International Conference on Renewable Energies and Power Quality (ICREPQ'18)
Salamanca (Spain), 21th to 23th March, 2018
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.16 April 2018

Efficient management of a dehumidifier in a greenhouse under warm weather conditions

J.M. Cámara-Zapata[1], J.A. Sánchez-Molina[2], F. Rodríguez[2] and J.C. López[3]

[1]Department of Physics and Computer Architecture, University Miguel Hernandez, Avda. Universidad, s/n, 03202, Elche, Spain.
[2]Department of Informatics, University of Almeria, Carretera Sacramento s/n, Almería, Spain. CeiA3. CIESOL.
[3]Experimental Station of Cajamar Foundation "Las Palmerillas", El Ejido, Almeria, Spain.
Phone/Fax number:+0034 966 749730, e-mail: jm.camara@umh.es

Abstract. The reduction of humidity inside a greenhouse is a key factor to ensure the quality of the crop and avoid the incidence of cryptogamic diseases. The method commonly used is a combination of heating and natural ventilation, although it is very deficient from the energy and environmental points of view. In cold and humid climates the use of a heat pump dehumidifier (HPD) can reduce energy consumption. To evaluate this technology in a Mediterranean climate, an HPD was installed in a greenhouse of the Cajamar Experimental Station in Almería. The environmental humidity inside the greenhouse decreased when using the HPD. The efficiency of the HPD was related to the value of the condensation temperature of the water vapor and to the temperature and humidity of the air inside the greenhouse. In addition, it was found that the energy efficiency of the system varied according to climate. For efficient management of HPD it is essential to know the influence of climate on energy efficiency. The flow of condensed water vapor and the power consumed presented differing behaviors. Thus, the production of liquid water correlated linearly with the condensation temperature, increasing the slope of the linear relationship with the temperature of the air inside the greenhouse. However, the power consumption was correlated linearly with the air temperature. The management of the system is efficient when the air temperature is above 15.0ºC and the relative humidity is less than 90%.

Key words

Water vapor, temperature, humidity, power, condensation.

1. Introduction

Protected cropping is a specialized form of agriculture which allows greater control over the crop. Most Mediterranean greenhouses are very simple constructions, covered with a plastic film and with a natural ventilation system to maintain a certain control of temperature and humidity. In general, humidity tends to be high, due to the transpiration of the crop and the low temperature, especially during the autumn and winter. High humidity favors the incidence of diseases and physiological disorders [1]. In general, for a vapor pressure deficit (VPD) lower than 0.20 kPa, plant diseases are favored and physiological disorders may occur [2].

An adequate dehumidification method should be able to prevent condensation of water on plant surfaces and keep the greenhouse closed to obtain a homogeneous climate and high CO_2 levels when enrichment systems are installed. The control of humidity in greenhouses through a heat pump dehumidifier (HPD) allows recovery of the latent heat of condensed water vapor for heating. This technology is effective in cold and humid climates [3]. In order to evaluate its functioning in the Mediterranean climate, an HPD was installed in a greenhouse in Almería used for tomato cultivation. The effectiveness of HPD in the reduction of humidity was determined. In addition, the influence of climate on its energy efficiency was observed [4]. The condensation temperature of water vapor (T_c, ºC) is one of the most influential parameters in the energy efficiency of the HPD. It is evident that when the T_c values are lower than the sublimation temperature, frost appears on the finned condenser pipe and affects the operation of the HPD. However, the influence of T_c, when it is greater than 0.0ºC, on energy efficiency and how that relationship is affected by climate is not clear. In addition, other parameters, such as the air flow treated, can be affected by the climate and influence energy efficiency.

To establish the conditions that allow efficient management of HPD in a greenhouse under warm conditions, the effect of climate on condensing capacity and power consumed is analyzed. Due to the importance of the T_c to avoid frost formation in the evaporator, it is considered necessary to analyze its influence on the efficiency of the HPD.

2. Materials and methods

A. Greenhouse Facilities

The data used in this research was acquired from the Cajamar Foundation Experimental Station greenhouse in El Ejido, Almería Province, Spain (2º 43W, 36º 48N, and 151 m a.s.l.). The crops grew in a multispan Parral-type greenhouse (Figures 1a and 1b). The greenhouse is 877 m^2 (37.8 x 23.2 m) with a variable height (between 2.8 and 4.4m), having a polyethylene cover. The structure of the greenhouse is symmetric in area and the roof runs from East to West, and crop rows are aligned north–south. Furthermore, the greenhouse counts on automated ventilation with windows in the north and south walls, and flap roof window in each span, 20 x 10 threads x cm^{-1} mesh bionet anti-insect screen, a heating system with an aerothermal generator of 95 kW (Ernaf RGA95), a dehumification system by condensation (FRAL FD980, Figure 1c), humidification (Alarcontrol) and a biomass-based system with CO_2 recovering from flue gases (Carsan Missouri 150 kW).

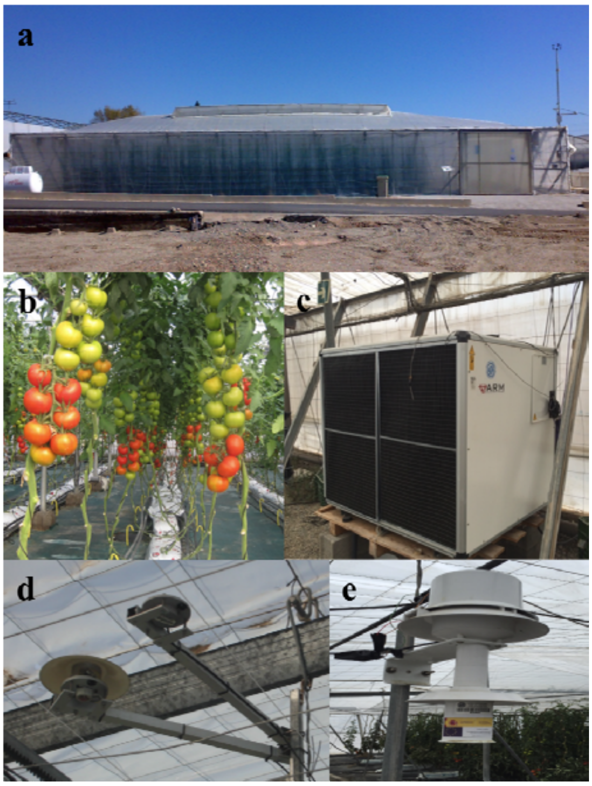

Fig. 1. Greenhouse facilities used for the experiments performed: (a) Multispam greenhouse, (b) Tomato plants, (c) HPD system, (d) Radiation sensors, (e) Temperature and humidity sensors.

Throughout the crop season, several internal and external measurements were continuously monitored. Outside the greenhouse, a weather station measured air temperature and relative humidity with a ventilated sensor (Vaisala HMP45P), solar radiation (Delta-Ohm LP PYRA 03), photosynthetic active radiation with a silicon sensor (PAR, Kipp&Zonnen PAR Lite), rain detector, CO_2 concentration (Vaisala GMP222), wind direction (Met One 020C-L), and wind speed (DeltaT AN3). The cover temperature (Thermopars T type) sensors were located on the east (two sensors) and west sides (two sensors). During the experiments, the indoor climate variables were also taken, especially solar radiation with a pyranometer (Delta-Ohm LP PYRA 03, Figure 1d), air temperature, relative humidity (Vaisala HMP45P, Figure 1e), photosynthetic active radiation (PAR, Kipp&Zonnen PAR Lite), soil temperature (Decagon Devices RT-01), leaf wetness sensor (LWS, decagon devices), CO_2 concentration (Vaisala GMP222) and power consumption (Sineax m563). The greenhouse counts on three Compact Fieldpoints®, and one CompactRIO® to collect data from the installation every 30 s; these are connected by means of industrial Ethernet to a WIFI router. The SCADA system developed with LabVIEW® is installed on a personal computer, which has a wireless connection to the router. Finally, to access the acquired data from outside of the Cajamar Foundation, a VPN (Virtual Private Network) connection was set up.

B. Heat pump dehumidifier

The heat pump dehumidifier (HPD) involved a compressor cooling system which allows reduction of the air humidity. In a cycle of refrigeration by compression, the energy content of the refrigerant increases in the evaporator and in the compressor (the pressure and the temperature increase) and decreases in the condenser, returning to its initial value after an expansion. Dehumidification occurs when the air in the greenhouse circulates around the evaporator and its temperature and water vapor content decrease. For this, the outer surface temperature of the evaporator must be lower than the dew point temperature of the greenhouse air. The air then flows along the outside of the condenser and its temperature increases. Thus, the latent heat initially supplied by the air to the refrigerant in the evaporator, due to the condensation of the water vapor, is then transferred from the refrigerant to the same air as it circulates around the condenser. The mixture of the air treated in the HPD with the interior air of the greenhouse supposes a saving of the energy consumed in heating equal to the latent heat of the steam of the condensed water.

Figure 2 shows a scheme of the HPD components and the probes used in the experiments. The temperature and RH at the inlet to the HPD, the outer surface temperature of the evaporator, the temperature of the air at the outlet of the HPD and the mass of condensed water vapor (mw_d) were measured.

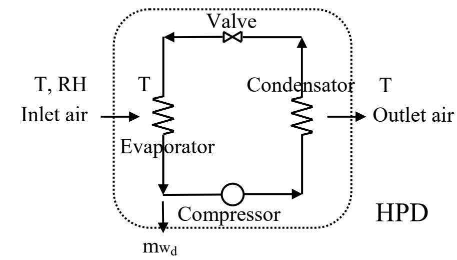

Fig. 2. The refrigeration-based dehumidifier scheme

C. Instant flow of condensed water vapor

At time t (s) an amount of air mass that is inside the greenhouse ($ma_{g,t}$) and in an adjacent region called entrance (ma_e) is analyzed. At time $t'=t+\Delta t$ (s), the mass of dry air is located in the greenhouse ($ma_{g,t'}$) and in a different area called outlet (ma_o). The mass balance for the dry air is given as:

$$ma_{g,t}+ma_e=ma_{g,t'}+ma_o \quad (1)$$

For the water vapor it is necessary to consider two additional transfers, transpiration (tr) and natural condensation (n):

$$mv_{g,t}+mv_e+mv_{tr}=mv_{g,t'}+mv_o+mw_n \quad (2)$$

Where mv_{tr} (kg) represents the mass of water vapor incorporated into greenhouse air in the time interval Δt (s) due to transpiration (zero or positive). In turn, mw_n (kg) represents the mass of water vapor that naturally condenses in this interval (negative, zero, or positive).

Initially, the energy balance of the greenhouse (g) air is $E_t=ma_{g,t}\ h_{g,t}+ma_e\ h_e+mv_{tr}\ hw_{tr}$ (J). Where ($mv_{tr}\ hw_{tr}$) represents the energy incorporated into the air due to the transpiration during Δt. At time t′, $E_{t'}=ma_{g,t'}\ h_{g,t'}+ma_o\ h_o+mw_n\ hw_n$ (J); where ($mw_n\ hw_n$) represents the variation in the energy of the air due to the natural condensation inside the greenhouse during Δt. The balance of energy between t y t′ can be expressed as $E_{t'}-E_t=Q-W$. In this case, W=0, so that:

$$Q=ma_{g,t'}\ h_{g,t'}-ma_{g,t}\ h_{g,t}+ma_o\ h_o-ma_e\ h_e+mw_n\ hw_n-mv_{tr}\ hw_{tr} \quad (3)$$

It is convenient to express the transfer of energy in the form of heat, Q, as a function of the properties of the air and whose value is independent of the performance of the HPD. For this, mw_n in (2) is removed and substituted in (3), giving:

$$Q=ma_{g,t'}\ (h_{g,t'}-\omega_{g,t'}\ hw_n)-ma_{g,t}\ (h_{g,t}-\omega_{g,t}\ hw_n)+ma_o\ (h_o-\omega_o\ hw_n)-ma_e\ (h_e-\ \omega_e\ hw_n)-mv_{tr}\ (hw_{tr}-hw_n) \quad (4)$$

When the operation of the desiccator is considered, the mass balance of the dry air in the greenhouse (1) is maintained, but that of the water vapor in the greenhouse (2) changes because the mass of condensed water vapor in the desiccator in Δt must be considered (mw_d), giving:

$$mv_{g,t}+mv_e+mv_{tr}=mv_{g,t'}+mv_o+mw_n+mw_d \quad (5)$$

In this case, it can be considered that in a time interval Δt, the interior air of the greenhouse exchanges Q and further experiences a heat transfer in the evaporator and the condenser of the desiccator. If the vapor compression cycle of the desiccator had the characteristics of a reversible cycle, the net work would coincide with the net heat exchanged in each cyclic process. Since it is a real steam compression cycle, it is only possible to establish a relationship between the work consumed by the desiccator, W_d, and the heat exchanged by the air in the greenhouse, in each cyclic process of the desiccator. In Δt, this ratio must be maintained, so that the energy balance of the air in the greenhouse can be written as:

$$ma_{g,t'}\ h_{g,t'}-ma_{g,t}\ h_{g,t}+ma_o\ h_o-ma_e\ h_e+mw_n\ hw_n+mw_d\ hw_d-mv_{tr}\ hw_{tr}=Q-W_d \quad (6)$$

In our experimental conditions, it is considered that the operation of the HPD only affects the value of the mass of naturally condensed vapor (mw_n), which can be removed from (5) and inserted in (6), giving:

$$Q=W_d+ma_{g,t'}\ (h_{g,t'}-\omega_{g,t'}\ hw_n)-ma_{g,t}\ (h_{g,t}-\omega_{g,t}\ hw_n)+ma_o\ (h_o-\omega_o\ hw_n)-ma_e\ (h_e-\omega_e\ hw_n)+mw_d\ (hw_d-hw_n)-mv_{tr}\ (hw_{tr}-hw_n) \quad (7)$$

Expressions (4) and (7) allow determination of the heat transfer of the air in the greenhouse as a function of the values of the properties of the interior air and of the mass of the interior air at times t and t', the masses of air entering and leaving the greenhouse in the interval Δt, and the transpiration. In general, the values of these quantities are independent of the operation of the desiccator whereby both expressions can be subtracted to determine mw_d:

$$mw_d=W_d/(hw_n-hw_d) \quad (8)$$

Where $W_d>0$ for the greenhouse air, since it is energy in the form of work transferred from the system (the enthalpy of the air circulating through the desiccator decreases). In each drying interval the mean value of the facility's performance is obtained based on the premise that the sum of all the values of mw_d determined by (8) must correspond to the total mass of liquid water obtained during said interval. Also, the values of the enthalpy of the liquid water in expression (8), hw_n and hw_d, are set at the air dew temperature and the temperature of the surface of the HPD evaporator battery, respectively.

On the other hand, the power unit consumption (PUC, W m^{-2}) is the ratio between the power consumed and the covered area of the greenhouse. The specific moisture extraction rate, SMER (kg (kW h)$^{-1}$), was determined as the ratio of the mass of condensed water vapor, MCV (kg), and energy consumed, W (kW h).

3. Results and discussion

Thirty-five dehumidification processes were carried out at different times during 26 days of autumn, winter, and spring. The duration of the experiments varied from 2 to 3 hours, so that the HPD worked for about 85 hours, resulting in more than 10,000 values of each parameter measured. During the experiences, there was no ventilation, neither lateral nor aerial. Table 1 shows the results of the treatments according to the risk of moisture damage [2]. The results of five processes in which the average temperature (T) is higher than 20ºC and the relative humidity (RH) less than 70 % are not presented. Under these conditions it is not necessary to perform dehumidification. However, these experiences have been scheduled because the objective of this study was not to eliminate the risk of moisture damage, but to evaluate the operation of HPD in a mild wheather greenhouse.

Table 1. Mean values of the T (ºC), RH (%) and VPD (kPa) during dehumidification processes performed in the greenhouse

No risk of moisture damage			With risk of moisture damage		
T_{med} (ºC)	RH_{med} (%)	VPD_{med} (kPa)	T_{med} (ºC)	RH_{med} (%)	VPD_{med} (kPa)
12.2	85	0.21	14.4	100	0.00
10.9	84	0.22	11.0	97	0.05
14.5	86	0.23	11.3	95	0.08
14.6	88	0.24	13.1	94	0.09
15.0	85	0.26	12.5	93	0.10
17.3	88	0.28	11.6	93	0.10
9.9	75	0.31	12.2	92	0.11
18.7	88	0.31	12.3	91	0.13
12.0	76	0.34	11.3	90	0.13
9.9	72	0.35	11.1	88	0.15
18.5	86	0.39	13.8	89	0.17
11.9	72	0.40	14.1	90	0.17
15.5	69	0.56	18.0	93	0.17
17.2	69	0.61	12.4	87	0.19
18.1	67	0.70	19.5	92	0.19

The classification of the effectiveness of the HPD according to the VPDmed is not completely correct. The value of the VPD can vary widely throughout the dehumidification process. Frequently, the final value of the VPD is sufficient to avoid the risk of moisture damage although its average value in the test can be VPDmed<0.2 kPa. However, this initial classification allows interesting results to be obtained. The result of the dehumidification treatment depends on the average T and, basically, on the average RH inside the greenhouse.

In our conditions, when the average RH is greater than 88% it was not possible to eliminate the risk of damage by humidity.

To increase the knowledge of the relationship between the climate in the greenhouse and the efficiency of the HPD to avoid damages by humidity in the crops, four dehumidification tests were analyzed in the first hours of the day. According to our experience, this may be the moment with the greatest risk of damage by moisture, due to an increase in temperature and the transpiration of the crop. Tables 2 and 3 shows the most important values of T, RH, and vapor pressure deficit (VPD). In the four tests analyzed, the evolution of the values of these properties is increasing, and approximately continuous for T and VPD and decreasing, with brief increasing stretches, for RH. On February 25th the experiment was realized with lowest T and VPD. Contrarily, on March 2nd experiment obtained the highest T and intermediate VPD. On 23 February, dehumidification takes place with intermediate T and VPD. Finally, on 26 February, dehumidification took place with high T and highest VPD.

Table 2. Characteristics of air properties during dehumidification processes performed in the greenhouse 1/2

Date	Start	Final	Length (h)	T_{max} (ºC)	T_{min} (ºC)	T_{med} (ºC)
17/02/23	8:33	10:25	1.87	24.3	10.7	17.4
17/02/25	8:03	11:27	3.40	23.1	9.2	14.8
17/02/26	8:18	10:32	2.23	27.0	10.3	18.4
17/03/02	8:33	10:22	1.82	25.9	11.6	18.8

Table 2. Characteristics of air properties during dehumidification processes performed in the greenhouse 2/2

Date	RH_{max} (%)	RH_{min} (%)	RH_{med} (%)	VPD_{max} (kPa)	VPD_{min} (kPa)	VPD_{med} (kPa)
17/02/23	100	70	88	0.86	0.01	0.28
17/02/25	100	71	87	0.77	0.01	0.26
17/02/26	100	69	86	1.12	0.01	0.40
17/03/02	100	72	88	0.92	0.04	0.33

In the four trials, the air inside the greenhouse was initially saturated (100% RH) at similar temperatures (10.7 °C on February 23, 9.2 °C on February 25, 10.3 °C on February 26 and 11.6 °C 2 of March). Figure 3 shows the evolution of the temperature (T, °C), the RH (%) and the VPD (kPa) of the air in the interior of the greenhouse during the assays. In chronological order, the values of the condensed steam production, CSP (kg h^{-1}), were 15.8, 12.9, 16.1 and 17.6 kg h^{-1} and the HPD eliminated the risk of moisture damage in 53 min, 104 min, 55 min and 49 min (Figure 3). The mean values of T_c (ºC) were 3.4, -0.1, 3.5 and 4.5 ºC respectively. The mean values of P were 6.5, 5.5, 6.4 and 6.8 kW respectively. Mean VPD values at the end of the HPD operation were greater than 0.2 kPa (chronologically, 0.28, 0.26, 0.39 and 0.32 kPa) (Figure 4). Of course, overall energy consumption of HPD (12, 19, 14 and 12 kWh, in chronological order) and the total masses of condensed water vapor (29.5, 44.0, 36.0 and 32.0 kg, respectively) were proportional to the duration in the essays.

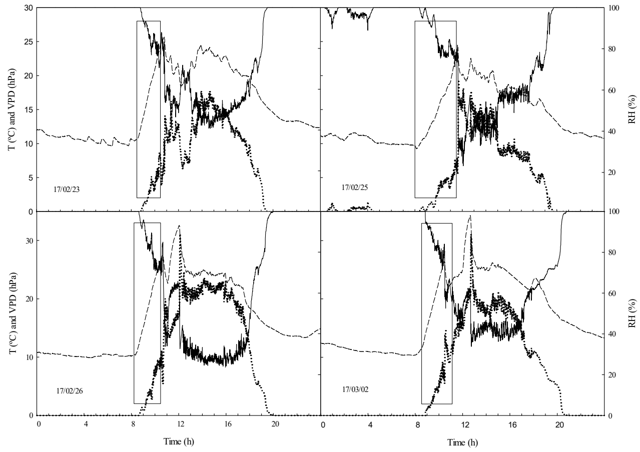

Fig. 3. Evolution of temperature (T, °C, dash line), relative humidity (RH,%, continuous line) and vapor pressure deficit (VPD, kPa, dotted line) inside the greenhouse during the HPD dehumidification assays, represented by black rectangles (HPD on). The base of the operation rectangles is at VPD = 2 hPa.

The differences in HPD behavior among the assays analyzed appear to be associated with different values of T and RH outside the greenhouse (15.7 °C and 38.4% on 23 February, 13.3 °C and 25.2% on 25 February, 17.8 °C and 32.4% on 26 February and 16.4 ºC and 57.3% on 2 March, during the assays). The low value of T on the outside could explain the poor efficacy of the HPD on 25 February. Given the values of VPD, the effects of dehumidification on the indoor climate of the greenhouse seem more favorable after the assay of 26 February. This result could be logical, due to the longer duration of this assay. However, the explanation may also lie in the higher humidity of the outdoor air during the assay of 2 March. In our experimental conditions, the outside climate could have influenced the effectiveness of the HPD, due to the lack of watertightness of the greenhouse.

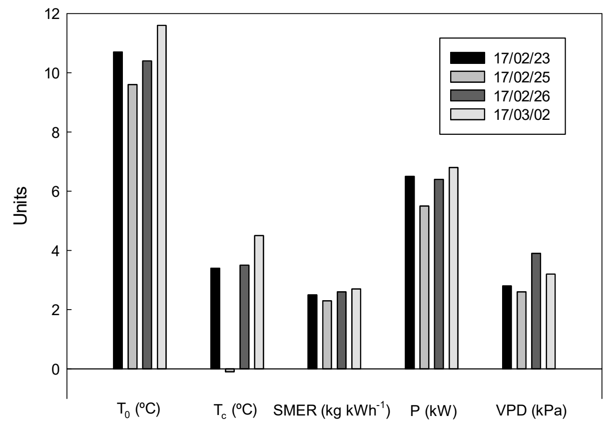

Fig. 4 Initial values of the temperature inside the greenhouse (T) and mean values of the VPD (kPa), the SMER (kg kWh^{-1}) and the P (kW) during the dehumidification tests carried out on the dates indicated.

The climate influences the magnitudes of the operating parameters, such as the value of T_c, and also parameters related to energy efficiency, such as condensed flow vapor, VCF (g h^{-1} m^{-2}), and the power unit consumption, PUC (W m^{-2}).

In order to efficient management it is necessary to reduce the risk of moisture damage (vapor pressure deficit, VPD, must be greater than 0.2 kPa) and ensure proper functioning of the HPD (T_c>0ºC). In this way, the duration of the defrosting operation is prevented from being too prolonged, which prevents the normal operation of the HPD.

To determine the greenhouse climate that is compatible with this objective, the values of T_c, T, and P were plotted as a function of VPD. Of the 10,034 measurements of each variable recorded during the dehumidification tests, 8,958 were made with the HPD in operation and 1,076 during defrosting intervals. Figure 5a shows the relationship between T_c and VPD during HPD operation (values recorded at RH = 100.0% are not included). The values of VPD varied between 0.0 and 1.5 kPa and those of T_c between -9.2 and 19.6 ºC. In order to clarify the results, the relationship between these values for certain constant values of RH is shown in Figure 5b. At constant RH, VPD increased in step with T_c. In our experimental conditions, the target VPD (≥0.2 kPa) was achieved at T_c≥0.0 °C and RH≤88.0%. When RH was 89.0%, it was necessary for Tc to be 1.0 °C - and if RH was 90.0%, T_c had to be 3.0 °C - to obtain a VPD of 0.20 kPa. For higher values of RH, the T_c values that reduced the risk of damage due to humidity were too high and not feasible in practice.

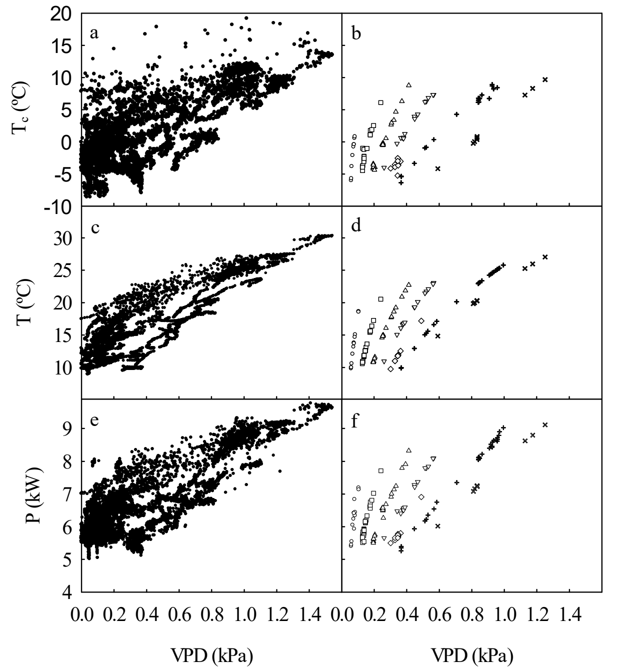

Fig. 5. Relationship between the VPD (kPa) and the T_c (°C), T (°C) and P (kW) in all the dehumidification assays (a, c and e, respectively) and ordered according to the value of the RH (%); 95.0% circle; 90.0% square; 85.0% triangle up; 80.0% triangle down; 75.0% diamond; 70.0% plus and 65.0% x (b, d and f, respectively).

The values of T during the tests varied between 9.4 and 30.2 °C (Figure 5c). Figure 3d shows that when the RH varied between 80.0 and 88.0%, a VPD value of 0.20 kPa was reached if T was 15.0 °C. If the RH was 89.0%, the objective VPD of 0.20 kPa was fulfilled at T=16.0 °C; if RH was 90.0%, a T of 18.0 °C was necessary. Above this value of RH, the values of T necessary to avoid the risk of humidity damage are hardly feasible in our experimental conditions.

The value of P varied between 5.0 and 9.8 kW (Figure 5e). The objective (VPD=0.20 kPa), when RH varied between 80.0 and 88.0%, was fulfilled at P = 6.4 kW. When RH was 89.0%, the P required was 6.8 kW; at an RH of 90.0%, the P needed to be 7.1 kW to achieve VPD=0.20 kPa (Figure 5f).

Dehumidification by the HPD, to avoid the risk of moisture damage (VPD=0.20 kPa), was adequate (T_c≥0.0 °C) if the HR varied between 80.0 and 88.0% and the T was 15.0 °C. At higher RH values, it would be necessary to increase the value of T to maintain the VPD at an appropriate value (at an RH of 89.0%, T must be 16.0 °C; at 90.0% RH, T must be 18.0 °C). These conditions, in which RH is between 89.0 and 90.0%, would be sufficient to ensure a T_c value >0.0 °C.

The relationship between T, T_c and P is linear when the RH varies between 80 and 88% (Figure 6). The relationship between P and T is P=0.2 T + 3.6; R^2=0.97***. The relation between P and T_c is P=0.2 T_c + 6.5; R^2=0.96***. Finally, the relationship between T and T_c is T =T_c + 15.0; R^2=0.98***.

Therefore, T=15.0ºC it could be adopted as a set value of T for optimum performance. However, it is necessary to analyze the energy efficiency of the HPD in these conditions. Figure 6 shows the value of the vapor condensed flow, VCF (g h^{-1} m^{-2}) and the power unit consumption, PUC (W m^{-2}), as a function of the T_c for different values of the air temperature in the interior of the greenhouse (T, ºC).

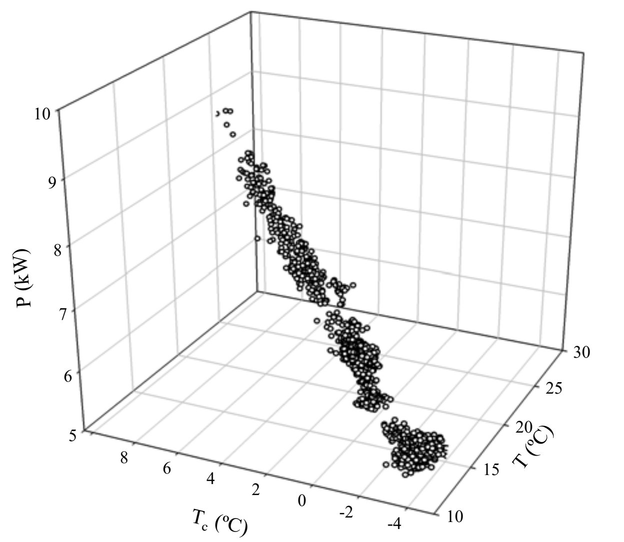

Fig. 6. Relationship between the T (°C), T_c (°C) and P (kW) when RH varies between 80 and 88%.

The relationship between VCF and T_c is linear and increasing the slope with the value of the T (Table 3). The values of the PUC increase proportionally with the value of the T, independently of the value of the T_c.

A linear correlation between the values of the T and the PUC has been found. Although the values of the slope and the ordinate at the origin vary slightly with the value of RH, the linear relationship is highly significant (PUC=0.2 T + 4.0; R^2=0.98***).

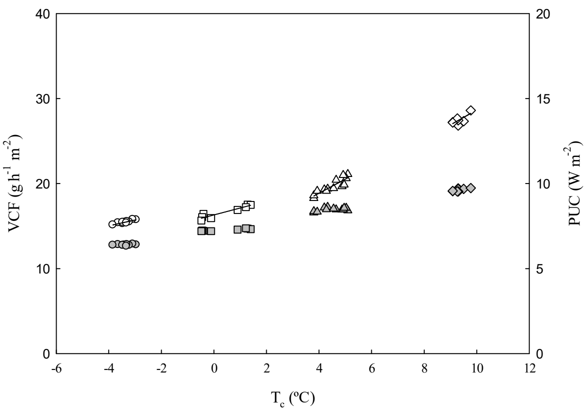

Fig. 7. Relationship between the vapor condensed flow, VCF (g h^{-1} m^{-2}) (main axis, in white) and the power unit consumption, PUC (W m^{-2}) (secondary axis, in gray), as a function of T_c for different values of the air temperature inside the greenhouse (○ 10ºC; □ 15ºC; Δ 20ºC; ◊ 25ºC).

To ensure a T_c value close to 0.0ºC, the value of T must be around 15.0ºC and the RH between 80% and 88%. Under these conditions, the mean values of VCF and PUC are 16.6 g h^{-1} m^{-2} and 7.3 W m^{-2}, respectively.

Table 3. Values of the slope (A), the ordinate at the origin (B), and the coefficient of determination (R^2) of the linear relationship between the VCF (g h^{-1} m^{-2}) and the T_c (ºC) as a function of T (ºC). N is the number of values; *** means P-values <0.001; ns means P-values >0.05.

N (-)	T (ºC)	A (g h^{-1} m^{-2} $ºC^{-1}$)	B (g h^{-1} m^{-2})	R^2 (-)
8	10.0	0.68	17.8	0.796***
11	15.0	0.81	16.3	0.885***
8	20.0	1.65	12.3	0.793***
13	25.0	1.76	11.1	0.573ns

4. Conclusion

The use of a desiccant heat pump (HPD) was shown to reduce the humidity in a greenhouse under warm weather conditions. The flow of condensed water vapor and the power consumed presented differing behaviors. Thus, the production of liquid water correlated linearly with the condensation temperature, increasing the slope of the linear relationship with the temperature of the air inside the greenhouse. However, the power consumption was correlated linearly with the air temperature. The management of the system is efficient when the air temperature is above 15.0ºC and the relative humidity is less than 90%.

Reducing the risk of moisture damage is a relatively new application of HPD. It is a technology that allows greenhouse cultivation with less use of fungicides. In case of carbon fertilization, HPD helps improve the results, reducing the need for ventilation, with the consequent beneficial effect on crop production and quality. Currently there are specialized companies marketing this type of facility in warm weather such as Almería. It is necessary to continue studying the operation of HPD to determine its energy consumption under optimal conditions, as well as its effect on the use of fungicides, production and crop quality, in order to evaluate its technical-economic viability.

Acknowledgement

This work was financed by the Proyecto R+D+i del Plan Nacional DPI2014-56364-C2-1-R del Ministerio de Economía, Industria y Competitividad y Fondos FEDER.

References

[1] Rodríguez, F., Berenguel, M., Guzman, J.L., Ramírez-Arias, A. 2015. Modelling and Control of Greenhouse Crop Growth; Springer International Publishing; London (UK); 250 pp.

[2] Picken, A.J.F. 1984. A review of pollination and fruit set in the tomato (*Lycopersicon esculentum* Mill.). Journal of Horticultural Science 59 (1984) 1–13. doi:10.1080/00221589.1984.11515163.

[3] Chantoiseau, E., Migeon, C., Chasseriaux, G., Bournet, P.E. 2016. Heat-pump dehumidifier as an efficient device to prevent condensation in horticultural greenhouses. Biosyst. Eng. 142, 27–41. doi: 10.1016/j.biosystemseng.2015.11.011.

[4] Sánchez-Molina, J.A., Rodríguez, F., Guzmán, J.L., Cámara-Zapata, J.M. y Sánchez-Garrido, G. 2017. Modelado del contenido de agua en el aire interior de un invernadero con sistemas de actuación de humidificación y deshumidificación. IX Congreso Ibérico de Agroingeniería. Libro de resúmenes, 148.