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Study of the vertical temperature profile in a tomato greenhouse equipped with lighting, two screens and a VentilationJet system

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Abstract

The application of Next Generation Growing (NGG, in Dutch "Het Nieuwe Telen") in Dutch greenhouses has resulted in energy savings, accompanied by the extensive use of screens. The latter has affected the control of greenhouse climate which strongly depends on the air and humidity exchange between the top and bottom greenhouse compartment, as they are separated by the screen itself. When the screens are fully deployed an air exchange/mix system (VentilationJet) that blows dry and cold air from the top compartment into the greenhouse can be used to lower the greenhouse air temperature and relative humidity in a controllable way. The effect of this greenhouse climate control equipment use on vertical air temperature profile as well as on energy use was studied in a commercial greenhouse. Effects of artificial lighting, heating with pipes below the crop, activation of vertical fans and air exchange rate were analyzed during the winter of 2018. It was observed that when significant heat input (radiation) at the top of the crop occurred a vertical temperature gradient up to 2°C exists, with the bottom of the crop being colder than the top. This temperature gradient cannot be reduced by using only vertical air circulation fans but it can be minimized by additional heat input at the bottom; this may result in excess heat that has to be removed through either natural ventilation or with the use of VentilationJet when the screens are deployed. During the studied period about a quarter of the daily gas use for heating took place at the same time as the VentilationJet was removing warm and humid air from the top of the greenhouse.

Keywords: air temperature, vertical temperature profile, air mixing systems, microclimate, tomato temperature

INTRODUCTION

Commercial greenhouse climate control is usually based on a number of measured climate data which serve as input to a number rules (if…then), influences and associated settings, that the grower tries to manage in order to achieve the most favorable climate for crop growth and production, when at the same time the applied strategy should not result in unnecessary resource use. Climate homogeneity is also one of the main targets of a greenhouse control system as it is linked to a number of obvious advantages, such as homogenous crop, lesser diseases and potential energy saving. Usually the aforementioned climate data include temperature and humidity measurements collected at a representative point in the greenhouse. Obviously the accuracy of the measurements affects the efficiency of the control. However, despite the accuracy of the measurements obtained by a single sensor, hardly any information is provided about the spatial distribution of these measurements. Previous studies have shown that temperature and humidity variations are common in greenhouses (Balendonck et al., 2014).

The application of different climate control equipment in modern greenhouses strongly affects the climate homogeneity. One of the most representative examples is the air exchange/mix system (VentilationJet) that are commonly used to lower the greenhouse air

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temperature and relative humidity in a controllable way by blowing dry and cold air from the top compartment into the greenhouse when screens are deployed. The use of more than one climate control system at the moment (e.g., heating, artificial lighting, screens and VentilationJet) increases the complexity and makes difficult to predict the local microclimate at different places in the greenhouse. The emergence of wireless sensors allows the collection of more information regarding the climate homogeneity.

Aim of the current study is to investigate how the climate control strategy and especially the use of VentilationJet in combination with other climate control equipment affects the vertical temperature profile in a commercial greenhouse.

MATERIALS AND METHODS

The experiment took place in the facilities of Gardener's Pride, a tomato grower at the north of The Netherlands. The greenhouse where the climate was monitored was built in 2014 and equipped with artificial lights (installed intensity: 120 W m^{-2} providing 200 μmol PAR m^{-2} s^{-1}), double screens (LUXOUS 1347 FR (energy screen) and OBSCURA 9950 FR W (Blackout screen)), rail-pipe (51 mm - 1.17 m pipe m^{-2} greenhouse area) and grow- pipe (51 mm - 0.58 m pipe m^{-2} greenhouse area) heating systems, VentilationJets (capacity 15 m^3 m^{-2} h^{-1}) and lower air circulation fans. In this greenhouse cherry tomatoes ('Juanita') were growing since summer (transplanted in June 2017).

The vertical temperature profile was monitored with the use of five vertically placed ventilated temperature sensors[b] from AgriSensys (The Netherlands). Data were recorded at three locations in the greenhouse on a 5-min frequency for a period of 2 months starting from the end of January 2018. As soon as the effect of VentilationJets and lower air circulation fans was an aim of the study, the sensor's locations were selected to be below a VentilationJet, between and in-line with two VentilationJets and as far away as possible from VentilationJets; from now on the report these three locations are called "Between VJ", "Below VJ" and "No VJ", respectively.

The tomato temperature was also monitored. That was achieved with the use of thermocouples placed inside the tomato fruits and re-placed when a tomato fruit was physically destroyed due to the small hole made to insert the thermocouple. Furthermore, the tomato temperature was monitored with the use of an infrared camera (FLIR A655[c] from FLIR Systems, Inc., Täby, Sweden). Additionally, temperature of bigger tomato fruits was monitored with the use of artificially made tomatoes (SensorTom from HortiMaX, The Netherlands) equipped with temperature sensors (PT1000), with the same physical characteristics real tomatoes; the size of the artificial tomatoes is comparable to the size of a tomato fruit of about 220 g. The tomato temperature measurements took place at the measuring spot between and in line with two VentilationJets ("Between VJ").

RESULTS

During the analyzed period it was found that the air temperature around the top of the crop was on average 0.4°C higher than the air temperature at the bottom of the crop (varying between 0 and 1°C on a daily basis). During the light period (either sun radiation or use of artificial illumination) this temperature difference was almost double on average (0.7°C) when during the dark period the bottom of the crop was warmer by 0.6°C on average. Regarding the homogeneity of the vertical temperature profile, it was not significantly different between the light and the dark period; the average standard deviation of the temperature measured at 5 different heights was found to be 0.4°C. The recorded data are not different than expected; during the light period the main heat input comes either from the sun or from the artificial lights, resulting in higher temperature at the top when during the dark period almost always (at this time of the year) there was heat input from the heating system resulting in warmer bottom than top of the crop.

In order to analyze in more details the effect of climate control actions in combination

[b]Accuracy: 0.4°C at temperature values between 10 and 40°C.

[c]Spectral range: 7.5-14.0 μm, Accuracy: ±2°C or ±2% of reading.

with the weather on the vertical air temperature profile, three different periods are defined within each day and the results of each of those periods are discussed separately.

Air temperature

1. Period with artificial lighting and no sunlight.

This is the period of the day when the artificial lights were used and the screens were deployed. This is the period where this study mainly focuses on, as it is the period when most of the climate control actions take place. Figure 1 (top graph) shows the temperature difference between the top and the bottom of the crop, averaged per day, during the hours when the artificial lights were on, at least one screen was deployed and there was no sun radiation. During the analyzed time and regarding the vertical temperature differences, 5 sub-periods can be distinguished (Figure 1):

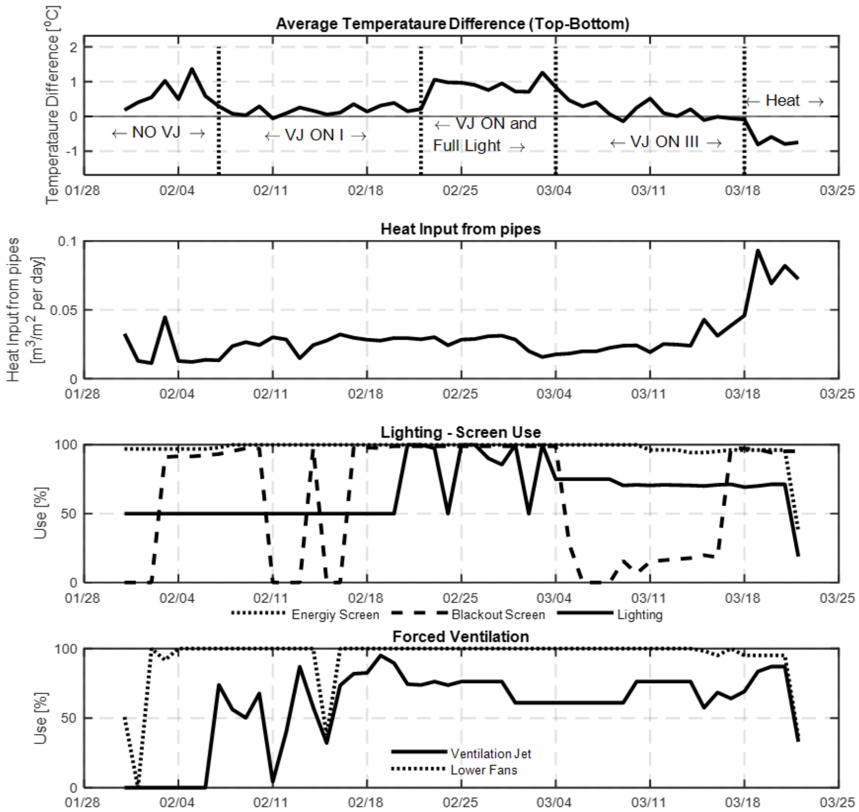

Figure 1. Daily averages of the vertical temperature differences (above) and climate control equipment (heating, lighting, screen use, vertical fans and VentilationJets) during the hours that the lighting was switched on and there was no sunlight.

Sub-period 1: use of only lower ventilator.

First week of February when the temperature difference was high. During that period the air around the top of the crop was on average 0.8°C warmer than the air at the bottom, reaching during some nights values up to 1.5°C. This period is characterized by: use of artificial lights (half of the total capacity), low (except of one day) heat input from the pipes, unfolded screens, no use of the VentilationJets but only the lower air circulation fans were used. It can be concluded that the heat provided by the lights is not homogeneously distributed to the greenhouse in the vertical direction; possibly the resistance of the crop to the air flow plays a significant role on that (especially for the measurements which were recorded by sensors between the plants). Comparing the vertical temperature differences on nights where the lower air circulation fans were used with nights that there were not used (e.g., on February 1 and 2) it can be concluded that the use of the fans does not reduce the vertical temperature differences. A possible reason for that is the resistance of the crop that forces the warm air to move mainly horizontally and not vertically downwards.

Sub-period 2: VentilationJet ON I.

The next two weeks (2^{nd} and 3^{rd} week of February) when the temperature difference between the top and the bottom were minimised. During this period the average temperature difference was less than 0.2°C (from 0 until 0.4°C on a daily basis). During that period the VentilationJets were used and in addition the heat input from the pipes was on average more than double than during the first week of February (estimated on average 23.5 and 11 W m^{-2}, respectively). Apparently the heat input from the top (artificial illumination) and the bottom (heating system) was more balanced resulting in more homogeneous vertical temperature distribution. We can assume that the cold air input from the VentilationJets was quite homogeneously distributed from the lower air circulation fans as there were no big differences in the measured locations closer or further from the VentilationJets. Also, due to density difference the cold air was allowed to move downwards more easily, helping also in a more homogeneous temperature profile.

Sub-period 3: VentilationJet ON and full light.

The last week of February and first 10 days of March when the temperature difference between the top and the bottom was increased again to 0.8°C (on average). During this period the artificial illumination was used at full capacity, resulting in a twice as high heat input at the top of the greenhouse than in the previous days; the heat input at the lower part (heating system) was not significantly different than before. On the other hand, the outside air temperature in period 3 was on average 5°C lower than in period 2 (-5.3 and -0.2°C, respectively) but due to less window opening there was only little additional heat removal from the cold air input (VentilationJets) which was apparently not enough to compensate for the additional heat input from the lights. To provide an order of magnitude of the aforementioned heat fluxes, supposing that in period 3 the cold air input was 2°C lower than in period 2, then that would result in removal of about only 8 W m^{-2} more when the double light intensity adds to the greenhouse energy balance about 30 W m^{-2}.

Sub-period 4: VentilationJet ON III.

The period of 2 weeks starting at March 5 when there was again little air temperature difference between the top and the bottom. The light intensity during that period was set to 75% of the total capacity and additionally one screen was mainly kept folded allowing easier (hot) air removal to the top compartment (above the screens). During that period the average recorded air temperature difference between the top and the bottom was only 0.1°C.

Sub-period 5: heat.

The 5 days of the analyzed period when the bottom of the crop was (on average 0.8°C) warmer than the top. During this period the heat input from the heating system was increased by a factor 4 (compared to period 4) as a result of pipe temperatures of around 50°C. The result of this additional heat input at the bottom was the aforementioned negative temperature difference between the top and the bottom.

Summarizing, it was found out that the use of artificial lights without heat input from the pipes and without the use of VentilationJets results in vertical temperature gradients as the top of the crop remains about 1°C warmer than the bottom. This temperature difference cannot be controlled by the use of only the lower vertical fans, but it can be controlled when both the VentilationJets and the heating system are used. Specifically, when the VentilationJets remove part of the heat from the top of the greenhouse and at the same time almost the same amount of heat is added from the heating system then the temperature distribution over the vertical dimension is very homogeneous. However, a balance between these heat fluxes is needed; it was found that more energy input from the lights (period 3) or from the pipes (period 5) can still result in vertical temperature differences and warmer top or bottom, respectively.

2. The daytime period (with sun radiation).

During the light period, the air around the top of the crop was almost always warmer than around the bottom. It can be concluded that the heat supplied by the sun and the lamps contributes relatively more in heating up the top rather than the bottom part of the greenhouse air; taking into account that a well-developed tomato canopy (with leaf area index 3.5 m^2 m^{-2}) absorbs more than 90% of the direct sun radiation the aforementioned result was expected. Until half February, when the days were relatively cold, short and dark smaller vertical temperatures differences were recorded. The temperatures differences were slightly higher during the second half of February and in March there were both days with high and days with low vertical temperature differences.

During the light period a strong relationship between the amount of heat input and the vertical temperature differences was observed; the more heat input from the rail and grow-pipes the less temperature differs between the top and bottom of the crop, mainly due to warmer bottom part. This is even more clear in March when during the days with lower heat input from the pipes the vertical temperature difference was much higher than during the days with more heat input from the pipes (Figure 2). Of course the days when heat input from the heating pipes was realized were also the most dark days so the effect of sun radiation also affects the vertical temperature distribution. It can be roughly concluded that between very dark days (<2 MJ m^{-2} daily global radiation sum) and days when a radiation sum of about 17 MJ m^{-2} day^{-1} was achieved, the vertical temperature difference increases by about 0.2°C (top warmer) per 1 MJ m^{-2} additional radiation (Figure 2).

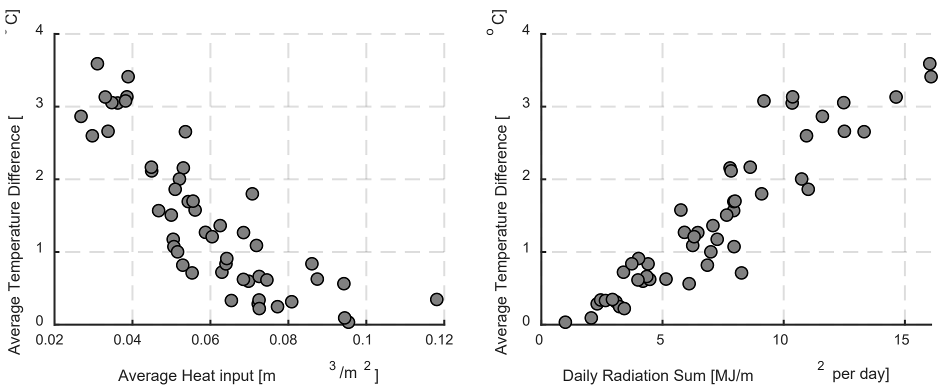

Figure 2. Average daily vertical temperature differences (top-bottom) during the light period versus the heat supply of the heating system (left) and the daily radiation sum (right).

Concluding, on sunny days it should be expected that a vertical temperature gradient will exist. If one wants to minimise these differences, it was observed that this is well possible by using the heating system; if the additional heat supply results in excess of heat which has to ventilated out it is expected that the increased ventilation rate will help toward a more homogeneous vertical temperature profile, but it has to evaluated whether this is preferable in comparison to other side effects such as higher CO_2 losses.

3. The dark period.

A dark period of about 6 h, from 18:00 to 00:00 was usually realized in Gardener's Pride during the analyzed period. During the dark period, the heating system was almost continuously used in order to achieve the temperature set-point. This resulted almost always in negative vertical temperature differences, or in other words, warmer bottom than top of the crop. Taking into account that the windows were always a bit open during this period, the inlet of cold air from outside (up to 15°C colder than the greenhouse air) in combination with the heat input from the heating system created the described difference. The vertical temperature profile tends to homogenize due to buoyancy but as soon as the heat input at the bottom continues and the cold inlet continues as well the difference was maintained. The vertical temperature difference tended to be higher (warmer bottom) when the outside air temperature was lower (e.g. at the end of February and beginning of March).

Tomato temperature

It was observed that the fruit temperature was usually following very closely the air temperature. The cherry tomato temperature hardly differed from the air temperature (Figure 3) and even during the heating up period in the morning and the cooling down period in the afternoon, only slight delays between the air and tomato temperature changes were observed. More specifically, in the morning, the tomatoes were heated up from the sun slightly faster than the air and in the afternoon they were cooling down a few minutes slower than the air. During the day period, the tomato temperature was very close to the air temperature; only few times on sunny days the tomato temperature exceeded air temperature (Figure 3). During the dark period the tomato temperature tended to be slightly higher than the air temperature mainly because the tomatoes cooled down a bit slower than the air. Finally, during the period with the artificial lights, the tomatoes maintained at slightly higher temperature than the air. On a 24-h basis, the average tomato temperature was about 0.12°C higher than the average air temperature.

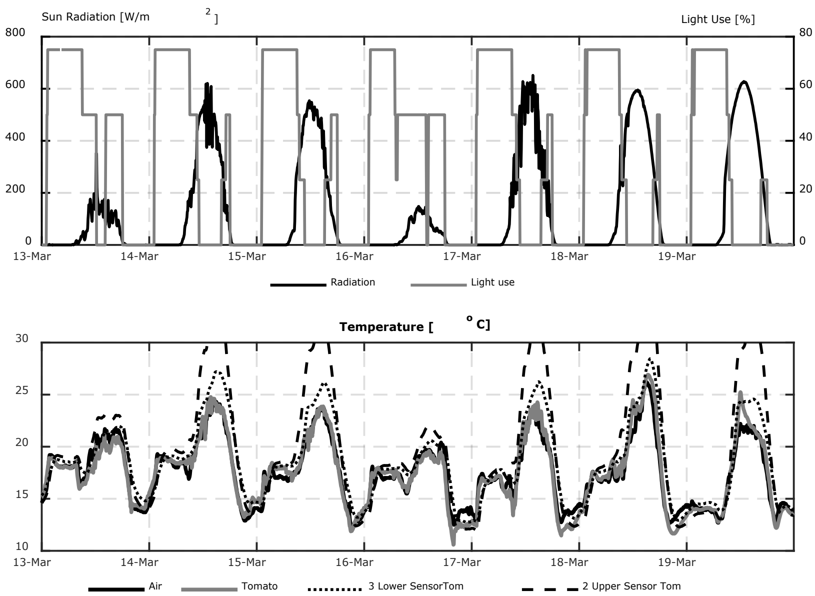

Figure 3. Solar radiation intensity and lighting (above) and air, real (cherry) tomato and artificial (large) tomato (lower SensorTom) temperature during one week in March 2018.

In general, there were no significant differences recorded in the tomato temperature in different heights; the tomato temperature followed the air temperature and when the air temperature was similar in different heights, the same happened with the tomato temperature.

The outcome was quite different for the artificial tomato, which showed significant delays in warming up and cooling down in comparison with the greenhouse air temperature (and the real (cherry) tomato temperature). Obviously, there is a strong effect of the tomato size (and so heat capacity) on the time needed to follow the climate conditions' changes.

Additionally, during sunny days the temperature of the artificial tomato was up to 5°C warmer than the air temperature when the real (cherry) tomato temperature hardly differed more than 1°C from the greenhouse air temperature. Additionally, during those days there was a big temperature difference between the top 2 and lower 3 artificial tomatoes, demonstrating the effect of direct sun radiation on tomato temperature (Figure 3).

DISCUSSION AND CONCLUSIONS

A lot of data were gathered as part of the current research in order to make as clear as possible how the applied climate control actions affect the vertical temperature profile as well as whether additional energy input results in more favorable climate for crop growth. In general, it can be concluded that when significant heat input (radiation) at the top of the crop takes place it can be expected that the bottom of the crop will remain colder; this was clear both during the sunny period of the day and also during the dark illuminated period. These temperature differences were found to exceed 3°C during sunny days and 1°C during the illuminated dark period. In that case, it was found very difficult to create vertical air movement capable to transfer the heat from the top to the bottom of the crop. As a result the use of only the lower vertical circulation fans had no effect on the vertical temperature profile. The vertical temperature gradient becomes smaller by additional heat input at the bottom of the crop. It was found that during dark days when more intense use of the heating system took place, the temperature at the top and bottom were similar. Similar results were found during the illuminated dark period when the heating system was used more. In that case the VentilationJets were used to remove around the top of the crop almost as much energy as added by the heating system resulting in a homogeneous vertical temperature profile.

During the months when the VentilationJets were used about 26% (about 2 m^3 gas) of the total daily use of the heating system took place at the moments that the artificial lights and VentilationJets were used. The amount of heat that was removed from the greenhouse by the VentilationJets equalled more or less the amount of heat added by the heating pipes. As a consequence a homogeneous vertical temperature profile was created. In other words, a more homogenous vertical temperature profile can be created by using more heat input from the pipes and more heat release by the VentilationJet. From an energy point of view this is not clever since theoretically, it looks like the same net energy balance could have been achieved almost without the heat removal from the VentilationJets and without the heat input from the heating system at the same time.

However, a more detailed observation of the relative humidity values (which was reaching or exceeding the maximum acceptable limits for growth and production of high quality tomatoes in greenhouses) during the period when the screens were deployed, makes clear that stopping the use of the VentilationJets without any other changes to the greenhouse equipment (screen type) or climate control (e.g., screen position, lighting, temperature set-point) would result in big problems due to supra-optimal humidity levels (Figure 4).

Summarized the heat input from the pipes was used with the aim to lower the relative humidity. As a result the surplus of heat and humidity were removed by the VentilationJets and the vertical temperature profile was influenced both by the pipe heating and VentilationJets.

Additionally, scientific research has shown that for the same air temperature around the top of the crop, the presence or not of vertical temperature gradient (so lower air temperature around the bottom of the crop or maintaining the same temperature, respectively) has minimum effect on crop growth and fruit yield as most physiological processes such as assimilates production and partitioning are not affected (Qian et al., 2012, 2015).

Summarizing, the current research has shown in details how climate control actions affect the vertical air temperature gradient and what the (energy) cost is to maintain a homogeneous temperature over the vertical dimension. It has been also explained when and how the applied by the grower climate control approach which can be characterized as a “high energy input-high energy output” approach, results in a homogeneous vertical temperature profile. It is a bit beyond the scope of the current research to examine whether and how much a homogeneous temperature distribution favors more crop growth and yield in comparison to a vertical temperature gradient, but based on published research data it can be noted that the vertical temperature gradients within certain limits will not have significant negative impact on crop growth only on fruit growth rate and size. However, it was also shown that even if the expected benefits in terms of crop growth and yield are not a strong argument for maintaining the applied climate control approach, the high demand for dehumidification does not allow big changes in the aforementioned strategy, unless an alternative way for dehumidification becomes available.

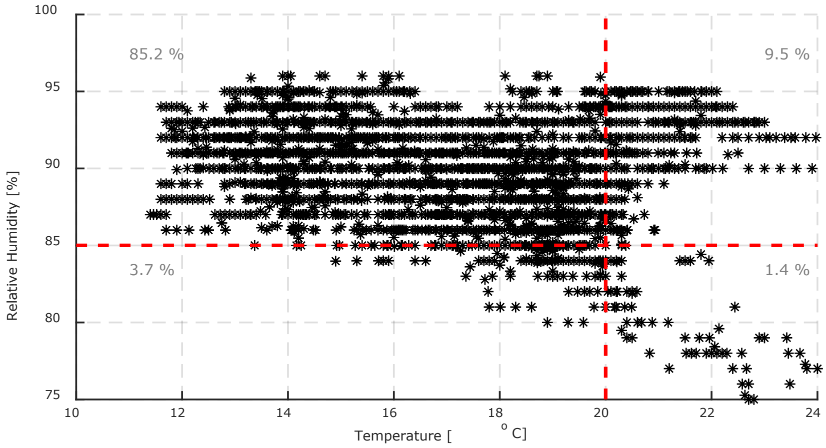

Figure 4. Greenhouse climate (air temperature and relative humidity) during the period that the VentilationJet was used.

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