Numerical estimation of external pressure coefficients of a pitched-type roof greenhouse and comparison with Eurocode in different flow-type circumstances

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Abstract

Wind and snow are the most important key stress factors for greenhouse structures. The maximum values of these two factors are directly affecting both safety and cost of the structure. The air flow over a greenhouse structure is a complex and complicated phenomenon which mainly depends on the wind characteristics (speed, direction etc.), the geometry of the structure and the type of the greenhouse (single or multispan with arched-type or pitched-type roof). The prediction of wind loads on greenhouses is essential to their safe design. For the calculation of the structures’ load by the wind, the external wind pressure coefficient ($C_{pe}$) is used. The wind pressure coefficient is obtained from the EC1 (prEN 1991-1-4) in conjunction with EN 13031-1:2001, which is specialized for greenhouses, gives values for this coefficient. A high external pressure coefficient value leads to an increase of the construction weight and subsequently to an increase in the construction cost. The proper design of the greenhouses would have to ensure not only the functionality and the static safety of the structure but also to keep the construction cost at low level.

In this work a numerical wind tunnel study was conducted to investigate the influence of flow type (study and unsteady) in two different Reynolds Numbers ($Re=1000$ and $2000$) on local pressure coefficients measured on a pitched-type roof obstacle (greenhouse). The Navier-Stokes and continuity equations are solved numerically with the finite element method (Galerkin Method) in order to simulate the two dimensional, incompressible, viscous air flow over the pitched-type roof greenhouse. The simulation was carried out in a numerical wind tunnel. The numerical results of external pressure coefficients are compared and discussed with data of Eurocode (EN 13031-1:2001) for wind actions.

The results of the numerical experiment were close to the values given by the Eurocode mainly on the leeward area of the roof while on the windward area a further segmentation is suggested. The Eurocode divides the greenhouse roofs in areas and gives only one $C_{pe}$ value for each area, while with a CFD model it is possible to predict the value for every point in the roof, which may become useful in solving the static body.

Keywords: Eurocode, external pressure coefficient, fluid mechanics, greenhouse, wind flow

1 Introduction

The air flow over a greenhouse structure is a complex and complicated phenomenon which mainly depends on the wind characteristics (speed, direction etc.), the geometry of the structure and the type of the greenhouse (single or multispan).
One of the main stress factors of the bearing structure of the greenhouse is the wind. For the calculation of the wind load, the external wind pressure coefficient is used. The wind pressure coefficient is obtained from the EN 13031-1:2001, which is specialized for greenhouses. However, those values given by Eurocode lead to heavy construction which has an inverse effect on the construction cost. Therefore, further research is required in this area.

The safety of the structures is of major importance but the cost of the construction must not be overlooked, particularly as far as livestock buildings are concerned, as livestock farming is an agro-business sector that faces financial problems. A possible solution could be to use greenhouse-type livestock structures (Nikita-Martzopoulou, 2007; Ntinas et al., 2014). Therefore, a reliable experimental and/or a computational approach for estimating the pressure coefficient is required, as well as, performing an analysis of its distribution on the roof of the structure. It has to be noted that the greenhouse structures belong to the general category of the low-rise buildings (Mistriotis & Briassoulis, 2002).

The distribution of pressure coefficients for various geometrical low-rise buildings is obtained by full-scale or wind-tunnel numerical simulations and experiments (Blackmore & Tsokri, 2006; Ginger & Holmes, 2003; Robertson et al., 2002; Tieleman, 2003). The full-scale experiments as well as experiments using air-tunnels are more reliable for the detection of the pressure distributions, however, their implementation cost is high and they are not applicable to every structure. Alternatively, the pressure distribution can be estimated using computational and numerical models. The numerical models have proven their value for the design of livestock buildings (Norton et al., 2009). Up to now many researchers have studied the $C_p$ distributions computationally. Reichrath & Davies (2002) have used the commercial CFD package Fluent in order to estimate the pressure distribution on a 7 span Venlo-type glasshouse. Wright & Easom (2003) have used a non-linear k–e model to find the pressure coefficient on a surface mounted cube. Shklyar & Arbel (2004) have used a standard k–e model and RSM model to predict the pressure coefficient distribution on a pitched-roof greenhouse.

In the present study, the air pressure coefficients are calculated with a non-commercial Computational Fluid Dynamics (CFD) model. The two dimensional, steady and unsteady, incompressible, viscous, turbulent air flow over single duo pitched roof greenhouse was studied. The dynamic and steady state model simulate the air flow inside an air-tunnel with the appropriate boundary conditions. The calculated wind pressure coefficients for steady and unsteady air flow are compared and discussed with the corresponding rates given by the Eurocode (EN 13031-1:2001) for two different Reynolds numbers ($Re$=1000 and $Re$=2000).

2 Materials and methods

2.1 Governing Equations

The dimensionless Navier-Stokes (1) and continuity (3) equations are used to solve the two-dimensional, viscous, incompressible, steady flow over a pitched-type roof greenhouse in a wind tunnel. Also, the dimensionless Navier-Stokes (2) and continuity (3) equations are used to solve the corresponding unsteady flow:

\[
U \nabla U = - \nabla p + \frac{I}{Re} \nabla^2 U, \quad (1)
\]

\[
\frac{\partial U}{\partial t} + U \nabla U = - \nabla p + \frac{I}{Re} \nabla^2 U, \quad (2)
\]

\[
\nabla U = 0, \quad (3)
\]
where, $U=(u,v)$ is the velocity vector of the fluid with $u$ and $v$ its components in the x and y direction respectively, $p$ is the pressure and $Re$ is the Reynolds number.

The governing equations have been rendered dimensionless by using the following characteristic magnitudes $(L, V, P_o, Re)$, where $L$ is the length of the ridge above ground level (m), $V$ is the uniform approaching velocity of the fluid (inlet free stream velocity, $\text{ms}^{-1}$), $P_o = \rho V^2$ is the pressure intensity ($\text{Nm}^{-2}$), $\rho$ is the density of the fluid ($\text{Ns}^2\text{m}^{-4}$), $Re = VL\nu^{-1}$ is the Reynolds number and $\nu$ is the kinematic viscosity of the fluid ($\text{m}^2\text{s}^{-1}$).

### 2.2 Boundary Conditions

In the present work, a uniform free stream flow is used as boundary condition at the entrance of the computational domain. The no-slip boundary conditions are imposed along the walls of the wind tunnel and the greenhouse structures. The outlet boundary condition is a free boundary condition that permits the fluid to leave the computational domain freely without any distortion (Malamataris, 1991; Papanastasiou et al., 1992), (Figure 1 a)). Standard Galerkin finite element method was used in order to solve the governing Eqs. (1) and (2) along with the appropriate initial and boundary conditions (Owen and Hinton, 1980; Gresho and Sani, 1998; Zienkiewicz et al., 2000). The finite element code was written in the programming language VISUAL FORTRAN 90/95. The computational mesh in the flow field is shown in Figure 1 b).

![Figure 1: a) Computational domain and boundary conditions of the two-dimensional flow over single greenhouse and b) Computational mesh used in this work.](image)

### 2.3 Pressure coefficient calculation

The determination of the external pressure coefficient on the roof of the greenhouses was based on the pressure values that were calculated by solving equations (1) to (3) of the mathematical model. The equation used to calculate the external pressure coefficient is the following:

$$C_{pe} = 2\left( p - p_o \right)$$

where $C_{pe}$ is the external pressure coefficient, $p$ is the pressure on the roof of the building calculated by the Finite element code and $p_o$ is the reference pressure.

### 3 Results and Discussion

In Figure 2 steady state and time-mean averaged streamlines are presented in the computational flow field. The steady solution shows a recirculation length, downstream of the greenhouse, which is too long compared to the unsteady solution. This result is in good agreement with the results reported by Iaccarino et al. (2003), who found very good agreement between the unsteady solution and the experimental measurements. The different vortex formation is
depicted downstream of the greenhouse, which can lead to different conclusions about the flow configuration. However, the presentation of the time-mean averaged streamlines is more reliable because it results from the instantaneous values of the flow parameters. Also, the shape of the recirculation zone downstream of the structure is decreasing as the Reynolds number is increasing. Similar behavior of recirculation zone downstream of the rib has been observed by Fragos et al. (2012).

Figure 2: a) Steady state streamlines of the flow, for Re=1000, b) Unsteady state streamlines of the flow, for Re=1000, c) Steady state streamlines of the flow, for Re=2000, d) Unsteady state streamlines of the flow, for Re=2000.
The time series of the predicted pressure coefficient at point of computational domain $x^*=5.550$, $y^*=0.795$ for $Re=1000$ and $Re=2000$ are shown in Figure 3 a) and b). It can be observed that the number and magnitude of the pressure coefficient peaks increases as the Reynolds number is increasing.

In Figures 4 and 5, the external aerodynamic pressure coefficients along the roof surface of the single duo pitched greenhouse are presented and compared against the $C_{pe}$ values given by EN 13031-1:2001 for the same structure design in different flow conditions (steady and unsteady flow). The values of $C_{pe}$ in each point of the roof and for $Re$ numbers 1000 and 2000 are presented.

As it can be seen, the pressure coefficients distribution calculated by the two CFD models and for all cases of Reynolds number takes negative values along the roof. The above finding is in agreement with the proposed values of the Eurocode in all cases to be considered.

The two CFD predictions of $C_{pe}$ values, in general, lie within the range of those given by the Eurocode especially for the windward area of the roof. The unsteady model gives lower predictions of the pressure coefficients for the windward area of the roof and higher for the leeward area than that the steady state model and Eurocode values.
4 Conclusions

In this study, the external air pressure coefficients distribution along the roof surface of a single duo pitched greenhouse were calculated by a steady and unsteady model, which simulate the airflow in a wind tunnel. The predicted values were compared with those given by the Eurocode. The following conclusions were made:

- In general, the predicted $C_{pe}$ values are within the range of those given by the Eurocode.
- In the windward area, the calculated $C_{pe}$ of both models were more close to the Eurocode values, than those in the leeward area.
- The unsteady model predict lower values of $C_{pe}$ for the windward area of the roof and higher for the leeward area than that the steady state model and Eurocode.

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6 References


Figure 5: Values of external pressure coefficients in specific points (green-Steady flow, blue-Unsteady flow, red-Eurocode) for single duo pitched greenhouse for $Re=2000$. 


