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On air temperature distribution and ISO 7726-defined heterogeneity inside a typical greenhouse in Almería

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ABSTRACT

Studies about the air temperature inside greenhouses are usually focused on the crop growth. However, the thermal environment inside greenhouses can affect the safety of the workers and also their productivity. This work focuses on the study of air temperature conditions with respect to workers following the requirements and methods gathered in ISO 7726, which indicates that measurements should be taken at different points in both, horizontal and vertical directions in order to study heterogeneous thermal environments. For the present work, data were gathered by the Wireless Sensor Network (WSN) designed in our previous work, hereby extended by an experimental campaign carried out during a complete year in a typical greenhouse in Almeriía. The aim is performing a long-term study of air temperature inside a greenhouse as well as the assessment of air temperature heterogeneity. The results, which allow characterizing air temperature inside the greenhouse, prove the existence of patterns of heterogeneity as a function of the incidence of sunlight and time of day. During the analysed period, air temperature heterogeneity is mainly present in the central hours of the day and it is higher in the horizontal dimension rather than vertically. In addition, it has been observed that the vast majority of homogeneous days correlate with cloudy days. Finally, based on the results obtained some recommendations are presented for assessing the thermal environment of greenhouses.

1. Introduction

Areas of the South of Europe and specially Mediterranean coastal areas meet the optimum environmental conditions for growing vegetables in plastic-covered greenhouses (Hernández et al., 2017). Specifically, in Almeriía (Spain) they cover approximately 30,000 ha, the largest extension of greenhouses worldwide. Consequently, around 55,000 workers are employed each year in Almeriía (Cabrera et al., 2016). Greenhouses are agricultural buildings that consist of light metal structures covered with transparent plastic, with ventilation through the walls and ceiling, and diffuse solar radiation. These buildings maintain an adequate temperature and humidity allowing to extend the crops for almost the complete year (from the end of July to the beginning of June of the following year). However, these conditions are not the better for the wellbeing of the greenhouse workers, whose working period lasts practically the complete year, since maintenance work is also carried in non-crop periods (Pérez-Alonso et al., 2011; Callejón-Ferre et al., 2009; Callejón-Ferre et al., 2011b).

Despite greenhouses soften the outdoor climate environment, large variations in air temperature and humidity do still occur throughout the day. Humidity and specially air temperature are the main parameters that affect workers and crops inside of greenhouses (Vox et al., 2010; Zhao et al., 2001). In greenhouses of Almeriía, air temperature vary from around 50 °C in the middle of the day in summer to near 0 °C at night in winter.

Several authors (Callejón-Ferre et al., 2011a; Riemer and Bechar, 2016; Cecchini et al., 2010; Marucci et al., 2012; Diano et al., 2016; Okushima et al., 2001) have reported heat stress risk fundamentally during the warmer months (spring and summer). Environments with high temperatures and humidity can affect the safety of the workers, causing severe problems to the cardiovascular system and the thermoregulatory system of workers (Chad and Brown, 1995; Zhao et al., 2009). Moreover, these environments also have a negative impact in the productivity of workers. Additionally, Risk of cold in winter have been also pointed out (Callejón-Ferre et al., 2011a).

To assess the thermal environment and its influence to the workers,

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we need to follow several rules (Parsons, 2013). According to the International Standard Organization (ISO), the environment is classified in moderate or extreme. Depending on the category, a different index and ISO Standard must be used. To calculate these indexes, in any case, the measurement of several climatic parameters are required and in some cases also the metabolic rate of the activity carried out by the workers, based in ISO 8996 (ISO 8996:2004,), and the clothing insulation and sweat rate, ISO 9920 (ISO 9920:2007, 2007). Moreover, the ISO 7726 Standard (ISO 7726:1998, 1998) defines the specifications and methods that must to be fulfilled to asses the thermal environment. The specifications address the expected parameters of measuring instruments such as measurement range, accuracy, and response time. Regarding the methods, physical magnitudes may vary with the space as much horizontally as vertically and the environment can be considered homogeneous or heterogeneous. An environment will be considered as homogeneous if the physical magnitude under consideration is practically uniform in the analysed area. On the other hand, an environment will be heterogeneous if there are significant variations in the physical magnitude. The limits for each climatic parameters that define the environment as heterogeneous or not, with respect that parameter, are established in the ISO 7726. In case of heterogeneous environments, the rule states that the physical magnitudes need to be measured at different points both horizontally and vertically. In the latter, ISO 7726 specifically establishes three heights where the measurements must to be carried out: ankle, abdomen, and head.

Related to the thermal assessment inside a greenhouse and the heat stress in workers, only the work presented by Marucci et al. (2012) comply with the requirements for the measuring instruments described in the ISO 7726. However, these work only perform measurements in one position inside the greenhouse and in one height. Recent work carried out by López-Martínez et al. (2018), fulfilling with ISO 7726, reveals heterogeneity conditions of the greenhouse analysed. In this work, twelve measuring stations were distributed along the greenhouse, each one measuring climatic parameters at the three heights specified by the rule. According to that results obtained, it is pointed out that greenhouses are environment where the heterogeneity conditions can be achieved.

Others works, focused in the crop growth conditions, have shown large air temperature differences in vertical and also in horizontal direction inside greenhouses. Zhao et al. (2001), Soni et al. (2005) and Zorzeto and Leal (2017) measured vertical differences of around 7 °C, 10 °C and 14 °C, respectively. López et al. (2013) and Kittas et al. (2003) obtained horizontal differences of around 6 °C and 8 °C, respectively. Granados et al. (2016) measured the average temperature during January to March in a greenhouse, observing temperature differences of up to 4.4 °C at 6 a.m. and up to 9.1 °C at 2 p.m. between 0.2 and 2.6 m in height. In three different greenhouses in Almeriía studied by López et al. (2012b), it was recorded maximum air temperature differences between 10 and 12 °C for different tests performed between 11:30 a.m. and 2:30 p.m.. In simulations with computational fluids dynamics (CFD), large variations of temperature inside the greenhouse have been also observed: Boulard et al. (2017) obtained vertical differences of up to 12 °C, Molina-Aiz et al. (2004) obtained variations of temperature of around 9 °C in a similar greenhouse and in a location very close to the greenhouse studied in this work, and Tong et al. (2009) obtained variations of temperature as large as 12 °C. All these results also suggest that greenhouses may be heterogeneous environments when are evaluated according the ISO 7726.

To carry out the measurements inside of a greenhouse at different points at the same time, a sensor network is required. In recent years, Wireless Sensor Networks (WSNs) have been used to carry out measurements in different points. This type of networks are composed of battery-powered nodes provided with sensors that supply the corresponding information in real time and transmit it to a central base-station (BS) where it will be stored and from where nodes can be monitored and controlled (Ferentinos et al., 2017). The main advantages of WSN are the capability of measuring multiple points avoiding the use of wires, which are usually damaged and wore out when exposed to aggressive environment (high variations of air temperature and humidity) and could hinder the cultivation practices. Furthermore, thanks to the advances in electronics and wireless communications, it is possible to develop WSNs with a low cost and low energy consumption.

In the present work we have used a WSN to overcome the scarcity of real measured air temperature data inside a greenhouse during a complete year, also allowing us to assess whether air temperature is heterogeneous or not (according to ISO 7726) inside a typical greenhouse. This work is a continuation of our previous one (López-Martínez et al., 2018), in which the WSN and twelve measurement stations where designed and put into operation in a greenhouse. The present work carries out a measurement campaign during a complete year with the objective of evaluating the heterogeneous conditions of a greenhouse with respect to the air temperature.

To sum up, the aim of the present work is twofold:

- Monitoring, using a WSN, the air temperature distribution inside a typical greenhouse during a complete year, at three different heights and multiple points equally distributed horizontally. These data will allow to characterize the air temperature distribution of the greenhouse and its variations along the four seasons of the year.
- To study the air temperature heterogeneity inside a typical greenhouse according to ISO 7726 and providing some recommendations for the assessing of the thermal environment of a greenhouse.

This paper is organized as follows: initially, the material and methods are explained in Section 2. The experimental results and their discussion are detailed in Section 3. Finally, we outline some conclusions in Section 4.

2. Material and Methods

2.1. Experimental setup

The experiment was carried out in a greenhouse located at 15 km east of Almeriía (36°52′*N* - 2°17′255 *W* and 98 m above sea level), in the southeastern Spain. The experimental campaign was performed during a complete year, since December 2016 to November 2017 and the time between measurements was 30 s. The greenhouse is raspa y amagado type, the most common in this region. Its surface area is 1024 m^2 (32 × 32 m) and the heights of the gutter and ridge are 3.4 m and 4.1 m, respectively. The drawing of the greenhouse is defined in Fig. 1. The structure is made of steel, with the resistant elements of wire mesh type and is covered by three polyethylene layers of 200 μm, with 81% visible light transmittance and 29% diffuse light transmittance. Inside the greenhouse, the soil is covered of gravel and sand, and tomato plants are cultivated. Ventilation is natural through lateral windows and roof vents. There are windows on all four sides of the greenhouse and 4 roof vents. The area of each window is specified in Fig. 2. Each window is opened and closed by means of an electric engine with a power of 0.5 hp, being all of them controlled by a central control station. The central control station closes the windows either air velocity is greater than 35 km/h or air temperature is lower than around 8 °C, since this temperature value is also related with relative air humidity. These values are selected in order to achieve the optimal physiologic and production conditions for the plants cultivated, in this case tomato plants.

The implemented WSN comprises 12 measurement stations distributed inside the greenhouse (Fig. 1). Each station consists of a structure with three heights where the sensors are installed. Air temperature (*ta*), globe temperature (*tg*), relative air humidity (*RH*) and air velocity (v_a) have been measured at the three heights, while UVI ultraviolet radiation (UVI) is measured only at the higher height of each