Computational Fluid Dynamics for Greenhouse Aerodynamics

E. Rico-García[1]*, G. M. Soto-Zarazúa[1], O. Alatorre-Jácome[1], G. A. De la Torre-Gea[1] and D. J. Gomez-Melendez[2]

[1]Department of Biosystems, School of Engineering, Queretaro State University, C.U. Cerro de las Campanas,Querétaro, México.
[2]Deparment of Mechatronics, Polytechnic Queretaro University. Carretera Estatal 420 S/N, El Marqués,Querétaro, México.

Abstract

In the last decade, computational fluid dynamics (CFD) has been used to evaluate ventilation on agricultural facilities, mainly on greenhouses. However, there is lack of information on aerodynamic design on greenhouses. In this work, a CFD model has been used to evaluate wind forces over plastic greenhouse covers. Two different greenhouse geometries plane and round, were studied. The effect of wind velocity on the pressure profile over the greenhouses was evaluated. Results showed that almost the entirely roof is subjected to suction forces for both geometries. For the round geometry, these forces are bigger than for plane geometry. However, a bigger damage is observed on plane geometries. From the results, it can be concluded that flapping is the cause of plastic tearing.

**Key words:** Negative pressure, plastic covers, plastic damage.

INTRODUCTION

The use of computational fluid dynamics (CFD) has increased in the study of natural ventilation in greenhouses (Campen and Bot. 2003; Molina-Aiz et al., 2004; Rico-García et al., 2006, 2008). This technique has become a tool for the study of natural ventilation in greenhouses dealing with window configurations, crop distribution or the whole greenhouse configuration with the surrounding buildings. However, there is lack of infor- mation regarding aerodynamic design on greenhouses; in particular for plastic greenhouses, the aerodynamic design is of great interest since constantly the plastic covers get damage by the wind action. In this work, CFD has been used to evaluate the pressure profiles over two different greenhouse geometries to understand the mechanism of how wind damages greenhouse plasticcovers.

CFD fundamental theory

The governing equations of a fluid flow and heat transfer can be considered as mathematical formulations of the conservation laws that govern all fluid flow, heat transfer and associated phenomena. These conservation laws describe the rate of change of a desired fluid property asa function of external forces and can be written as:

1. Continuity equation: Net mass flow out of control volume through its surface; the time rate of decrease of mass inside the control volume (Equation 1).
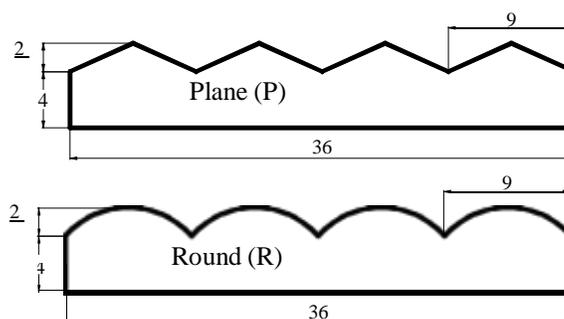
(a)
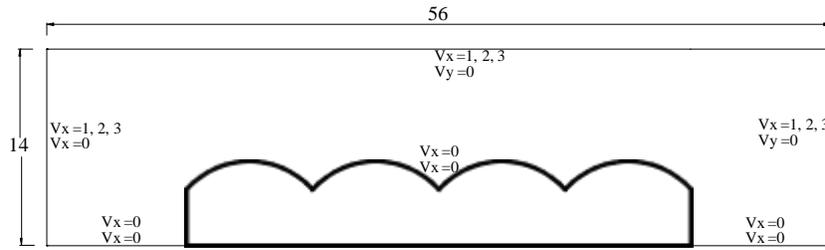
(b)

Figure 1. Configuration under study. (a) Greenhouse geometries under study. All dimensions are in meters. (b) Geometrical model and boundary conditions. All dimensions are in meters.

Table 1. Properties values used to simulate air in the CFD model.

Variable	Model*	Value
Specific heat (J kg^{-1} K^{-1})		1004
Thermal conductivity (W m^{-1} K^{-1})	$\lambda = (2.502E^{-3}T^{3/2})/(T+194.44)$	
$T_o = 291$ (K)		0.0256
Dynamic viscosity (kg m^{-1} s^{-1})	$\mu = (1.459E^{-6}T^{3/2})/(T+110.56)$	
$T_o = 291$ (K)		1.804×10^{-5}
Density (kg m^{-3})	$\rho = P/(287.05T)$	
$T_o = 291$ (K)		0.9743
Atmospheric pressure (Pa)	(1800 m o.s. l.)	81388
Gravitational acceleration (m s^{-2})		9.81

*Rico-García et al. (2008); m. o. s. l., meters over the sea level.

easily on plane surfaces while on round surfaces they are maintained in good condition.

Geometrical model

A commercial package ANSYS-FLOTRAN v11 based on the finite element method (ANSYS, 2007) was used to to calculated the pressure over the greenhouse roofs.

A large 2D geometrical model domain, including the greenhouse at the centre of 56 m long and 14 m high was used. This domain was proposed in order to allow the flow to be naturally developed (Figure 1b).

Meshing

The meshing was carried out using the finite element 2D FLUID141 being the degrees of freedom: velocities, pressures and temperatures. This element is able to simulate fluids and non-fluids materials. However in the model, only air was considered (Table 1). The mesh was an un-structured meshing with squares and triangles. The mesh density was greater near the surfaces. This refinement allows obtaining a better solution near the areas where strong gradients could take place, in this case, near the surfaces representing the greenhouse roof.

Boundary conditions

A constant value of wind velocity were imposed at the side and upper part of the geometrical model domain, and in all lines representing the soil and plastic cover the velocity condition imposed was equal to zero (Figure 1b).

Model set-up

The analysis was carried out as a steady state and adiabatic simulation; for this study, Equation 3 was not considered, and as condition of turbulent flow; the shear stress transport (SST) model was adopted for this study, because of its favourable convergence behaviour and reasonable accuracy (Norton et al., 2007).

Analyzed cases

For each greenhouse geometry, five wind velocities were studied: 1, 2, 3, 6 and 9.5 m s^{-1}, for the three first wind velocities complete pressure profiles were computed along roof greenhouses and for the last two values just the forces due to pressure acting per meter of roof were computed in windward and leeward half spans as the suction forces are larger at these locations (Figure 2a).

In all cases, the greenhouse windows were closed. The reason why these velocities were considered is that for velocities under $1 \, m \, s^{-1}$, no wind damage on the plastic cover is to be expected and velocities above $9.5 \, m \, s^{-1}$, according from data recorded at the place of study, are unusual and plastic damage is expected (Figure 3).

CFD model validation

To gain confidence on the results generated by the model, a self calibration was performed. If the model is considered as a tube from the continuity Equation (1), the total flow at the inlet and at the outlet must be the same. So from the model, two wind velocities profiles were determined at three meters from inlet and outlet (Figure 2a) in order to compute the total flow coming in and the total flow going out. Finally the standard error was computed, finding only 3.24% of variation between output and input flows, with a standard deviation of 1.75 (Figure 2b). So the results generated by the model can be trusted.

Computation of pressure over the greenhouse covers

Pressure values were computed from the model at 10 cm over the greenhouse roof covers (Figure 4).

RESULTS AND DISCUSSION

From the comparison between the two types of greenhouse roof geometries (Figure 5a), we observed that for the plane geometry, the pressure profile presents pronounced gradients, especially at the top of each span,
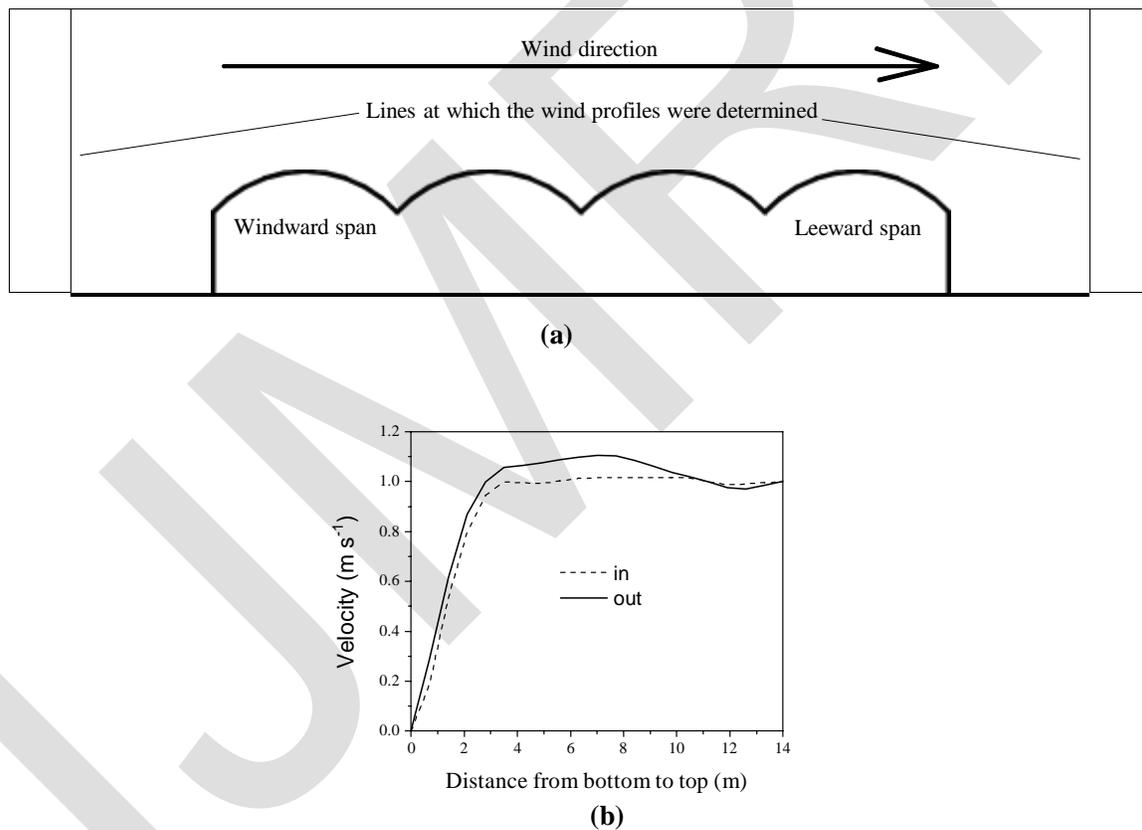

(a)

(b)

Figure 2. Calibration of the CFD model. (a) Locations for determining wind profiles and definition of windward and leeward spans regarding wind direction (b) Wind profiles for R1.
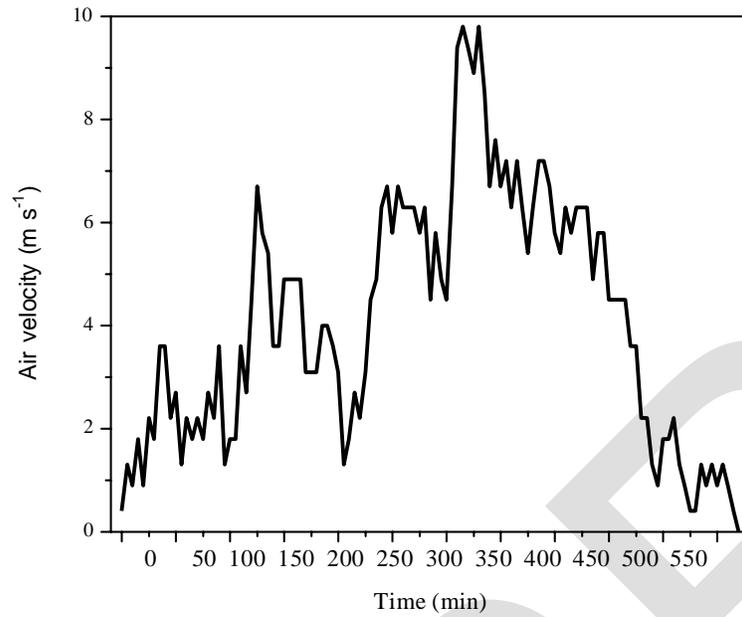
Figure 3. Wind behavior at the site of the study, 17-08-2009.

Figure 4. Location at which the pressure was evaluated (dashed line).
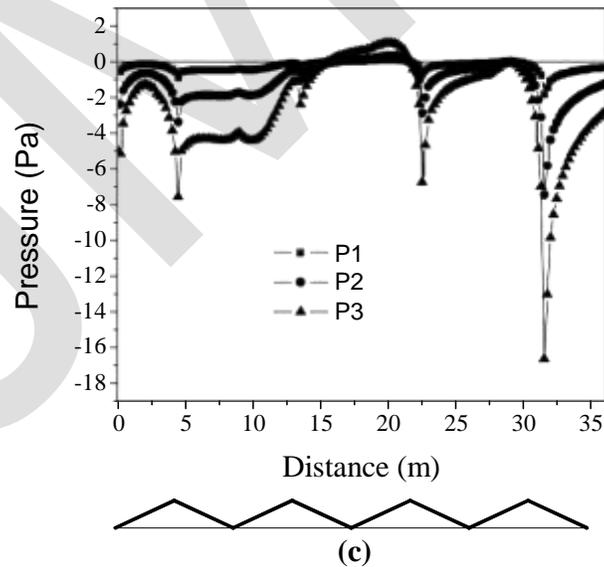

(c)

Figure 5. Pressure profiles over the two types of greenhouse roof geometries: (a) Comparison of pressure profiles over thetwo types of roof geometry for $V = 3$ m s^{-1}. (b) Round geometry; (c) Plane geometry.
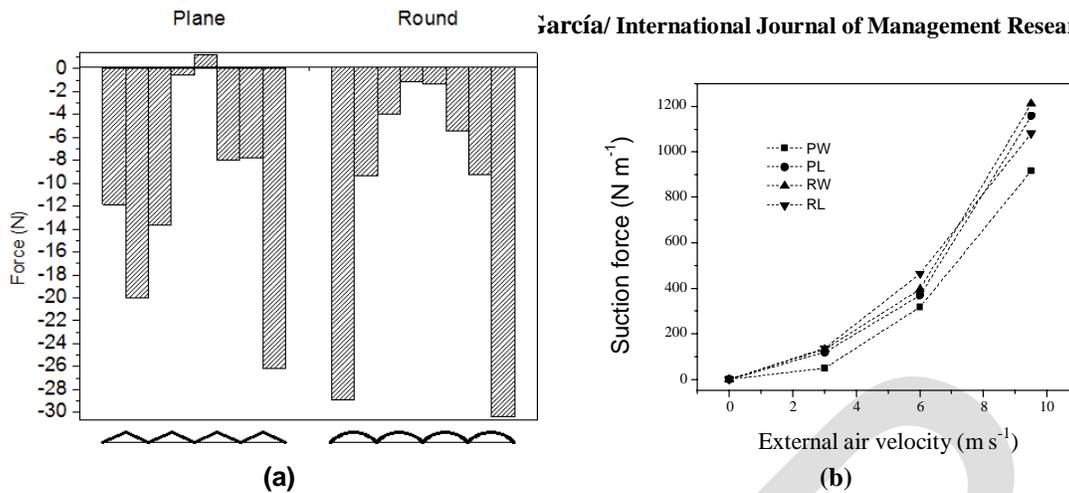
Figure 6. Forces over greenhouse roofs. (a) Force due to pressure over the roof, computed for half spans; V = 3 m s-1. (b) Variation of suction force due to wind velocity for windward (W) and leeward half spans (L).

while for the round geometry, the profile pressure presents soft changes. This can be explained if we consider the model like a tube in which a reduction on diameter will increase the flow velocity and reduce the pressure; for the plane greenhouse, the geometry presents a sudden change at the very top of the greenhouse which is reflected in an abrupt change in the pressure profile. For the round geometry, this change in geometry is gradual so the pressure gradient is soft. We also observed that the pressure tends to be greater for the round greenhouse.

An interesting finding is to note how a defined pressure profile matches each roof shape (Figure 5b and c). This can be use as a fingerprint to identify roof geometries, and also reinforces the widely use to locate roof windows on the top of greenhouses. As a consequence, natural ventilation will be improved by wind action, especially on hot seasons.

From Figure 6a, it is clear that plane and round geometries are almost entirely subjected to negative pressures that cause higher forces on the plastic cover, especially on the first and last spans in which the forces are much bigger than in the central spans. This indicates that these two lateral spans should be reinforced to resist the negative pressures caused by the wind action. Figure 6b presents the forces acting in those spans and for wind velocities above 9 m s^{-1}, the forces reach values up to 1000 N m^{-1}. If one consider the variable and unstable behavior of wind action (Figure 2), it is understandable that these forces are intermittent and they vary suddenly from very low to high values causing a violent flapping movement of the plastic covers, especially for the plane geometry, and eventually mechanical damage occur, even, before the optical properties of the plastic are lost. This is consistent with the analysis presented by Briassoulis et al. (1997) where they say that flapping is the cause of plastic tearing mainly at the location where the film is fixed to the structure. However they do not present any way to evaluate these forces.

Conclusions

From the beginning of this study, we expected that the negative pressure profiles over the plane greenhouse would be stronger than in the round greenhouse and that would explain why in this geometry the flexible plastic cover gets damage very easily. However from the results of this study, we found out that the negative forces over the round geometry are bigger than in the plane geometry. So we suggest that the damage for plastic covers is due to the way the plastic is laid down on the structure. In the round geometry, the plastic is kept tied to the structure due to the round shape while in the plane greenhouse, the plastic cannot be tied. It allows plastic flapping and eventually mechanical damage is presented along the edges, where the plastic is fixed to the structure.

This study presented a quantitatively way to evaluate wind action over greenhouses.

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