Spanish Journal of Agricultural Research
16 (1), e0201, 10 pages (2018)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2018161-11484
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, O.A, M.P. (INIA)

RESEARCH ARTICLE

OPEN ACCESS

Comparison of vapour pressure deficit patterns during cucumber cultivation in a traditional high PE tunnel greenhouse and a tunnel greenhouse equipped with a heat accumulator

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Abstract

Plant productivity in protected cultivation is highly influenced by air temperature and humidity. The conditions relating to the moisture content of the air in protected plant cultivation are preferably defined by vapour pressure deficit (VPD), which describes the difference between the maximal and actual water vapour pressure (kPa). VPD is widely used as the parameter describing the climate conditions favourable for the development of fungal diseases and for highlighting conditions unfavourable for plant development. In protected cultivation, both the air temperature and the humidity are influenced by heating systems, and one such system is a heat accumulator, which may store the excessive heat produced during the day by converting the solar energy inside the plastic tunnel, and using it when plant heating is required. The tunnel equipped with a heat accumulator maintained an optimal level of humidity for a longer period, and significantly reduced the time of excessive air humidity. The longest time with an optimal VPD was recorded in August in a tunnel with an accumulator – 30.5% of total time *vs.* 22.3% of time for control tunnel. The highest difference of total time where the VPD was too low (below 0.2 kPa) was recorded in July – 12.4% of time in a tunnel with an accumulator *vs.* 39.1% of time for control tunnel. The highest difference of total time with an excessive VPD (over 1.4 kPa) was recorded in May – 12.1% of time in a tunnel with an accumulator *vs.* 17.9% of time for control tunnel. However, a situation beneficial for plant growth occurred every month during the investigated season.

Additional keywords: rock-bed; *Cucumis sativus*; microclimate; air humidity.

Abbreviations used: AEAC (ascorbic acid equivalent antioxidant capacity); PE (polyethylene); RH (relative humidity); VPD (vapour pressure deficit).

Authors' contributions: Conception, design, acquisition, analysis, interpretation: PJK. Analysis, interpretation, drafting the manuscript: WT. Analysis, interpretation, critical revision of the manuscript: KK.

Citation: Konopacki, P. J.; Treder, W.; Klamkowski, K. (2018). Comparison of vapour pressure deficit patterns during cucumber cultivation in a traditional high PE tunnel greenhouse and a tunnel greenhouse equipped with a heat accumulator. Spanish Journal of Agricultural Research, Volume 16, Issue 1, e0201. https://doi.org/10.5424/sjar/2018161-11484

Received: 30 Mar 2017. **Accepted:** 02 Mar 2018.

Funding: European Regional Development Fund under the Polish Innovative Economy Operational Programme (Project WND-POIG.01.03.01-10-115/09).

Competing interests: The authors have declared that no competing interests exist.

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Introduction

Temperature and humidity are the most important air properties influencing plant productivity in protected cultivation. Humidity is the content of water vapour in the atmosphere, and may be characterized by several different physical parameters. It may be described as specific humidity (g_{H2O}/kg_{air}) or absolute humidity (g_{H2O}/m^3_{air}). It may be also expressed in pressure units (hPa) as the partial pressure of water vapour in the air. The widely used parameter describing air humidity is relative humidity (RH), expressed in % units, defined as the ratio of the partial pressure of water vapour in the air to the saturated vapour pressure at a given temperature and atmospheric pressure. The maximum amount of water vapour in any given amount of air depends strongly on the air temperature. The higher the temperature, the more water vapour the air may contain. Thus RH describes the proportion between actual water vapour content and the maximal capable water content at an actual air temperature. A reduction of temperature may cause the water content to exceed the maximal capable level (dew point) and hence the condensation of vapour on the surface of plants and greenhouse construction or cover material. Maintaining the desired air humidity influences crop level and quality (Bakker *et al.*, 1987; DeHalleux & Gauthier, 1995). Even a short moistening of plant leaves carries the risk of an infection of fungal diseases (Flechter, 1974; Mortensen, 2000; Mortensen & Gislerød, 2005). Since the air humidity depends on temperature, the optimal air humidity for plant cultivation is different during a hot summer day, and different at dawn, when the temperature is lower, and the maximal capable water content in the air is much lower. This phenomenon makes it a problem for automatic greenhouse systems to maintain the desired air humidity level. According to Körner & Challa (2003), the air moisture content conditions in protected plant cultivation are better defined by vapour pressure deficit (VPD), which describes the difference between the maximal and actual water vapour pressure (kPa). This parameter is especially useful when a sharp drop in temperature is observed, *e.g.* during the night. VPD is used more and more frequently in automatic climate steering systems for protected cultivation, and might be used as the parameter describing the climate conditions favourable for the development of fungal diseases. According to Prenger & Ling (2009) fungus pathogens develop well when the VPD is below 0.43 kPa, and infection occurs usually when the VPD is below 0.2 kPa. Dickens & Potter (1983) showed that spores of chrysanthemum white rust survived for less than 5 min when the VPD level was 0.4 kPa, while a VPD of 0.22 caused a threat of infection for over 60 min. One of the most common fungal diseases is powdery mildew, which has spores that spread depending on air humidity conditions. Although this fungus prefers low air humidity, it also requires high air humidity during some stages of its life cycle (Aust & Hoyningen-Huene, 1986). Sporulation and spore dissemination requires low air humidity, while plant infection occurs when air humidity is high. Fungal spores may germinate only when the water drops are present on the surface of the leaf (the temperature is below dew point). Strong fluctuations of temperature and air humidity are especially favourable for the development of disease. The shortest infection period is observed when the air humidity is above 80% (Elad *et al.*, 2007). Itagaki *et al.* (2014) showed, that a high VPD level restricts germination of fungal spores in cucumber seedlings. However, air which is too dry, resulting in an excessive VPD level, exposes cucumber plants to drought stress and significantly decreases the efficiency of water use (Loomis & Crandall, 1977).

The VPD level directly influences stomata conductance and plant photosynthesis. Hand (1988) says that VPD within the range 0.2–1.0 kPa does not influence the photosynthesis intensity, however, photosynthesis is slowed down outside of that range. When the air humidity is high (VPD < 0.2 kPa) the stomata close, which reduces CO_2 assimilation. But when air humidity is low (VPD > 1.0 kPa) the potential transpiration rate is high, but plant stomata again close, in an effort to conserve water, which also causes a reduction in photosynthesis. Sinclair *et al.* (2007) showed, that the highest increase of mass in tall fescue (*Festuca arundinacea*) grown at a temperature of 22°C was obtained at a VPD of between 0.9 and 1.2 kPa. For a VPD at a level of 1.4 kPa the mass increase was 32% lower. However, the detailed comparison of results obtained by Bunce (1984), Hand (1988), and Sinclair *et al.* (2007) showed differences between VPD levels, specified by these authors as optimal photosynthesis conditions.

High air humidity also influences plant hormone behaviour and morphology. Plants acclimatize to the varying environmental conditions through morphological changes (Hand, 1988; Itagaki *et al.*, 2014). Differences in the thickness of leaves, and stomata size and density between plants grown in different air moisture conditions might be an example of such acclimatization (Torre *et al.*, 2003). The air moisture level also influences the efficiency of plant pollination. Picken (1984) revealed that, when exposed to air with a RH of above 90%, the individual pollen grains of tomato plants get stuck together, and cannot leave the thecae. Conversely, when air RH is below 55%, pollen cannot stick to the stigma, which is also unfavourable for pollination.

Although the air humidity expressed in any of the above mentioned physical parameters is unequivocal, and may be converted to any other equivalent parameter, assuring the temperature value, such conversion provides reliable results only for data collected within short periods. Conversion of humidity data averaged over long periods of time leads to erroneous, or at least vague results.

The pertinent acquisition of microclimate data becomes especially important when a heating system is used in protected cultivation. Among the possible methods for greenhouse heating, varied solar powered systems are increasingly popular, particularly those providing storage for surplus energy. The majority of results available on research conducted on solar heating are directed towards the energy performance of system, with very few papers providing information on greenhouse microclimate changes, and even less attention is given to the effect a solar heating system has on cultivated plants.

Similar to traditional heating systems, a solar powered system also increases the temperature and reduces daily fluctuations of temperature in a greenhouse. Bonachela *et al.* (2012) demonstrated that a simple black mulch installed in an unheated greenhouse can increase both soil and surrounding air temperatures during a cold period (late autumn and early winter) in the Almería region of Spain. Ghosal *et al.* (2005) compared the thermal performance of a ground air collector and an earth air heat exchanger for heating a greenhouse. They noted a 2–3°C rise in temperature and smaller relative fluctuations of temperatures in the greenhouse air during the winter period due to the use of the ground air collector when compared to the earth air heat exchanger. Kurpaska & Latala (2010) used a soil accumulator comprising a number of perforated coils located in the soil below the greenhouse, and observed a similar increase of air temperature inside the greenhouse when comparing to conditions when the accumulator was not used. A sensible heat type storage system consisting of two rock-bed canals excavated in the subsoil of the greenhouse and a centrifugal pump was used by Kürklü *et al.* (2003), and in this case the air temperature in the experimental greenhouse was higher during the night and lower during mid-day when compared to the control greenhouse, and resulted in a reversed pattern of RH changes.

The same pattern was observed by Ntinas *et al.* (2015) when a heat storage system composed of water filled transparent cylindrical polyethylene (PE) sleeves was examined during tomato production in Greece, with no significant effect of heat storage reported on either the total yield or the marketable yield of the tomatoes. However, the antioxidant capacity (AEAC) of fruits grown over water sleeves was 18% higher than AEAC of fruits grown in the control part of the greenhouse. Also worth noting is that the energy savings of the presented hybrid solar powered system were up to 36% higher when compared to the control part of greenhouse, for the total research period (Ntinas *et al.*, 2011). Water sleeves for heat storage were also used by Liang *et al.* (2015) in Northern Israel. The temperature and RH values were significantly different during afternoon and night comparing greenhouses equipped with water sleeves and those without sleeves. High energy savings were noted also by Kempkes *et al.* (2013) when double glazing with a gap of 10 mm filled with argon gas, and an anti-reflection coating was used for covering the greenhouse, with heat consumption reduced by up to 60% comparing to a greenhouse covered with traditional single glazing, and no negative effect on cultivated tomato crop parameters was observed. Tomatoes were also used as a test crop by Goto *et al.* (2015) in two greenhouses of which one was heated by an air-source heat pump, while the other was equipped with a kerosene combustion fan heater. The total energy consumption was about 70% lower in the first greenhouse, but again, the total yield of tomatoes was almost the same in both greenhouses. The vitamin C content in the fruits grown in the greenhouse with the heat pump was slightly higher compared to fruits grown in the greenhouse with the oil fan heater, but the difference was not significant. However, significant differences in growth and productivity were observed by Baeza *et al.* (2015) in the case of bell pepper cultivation near the PE film sleeves filled with water and placed horizontally in a greenhouse located in Almería (Spain). The ambient temperature in the test greenhouse was almost constantly higher than the temperature in the reference greenhouse. As a result of such cultivation conditions the leaf dry matter production was significantly higher in the reference greenhouse, while the fruit dry matter production was significantly higher in the greenhouse equipped with the water sleeves. The marketable yield of peppers and number of fruits were also significantly higher in favour of greenhouse with heat storage system.

The rock-bed solar powered storage system built below PE tunnel greenhouses was tested in Skierniewice (central Poland). Konopacki *et al.* (2015) observed that during the discharge of the accumulator the decrease of the greenhouse air temperature was slower than during similar periods when the storage system was not used.

The aim of the presented paper is to analyse the pattern of air humidity changes in two high PE tunnel greenhouses used in the cultivation of cucumbers, with one greenhouse additionally equipped with a heat accumulator. For an easy assessment of periods of microclimate conditions considered too dry or too moist, the air humidity is expressed as VPD.

Material and methods

The research was conducted in the Institute of Horticulture in Skierniewice, Poland during the season 2013. The cucumber plants (*Cucumis sativus*, cv. Melen F) were grown in two high polyethylene tunnel greenhouses of 9 m width, 15 m length and 5.15 m total height. The plants were planted in the tunnels on 9 April, with replantation carried out on 15-16 July, and cultivation lasting until 8 October 2013. The construction was made of bent steel pipes, with a single window vent along the whole climatic chamber, and a double pumped PE 150 µm foil cover. The tunnel greenhouses were equipped with shading screens HS 880 (Novavert, Germany) of 60% shading and 52% thermo insulation, covering the tunnel surface and both sides to ground level. The climate was controlled by means of a MasterClim controller (Anjou Automation, France) integrated with internal temperature and RH sensors (located in the middle of the tunnel length at a height of 1.5 m), and external sensors for temperature, RH, sunlight (W/m^2) and luminosity (Lux). The climate controller was regulating the opening of window vents and shading screens. One of the tunnels was equipped with a rock-bed heat collector located below the ground surface (Hołownicki *et al.*, 2014; Konopacki *et al.*, 2014). The rock bed was split into three sections (with individual dumpers for opening the air flow) filled with 31.5-63 mm porphyry breakstone with a total volume of 51.5 m^3 (Konopacki *et al.*, 2015). The charging of the accumulator was conducted during the day by extracting warm air from the top part of the tunnel (above the level of the shading screens) employing a radial fan, which pumped the air through the breakstone (Fig. 1, left). Charging was started when the air temperature between plants (at 1.5 m) exceeded 18°C and the temperature at the tunnel top exceeded the temperature of the accumulator's rock-bed by 4°C. It was stopped when either the air temperature between plants dropped below 18°C, or the difference in the air temperatures between the accumulator inlet and outlet dropped below 4°C. For discharging the accumulator and heating the plants (occurring mainly at night, or in the event of low temperatures) the air was sucked by the same fan, but from between plants. After passing through the warm rock-bed the warmed air was distributed through the perforated pipes along the gutters (Fig. 1, right). The heating of the plants was started when the temperature between plants dropped below 21°C while the accumulator rock-bed was warmer. The heating of the plants was terminated when either the temperature between plants reached 22°C, or the difference in the air temperatures between the accumulator outlet and inlet dropped below 4°C, or the air temperature at the accumulator outlet was lower than the temperature between plants. The temperature was measured using resistance thermometers Pt1000 (with an accuracy of ±0.1°C), and the RH of the air by means of RH sensors SEM161 (Status Instruments Ltd., UK) (with an accuracy of ±2.0% within the range 10-90%). Both parameters were recorded every 2 min by a KSP data logger (DKR-Elektronik, Poland). The VPD values were calculated according to standard ISO 13788: 2012.

The obtained VPD values were divided into four ranges:

- VPD ≤ 0.2 kPa: very high humidity – conditions favouring infection of fungal diseases, and reducing photosynthesis.
- 0.2 < VPD < 0.4 kPa: high humidity – conditions favourable for the survival of fungus pathogens and its development in already infected plants.
- 0.4 ≤ VPD < 1.4 kPa: optimal humidity for plant cultivation.
- VPD ≥ 1.4 kPa: insufficient humidity – conditions unfavourable for water use efficiency (efficiency reduction).

Analyses were presented as percentage shares of cultivation time in separate months for optimal, insufficient and excessive air humidity conditions.

Results and discussion

Higher air temperatures were recorded in the tunnel greenhouse equipped with a heat accumulator when compared to the temperature in the regular tunnel greenhouse. Such a tendency was observed throughout the whole cultivation period. The monthly means were significantly higher for all the investigated months (Table 1). The highest differences were recorded during spring and the lowest during autumn. The difference in April was 2.4°C, while in September and October 0.72°C and 0.70°C, respectively.

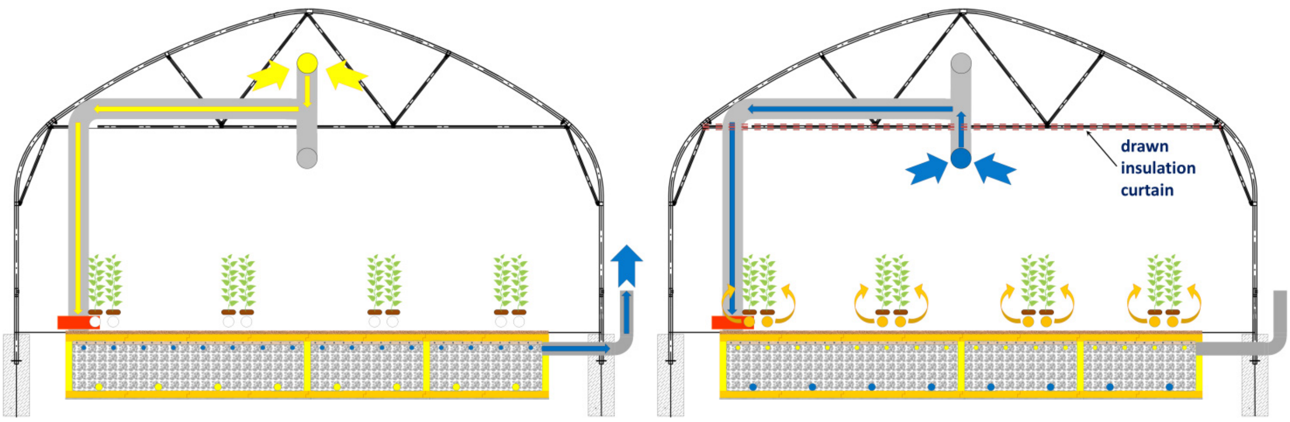

Figure 1. Charging the heat accumulator during a warm day (left) and discharging the accumulator for plant heating during the night or cold day (right).

The change in RH within the tunnel greenhouse brought about by using a heat accumulator does not present, however, such a monotonic pattern during the studied period (Table 1). The use of the accumulator caused an increase in RH by 4.73% in April, and only by 0.35% in May. Later in the season using the heat accumulator resulted in a decrease of RH, but the difference fluctuated between -1.85% and 3.09%.

Regardless of whether the monthly mean RH difference was positive or negative, the daily pattern of hourly mean RH values reveals regular differences between heated and control tunnels (Figs. 2). Although the daily range of RH changes is a normal phenomenon, caused by, among others, a decrease in night temperature, a high transpiration rate during the day and tunnel ventilation, the observed differences in amplitude are inevitably caused by the heat accumulator. Since pattern of changes in monthly RH means is not monotonic, the pattern of monthly VPD means is also irregular. In April and May the VPD means were higher in the control tunnel (Table 2), and in September and October the air was too humid (mean VPD < 0.4 kPa). Although monthly mean differences between the control tunnel and the tunnel with the heat accumulator were rather small, below 80 Pa each month, they were significant. A study of the changes in daily VPD means (Fig. 3, left) reveals that day-to-day changes may be very rapid, from very humid conditions (VPD < 0.4 kPa) to very dry conditions (VPD > 1.4 kPa). Such data, however, does not indicate the real amplitude of VPD changes. The individual, momentary records of VPD reveal that VPD may quickly change from < 0.1 kPa to > 4 kPa (Fig. 3, rigth), and the amplitude of VPD changes is smaller in the tunnel with the heat accumulator almost every day. The mean amplitudes for the whole studied period were significantly different, amounting to 1.83 kPa for the tunnel with the heat accumulator, and 1.58 kPa for the control tunnel.

The period 1-7 May 2013 was characterized by fluctuating weather conditions (Fig. 2, left). The first four days were cloudy with relatively low air temperature (mean daily outdoor temperature ranged from 10.2°C (1 May) to 12.8°C (4 May), but the following days were sunny, with the mean daily

Table 1. Mean air temperature and relative humidity (RH) values for separate investigated months of research.

Month	Air temperature (°C)		Temperature difference[1] (°C)	Relative humidity (%)		RH difference[1] (%)
	Control tunnel	Tunnel equipped with a heat accumulator		Control tunnel	Tunnel equipped with a heat accumulator	
April	15.02	17.42	2.40 f	66.9	71.6	4.73 f
May	19.29	21.17	1.88 e	83.3	83.7	0.35 e
June	21.23	22.60	1.37 d	85.0	82.3	-2.69 b
July	23.01	24.23	1.14 b	73.4	71.3	-2.11 c
August	21.59	22.76	1.17 c	79.8	78.0	-1.85 d
September	15.62	16.34	0.72 a	92.0	89.9	-2.14 c
October	13.69	14.39	0.70 a	93.2	90.1	-3.09 a

[1]Means followed by different letters are significantly different at $p \leq 0.05$ according to Duncan's test

Table 2. Mean vapour pressure deficit (VPD) values for separate investigated months of research.

Month	VPD (Pa)		VPD difference[1] (Pa)
	Control tunnel	Tunnel equipped with a heat accumulator	
April	797.6	769.0	-28.7 a
May	544.8	520.7	-24.1 b
June	494.9	560.0	65.1 f
July	930.4	1003.8	73.4 g
August	680.7	724.2	43.4 d
September	197.0	231.5	34.6 c
October	149.7	205.8	56.0 e

[1]Means followed by different letters are significantly different at $p \leq 0.05$ according to Duncan's test

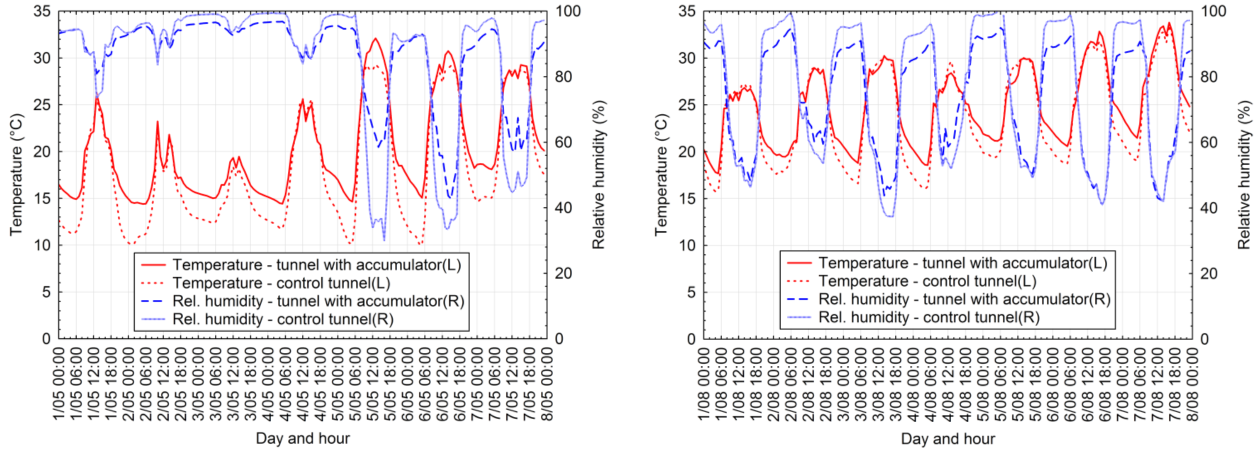

Figure 2. The course of temperature and relative humidity (RH) changes during the periods 1-7 May 2013 (left) and 1-7 August 2013 (right) (hourly mean values).

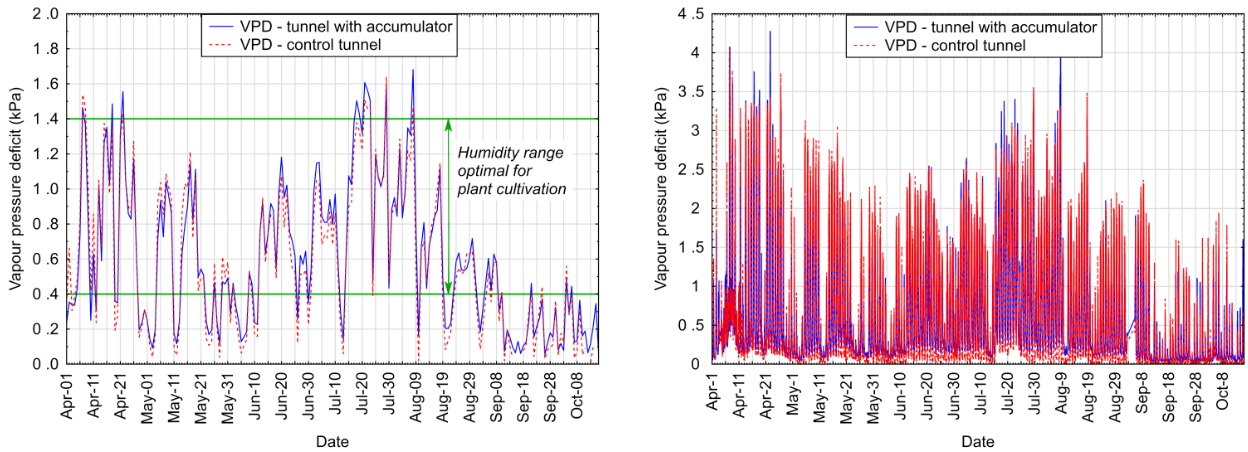

Figure 3. Pattern of air vapour pressure deficit (VPD) changes during the 2013 season. Left: mean daily values from the beginning of April until mid-October. Right: data collected with 2 min intervals from the beginning of April until mid-October.

outdoor temperature rising to between 15.5°C (5 May) and 18.2°C (7 May). During the initial four days the RH level was high in both tunnels, due to the relatively low temperature and restricted tunnel ventilation. The transpiring water was kept inside the tunnels and the moisture level in the air was rising. However, even in such a cold period, the heat released from the accumulator caused an air temperature increase and a RH reduction. Additionally the VPD in the tunnel with the accumulator was higher at night (Fig. 4, left). Such a phenomenon is very favourable for plants, as a higher VPD reduces infection of fungal diseases. The increase in the external temperature and solar radiation during the next few days caused significant differences in the observed day and night air humidity (Fig. 2, left). A very interesting observation was that on 5 and 6 May the daytime RH levels in the control tunnel were distinctly lower, despite the lower maximal air temperatures. The RH decreased to a level below 35%, which is unfavourable for plant physiology due to the air being too dry (Körner & Challa, 2003). During heat accumulator charging, the warmest air is removed from the upper part of the tunnel, and hence the increase in temperature between plants is delayed. This process influences the tunnel ventilation – the window vents are opened later, or opened only partially. Such a change in ventilation influences, in turn, the humidity changes during hot spring and summer days, as smaller amount of dry air flows into the tunnel and air humidity between plants is reduced to a lesser degree than in the tunnel without the heat accumulator. The VPD data confirms (Fig. 4, left) that the heat accumulator also positively influenced the air humidity during the day. The effect of the heat accumulator during both daytime and at night was also observed later in the season, when cucumber plants grew very large and transpired large quantities of water (Figs. 2 and 4, right).

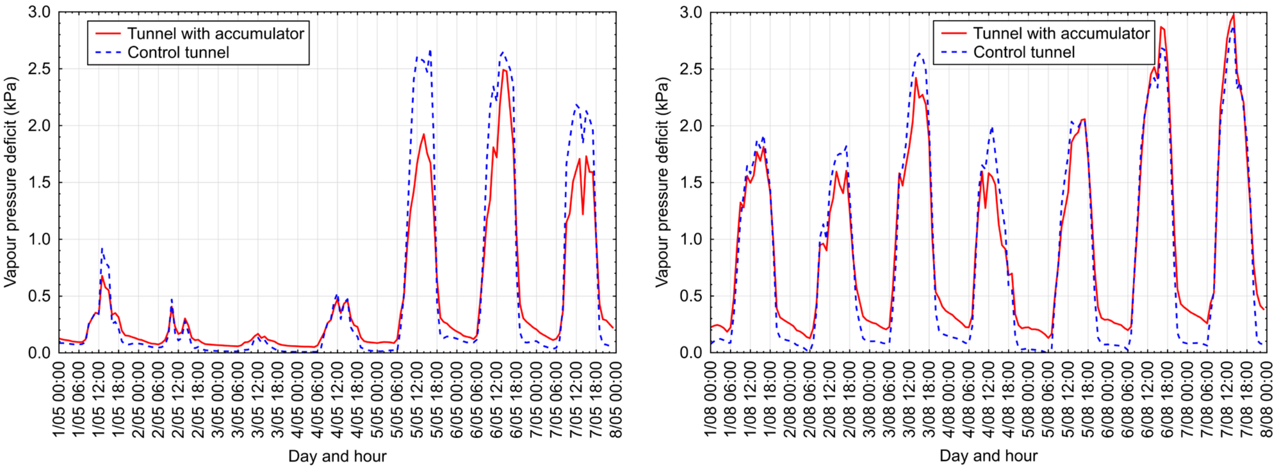

Figure 4. The course of vapour pressure deficit (VPD) changes during the periods 1-7 May 2013 (left) and 1-7 August 2013 (right) (hourly mean values).

When RH and temperature values are converted to VPD one may observe that, in some weather conditions, time of the day, and the way the heat accumulator is working, the VPD often reaches values unfavourable for plants (Figs. 4). For example, on 1 May 2013 the humidity level in both tunnels was optimal for plants for only a few hours (Fig. 4, left). On 3 May the humidity in both tunnels was too high (VPD too low) for the whole night and day. But when the weather condition improved, the VPD increased over the 1.4 kPa level, which is assumed as the threshold for excessively dry air. The course of VPD changes for the demonstrated periods in May and August shows the distinct influence of the heat accumulator on the VPD values in the tunnel. It is especially clear for the days 3, 4, 6 and 7 August (Fig. 4, right), when the VPD in the tunnel equipped with a heat accumulator never dropped below the level 0.2 kPa, which is considered the threshold for excessively moist air.

The analysis of time percentage shares by month for the investigated ranges of VPD clearly displays the direct influence of the heat accumulator on the dehumidification of night air inside the tunnel, and the extension of time periods with the optimal level of humidity (Fig. 5). The dehumidification of night air inside the tunnel equipped with the heat accumulator was clearly observed during spring and summer. The air humidity during April was too high (VPD ≤ 0.2 kPa) for 35.5% of the total time in the control tunnel, and only 22.6% of the total time for tunnel with the heat accumulator. That difference was even higher for May, June, July and August 2013. Such a decrease in humidity at night in the tunnel with the accumulator caused a significant increase in the time when humidity was still high (0.2 kPa < VPD < 0.4 kPa), but not sufficiently high to threaten plant infection by fungus pathogens (Prenger & Ling, 2009). The use of the heat accumulator also reduced the time when very dry conditions (VPD ≥ 1.4 kPa) were recorded. During April such low humidity was observed for only 17.7% of the total time for the tunnel with the heat accumulator, compared to 19.8% of the total time for the control tunnel. Similar differences were observed almost every month during spring and summer, except for July when both tunnels were intensively ventilated, and very dry conditions prevailed for the same time periods. Such results suggest that in order to improve air humidity conditions in the intensively ventilated tunnel, a humidification system should be used during the summer months.

Humidity within the optimal range of VPD was recorded for a longer time in the tunnel with the heat accumulator every month during the cucumber growing season. In April optimal humidity was observed for 25.8% of the total time for the tunnel with the heat accumulator, compared to 23.6% of the total time for the control tunnel. In May the difference was even greater – 19.3% vs. 12.1% of the total time, which means that optimal humidity was recorded for 1 hour and 44 min longer in the tunnel with the heat accumulator, on average every day in May. The heat accumulator additionally caused an increase in the time when air humidity was optimal for growing and yielding plants throughout the remainder of summer, until August (Fig. 5).

Later in the season, when the outdoor air temperature and solar radiation were lower (during September and October), the heat accumulator was not so efficient and the air humidity inside the tunnel was distinctly higher. During the autumn, for a large majority of the time the air in both tunnels was too

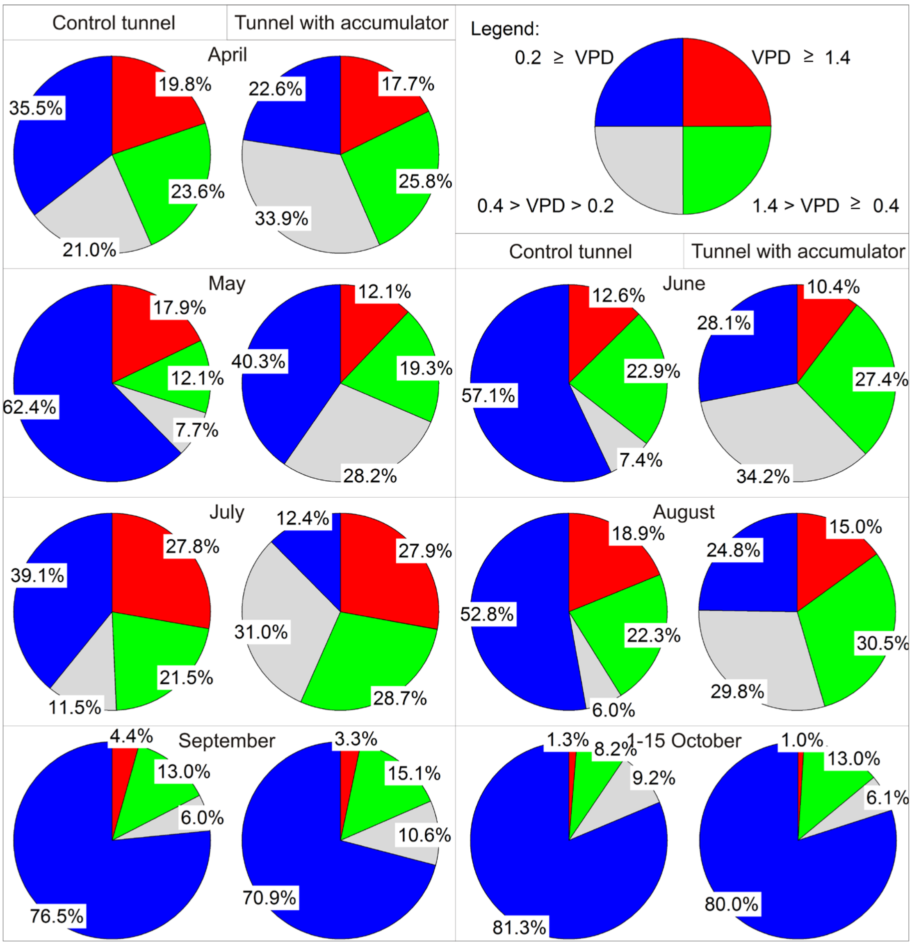

Figure 5. Percentages of time (for separate months from April to mid-October 2013) when air humidity conditions fitted the predefined vapour pressure deficit (VPD) ranges.

humid. The large leaf area of high grown plants resulted in high transpiration, which remained inside the tunnels due to reduced ventilation caused by low temperature.

As conclusions, the acquired VPD pattern of microclimate during cucumber cultivation in a traditional tunnel greenhouse simultaneously compared to that in a tunnel greenhouse equipped with a heat accumulator indicates that the latter ensures better growth conditions for plants.

The higher air temperatures obtained due to use of an accumulator caused lower RH. Periodical reductions of tunnel ventilations allowed longer periods with air humidity within an optimal range. The tunnel equipped with an heat accumulator maintained an optimal level of humidity for a longer period, and significantly reduced the time where the air humidity was too high.

Changing the VPD pattern into one more favourable for plant growth, by employing a heat accumulator from the start of the cultivation season will also result in slower germination of plant diseases and therefore, a reduction in plant protection treatments.

The heat accumulator's influence on plant growing conditions was obtained with an accumulator steering system focused only on the energetic effect. Further research should use the installation not only for the accumulation and reclaim of energy, but also for the optimization of air humidity in the tunnel, *i.e.* taking into account, whether the air humidity is within the optimal range for plant development.

The recorded pattern of VPD during hot summer days also indicates that using an additional humidification system would be advisable.

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