A DEHUMIDIFYING HEAT PUMP FOR GREENHOUSES

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Keywords: dehumidification, heat pump, greenhouse climate, energy

Abstract

In heated greenhouses, attempts have been made to produce potted plants while reducing the amount of energy used. In fact, improvements in greenhouse structure and equipment (double walls, etc.) have led to better insulation and tightness. However, this tightness induces microclimatic changes, especially on night time humidity levels. The increase of indoor humidity leads to the development of condensation and dripping and, consequently, to the increase in the occurrence of fungal diseases and physiological disorders. It is therefore necessary to decrease the humidity in the air. To do this, growers have to dehumidify the air by ventilation-heating, involving a major increase in energy consumption. Humidity control is therefore a limiting factor for saving energy, making it necessary to find alternatives to the ventilation-heating method used to reduce indoor humidity. We analyzed the effectiveness of a dehumidifying heat pump installed in a 2350-m² double wall inflatable greenhouse located in northwestern France, during spring 2010. Hydrangeas in containers were placed on the ground (heated). The temporal evolution of climatic, thermodynamic and ecophysiological data is presented and analyzed. The thermodynamic efficiency of the machine is also taken into account. Depending on the weather outside, the energy consumption of the device (power: 4W m^{-2}) used to dehumidify the air is three to four times lower than that which would have been used by the ventilation-heating method. By condensing approximately 30 liters of water per hour during the operating phase of the heat pump, the machine balances crop evapotranspiration and avoids condensation and the occurrence of fungal diseases.

INTRODUCTION

The use of increasingly airtight greenhouses to save energy has led to increasing humidity levels inside the greenhouse. High humidity and poor ventilation are linked to common greenhouse plant diseases such as *Botrytis cinerea*. The most common method used by growers to decrease humidity at this time consists of simultaneously heating and ventilating the greenhouse.

In order to find alternative solutions, theoretical studies (Seginer and Kantz, 1989) and experimental attempts with dehumidifying systems (Boulard et al., 1989; Chassériaux, 1987, Campen et al., 2003) have been conducted, mainly on crops with a high level of transpiration such as tomato. For this type of crop, the water losses (dehumidifier, roof) seem to be largely compensated for by an increase in crop transpiration. Studies on the energy consumption required to dehumidify also mainly focussed on greenhouses where tomato is cultivated.

In this study, we tested a dehumidifying system prototype inside an ornamental 2350-m² greenhouse with potted plants placed on the ground. Even if this ventilation-heating method remains acceptable for this type of crop during the day when solar radiation and outside air temperature are high, it is necessary to reconsider the economic and environmental acceptability of this method during the night (which inevitably leads to an increase in energy consumption).

The machine we propose must be capable of reducing water condensation on plant surfaces, which is the first step towards disease prevention (the leaf temperature must not drop below the dew point temperature). The major constraints for the design of this machine were: low energy consumption, a homogenous greenhouse climate, and a minimum of difficulties for the grower in terms of work and plant handling. This system recovers both sensible and latent heat released during dehumidification and uses it to heat the greenhouse air.

In order to assist in the design of the system, a model was developed to simulate the coupled exchange of water vapor in a greenhouse equipped with a dehumidification heat pump (Chassériaux and Gaschet, 2009).

MATERIALS AND METHODS

Experimental site and plant material

The experiment was conducted inside a 2350-m² double wall inflatable greenhouse located in northwestern France during spring 2010 (Figs. 1 and 2). Potted *hydrangea* plants (0.35 m in height) were placed on the heated cement floor of the greenhouse with hot water distributed through EPDM rubber tubing (gas was used to heat the water). The plant density was 5 m^{-2} and the leaf area index was 1.86 m² of leaf per m² of ground. Plants were watered by capillarity via a mat placed on the ground.

The dehumidifying heat pump system

The heat pump dehumidifier was manufactured by the ETT Company. The machine was specifically designed to remove water vapor from moist air using two identical electrically-driven refrigeration cycles. It works by circulating the moist air, first through the evaporators, which causes the water vapour to condense, and then through the condensers that heat the air (Fig. 3). The flow of the recycling fan (turbine) is qv = 10,000 $m^3\ h^{-1}$.

Air is sucked in at 1 m above the ground and injected using polyethylene (PE) vent tubes at 3 m above the ground (Fig. 2). These PE tubes are inflated when the blower fan is turned on. The dry and heated air is forced through the tube and distributed into the greenhouse through holes perforated in the PE. The dehumidification takes place when the greenhouse openings are closed and the Vapor Pressure Deficit VPD of the inside air is less than 3 hPa.

Air temperature and relative humidity at the inlet and the outlet of the machine were measured as was the total power consumption of the machine (P_t), the consumption of the two compressors (P_{cp}) and the condensed vapor mass flow (q_{mvc}).

Measurements inside the greenhouse

In order to quantify the influence of the heat pump on the greenhouse climate and plants, the following data were recorded (Fig. 4):

- air temperature (T_a) and relative humidity (RH_a) at four vertical positions in the center of the greenhouse (square symbols on Figs. 1 and 4),
- air temperature and relative humidity at four horizontal positions (circle symbols on Figs. 1 and 4).

Air temperature and humidity were measured using aspirated Vaisala HMP45C sensors. For the requirements of the analysis, the dew point temperature (T_{dew}) of the air was deduced from the above-mentioned measurements.

- roof wall temperature (T_w) at two positions by PT100 sensors,
- leaf temperature in the upper ($T_{l\text{-}up}$), middle ($T_{l\text{-}mid}$) and lower ($T_{l\text{-}low}$) parts of the plants by six thermocouples,
- plant evapotranspiration (ETR) by a balance that was specifically designed for the purpose. Ten plants were placed on the balance plate (2 m^2). The mat plant watering system was the same on the balance as on the ground. A tension weighing load cell measured the water loss by evapotranspiration.

All the measurements were made on a one-minute basis and then averaged online over 10-min periods by a data logger.

RESULTS

Only the results obtained during the operating phase of the machine between 25th and 26th March 2010 (from around 5 p.m. to 10 a.m.) are presented here. Similar results were obtained for other nights during spring 2010.

Climate analysis

During the dehumidification phase, no vertical stratification of the temperature and humidity was observed, probably due to the mixing induced by the air jet coming out from the holes of the PE ducts. Only a small difference of about 1°C was observed for the temperature distribution on the horizontal plane.

During the operating phase of the machine, the air relative humidity inside the greenhouse stabilized at around 92%, with a VPD of approximately 1 hPa. The dehumidifier was therefore not able to maintain the VPD set point of 3 hPa (value used to start the machine).

However, as can be observed in Fig. 6, the dew point was never reached, neither in the atmosphere ($T_{air} > T_{dew}$), nor on the roof surface ($T_w > T_{dew}$) nor on the plant leaves ($T_{l\text{-}up} > T_{dew}$). It can also be observed that the most critical phase (T_{dew} is close to $T_{l\text{-}up}$) occured just after sunset (Fig. 6). Moreover, no disease was observed on the crop during the entire measurement period.

Water balance (dehumidifier – evapotranspiration)

The difference in air temperature and relative humidity between the inlet and the outlet of the dehumidifier was constant and was equal to 10.5° C and 44%, repectively, with 18°C and 92% at the inlet and 28.5°C and 38% at the outlet, respectively.

The average condensed vapor mass flow (q_{mvc}) was approximately 32 l h^{-1} (10 W m^{-2}). This amount of condensed vapor appeared to be equal to the mean of plant evapotranspiration (Fig. 6).

Energy aspects

Electrical power

Measurements indicate that the average electrical power of the two compressors was P_{cp} = 7.62 kW and the total power consumption of the machine was P_t = 10.23 kW (4 W m^{-2}). Consequently, it was deduced that the power dissipated by the fan and accessories was approximately 2.61 kW.

***Efficiencies* (**dehumidification and energy)

The average dehumidifier energy efficiency, expressed in liters of water removed per kilowatt-hour of energy consumed, was 3.2 l kWh^{-1} (with two compressors). It may have exceeded 4 l kWh^{-1} at sunset and sunrise.

The thermodynamic efficiency of the heat pump is defined by the following ratio:

$$e_p = \frac{\text{- power exchanged at the condensor}}{\text{compressor power consumption}} = \frac{-P_c}{P_{cp}}$$

The global (overall) efficiency of the heat pump is defined by the following ratio:

$$e_g = \frac{\text{- power exchanged at the condensor}}{\text{total power consumption of the machine}} = \frac{-P_c}{P_t}$$

The powers exchanged at the condenser (P_c) and at the evaporator (P_{ev}) were calculated using mass and heat balance between the air entering the machine and the air leaving the machine (at the outlet of the evaporator, it was considered that the relative humidity of the air was equal to 95%). It was shown that the average power exchanged at the condenser was P_c = 48.7 kW, and P_{ev} = 41.1 kW at the evaporator, 57% of which corresponded to the latent heat generated from water vapor condensation. Thus, the calculated thermodynamic and the global efficiencies of the heat pump were e_p = 6.4 and e_g = 4.6, respectively (Fig. 7).

CONCLUSION – DISCUSSION

In order to effectively manage the greenhouse climate at this time, it is necessary to reconsider the economic and environmental acceptability of the ventilation-heating method, especially during the night. In order to limit the use of this method, we have proposed the development of a dehumidifying heat pump whose main role is to maintain the leaf temperature above the dew point during the night with low energy consumption.

The results clearly demonstrate that in a 2350-m² greenhouse with potted plants, a heat pump with a low total consumption of approximately 10 kW (4 W m^{-2}) was able to maintain the temperature above the dew point on the leaves, the roof surface and in the air by condensing an average of 32 l of water per hour during the machine operating phase. It was shown that this water outlet almost compensates the water inlet induced by plant evapotranspiration. Moreover, no signs of *Botrytis cinerea* development were observed, unlike in the past without the dehumidifier.

Since dehumidification is one of the most important tasks of greenhouse climate control, we compared the energy consumption of the heat pump dehumidifier with that of the ventilation-heating method. In that way, we simulated the heat and mass exchanges when the ventilation-heating is used. Results indicate that, depending on the weather outside, the energy consumption of the ventilation-heating method necessary to remove the same amount of water vapor as the dehumidifier is 3.6 to 4.7 times higher. Moreover, this difference does not include the fact that the dehumidifier system combines dehumidification, heat recovery and heating, leading to increased energy savings.

More experimental data *in situ* and adjustments are still necessary to validate climate control algorithms that will be required to assist in the choice between the different modes: dehumidification by pump or ventilation-heating with heating by heat pump or boiler.

Acknowledgements

This project was initiated by the VEGEPOLYS Competitivity Pole, Angers, France.

We would especially like to thank ETT (Energie Transfert Thermique, France; heat pump manufacturer), the Groupe Chauvin (plant producer, France) and BHR (Bureau Horticole Régional, Angers, France) for their valuable assistance with this study.

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Figures

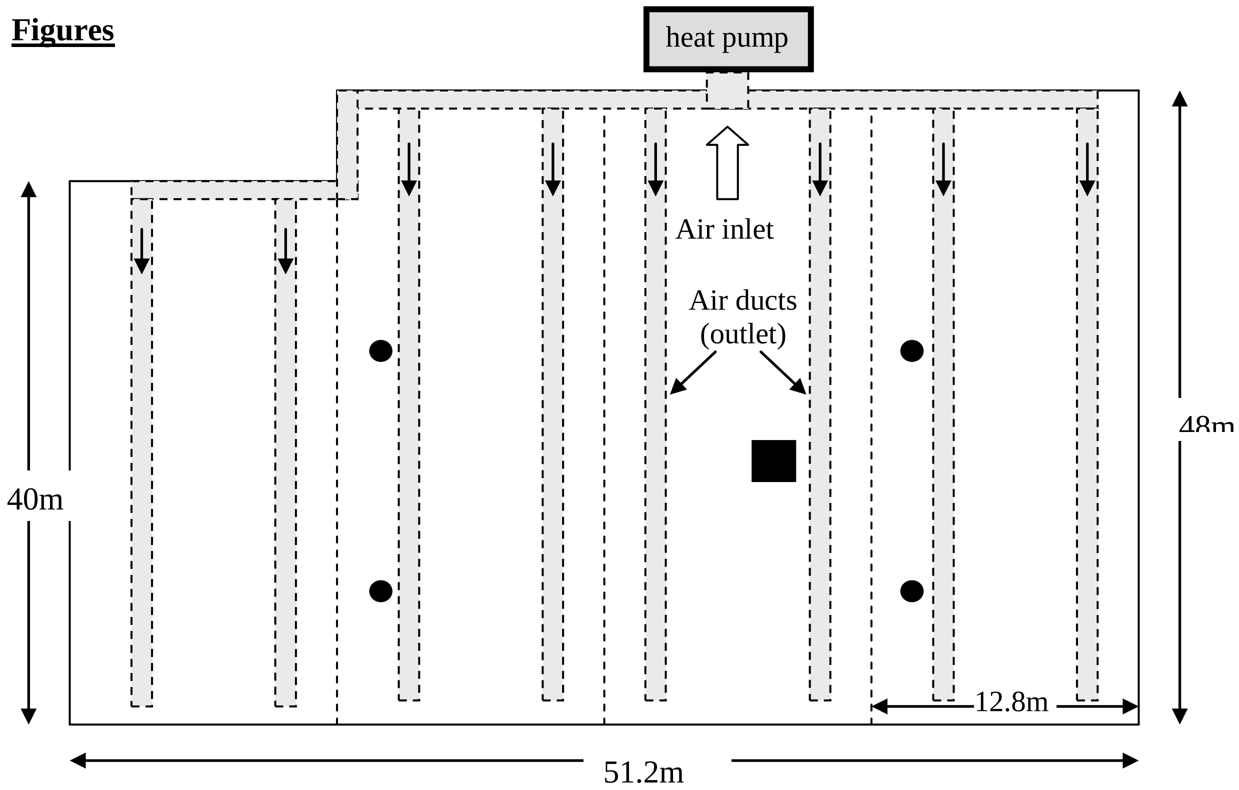

Fig. 1. Aerial view of the greenhouse and dehumidifier system ducts (filled circles and squares indicate indoor greenhouse climate measurement positions; see Fig. 4).

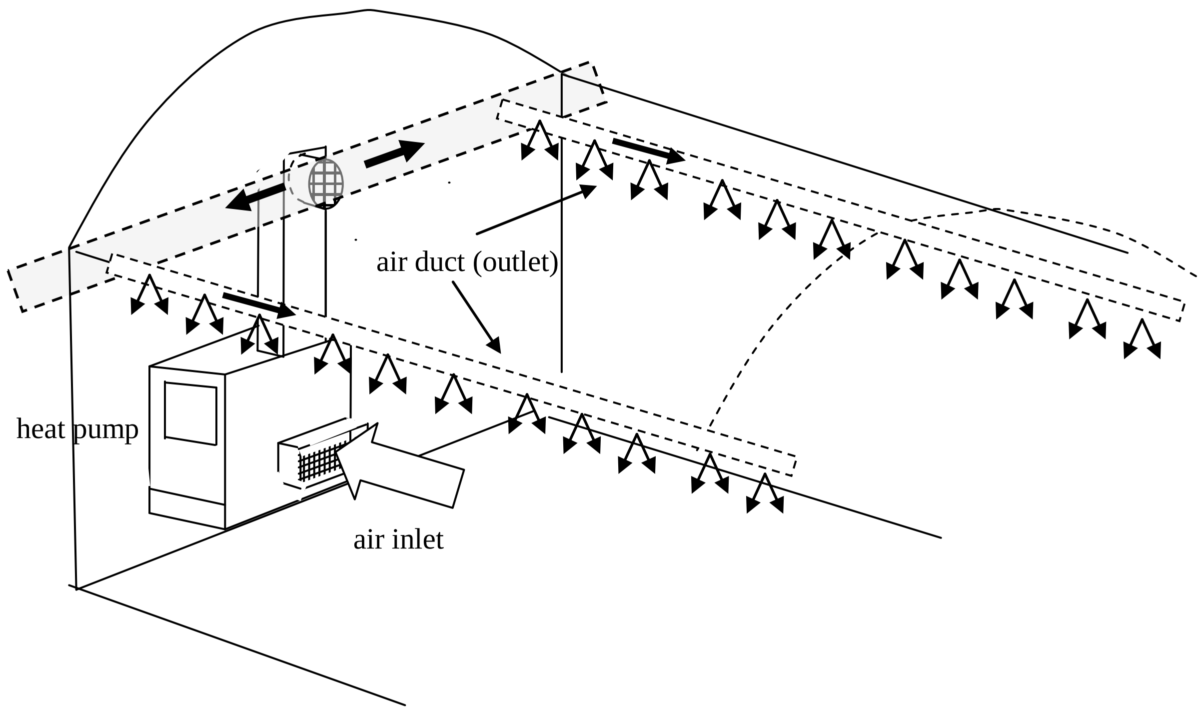

Fig. 2. Schematic view of the dehumidifier system.

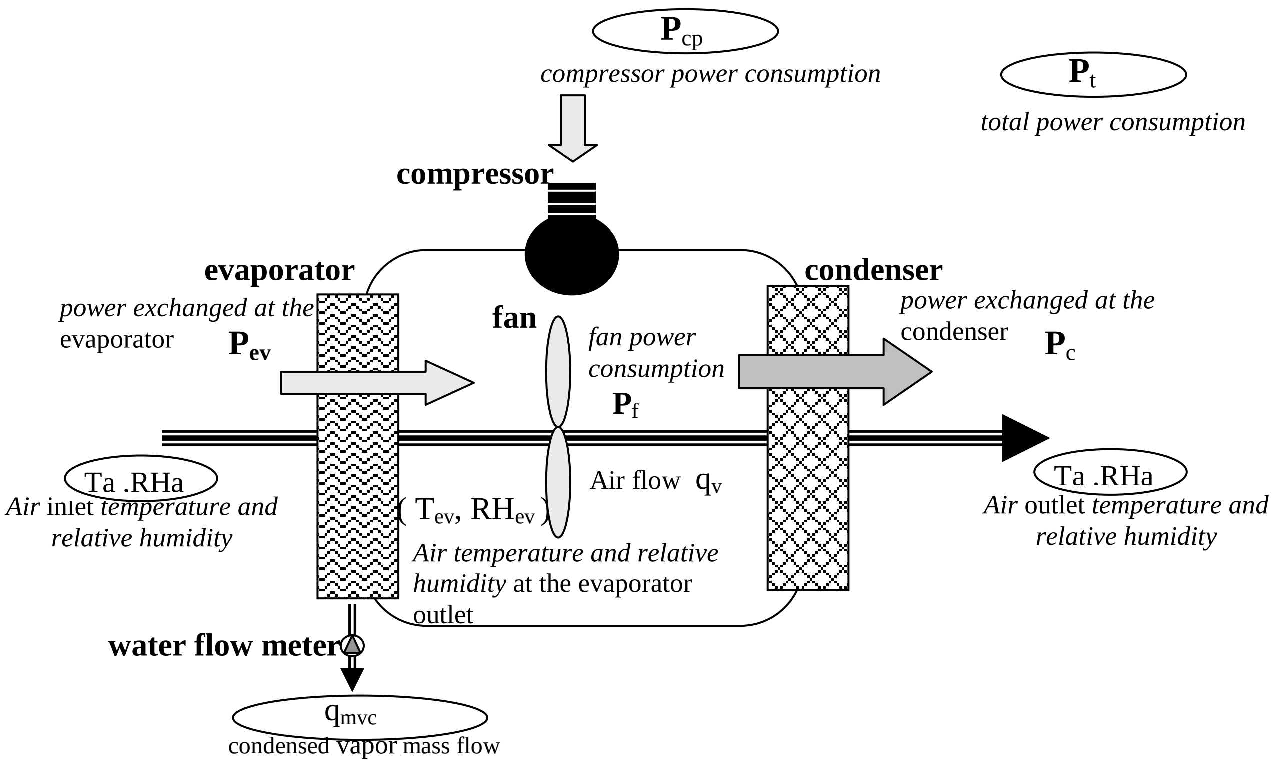

Fig. 3. Measured and calculated parameters of the heat pump dehumidifier (measured parameters are indicated by ellipses).

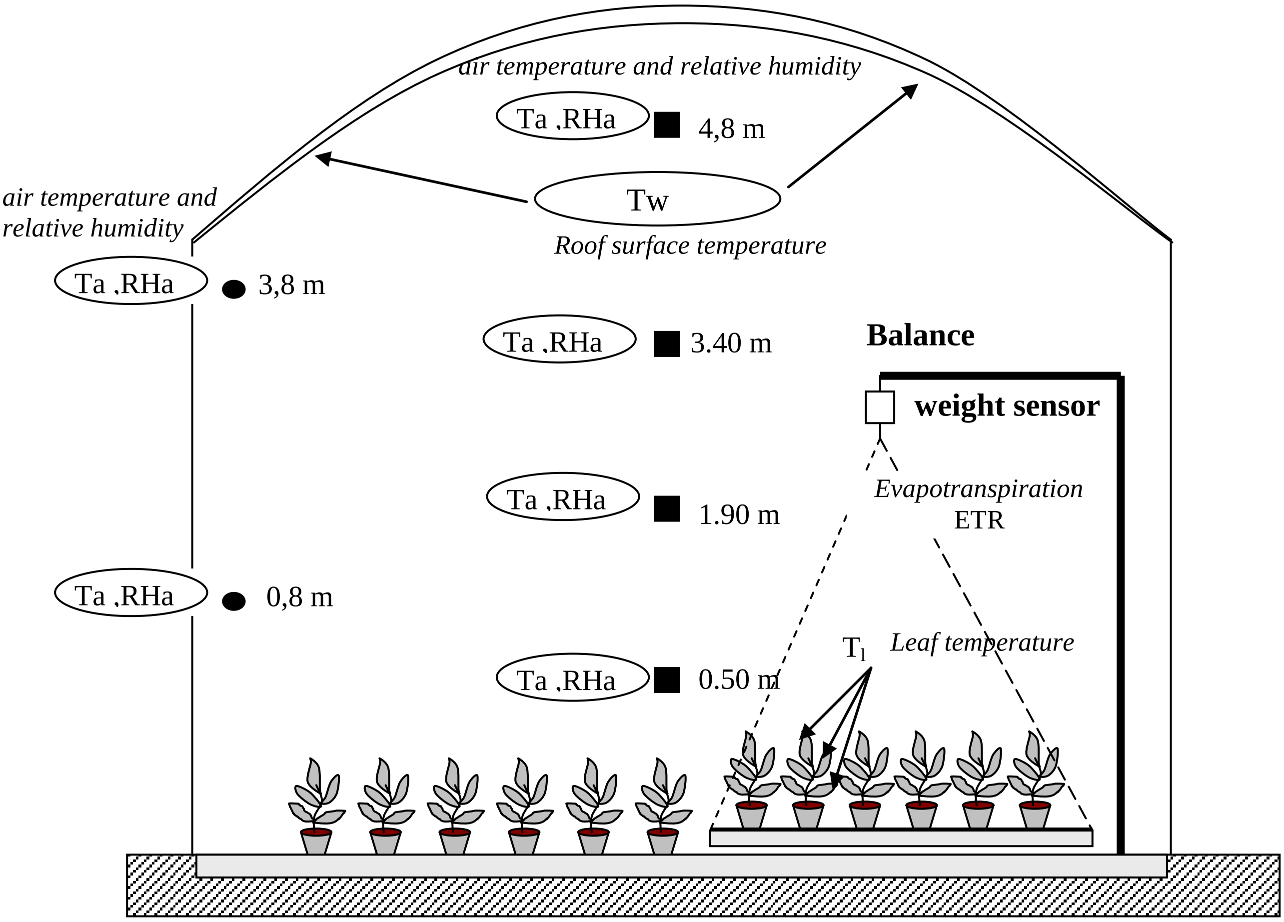

Fig. 4. Schematic view of the experimental set-up with measurement positions.

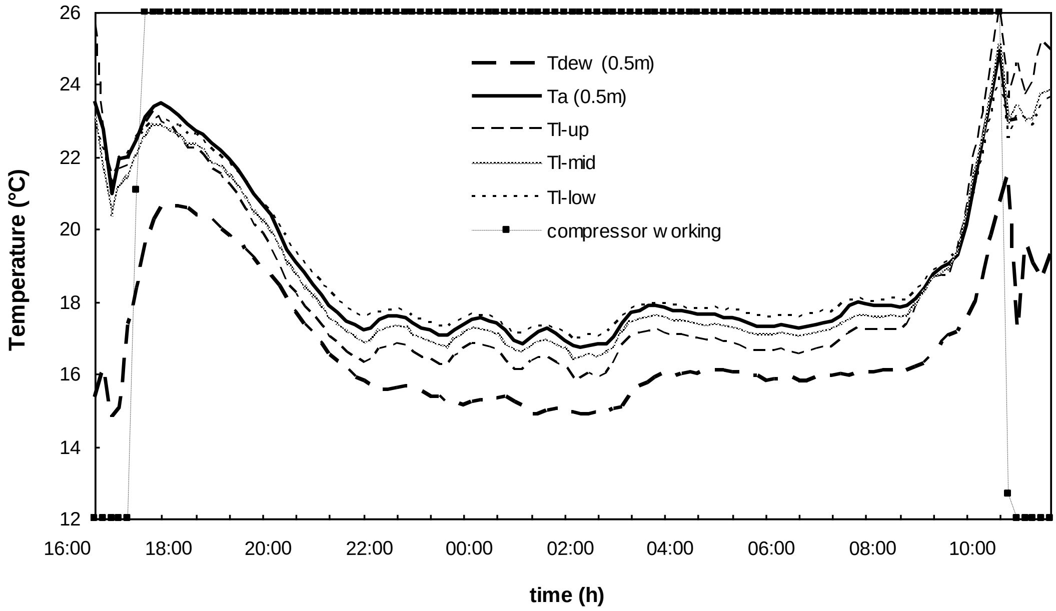

Fig. 5. Evolution over time of air (0.5 m), leaf and dew point (0.5 m) temperatures (during the night of 25th–26th March).

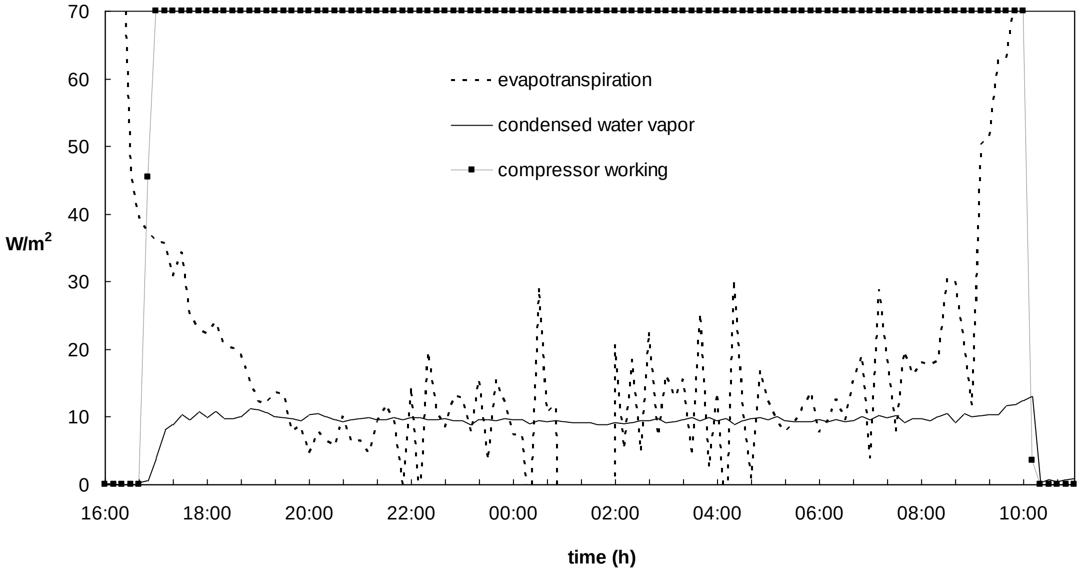

Fig. 6. Evolution over time of the condensed vapor by the dehumidifier and crop evapotranspiration (during the night of 25th–26th March).

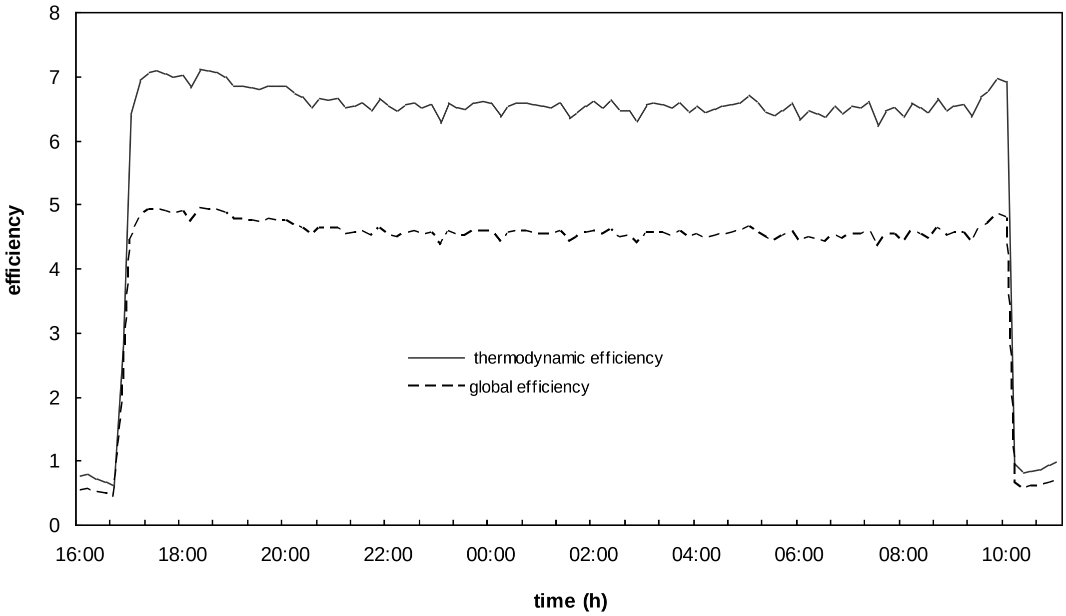

Fig. 7. Variations of the thermodynamic efficiency and of the global efficiency (during the night of 25th–26th March).