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Monitoring and energetic performance analysis of an innovative ventilation concept in a Belgian greenhouse

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ABSTRACT

Greenhouse cultivation is an intensive part of horticulture in Flanders in which large production volumes are accompanied by significant energy consumptions. Demand for energy efficient solutions is rising due to fluctuations and increases in energy prices, ongoing pressure from international competition and incentives from governments in the scope of climate change. Over a two-year period, a compact ventilation concept was monitored in a Belgian semi-closed greenhouse. The installation was one of the first ventilation concepts in Belgium and is based on intensive thermal screening in combination with controlled ventilation. Air flow rates, indoor and outdoor climatic parameters were monitored as well as the energy flows of the ventilation unit, the energy demand of the greenhouse and the crop results. The measured energy consumption of the concept was 9.6% higher than the reference case in 2010, partly due to its location within the greenhouse complex. However, during the second growing season of 2011, two more similar compartments were compared, showing the potential of the ventilation concept with a 12% energy saving. In addition, improved crop growing conditions become possible as the installation allows for a better control of the greenhouse climate.

1. Introduction

Greenhouse cultivation is an intensive part of horticulture in Western Europe. The main objective is an increased crop yield and year-round production, made possible by maintaining optimal indoor conditions [1]. Available heating and cooling solutions require high investment costs and often lead to significant relative energy costs. Due to the increase and instability of energy prices, the ongoing pressure from international competition and governmental incentives, it is crucial to search for energy efficient solutions without reducing crop yield or quality.

Additional heat in greenhouses is commonly provided by fossil fuel fired engines or boilers, which consume large amounts of energy. Tiwari et al. [2,18] state that the development of low-cost heating systems is of primary importance for the greenhouse industry. Several solutions have been presented to date, for example the use of heat pumps or solar collectors as an alternative to fuel-based heating. Other techniques involve the intermediate storage of greenhouse generated heat into containers such as rock-piles, soil or embedded reservoirs. These storage solutions can accumulate the heat of warm greenhouse air and solar energy during the day, making it available for heating during colder periods such as night-time. Sethi and Sharma [1] surveyed and evaluated several of these innovative heating technologies (rock bed heat storage, phase changing materials, a ground air collector, an earth-to-air-heat exchanger system and an aquifer coupled cavity flow heat exchanger system). They concluded that these solutions continue to involve high installation and operational costs.

Several cooling techniques are available to remove excess heat or to prevent it from building-up in the greenhouse [18]. Popular examples are cooling by ventilation (natural or mechanical), evaporative cooling (on the rooftop or with a pad and fan system) and shading with movable screens. Another cooling solution is to use an earth-air heat exchanger, which enables a heat transfer between the greenhouse air and the under ground soil. The air passing through the heat exchanger will be cooled in summer and heated in winter. Foggers can be installed to create a higher relative humidity, while also providing cooling inside the greenhouse. This technique has better performance than the pad and fan system because of the uniformity of the cooling.

Today, most Belgian greenhouses use thermal screens, which can save significant quantities of fuel used for night heating [3]. Thermal losses can be reduced by decreasing the convective heat transfer and, to a lesser extent, the radiative losses. Applying multiple screens can therefore result in a better insulation performance than merely improving screen radiation characteristics [4].

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However, some disadvantages of screens include poor mechanical reliability, incomplete sealing after closure and condensation damage to curtains and plants [1]. In addition, intensive screening may also lead to higher humidity levels. Excessive humidity can have a negative impact on plants and will enhance mineral depletion and fungal diseases such as Botrytis [5,6]. Therefore, dehumidification is essential when striving towards intensive screening.

Ventilation can contribute to maintaining an optimal control of humidity and can also improve control over temperature and concentration of CO_2 levels in the greenhouse [6]. Common practice in humidity control is the replacement of moist greenhouse air by dry outside air through opening of windows and screens. These greenhouses, employing natural ventilation, are considered to be ‘open’ systems. While natural ventilation is a cost effective way of controlling the indoor climate, its efficiency depends on several environmental parameters and offers limited control over the in- and outgoing airflows of the greenhouse [6,7]. Therefore, dehumidification and cooling often exceeds demand, resulting in high energy consumptions [8]. Furthermore, open ventilation systems were described as less efficient for greenhouse cooling on sunny days without wind [9,10]. Additionally, an open window can cause local cold downdraught, which can result in crop damage [11].

Apart from natural ventilation, dehumidification can also be provided by mechanical ventilation. Carpenter and Bark [12] showed that air circulation fans reduced the vertical temperature gradients and eliminated the high temperature build-up in the ridge area of the greenhouse. Fan driven ventilation has shown no significant dependency on external wind and internal buoyancy forces, unlike natural ventilation [13]. This independency results in an increased control of ventilation rates. Moreover, by creating a continuous movement of air mechanical ventilation can reduce the inside temperature significantly when dealing with warm greenhouse conditions [14]. When the possibility of natural ventilation is removed and instead only mechanical ventilation is provided, the greenhouse can be considered as a ‘closed’ system. Heating, cooling, humidification and dehumidification are then supplied by a mechanical ventilation unit. A higher CO_2 concentration can be maintained, which leads to the expectation that the higher investment costs can be earned back from higher crop yield. Completely closed greenhouses could also reduce the use of pesticides, meaning a minimisation of effects on the environment and a better product safety [19].

While heat losses can be reduced by closing the greenhouse, because this allows for more screening and increased sealing of the greenhouse shell, this does not guarantee a total energy reduction. In a study conducted by the University of Wageningen, the monitoring of nine closed and semi-closed greenhouses showed that mechanical ventilation (and dehumidification in particular) use a fair amount of electricity [15]. This additional consumption might outweigh the benefits of an increased insulation and thus render the system economically unviable. It was recommended to include natural ventilation as an option for climate control in addition to the ventilation system. An alternative solution is therefore found in the combination of natural ventilation, which provides inexpensive cooling and dehumidification, with mechanical ventilation, applied when energetically and economically viable.

This paper reports on the results obtained in a monitoring project of a ventilation unit in a Belgian greenhouse spanning over 2 growing seasons in 2010 and 2011 at the Research Station for Vegetable Production in Sint-Katelijne-Waver. A brief overview of the set-up and monitoring of the ventilation concept is presented in Section 2. Section 3 provides detailed information on the results obtained in the monitoring campaign, considering: (a) the indoor climate and crop conditions, (b) the system behaviour and (c) the energetic performance, while in Section 4 the results of the ventilation concept are discussed. Finally, conclusions are drawn in Section 5.

2. Experimental set-up and monitoring

A schematic layout of monitored compartments within the greenhouse complex at the Research Station for Vegetable Production, Sint-Katelijne-waver, Belgium, is shown in Fig. 1a. The climate of the region is a Cfb climate according to the Koppen-Geiger climate classification, i.e. a warm temperate humid climate with the warmest month on average lower than 22 °C and four or more months above 10 °C [16]. The research facility has been divided into several compartments. The monitoring campaign focused on a ‘ventilated’ compartment equipped with the ventilation system (compartment 1) and ‘reference’ compartments based on natural ventilation (compartment 6 and 3 for the growing seasons 2010 and 2011, respectively).

2.1. Reference greenhouses

In each growing season, a specific compartment served as reference case, resembling more traditional Belgian greenhouses with natural ventilation for climate control. Greenhouse ventilation in the reference greenhouses was achieved by natural ventilation through small windows of 1.25 m × 1.35 m and larger windows of 2.5 m × 1.35 m, which were distributed as follows: 2 small and 2 large windows in the southeast direction and 3 large windows in the northwest direction. Thermal heating was done by two tube rails and two growing tubes for each growing gutter (Fig. 1b) with a length of circa 27 m and a diameter of 51 mm. Reference greenhouses were equipped with double screens, an XLS10 and an attached AC foil as shown in Table 2. The XLS10 is a retractable thermal screen with high optical transparency and mediocre thermal insulation capabilities. The AC foil was manually attached to the greenhouse structure, thus limiting its application to one single continuous period of use. The high transparency allowed this foil to remain closed during the daytime, but it has a low insulation potential. Reference greenhouses in 2010 and 2011 are differentiated only by location within the research facility. The shift from reference greenhouse 2010 in compartment 6 to reference greenhouse 2011 in compartment 3 was done to improve the comparability between the reference and ventilated greenhouse since the location of the compartments was crucial for heat gains and losses that occur through compartment walls. This was confirmed by insulation tests taken during a winter period under specific conditions (closed compartments, no screens, no crops, constant indoor temperature). The results of which are presented in Table 1, giving the energy consumptions for the different compartments recorded during the tests, which can be associated to the compartment’s heat loss and therefore the degree of insulation of the compartment.

2.2. Ventilated greenhouse

A pilot compartment was set up with an innovative ventilation concept based on intensive screening and controlled ventilation through combined mechanical and natural ventilation. The technical specifications of the ventilated greenhouse illustrated in Fig. 1b are similar to the reference greenhouses, except for the screens and additional mechanical ventilation. The ventilated greenhouse was insulated with two movable screens, a XLS17 and an AC foil as given in Table 2. The first screen has high thermal insulating qualities at the cost of optical transmission and could therefore only be closed during night-time. The second screen was a movable AC foil that could be used throughout the entire growing season, in contrast to the AC foil in the reference compartments. In addition to the adjustable screens, the ventilated greenhouse was equipped