions (Ajwang et al., 2002). Mesh size and porosity not only determine which insects are able to enter the greenhouse

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but also how much the flow resistance of the opening is increased. Smaller mesh sizes stop small insects, like white fly or even thrips from entering the greenhouse. At the same time airflow is limited significantly, so greenhouse air temperature will rise (Sase and Christianson, 1990; Fatnassi et al., 2003). Wider mesh sizes allow better air exchange, but also allow white fly and aphids to come in. Next to this the covering material can contribute to the proper indoor climate if near infrared radiation (NIR, 800-1100 nm), contributing to the warming-up effect of the greenhouse, can be reflected and photosynthetic active radiation (PAR, 400-700 nm), important for plant photosynthesis, is still transmitted (Brown, 1939; Hoffmann and Waaijenberg, 2002; Verlodt and Verschaeren, 1997).

All these aspects are important for the design of a new greenhouse system for tropical lowland of Indonesia. The main purpose of this project is to find whether the designed greenhouse has enough ventilation capacity, which strongly influences the inside temperatures.

MATERIALS AND METHODS

The CFD program Fluent v.5.2 was applied to optimise the new design of a greenhouse for tropical lowland examining the inside temperature distribution in relation to the size and location of ventilation openings, netting material, light transmission of the covering material and local climate data like: outside wind speed, irradiation and temperatures. Computational fluid dynamics (CFD) is a tool to determine flow field and temperature distributions in and around geometries. Mistriotis et al. (1997) gave a general description of CFD. In a CFD program a system is modelled by discretising space and time (integrated volume method) and by solving the conservation equations of the discretised parts for the relevant quantities considered. The conservation equation reads:

$$\frac{\partial \varphi}{\partial t} + \vec{\nabla} \cdot \varphi \vec{v} = \vec{\nabla} \cdot \left(\Gamma_\varphi \vec{\nabla} \varphi \right) + S_\varphi \tag{1}$$

where $\vec{v}$ is the air flow velocity vector in m s^{-1}, Γ_φ is the diffusion coefficient in m^2 s^{-1} and S_φ is the source term, φ represents the concentration of the quantity considered (total mass, momentum, energy or mass of a component). Solving these equations provides transport between the parts of the model, thus the flow field and temperature and concentration distribution can be determined. Separate models describing the fluctuating part of the flow account for turbulence. The k-ε model is widely used as a turbulence model. (Launder and Spalding, 1974).

Various greenhouse constructions are investigated in this study (Fig. 1) with different lengths and different ventilation openings. The mean outside temperature is assumed to be 30°C. The mean irradiation is assumed to be 600 W m^{-2} (reference film) or 300 W m^{-2} (ideal NIR-reflecting film); in the greenhouse 50 % of the irradiation is assumed to be released in the air as sensible heat and 50 % is assumed to be released by the crop as latent heat. The wind velocity is assumed to be 0 m s^{-1} or 3 m s^{-1}. The buoyancy effect is dominant when the wind speed is below 2 ms^{-1}, according to theory on ventilation (Bot, 1983; Campen and Bot, 2003). The airflow resistance of a 2 m high crop is also included in the model. Two different insect screens are investigated. Based on the CFD calculations the optimum greenhouse design for ventilation and insect screens is chosen for this project.

Air Flow through Insect Screens

The influence of the insect screening material on the ventilation is taken into account in the CFD model by a porous medium. Miguel, 1998 did a study on transport of air through insect screens and found the following relation between the pressure difference $\frac{\partial p}{\partial x}$ over the screen and the resulting air velocity v:

$$-\frac{\partial p}{\partial x} = \frac{\mu}{K} v + \rho \frac{Y}{K^{1/2}} v^2 \qquad (2)$$

where μ is the dynamic viscosity in Pa s; K is the permeability of the screen in m^2; ρ is the density of air in kg m^{-3};and Y is the inertial factor. Miguel (1998) measured the properties of the two nets (Econet FL, $K = 6.51 \cdot 10^{-9}$ m^2, Y=0.457 and Econet SF, $K=1.39 \cdot 10^{-9}$ m^2, Y=0.758 both with a thickness of $5.06 \cdot 10^{-4}$). The results are used in the CFD model.

RESULTS

CFD-calculations are made for the commercial greenhouse designs (Fig. 1 A-D). Insect nets cover the open gables and sidewalls of the greenhouse and the ridge ventilation openings. Conventional plastic films cover the greenhouse. The effect of the insect screens on the ventilation is investigated in the different greenhouse designs. The average ventilation in the different designs is summarized in Table 1 in renewals per hour (h^{-1}) at a wind speed of 3 m s^{-1}, leeward and windward. The ventilation of designs A, B and D is reduced for a leeward wind when no insect screen is present and for the Econet FL screen. The direction of the wind has little influence on the ventilation when the Econet SF is installed. The influence of the air resistance is high compared to the influence of the wind direction. The larger opening area of the top ventilation (A vs.B) has only a positive effect when Econet SF insect gauze is used. The overall ventilation of the design with a top opening is less than the design without a top opening when no insect gauze or Econet FL is present. The top opening obstructs the flow reducing the ventilation of the second and third greenhouse down stream.

Fig. 2 shows the temperature distribution in a vertical plane of the greenhouse at a wind speed of 0.5 m s^{-1} with Econet SF insect screens for the commercial greenhouse design (A) and the commercial design with no top ventilation (C). The design with top ventilation shows higher temperatures in the central part of the greenhouse compared to the design without top ventilation. The top ventilation disturbs the airflow. The buoyancy force and the force due to the wind are similar but opposite, resulting in an accumulation of warm air in the greenhouse.

The ventilation of the individual greenhouses is presented in Table 2 when the Econet SF screen is installed. The individual greenhouse upstream in design A,B and C is ventilated more that the other two greenhouses. The shape of the greenhouse blocks the airflow for the greenhouses downstream.

The effect of the length of greenhouses is also considered (Table 3). In the short greenhouses (12 m) the ventilation rate and inside air temperature are influenced by the relatively large gable ventilation. By increasing the length of the greenhouse the influence of the side gable on the greenhouse climate can be investigated. From 0 it can be seen that at low wind speeds a long greenhouse (36 m), especially the design (C) is disadvantageous. The mean inside temperature rises from 34° C to more than 36° C. The maximum temperature is 40° C. But also in design (A) the maximum temperature reaches almost 39° C, while the mean temperature is less increased. In the multi-span greenhouse maximum temperatures exceeds almost 42° C making plant production almost impossible.

A new optimal design for the greenhouse was made based on the results discussed. (0 E). The insect net in the top ventilation is located horizontally below the lifted cover. The new Procult design combines the good performance of the individual designs (0 A-C) The performance of this new design is shown in 0 and 0. The direction of the wind does not affect the ventilation rate of the new Procult design since the design is symmetrical. The ventilation rate of the individual greenhouses is more equal for the different conditions than the previous designs.

The span width of the new Procult greenhouse is 9.6 m, the length 15 m, the column height is 4 m and the distance of the columns in the direction of the gutter is 2.5 m. The greenhouse is provided with a lean-to on all gables and sidewalls to prevent rain entering the greenhouse through the screens. Insect screens with openings of 0.6 x 0.6

mm (comparable to Econet SF) are closing all ventilation openings. Ventilation openings are in all side-walls and front gables from 1 m above ground level (0) to gutter level, except the triangle of the front gables above gutter level. This results in a total ventilation area of 40.4 % of the greenhouse-covering surface. Each greenhouse entrance is provided with an insect lock on the outside.

CONCLUSIONS

A new greenhouse system was developed for the production of high quality horticultural products in tropical lowland in Indonesia. The greenhouse design has a large opening area for ventilation (40.4 % of the greenhouse surface area). CFD proved to be a powerful tool for the design, which simulates airflow and temperature distribution. Provisional climate measurements carried out in the new built greenhouses in Indonesia showed that the boundary conditions assumed in CFD were suitable to give a good reflection of the local situation (data not shown here). Since CFD is only a tool to investigate a static situation, it remains necessary to validate the model and to collect dynamic data year around.

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Tables

Table 1. Average ventilation rate of various greenhouse designs in renewals per hour with different insect screens at a wind speed of 3 ms^{-1} coming windward and (leeward).

Configuration	No insect screen	Econet FL	Econet SF
A. Commercial design	205 (143)	104 (95)	87 (80)
B. Commercial design with a larger top ventilation	166 (132)	113 (101)	89 (85)
C. Commercial design without top ventilation.	221 (227)	130 (133)	74 (75)
D. Commercial design as multi-span	170 (148)	102 (82)	61 (59)

Table 2. Influence of the wind speed on mean inside air temperatures and ventilation rate in renewals per hour (*italics*) of various greenhouse designs with Econet SF insect screen per single greenhouse in a row (1-3), wind coming from left.

Configuration	Wind speed 3 ms^{-1}			Wind speed 0.5 ms^{-1}		
	Greenhouse			Greenhouse		
	1	2	3	1	2	3
A. Commercial design	31.5	32.0	32.3	34.6	34.7	34.7
	115	*84*	*73*	*38*	*37*	*37*
B. Commercial design with a larger top ventilation	31.4	32.0	32.1	34.4	34.3	34.3
	119	*85*	*78*	*38*	*39*	*39*
C. Commercial design without a top ventilation.	31.8	32.6	32.3	35.7	35.8	35.8
	98	*67*	*74*	*31*	*30*	*30*
D. Commercial design as multi-span		32.8			35.6	
		61			*30*	
E. New Procult design	31.9	32.0	32.0	34.6	34.3	34.2
	83	*79*	*79*	*37*	*40*	*41*

Table 3. Influence of the length of the greenhouse on mean air temperatures inside greenhouse with Econet FL insect screen for the different greenhouse designs at a wind speed of 0.5 ms^{-1}.

Configuration	Short greenhouse (12 m)			Long greenhouse (36 m)		
	Greenhouse			Greenhouse		
	1	2	3	1	2	3
A. Commercial design	33.3	33.4	33.3	33.6	35.0	34.7
B. Commercial design with a larger top ventilation	33.1	33.0	33.0	33.5	34.3	33.9
C. Commercial design without a top ventilation.	33.8	34.0	33.9	35.3	36.7	36.6
D. Commercial design as multi-span	33.9			35.1		
E. New Procult design	33.2	33.2	33.1	33.7	34.3	34.1

Figures

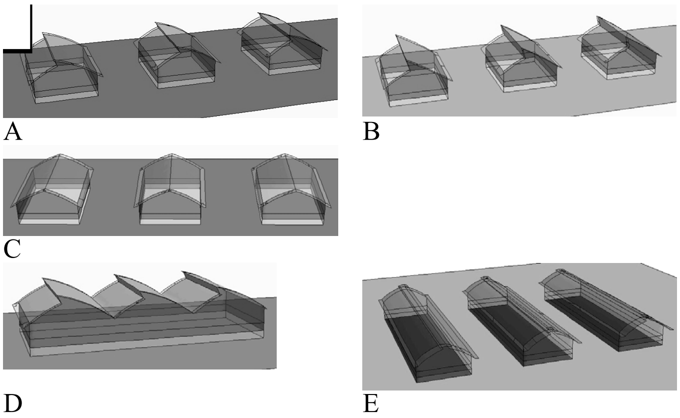

Fig. 1. Different greenhouse shapes are calculated with CFD. A. a commercial design, B. the commercial design with larger top ventilation, C. the commercial design without top ventilation, D. the commercial design as multi-span, E. the new Procult design.

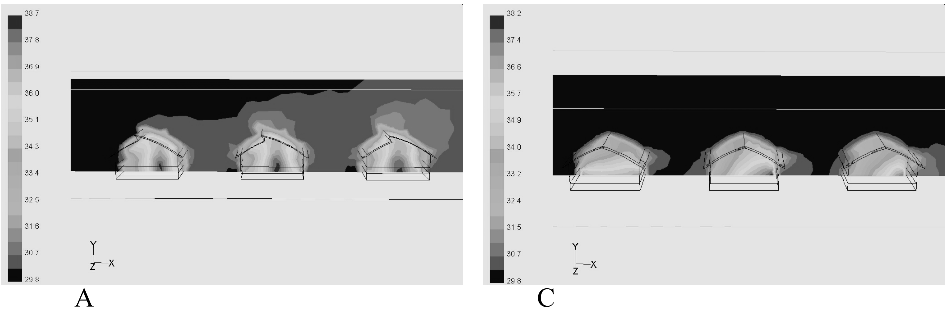

Fig. 2. Temperature distribution at a wind speed of 0.5 ms^{-1} with Econet SF insect screen for the commercial design (A) and the commercial design with no top ventilation (C).

Fig. 3. The new Procult greenhouse design, three greenhouses in a row.