BIOSYSTEMS ENGINEERING 164 (2017) 13–30

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Effects of ventilator configuration on the flow pattern of a naturally-ventilated three-span Mediterranean greenhouse

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ARTICLE INFO

Article history:
Received 12 May 2017
Received in revised form
3 October 2017
Accepted 10 October 2017

Keywords:
ventilation
airflow
sonic anemometry

Natural ventilation used in agricultural greenhouses is important to control greenhouse microclimate. The effect of the ventilator configuration on the flow pattern of a three-span Mediterranean greenhouse with an obstacle to airflow (a neighbouring greenhouse) was investigated. Two different ventilator configurations, two or three half-arch roof vents with two roll-up side vents, were evaluated using sonic anemometry. It was observed that the flow pattern through the greenhouse depends of the ventilation surfaces distribution and the obstruction to the ventilation system. Moreover, the magnitude and distribution of ventilation surface affected the overall ventilation rate and the ventilation rate at plant level. The ventilator configuration with two roof and two side vents improved air movement at the plant level, although the overall volumetric flow rate was lower than that with three roof and two side vents.

1. Introduction

Almería in Spain with its warm climate (3000 h yr^{-1} of sunshine) and extensive area of protected cropping (>30,000 ha) (Valera, Belmonte, Molina-Aiz, & López, 2016) is representative of the 700,000 ha worldwide of protected cropping (Katz & Weaver, 2003). Agricultural production in the greenhouses in this region requires control of excessively high temperatures. The aim is to achieve this control with systems that consume less energy and have less environmental impact (Valera et al., 2016). To control temperatures nearly all farmers in Almería whiten greenhouse covers and use natural ventilation, with side and roof vents having an average ventilation surface of 14.4% being commonly used (Valera et al., 2016).

Natural ventilation is a simple system that is energy-friendly, low-cost and requires little maintenance. The process allows the exchange of energy and mass between the external environment and the interior of the greenhouse (Boulard, Lamrani, Roy, Jaffrin, & Bouirden, 1998); thus, the system has a strong influence on the greenhouse microclimate. For these reasons, natural ventilation is widely used in Almería to control air temperature, humidity, and gas

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https://doi.org/10.1016/j.biosystemseng.2017.10.001
1537-5110/

Nomenclature

Acronyms

E	Relative measurement error of the flow rate, [%]
F	Pressure drop coefficient
G	Volumetric flow rate, [m^3 s−1]
K	Permeability, [m^2]
N	Hourly volumetric air exchange rate, [h^{-1}]
NS	Number of samples
OR	Inlet-to-outlet opening ratio
Ph	Plant height, [cm]
S	Surface area, [m^2]
T	Temperature of the air, [$^{\circ}$C]
t	Time, [s]
Tn	Test number
Ts	Sonic temperature, [$^{\circ}$C]
U	Wind speed, [m s^{-1}]
u	Air velocity, [m s^{-1}]
V	Volume, [m^3]
VX	Vent number X
Y	Inertial factor

Symbols

η	Transport efficiency coefficient
ψ	Side-roof vents flow rate ratio
φ	Porosity, [%]
ϑ	Roof and side opening surface ratio
ξ	Wind and thermal forces ratio, [$m^{\circ}C^{-0.5}s^{-1}$]

Subscripts

Θ	True north-based azimuth, [°]
c	Corrected measure
g	Greenhouse
i	Inside
io	Outlet
j	Elementary sample
l	Leeward
ne	Northeast direction
o	Outside
oi	Inlet
p	Porous medium
r	Roof
s	Side
sw	Southwest direction
v	Vent(s)
w	Windward
x	Component on the x direction on the coordinate plane

concentrations for most of the cropping cycle. Controlling the microclimate parameters leads to enhancement of the photosynthetic and transpiration processes of plants, and yield can be improved (Max, Horst, Mutwiwa, & Tantau, 2009).

The air exchange that occurs mainly through greenhouse openings as a consequence of temperature and pressure variations between the interior and exterior of the greenhouse is defined as natural ventilation. The main driving forces in the process are buoyancy and convection associated with wind (Kittas, Boulard, & Papadakis, 1997) and they contribute to the flow pattern in the greenhouse. When the wind speed is low, buoyancy forces induce an upward flow displacement and this can be observed as air circulation inside the greenhouse. Ventilation rate and flow pattern have also been attributed to wind intensity (Bot, 1983). Boulard, Foulloley, and Kittas (1997) observed that wind intensity has a linear dependence on the air exchange rate when buoyancy is disregarded. In order to determine when these forces assist or oppose each other, the ratio of buoyancy and wind forces is used (Li & Delsante, 2001).

Studies have shown that not only is wind intensity important in the ventilation process, but ventilation rates (Hong et al., 2008; Shklyar & Arbel, 2004), flow pattern (Boulard, Meneses, Mermier, & Papadakis, 1996; Teitel, Ziskind, Liran, Dubovsky, & Letan, 2008), and the microclimate (Bartzanas, Boulard, & Kittas, 2002; Roy & Boulard, 2005) inside the greenhouse also depend on the wind direction. Moreover, the natural ventilation process alters the air velocity (Bartzanas et al., 2002; Molina-Aiz, Valera, & Álvarez, 2004), temperature, and humidity (Molina-Aiz et al., 2004; Teitel, Liran, Tanny, & Barak, 2008; Teitel, Ziskind, et al., 2008) gradients within the greenhouse, which could affect crop development (Majdoubi, Boulard, Fatnassi, & Bouirden, 2009).

Crop within the greenhouse also contributes to the flow pattern inside the greenhouse (Majdoubi et al., 2009; Molina-Aiz, Valera, Álvarez, & Madueño, 2006; Molina-Aiz, Valera, Peña, & Gil, 2005) and greenhouse design parameters play an important role in the ventilation process. Several studies have confirmed that there is a decay relationship between the ventilation rate and the number of spans in a greenhouse (Esteban J Baeza et al., 2009; Kaçira, Sase, & Okushima, 2004a; Kaçira, Short, & Stowell, 1998; Lee et al., 2003; Molina-Aiz et al., 2005). This relationship also seems to depend on roof geometry (Perén, Van Hooff, Leite, & Blocken, 2016; Perén, Van Hooff, Ramponi, Blocken, & Leite, 2015).

The type of vent used in the greenhouse also affects ventilation efficiency (Bartzanas, Boulard, & Kittas, 2004; Kittas, Boulard, Mermier, & Papadakis, 1996; Molina-Aiz & Valera, 2011). Insect-proof screens installed in vents reduce the inlet airspeed and ventilation rate, resulting in higher temperature and humidity within the greenhouse (Esteban J Baeza et al., 2009; Bartzanas et al., 2002; Campen & Bot, 2003; Fatnassi, Boulard, Demrati, Bouirden, & Sappe, 2002; Harmanto, Tantau, and Salokhe, 2006; Katsoulas, Bartzanas, Boulard, Mermier, & Kittas, 2006; Molina-Aiz et al., 2004; Teitel, 2001).

Vent configuration, position, and dimensions also have a strong effect on flow pattern and ventilation rate. The use of side vents, and their size, influences ventilation rate, affecting the temperature distribution within the greenhouse (Bartzanas et al., 2004; Molina-Aiz & Valera, 2011; Short & Lee, 2002). Similarly, Baeza, Pérez Parra and Montero (2005) observed in a '*parral*' (Almería) greenhouse that has larger roof vents that can improve ventilation. The ratio between the open area of a roof and the area of the side vents and the ground area have been used to describe the quality of the ventilation system relative to the ground area covered (Kittas et al., 1997). Notwithstanding this, there are additional parameters that affect the ventilation process. The vertical