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Research Paper

An experimental study of the cooling performance and airflow patterns in a model Natural Ventilation Augmented Cooling (NVAC) greenhouse

Lucas McCartney*, Valérie Orsat, Mark G. Lefsrud

Bioresource Engineering Department, McGill University, 21111 Lakeshore, Ste-Anne-de-Bellevue, Quebec, H9X 3V9, Canada

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A Natural Ventilation Augmented Cooling (NVAC) greenhouse is a natural ventilation greenhouse that is improved by coupling natural ventilation with a non-conventional misting system. In the design, an added inside roof, called the NVAC roof, prevents unevaporated water droplets from reaching the crop foliage and guides the cooled air into the main area of the greenhouse. Previous work on the cooling performance of the NVAC greenhouse design investigated temperature and relative humidity within the greenhouse under field conditions. To investigate the cooling capabilities and the nature of the airflow in the NVAC greenhouse, a network of thermocouples and a three-dimensional sonic anemometer were used for the measurement of temperature, relative humidity and air velocities inside a 1:4 model single-span NVAC greenhouse. The cooling performance of the NVAC greenhouse design without plants varied from a temperature reduction of 1.9–12.6 °C and relative humidity increase of 1.4–31.2% RH depending on the ambient conditions. The NVAC greenhouse reduced vapour pressure deficit by 0.3–4.9 kPa. Although temperature distributions were more uniform under natural ventilation, the amount of cooling was significantly greater with the use of the NVAC design, compared to none. It was shown that the NVAC greenhouse can provide air movement in the greenhouse at velocities up to 0.38 m s^{-1} without the use of fans. The average turbulence intensity of the air inside the greenhouse was increased to 0.32 with the use of the NVAC design, compared to 0.19 under natural ventilation.

1. Introduction

In hot climates such as in arid and tropical zones, protected agriculture is mainly used to control temperature, relative humidity, light intensity and pests. Many ventilation and cooling solutions are available to growers. Natural ventilation is a passive greenhouse design that requires less energy input and equipment compared to active ventilation. It is the cheapest method of cooling a greenhouse. Although natural ventilation designs remain widespread (Muñoz, Montero, Antón, & Giuffrida, 1999), natural ventilation offers limited

* *Corresponding author.*
E-mail address: lucas.mccartney@mail.mcgill.ca (L. McCartney).

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
E	actual vapour pressure (kPa)
Es	saturation vapour pressure at the dry bulb temperature (kPa)
Ew	saturation vapour pressure (kPa)
i_u	turbulence intensity
NVAC	Natural Ventilation Augmented Cooling
P	station barometric pressure (kPa)
q	specific humidity
RH	relative humidity
rms	root mean square
t	time (s, min, h)
T_{db}	dry-bulb temperature (°C)
$T_{db\ air}$	corrected dry-bulb temperature measurements obtained from the sonic anemometer (°C)
T_{wb}	wet-bulb temperature (°C)
u	air velocity (m s^{-1})
$\bar{u}$	mean air velocity (m s^{-1})
VPD	vapour pressure deficit (kPa)
Z	site elevation (m)
ϕ	angle direction of the relative air movement tilted away from the x-axis
σ	standard deviation
η	efficiency of a pad and fan evaporative cooling process
η_c	cooling efficiency of the NVAC greenhouse
η_c'	cooling efficiency of the NVAC system
σ^2	variance in air velocity over a period of time

Subscripts

avg	average
c	cooled inside conditions of the model greenhouse
i	initial inside conditions of the model greenhouse
o	outside conditions i.e. conditions inside the research greenhouse
x	transversal
y	longitudinal
z	vertical

control of cooling and airflow in the greenhouse. The main driving forces of ventilation for a greenhouse equipped with both roof and side openings are caused by a combination of pressure differences induced by a multitude of effects, including the wind and buoyancy (chimney effect) (Baptista, Bailey, Randall, & Meneses, 1999; Boulard & Baille, 1995; Kittas, Boulard, & Papadakis, 1997). In the absence of any of these influences, such as in low wind conditions, these fluxes may be altered, minimised or eliminated entirely. To address times of low to moderate wind, it is of interest to investigate methods of improving the buoyancy effect.

The ASHRAE (1985) Fundamentals Handbook states that greenhouse air velocities in the range of 0.5–0.7 m s^{-1} are optimal (Kittas, Bartzanas, & Jaffrin, 2003). Furthermore, in terms of plant productivity and quality, the velocity of the air movement in a greenhouse is suggested to not exceed 1 m s^{-1} across the plants (ASHRAE, 1985). In the naturally ventilated greenhouses widely used in the Mediterranean region, the air velocity typically observed in the greenhouse varies from 0.1 to 0.5 m s^{-1}, which includes the wind effect (Jiménez-Hornero, De Ravé, Hidalgo, Giráldez, 2005; Molina-Aiz, Valera, & Álvarez, 2003; Molina-Aiz, Valera, & Álvarez, 2004; Teitel, Tanny, Ben-Yakir, & Barak, 2005). It is important to note that such airflow can vary depending on the weather and the season, and that in many regions, such airflow cannot be sustained by natural ventilation alone (Latimer, 2009). Moreover, the necessity of installing insect netting in order to prevent proliferation of diseases and pests induces a pressure loss, thereby further reducing the ventilation efficiency by up to 50% (Bailey et al., 2003; Kittas, Boulard, Bartzanas, Katsoulas, & Mermier, 2002; Miguel, Van De Braak, & Bot, 1997). In certain weather conditions, the air inside the greenhouse can stagnate for several minutes at a time, causing local peaks in temperature that may cause harm to the crop.

Systems comprised of vents, exhaust fans and circulating fans, combined with evaporative cooling, can supply immediate air movement, high air exchange rates and cooling whenever needed, at the expense of electricity consumption. In a study by Fernandez and Bailey (1994), air velocity was measured inside an empty greenhouse with side vents (no cooling pads), with and without circulation fans. The results showed that on average, the fans provided significantly greater velocities, at 0.64 m s^{-1}, up from 0.12 m s^{-1}. Pad and fan systems are effective at providing cooling by 4–6 °C if used alone, and 4–12 °C if used with shading (Jain & Tiwari, 2002; Kittas et al., 2003; Sethi & Sharma, 2007). Lopez, Valera, Molina-Aiz, and Peña (2010) studied the airflow and distribution of temperature and humidity in a multi-span greenhouse equipped with a pad and fan cooling system operating both with a tomato crop and without a crop. Results showed that the average air velocity inside the greenhouse with and without crop was 0.21 and 0.26 m s^{-1}, respectively. Arbel, Yekutieli, and Barak (1999) studied a fog system operating at varying pressures. The cooling performance varied from 8.5 to 12.0 °C, and the increase in relative humidity varied from 35 to 68%. However, the efficiency of fog or mist systems in natural ventilation greenhouses is often limited by insufficient natural air movement, the absence of wind, and the risk of wetting the plants when water droplet evaporation is not complete (Kittas et al., 2003).

An improved fogging system that includes air circulation and incorporates a protective structure to reduce wetting of the crop foliage may therefore be of interest. A novel greenhouse design, the NVAC greenhouse, takes into consideration some of the disadvantages of conventional greenhouse cooling solutions. A 1:4 scale model greenhouse was built inside a large research greenhouse allowing the design to be tested in a controlled environment. The model greenhouse was based on a full-scale NVAC greenhouse used in field tests of the design (McCartney & Lefsrud, 2018). The present paper examines the cooling capabilities, relative humidity control and air movement capabilities of the design under a variety of climatic conditions provided by the environmental control. Comparisons with traditional evaporative cooling techniques were therefore possible.