Thermal Energy Use in Greenhouses

The Influence of Climatic Conditions and Dehumidification

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Cover: Tomato greenhouse.
(photo: K. Maslak)

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Abstract

In the North European greenhouses, energy use for climatization accounts for a significant share of the operational costs. Air temperature and humidity are important factors whose control is crucial for assuring high productivity and limited use of energy.

The objective of this thesis was to examine the use of thermal energy in greenhouses and to investigate the impact of a number of climate parameters on that use. A specific goal was to compare the measured use of energy for heating with the values simulated employing a model developed in Powersim software and, by means of the model, to determine the amount of energy necessary for dehumidification of a tomato greenhouse. Another specific goal was to employ the experimentally obtained performance values for a rotary heat exchanger to estimate the potential energy savings when heat exchanger is used for dehumidification of a greenhouse.

Indoor and outdoor climate data were collected in three greenhouses located in southern Sweden, two with tomatoes and one with ornamental plants. The use of thermal energy in a tomato greenhouse was first measured and then modelled in Powersim for different levels of transpiration, i.e. for a leaf index area (LAI) of 3.5 and 4.0 m^2 m^{-2}. The impact of wind under no-sunlight conditions and at different outdoor temperatures was investigated. The performance of the heat exchanger operating at high humidity levels was tested in a series of measurements.

The study showed that the use of thermal energy in greenhouses with tomatoes was significantly higher than in the greenhouse with ornamental plants. Further, the amount of energy used increased together with the wind speed. The reduction of the wind speed by 50% could result in energy savings of 4-10%. The use of thermal energy as obtained in the Powersim simulations was fairly similar to the measured values, especially when the modelling was for higher transpiration levels. However, it was concluded that further work on the model is needed. The simulations indicated that 23-29% of thermal energy in a greenhouse was used for dehumidification purposes. It was experimentally shown that thermal and moisture efficiencies of the heat exchanger employed in the study were about 70% and 45%, respectively. Further, it was found by modelling that the usage of such a heat exchanger in the investigated greenhouse resulted in the energy savings of 15-17%.

Keywords: greenhouses, energy use, humidity, dehumidification, modelling

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Dedication

Dla Rodziców – za miłość, wsparcie i pomoc w każdym momencie mojego życia.

Science never solves a problem without creating ten more.
George Bernard Shawn

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Maslak, K. & Nimmermark, S. (2014). Thermal energy use in three Swedish greenhouses – the outdoor temperature-dependent variation and the influence of wind speed under no-sunlight conditions. *Agricultural Engineering International: CIGR Journal,* 16(3), 43-54.

II Nimmermark, S. & Maslak, K. (2014). Measured energy use in a greenhouse with tomatoes compared to predicted use by a mechanistic model including transpiration. *Agricultural Engineering International: CIGR Journal.* (Accepted 2014-11-28).

III Maslak, K. & Nimmermark, S. (2015). Modelling and simulation of thermal energy use in a greenhouse – dehumidification by ventilation and heat exchange. (Manuscript).

Paper I and II are reproduced with the permission of the publisher.

The contribution of Katarzyna Maslak to the papers included in this thesis was as follows:

I Participated in planning the study, processed and analysed the data and wrote the paper in collaboration with the co-author.

II Analysed the data together with the co-author.

III Participated in planning the study and collection of data, processed and analysed the data and wrote the manuscript in collaboration with the co-author.

Nomenclature

Abbreviations

COP	Coefficient of performance
RH	Relative humidity [%]
PAR	Photosynthetically active radiation

Latin symbols

A	Area [m^2]
C	Condensation rate [$kg_{water}\ m^{-2}\ s^{-1}$]
c_i	Indoor concentration of water vapour [$kg\ m^{-3}$]
c_o	Outdoor concentration of water vapour [$kg\ m^{-3}$]
C_p	Specific heat [$J\ kg^{-1}\ °C^{-1}$]
$C_{p\ av}$	Average specific heat capacity of water entering/leaving the boiler [$kJ\ kg^{-1}\ °C^{-1}$]
dq/dt	Change of humidity [$kg_{water}\ m^{-3}\ s^{-1}$]
e_a	Actual vapour pressure [kPa]
E_C	Energy transferred through greenhouse cover [$W\ m^{-2}$]
E_H	Energy added by greenhouse heating [$W\ m^{-2}$]
E_L	Energy lost by air leakage [$W\ m^{-2}$]
e_s	Saturation vapour pressure [kPa]
E_{soil}	Evaporation from the soil [$kg_{water}\ m^{-2}\ s^{-1}$]
E_S	Energy added by solar radiation [$W\ m^{-2}$]
E_{ST}	Energy stored in a greenhouse [$W\ m^{-2}$]
E_V	Energy lost by ventilation [$W\ m^{-2}$]
F	Water added through humidification [$kg_{water}\ m^{-2}\ s^{-1}$]
L_V	Latent heat of vaporization of water [$J\ kg^{-1}{}_{water}$]
N	Infiltration rate [s^{-1} or h^{-1}]
P_{latent}	Latent heat loss [$W\ m^{-2}$]
$P_{sensible}$	Sensible heat loss [$W\ m^{-2}$]
q	Concentration of water vapour in the air [$kg_{water}\ m^{-3}$]

q_{solar}	Solar radiation [W m^{-2}]
Q	Heat loss due to conduction, convection and radiation [W]
Q_i	Heat loss due to infiltration [W]
Q_t	Thermal energy [kJ]
Q_v	Water removed through ventilation and air leakage [kg_{water} m^{-2} s^{-1}]
T_{db}	Dry bulb temperature [K]
t_i	Indoor air temperature [°C]
t_{intake}	Temperature of the intake air [°C]
t_o	Outdoor air temperature [°C]
t_{return}	Temperature of the return air [°C]
T_s	Surface temperature [K]
t_{supply}	Temperature of the supply air [°C]
T_{wb}	Wet bulb temperature [K]
TR	Transpiration rate of the crop [kg_{water} m^{-2} s^{-1}]
U	Heat transfer coefficient [W m^{-2} $°C^{-1}$]
V	Greenhouse volume [m^3]
V_{vent}	Air exchange through the openings [m^3 s^{-1} m^{-2}]
V_w	Volume of water [m^3]
W_i	Humidity ratio of the indoor air [kg_{water} kg_{air}^{-1}]
W_o	Humidity ratio of the outdoor air [kg_{water} kg_{air}^{-1}]
x	Moisture content in the air [kg_{water} kg_{air}^{-1}]
x_{intake}	Moisture content in the intake air [kg_{water} kg_{air}^{-1}]
x_{return}	Moisture content in the return air [kg_{water} kg_{air}^{-1}]
x_{supply}	Moisture content in the supply air [kg_{water} kg_{air}^{-1}]

Greek symbols

ΔT_w	Difference between the temperature of water leaving/returning to the boiler [°C]
ε	Emissivity of the surface [-]
η_t	Temperature efficiency of a heat exchanger [%]
η_x	Moisture efficiency of a heat exchanger [%]
ρ_{air}	Density of greenhouse air [kg m^{-3}]
ρ_w	Density of water [kg m^{-3}]
σ	Stefan-Boltzmann constant [W m^{-2} K^{-4}]
Φ_{rad}	Energy flux density [W m^{-2}]

Definitions

COP	Coefficient of performance of a heat pump is a ratio between the heat output (from the condenser) and the power supplied (to the compressor).
Global radiation ($W\ m^{-2}$)	Solar radiation that reaches the Earth's surface on a horizontal plane. It can be split into direct solar radiation, i.e. radiation that after going through the atmosphere strikes the Earth directly, and diffuse solar radiation, i.e. radiation that before striking the Earth is scattered and reflected by molecules and particles contained in the atmosphere.
Infiltration rate ($N,\ h^{-1}$)	The number of greenhouse air exchanges in a unit of time.
Net radiation ($W\ m^{-2}$)	A sum of net shortwave radiation and net longwave radiation, according to the formula: Net radiation = $(S_{in} - S_{out}) + (L_{in} - L_{out})$, where S_{in} and S_{out} stand for incoming and outgoing shortwave radiation, and L_{in} and L_{out} designate incoming and outgoing longwave radiation.
PAR	A spectral range of solar radiation with wavelengths between 400 and 700 nm that can be used by plants as a source of energy for the process of photosynthesis.

Relative humidity (RH, %)	A ratio between the actual vapour pressure (e_a, kPa) (the amount of water vapour in a volume of air) and the saturation vapour pressure (e_s, kPa) (the maximum amount of water vapour that could be contained in the air), at any given temperature and pressure, expressed in %.
Stefan-Boltzmann law	$\Phi_{rad} = \varepsilon \cdot \sigma \cdot T_s^4$, where Φ_{rad} (W m^{-2}) denotes the energy flux density, ε (-) is the emissivity of the surface, σ is the Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-8}$ (W m^{-2} K^{-4}) and T_s (K) stands for the surface temperature. The emissivity factor has a value in the range of 0 – 1 (ε = 1 for black bodies).

1 Introduction

In greenhouses large amounts of vegetables can be produced without the use of soil on a very limited area facilitating the supply of food to the world's growing population. However, in order to maximize the yield, to obtain crops of high quality and to decrease the use of energy, optimal climatic conditions have to be assured (Dieleman *et al.*, 2006; Elings *et al.*, 2005). Among the environmental parameters that have to be carefully controlled are light intensity, CO_2 concentration, temperature and humidity. At northern latitudes, greenhouse climate control requires thermal energy supply during a large part of the year. Reducing the use of energy is relevant both from a sustainability perspective, as it helps to decrease the fossil fuel related emissions of greenhouse gases and to preserve non-renewable natural resources, and from an economic point of view of a grower.

Climate factors are dependent on each other and in some cases even a small change of one of them may trigger the change of another one. Hanan (1998) pointed out that for each environmental parameter, important for the greenhouse climate control, subdivisions are possible. The temperatures that can be used for control are those of the indoor and outdoor air, of the crop, of the root zone and of the inlet and return water in the heating system. As to the humidity, both indoor and outdoor values are measured. The amount of solar radiation influencing the climate inside the greenhouse can be considered for control in terms of global radiation, net radiation and photosynthetically active radiation (PAR). Finally, the level of CO_2 can be subdivided into the indoor and the outdoor values. As it is shown, there is a large variety of factors affecting the use of energy in greenhouse. The key issue is to identify the importance of these factors and to find the measures that allow for decreasing the consumption of energy.

1.1 Objectives of the thesis

The general aim of this licentiate thesis was to:

Study the use of thermal energy in greenhouses, investigate how different climate parameters influence that use and through that identify the energy conservation measures.

The specific objectives of the thesis reported in the included papers were to:

- Quantify and analyse the use of thermal energy in commercial Swedish greenhouses (Papers I, II, III).
- Investigate the use of thermal energy at higher outdoor temperatures (Paper I).
- Study how one of the outdoor climate parameters, the wind speed, affects the use of thermal energy at different outdoor temperatures and under no-sunlight conditions (Paper I).
- Develop a Powersim model that can be used for predicting the use of energy in greenhouses (Papers II, III).
- Compare the measured use of thermal energy in a greenhouse with the values modelled in Powersim software (Papers II, III).
- Determine the amount of energy required for dehumidification of a greenhouse (Paper III).
- Experimentally determine the performance of a non-hygroscopic rotary air-to-air heat exchanger (Paper III).
- Calculate, using the Powersim model, the energy savings that may be obtained when using a heat exchanger and mechanical ventilation for dehumidification (Paper III).

2 Energy use in greenhouses

The supplied thermal energy is used in greenhouses for keeping both the indoor temperature and the humidity of the air within a desired range. Besides that, the energy in the form of electricity is needed to drive equipment such as pumps, fans, etc. Furthermore, depending on the crop type and the geographical location of the greenhouse, it may be required to use artificial lights. At the northern latitudes, the application of artificial lighting allows for extending the growing season. In many cases a by-product of thermal energy generation is carbon dioxide which after the purification of the exhaust gas can be used to increase the rate of photosynthesis and subsequently to enhance the plant growth.

In the light of the targets adopted during the conference in Kyoto, i.e. targets concerning the limitation of emissions of greenhouse gases by the participating Parties (UNFCCC, 1997), and considering the increasing energy prices it is highly important to implement measures aiming at the reduction of energy use. It is beneficial to decrease the use of fossil fuels and to replace them by more environmentally friendly renewable energy sources. Nowadays, a wide range of energy sources is available for use in greenhouses. Except for fossil fuels, including natural gas, fuel oil and coal, various alternative energy sources are being employed: biofuels, solar, geothermal and wind energy, waste heat and electricity. Heat can be also produced by cogeneration systems (combined heat and power – CHP) or supplied by heat pumps extracting the energy from the air, ground or water (Hanan, 1998).

2.1 Energy balance

Heat is added to the greenhouse by the heating system (E_H) and by the incident solar radiation (E_S), whereas lost due to the ventilation (E_V), air leakage (E_L) and heat transfer through the greenhouse cover (E_C). Some heat energy is stored in the greenhouse cover, soil and various greenhouse components (E_{ST}). All the energy values are expressed in W m^{-2}. The energy balance equation can be written in the following way (Fernández & Bailey, 1992):

$$E_H + E_S - E_V - E_L - E_C - E_{ST} = 0$$

When it comes to the energy that is lost in the process of ventilation and due to air leakage, two types of losses are considered – latent and sensible ones.

The latent heat loss due the ventilation (P_{latent}, W m^{-2}) can be calculated by means of the following formula (Campen *et al.*, 2003):

$$P_{latent} = L_v \cdot V_{vent} \cdot (c_i - c_o),$$

where L_v (J kg^{-1}) is the latent heat of vaporization, V_{vent} (m^3 s^{-1} m^{-2}) is the air exchange through the openings in the greenhouse cover and c_i and c_o (kg m^{-3}) represent the concentrations of water vapour indoors and outside the greenhouse, correspondingly.

The sensible heat flux ($P_{sensible}$, W m^{-2}) can be expressed using the following equation (Campen *et al.*, 2003):

$$P_{sensible} = C_p \cdot \rho_{air} \cdot V_{vent} \cdot (t_i - t_o),$$

where C_p (J kg^{-1} °C^{-1}) is the specific heat of the air, ρ_{air} (kg m^{-3}) is the density of the air, V_{vent} (m^3 s^{-1} m^{-2}) is the air exchange through the openings and t_i (°C) and t_o (°C) are the temperatures of the air inside the greenhouse and outdoors.

Heat exchanges in the greenhouse are presented in Figure 1. In general, thermal energy is transported by three different mechanisms: conduction, convection and radiation, alone or in combination.

2.1.1 Conduction

Heat is transferred between molecules of bodies or between bodies having different temperatures and being in a direct contact with each other. This means that energy is transported through a medium, either solid or fluid, that is at rest (Bot & van de Braak, 1995).

In greenhouses, the process of conduction occurs through the soil/floor (heat is transferred from the surface to the deeper layers), and through the greenhouse cover.

2.1.2 Convection

Heat is transferred by a flowing fluid, either gas or liquid. Convection can be either forced, when the movement of the air is induced by some kind of an external device (e.g. a fan or a pump), or natural, when the air flow is caused by the differences in the density (resulting from the temperature gradient).

When it comes to a greenhouse, heat is transported by convection between the indoor air and various greenhouse components, including the cover, plants, floor and the heating pipes, and between the outdoor air and the external surface of the greenhouse cover.

2.1.3 Radiation

Energy in the form of electromagnetic radiation is transported between two bodies following the Stefan-Boltzmann law (see Definitions).

The energy that is emitted by the object depends both on the surface characteristics and on the temperature of that object. If the surface temperature is low, then also the amount of the energy emitted is small (and increases together with the increasing temperature). In order to be converted into thermal energy, radiant energy has to be absorbed by some body.

As it can be seen in Figure 1, in the greenhouse, diffuse thermal radiation comes, among others, from the internal surface of the cladding, from the floor surface, from the plants and from the heating system (Abdel-Ghany & Kozai, 2006).

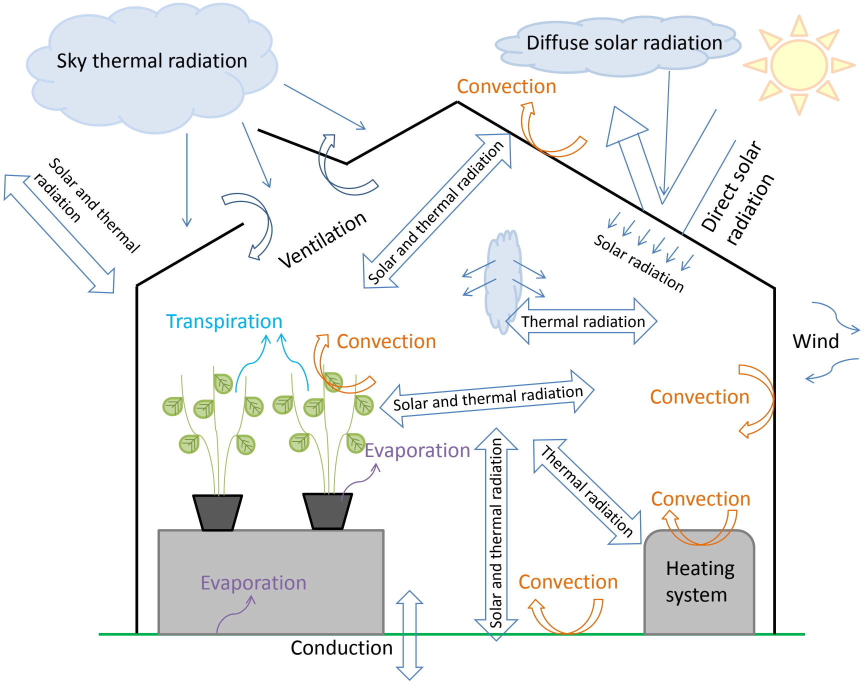

Figure 1. Heat exchanges between the components within the greenhouse and the outside environment (adapted from Abdel-Ghany & Kozai, 2006).

Solar radiation incident on the greenhouse is either absorbed by various greenhouse components, including the cover, plants, soil and water vapour, or lost to the outside (Abdel-Ghany & Al-Helal, 2011). As to the radiation lost to the outside, some portion of solar energy is reflected by the greenhouse cover and some, after being transmitted to the interior but not being absorbed, is reflected by the indoor components. A part of solar energy that becomes reflected by the indoor surfaces is not lost – it is again reflected or absorbed, this time by the inner surface of the cover, and thus does not leave the greenhouse.

Among the factors influencing the amount of solar energy that is transmitted through the greenhouse cover and reaches the plants are: a) the type of the structure and cladding materials, b) the orientation of the greenhouse, c) the shape and the angle of the roof and d) the position of the indoor equipment (Castilla, 2013).

The amount of heat (Q, W) that is lost through the greenhouse cover and the greenhouse floor due to the processes of conduction, convection and radiation can be expressed by means of the following formula:

$$Q = U \cdot A \cdot (t_i - t_o),$$

where U ($W\ m^{-2}\ °C^{-1}$) is the overall heat transfer coefficient, A (m^2) is the area of the greenhouse cover or floor, t_i (°C) is the temperature of the greenhouse air and t_o (°C) is the ambient temperature.

The amount of heat that is lost due to the process of air infiltration (Q_i, W) is given by the following equation (ASAE, 2003):

$$Q_i = \rho_{air} \cdot N \cdot V \cdot [C_p \cdot (t_i - t_o) + L_v \cdot (W_i - W_o)],$$

where ρ_{air} ($kg\ m^{-3}$) denotes the density of the indoor air, N (s^{-1}) is the infiltration rate, V (m^3) is the volume of the greenhouse, C_p ($J\ kg^{-1}\ °C^{-1}$) stands for the specific heat of the greenhouse air, t_i and t_o (°C) are the temperatures of the inside air and of the outside air, correspondingly, L_v ($J\ kg^{-1}{}_{water}$) is the latent heat of vaporization of water and W_i and W_o ($kg_{water}\ kg_{air}^{-1}$) are the humidity ratios of the air – inside and outside, respectively.

Examples of infiltration rates (expressed as a number of air exchanges per hour) corresponding to various types of glazing materials and to the condition of these materials can be found in Table 1.

Table 1. *Infiltration rates for different covering materials and different types of construction (adapted from ASAE (2003)).*

Material and construction	Infiltration rate N (h^{-1})
New construction	
Double-layer plastic film	0.75 – 1.5
Glass or fiberglass	0.50 – 1.0
Old construction	
Glass, good condition	1.0 – 2.0
Glass, poor maintenance	2.0 – 4.0

2.2 Energy use for heating

Traditional fuels used for heating of greenhouses are fossil fuels, i.e. oil, gas and coal. Due to environmental considerations and economic factors, e.g. governmental taxes, a change to renewable sources such as biofuels is nowadays on its way. Besides biofuels also a number of other energy sources are considered. Some studies investigating the use of waste heat from power plants or industrial processes have been performed (Andrews & Pearce, 2011; Pietzsch & Meyer, 2008; Rotz & Aldrich, 1979). The use of solar energy is another environmentally friendly option (Bargach *et al.*, 2000; Bot *et al.*, 2005; Kürklü *et al.*, 2003). Ozgener (2010) investigated a greenhouse heating system consisting of a solar-assisted geothermal heat pump combined with a small wind turbine. Tong *et al.* (2010) studied the performance of air-to-air heat pumps extracting heat from the ambient air. Three hybrid heating systems, using solar energy, a heat pump and cogeneration, were studied by García *et al.* (1998).

2.3 Energy use for dehumidification

In order to ensure that the relative humidity is maintained at a desired level both heating and ventilation are commonly used. Dehumidification is especially important in well-insulated greenhouses, in which the process of condensation on the cover is greatly reduced (Campen *et al.*, 2003). The energy savings obtained thanks to good insulation may be diminished if traditional ventilation is being practiced. In such a case, the warm and humid greenhouse air is replaced by colder and less humid air from outside. Thus, not only the humidity but also the temperature is reduced. If the temperature drops to a level that is below the optimal value for the growth of plants, the heating system has to be used. Even though this solution makes it possible to regulate the indoor conditions it is also associated with an increased energy use and with higher operating costs.

Table 2 includes the summary of some different methods used for dehumidification.

Table 2. *Dehumidification methods used in greenhouses.*

Dehumidification method	Working principle	Reference
By natural or mechanical ventilation and heating	The warm and humid greenhouse air is exchanged with the colder and less humid outdoor air through the vents in a greenhouse cover. Heating is used to increase the temperature of the indoor air when necessary.	Campen *et al.* (2009), de Halleux & Gauthier (1998)
By mechanical ventilation, heating and a heat exchanger	Humid greenhouse air is exchanged with drier outdoor air. The heat exchanger makes it possible to recover heat from the exhaust air and thus to increase the temperature of the air supplied to a greenhouse. When necessary, heating is used to additionally increase the temperature of the greenhouse air.	Campen *et al.* (2003)

Table 2. *(continued)*

Dehumidification method	Working principle	Reference
By mechanical ventilation, heating and the use of screens	Mechanical ventilation can be combined with using thermal screens. In such a case, less dry outdoor air is injected near the greenhouse floor and forces the more humid greenhouse air to pass through the screen.	
By condensation on a cold surface, e.g. a cold water fan coil or finned pipes	Humid and warm greenhouse air is blown through a coil that is cooled by water, e.g. ground water). As a result, the air cools down and the water vapour contained in it condenses on the coil.	Campen & Bot (2002), Campen *et al.* (2003), Vallières *et al.* (2014)
By a cold water curtain	The condensation of moisture contained in the greenhouse air occurs at the surface of a water curtain in which droplets are generated by special nozzles. The curtain generates a strong flow of air and through that cools the greenhouse air.	Huttunen (2011), Vallières *et al.* (2014)
By absorption by a desiccant	Desiccants (hygroscopic substances), either solid or liquid, have a strong affinity for water and thus when the greenhouse air gets into contact with them, its moisture is absorbed.	Campen *et al.* (2003), Longo & Gasparella (2012)
By a heat pump	Humid and warm greenhouse air passes through the evaporator and is cooled down below its dew point. As a result, water vapour contained in the air condenses.	Boulard *et al.* (1989), Chou *et al.* (2004), Gustafsson, & Nimmermark (1991)

2.3.1 Dehumidification by ventilation

A study investigating the consumption of energy to provide dehumidification in a tomato greenhouse located in Quebec was performed by de Halleux and Gauthier (1998). A software, enabling simulations of both heat and mass exchanges, was utilized to analyse three different scenarios: 1) no dehumidification (the indoor air is renewed exclusively through infiltration), 2) dehumidification by means of on-off ventilation (with one air change per hour), and 3) dehumidification by using proportional ventilation. It was concluded that during nine months for which simulations were carried out, in both scenarios involving dehumidification, the demand for heating was always higher compared to the "no dehumidification" scenario (by 12.6% and 18.4% for the on-off ventilation and the proportional ventilation, correspondingly). Furthermore, it was stated that dehumidification by proportional ventilation is more effective than that by on-off ventilation.

2.3.2 Mechanically controlled dehumidification

The system in which dry and cool outdoor air is supplied close to the greenhouse floor and forces humid greenhouse air to pass through the thermal screen and to rise to the vents is described by Campen *et al.* (2009). The system was first analysed in the dynamic simulation model KASPRO and then the model was validated in the experimental study. The simulation results showed that using the outside air instead of the air from above the screen is more energy efficient (slightly less heat has to be added to the greenhouse to account for the ventilation losses due to dehumidification).

Further, a variety of different dehumidification methods that do not rely solely on ventilation and heating have been proposed. The possible options are, among others, dehumidification by a cold water fan coil and by a cold water curtain, dehumidification by condensation on a cold surface, dehumidification by using a heat exchanger, dehumidification by absorption by a desiccant and dehumidification by condensation on finned pipes.

2.3.3 Dehumidification by a cold water curtain and by a cold water fan coil

An open water Novarbo^{TM} water curtain installed in a closed multi-span greenhouse located in the southwest of Finland was described by Huttunen (2011). In such a solution, special nozzles spread cold water droplets whose task is to absorb heat and moisture from the greenhouse air. Water vapour contained in the greenhouse air condenses on the cold droplets. The greenhouse air is cooled by a strong flow of air generated by the curtain. The condensed moisture is collected and carried to the outside, where the water is evaporatively cooled and subsequently returned to the greenhouse. The measurements were performed in a compartment containing cucumber plants and having an area of 540 m^2. It was concluded that even though the Novarbo^{TM} droplet curtain was effective, its operation depended on the outdoor temperature and relative humidity.

Two alternative methods of cooling and dehumidification, one involving the use of a Novarbo^{TM} curtain and another one using a cold water fan coil system, were studied and compared with natural ventilation by Vallières *et al.*

(2014). Cold groundwater was used in both solutions. The Novarbo^{TM} curtain consisted of 55 nozzles and was installed above the plant canopy. In the second system, the greenhouse air was passed over a cold coil resulting in the condensation of water vapour. It was shown that both for the fan coil and for the water curtain systems differences in relative humidity were smaller than for the natural ventilation method. Further, it was pointed out that for the fan coil less maintenance was needed and the risk of fungal disease was lower than for the water curtain. The water curtain required more space, reducing the available greenhouse area, and it created shadows.

2.3.4 Dehumidification by condensation on a cold surface, by using a heat exchanger and by absorption by a desiccant

Campen *et al.* (2003) investigated and compared the energy consumption and costs related to three different methods of dehumidification – 1) dehumidification by condensation on a cold surface, 2) dehumidification by means of forced ventilation together with a heat exchanger, and 3) dehumidification by absorption by a hygroscopic material. A system involving the use of traditional ventilation was used as a reference in that comparison. A venlo-type greenhouse covered either by a single- or by a double-layer glass was used in the study. The greenhouse was located at the northern latitude, under Dutch weather conditions, and contained four different crops – tomatoes, sweet peppers, roses and cucumbers. All calculations were done by means of the simulation model KASPRO. It was concluded that if dehumidification is performed by condensation on a cold surface (with the application of a heat pump) and if the method is to be cost-effective, the heat pump has to be also used for heating. Dehumidification by means of a hygroscopic material requires heat for the regeneration of that material, it is more complex and it involves environmental risks. It was pointed out that dehumidification system by means of forced ventilation (with the application of a heat exchanger) was the most promising though the system still requires more development and its cost has to be reduced.

2.3.5 Dehumidification by a heat pump

The performance of a heat pump used for heating and dehumidification of a 240 m^2 greenhouse located in Bangkok, Thailand was studied by means of an analytical model by Chou *et al.* (2004). Depending on the climatic conditions the obtained coefficient of performance (COP) was 1.2-4.0 and the specific energy consumption specifying how much energy is required for dehumidification (to remove a kilogram of moisture) was 1000-16000 kJ/kg. Gustafsson and Nimmermark (1991) studied the use of a heat pump for dehumidification of an experimental greenhouse of 360 m^2. During the study, the average COP of the dehumidification system was 3.53. It was found out that the air temperature and relative humidity significantly affect dehumidification capacity of a heat pump. Further, the calculations indicated that thermal energy savings in the studied greenhouse were of 56 000 kWh/year.

2.3.6 Liquid desiccant dehumidification

A study investigating the energy performance of an innovative air-conditioning system using H_2O-LiCl desiccant was performed for a winter season by Longo and Gasparella (2012). The measurements were done in two flower greenhouses located near Bergamo, Italy. In both greenhouses natural ventilation and unit heaters were used. Additionally, in one of the greenhouses a novel solution involving the use of a direct-contact desiccant-air heat exchanger was introduced. The water vapour contained in the humid air is absorbed by a liquid desiccant (a hygroscopic substance). As a consequence, the desiccant becomes diluted and in order to be regenerated it is sprayed on a hot water coil connected to a heater system. The water evaporated from the desiccant solution condenses on the inside of the heat exchanger. The heat absorbed by the desiccant is recovered and drawn to the air that is to be dehumidified. The results showed that the application of the desiccant-based system allowed for reducing the energy use by 10% during the winter season.

2.3.7 Dehumidification by condensation on finned pipes

Campen and Bot (2002) tested experimentally a system where the process of dehumidification occurs by condensation on finned pipes. The pipes where located below the gutter of a well-insulated, two span Venlo-type greenhouse. The results showed that one meter of a finned pipe at a temperature equal to 5°C removes 54 g of water vapour per hour from the air having a temperature of 20°C and relative humidity of 80%.

2.4 Use of energy – factors

The amount of energy that is consumed is influenced by a large number of factors, including the geographical location and orientation of the greenhouse, its design and the crop species that are cultivated.

Table 3 summarizes some of the factors that influence the use of energy in greenhouses.

Table 3. *Factors affecting the use of energy in greenhouses.*

Factors	Main components	Importance of components
Greenhouse location	Outdoor air temperature Solar radiation Outdoor air humidity Precipitation Wind speed	External climatic conditions affecting the demand for heating, cooling, dehumidification and lighting in a greenhouse differ between the locations around the world.
Greenhouse orientation	Solar radiation Wind speed	Climate parameters influencing the use of energy may have different importance for greenhouses oriented along north-south and east-west axes.
Greenhouse design	Size and shape of the greenhouse	Large area of the greenhouse cover results in higher heat losses.
	Construction (single-span, multi-span, venlo, lean-to, and tunnel)	Different constructions allow varying amounts of solar radiation to reach the crop.
	Covering materials (single/double glass, polycarbonate, acrylic, and polyethylene)	Covering materials have different heat transfer coefficients and different coefficients of transmissivity.
	Condition (cleanliness) of the greenhouse cover Screens Condensation on the greenhouse cover	A poor condition of the greenhouse cladding, water condensing on the greenhouse surfaces and thermal screens limit the amount of solar radiation available for the plants.
Greenhouse crops	Indoor air temperature Indoor relative humidity Light (natural/artificial) CO_2 concentration	For optimal growth, plant species require different temperature and humidity setpoints, different levels of light and CO_2 content in the greenhouse air. Therefore, varying amounts of energy to provide a proper indoor climate may be necessary.

2.4.1 Greenhouse location and orientation

Depending on the location of the greenhouse the external climatic conditions – the temperature of the air, solar radiation, humidity, precipitation and wind speed – differ substantially. When it comes to the climate conditions in Europe, two zones can be distinguished: Northern/Central where winters are cold and summers are moderate and Southern – with moderate winters and hot summers (von Elsner *et al.*, 2000).

The orientation of the greenhouse to a large extent determines the amount of solar radiation reaching the crop. The optimum orientation of the structure can allow for the reduction of heating and cooling requirements. Many studies aiming at the selection of the most beneficial greenhouse orientation have been performed.

2.4.2 Greenhouse design

The task of greenhouses is to provide and to maintain the optimum parameters for the growth of plants. The design of the greenhouse should be chosen with respect to the local meteorological conditions, especially considering the temperature, the solar radiation, the intensity of wind and the precipitation (von Elsner *et al.*, 2000). Depending on the climate and the latitude, different types of greenhouse structures and different cladding materials may be preferable. According to Castilla (2013) there are four main aspects that have to be considered while designing the greenhouse – it is important to: a) ensure high transmittance of light, b) avoid structural elements unnecessarily blocking the light, c) ensure good insulation and d) optimize the cost.

Among the climate factors that influence the design of greenhouses at the northern latitudes are low temperatures during the winter season, frequently accompanied by significant snow loads and poor availability of natural light in winter (von Elsner *et al.*, 2000). Under northern latitudes it is necessary to prioritize between good insulating properties and satisfactory optical characteristics of the greenhouse covering material. Different materials are shortly described below and their approximate values of heat transfer coefficients are listed in Table 4.

Table 4. *Approximate heat transfer coefficients of greenhouse covering materials (ASAE, 2003).*

Covering material	U-value $W\ m^{-2}\ K^{-1}$
Single glass, sealed	6.2
Single glass, low emissivity	5.4
Double glass, sealed	3.7
Single polycarbonate, corrugated	6.2 – 6.8
Rigid polycarbonate, double-wall	3.2 – 3.6
Rigid acrylic, double-wall	3.2
Rigid acrylic (panels 32 mm filled with polystyrene pellets)	0.57
Single polyethylene	6.2
Double polyethylene	4.0
Double polyethylene, IR inhibited	2.8

When it comes to the design of the greenhouse, it is relevant which construction and covering materials are used. Different covering materials are characterized by different coefficients of transmissivity influencing the amount of solar radiation that can reach the crop. A comparison of radiometric (transmissivity, reflectivity and absorptivity) and thermal properties (heat transfer coefficients) of a number of covering material was performed by Papadakis *et al.* (2000). The following covering materials are mainly used:

- *Glass*

The main advantage attributed to glass is its durability and high light transmittance – around 90% for single-wall sheets (Möller Nielsen, 2007; Rader *et al.*, 2013) – that basically does not deteriorate over time. The disadvantage is the weight – glass is rather heavy and thus requires strong supportive structures (Hanan, 1998). In greenhouses, it is either single layer or double layer glass that is used. Double layer glass has a lower value of heat transfer coefficient and thus the energy losses are also lower. On the other hand, such glass has lower light transmittance and therefore less sunlight reaches the crop.

- *Polycarbonate*

The advantage of polycarbonate material is its very high impact resistance and very low flammability (Tiwari, 2003). It is flexible and easy to shape into a desired form. The material is very light and thus does not require strong structures. The initial transmittance of double-wall polycarbonate is on the order of 70% (Möller Nielsen, 2007). The value of 83% has been reported by Rader *et al.* (2013). Unless UV stabilized, polycarbonate is vulnerable to UV radiation – it wears out over time and becomes more opaque/yellowish (Möller Nielsen, 2007).

- *Acrylic*

Acrylic has high light transmittance (around 80% for double-wall panels) that does not deteriorate with passing time (Möller Nielsen, 2007). It is characterized by a low value of heat transfer coefficient and thus has good insulation properties. Acrylic sheets are brittle and rather easy to scratch. Moreover, in contrast to polycarbonate, acrylic material is flammable (Hanan, 1998).

- *Polyethylene*

Polyethylene is employed in the form of single- or double-layer sheets. Its price is the lowest from among all other covering materials and it is available in wide widths (Hanan, 1998). Polyethylene sheets are easy to install but, on the other hand, have a short life time due to their susceptibility to weathering and yellowing (Rader *et al*., 2013; Tiwari, 2003).

Except for the type and the properties of the cladding material, a number of factors, including the actual condition of the cover (in terms of the cleanliness), the application of shading screens and the potential condensation on the greenhouse cover, influence the transmission of the sunlight (von Elsner *et al.*, 2000).

The material that is utilized and the openings in the greenhouse envelope are two of the factors determining the air leakage and, thus also the heat loss. A number of studies investigating the concept of a "closed greenhouse", i.e. the greenhouse without ventilation, which in a conventional greenhouse allow for the air exchange, have been performed. Opdam *et al.* (2005) demonstrated that in comparison to the traditional greenhouse the primary energy savings can be between 20% (in the case of a completely closed greenhouse) and 33% (if the closed greenhouse is combined with a conventional "open" section). According to the authors, higher energy savings in the latter case are due to the fact that the closed greenhouse acts as a solar collector delivering excess heat to the "open" section.

Using computer models Elings *et al.* (2005) investigated a number of energy conservation measures that were implemented in a representative tomato greenhouse in the Netherlands. One of the eleven tested solutions was to decrease the day and night setpoints of temperature by 2 °C. Another was to increase the setpoint of relative humidity from 85% up to 90%. The results showed that the reduction of the temperature setpoint allowed for energy savings of the order of 16%, when compared to the reference case. The increased setpoint of relative humidity resulted in lower energy savings – the energy consumption was reduced by roughly 5%.

In order to protect plants from the strong solar radiation and to ensure the optimum climate in the greenhouse it may be necessary to employ shadings. Reducing the amount of solar radiation entering the greenhouse allows for avoiding too high temperatures that may be detrimental for the crop. Additionally, some of the crops, depending on their species and also their growth stage, require periods of darkness. Some photoperiod sensible crops, for example tomatoes, may become chlorotic when being subjected to light longer than 18 hours (Castilla, 2013).

Another option is the utilization of movable screens, either over or inside the greenhouse. The use of such screens is a conventional method in north European greenhouses. They may be installed horizontally or parallel to the roof surface. Shading materials are available in many sizes, colours and in a wide range of threads and weave densities (Castilla, 2013; Hanan, 1998). Depending on the local conditions and on the cultivated crop, fabrics offering different percentages of coverage can be employed. A review of various types of shading/reflective screens and their influence on the indoor greenhouse conditions as well as on the growth of plants was performed by Sethi and Sharma (2007).

Besides using the screens a shading effect can also be obtained by the use of a whitening substance on the outside surface of the greenhouse cover. The durability of such a solution depends both on the type of paint that is used and on the outdoor climate conditions (the level of precipitation). The disadvantage of a permanent shading (whitening or permanent screens) is that it is not adjustable depending on the actual level of solar radiation. Even though that kind of shading effectively prevents the overheating of the greenhouse interior, it also negatively influences the process of photosynthesis and may lead to a yield reduction (Castilla, 2013).

2.4.3 Type of greenhouse crops

Cultivated plants, depending on their species, have distinct requirements for optimal growth, principally in terms of the temperature, humidity, light and CO_2 concentration.

Seemann (1974) pointed out that a constant temperature is not beneficial for the growth of plants and that it is recommended to differentiate between the day and night temperatures. Thanks to a lower temperature during the night, plants consume less of the absorbed nutrient substances. Tomatoes, for example, have an optimal temperature between 21 and 28°C during the day and between 17 and 18°C during the night. The relative humidity for tomatoes has been suggested to be in the order of 60-70% (Snyder, 2001). Nowadays, higher values of relative humidity, about 80%, are frequently used by growers.

3 Humidity in the greenhouse

3.1 The role of humidity

Both too high and too low humidity levels have a harmful influence on greenhouse crops. Relative humidity in the range of 60-90% is considered to be optimal for the growth of many greenhouse plant species (Kittas *et al.*, 2012). Persistent high humidity, exceeding 95%, results in an increased growth and spreading of fungal diseases (e.g. the leaf mould caused by the fungus *Fulvia fulva* (Babadoost, 2011) or the grey mould caused by *Botrytis cinerea* (Williamson *et al.*, 2007)) which, in turn, significantly reduce the quality of crops and decrease the yield. Moreover, it decreases the rate of transpiration of plants and subsequently diminishes the uptake of nutrients. A study performed by Bakker (1991) showed that due to the long-term high humidity levels the leaf area of tomatoes decreased (as a result of calcium deficiency) while that of cucumbers increased (due to a greater rate of leaf formation). Holder and Cockshull (1990) reported that calcium deficiencies caused by long-term elevated humidity levels reduced the leaf area of tomatoes by up to 50%. Moreover, they observed that high humidity impaired the quality of fruits. Furthermore, water condensing on the inner surfaces of the greenhouse cover prevents the sunlight from reaching the crop (Cemek & Demir, 2005; Jaffrin & Makhlouf, 1990; Pollet *et al.*, 1999).

Low humidity, in turn, with the values below 60%, causes water stress in the plant (Kittas *et al.*, 2012), resulting in a reduced leaf size and stem length (Farooq *et al.*, 2009; Jaleel *et al.*, 2009). For low humidity levels, Jaleel *et al.* (2008) reported on a reduced dry and fresh weight, an increased root length, a decreased total leaf area and a reduced amount of photosynthetic pigments (chlorophyll, both a and b, anthocyanin and xanthophyll) in two different varieties of *Catharanthus roseus* plants. Farooq *et al.* (2009) wrote a review investigating the negative influence of drought stress on the growth and yield of crops.

Humidity is one of the most important climate factors in a greenhouse influencing the processes of plant photosynthesis and transpiration. Both too low and too high humidity levels negatively affect plant growth and the development and quality of the greenhouse crops. As to transpiration, water that is absorbed by the roots moves upward through a transport tissue (xylem). This flow enables the distribution of nutrients required for the proper growth of a plant. Water that is not retained by the plant and not used in various chemical processes is lost through the transpiration to the atmosphere. Water vapour is expelled mainly through the stomata, i.e. through the pores in the leaf and stem surface. The amount of water that is transpired is regulated by the opening and closing of the stomata. When the stomata are open, CO_2 is absorbed, whereas water vapour is lost. In turn, when stomata are closed, both the process of transpiration and uptake of CO_2 are reduced. The long term and short term responses of the stomata to water stress are outlined by Arve *et al.* (2011). The process of transpiration is influenced by factors such as air temperature, relative humidity, solar radiation and concentration of CO_2 (Stanghellini, 1987).

3.2 Humidity balance

Humidity balance in the greenhouse is affected by a number of factors, acting as either humidity sources or humidity sinks. Among the processes that add humidity to the greenhouse are transpiration from plants and evaporation. Alternatively, in some greenhouses the level of humidity is increased due to the operation of misting- or evaporative cooling pad systems. Humidity is removed by ventilation, condensation and air leakage through the openings in the greenhouse structure.

The water vapour balance can be expressed using the following formula (Baille, 1999):

$$\frac{V}{A}\frac{dq}{dt} = TR + E_{soil} + F - Q_v - C$$

The rate of change of humidity is designated as dq/dt ($kg_{water}\ m^{-3}\ s^{-1}$), where q ($kg_{water}\ m^{-3}$) represents the concentration of water vapour in the greenhouse air. The volume of the greenhouse is V (m^3) and the area is A (m^2). As to the right side of the equation, TR represents the transpiration rate of the crop, E_{soil} – the evaporation from the soil and F – water supplied by a humidification system.

Q_v is water vapour removed due to the ventilation and air leakage and C – the condensation rate. All factors mentioned above have the unit of $kg_{water}\ m^{-2}\ s^{-1}$.

3.3 Humidity measurements

In order to assure both high productivity and quality of crops, it is necessary to be able to perform continuous and accurate measurements. Climate conditions have to be optimized to improve the yield and to keep the energy use and its related greenhouse gas emissions as low as possible. It is significant that climate parameters are influenced by each other. High levels of solar radiation increase the temperature inside the greenhouse, which in consequence decreases the relative humidity. In order to cool down the indoor air it may be necessary to open the vents but this, in turn, reduces the amount of CO_2 that is indispensable for the efficient growth of plants. Thus, since different climate parameters are dependent on each other, it is important to control them simultaneously.

While measuring different parameters inside the greenhouse, independently whether it is temperature, humidity, radiation or CO_2, it is very relevant to place the sensor at a spot that is representative for the greenhouse climate. The problem is that both in horizontal and vertical directions large variations in the measured parameters occur. The lack of homogeneity of climate parameters affects the development and behaviour of crops (Shilo *et al.*, 2004). The most desired location of the sensor is as close to the plant as possible, so that the parameters that are measured could reflect the actual conditions that affect the crop.

In order to be accurate, temperature sensors should not be exposed to the direct sunlight. They should be placed at a location that assures sufficient air movement but not close to the vents or fans. It is not recommended to mount sensors on the wall, near to the roof or in the vicinity of heating pipes.

Similarly, humidity sensors should not be placed close to the heating system (pipes or heaters). Bulbs of the thermometers should be protected from the effects of solar radiation. The sensor should not be subjected to high air flows, for example those generated by fans or appearing in the vicinity of vents. In order to ensure that the sensor is protected from the direct sunlight and wind it can be placed in a ventilated measuring box (Figure 2).

Figure 2. The measuring box used for the control of the temperature and the relative humidity (Photo: Katarzyna Maslak).

Humidity sensors have to fulfil a number of conditions to be considered as good and reliable measuring devices. According to Schurer and Visscher (1998), the sensors should enable accurate measurements in the temperature range of 10-40 °C, both at high humidity levels (with the deviation of ±2% RH) and at low humidity levels (with the acceptable error of ±5% RH). Furthermore, the sensor should allow for the measurements of humidity ranging up to the saturation point. Two other important factors are short response time (not exceeding one minute) and quick recovery from condensation. Humidity sensor should be made of a material that is resistant to both chemical and physical contamination. While selecting the sensor it is necessary to consider its stability, repeatability and interchangeability (Wilson, 2004). According to the World Meteorological Organization (2008), humidity sensors, as all other sensing instruments, should be convenient to operate, to calibrate and to maintain. Finally, the economic aspects have to be taken into consideration – humidity sensors should be cost effective. A review of miniaturized humidity sensors, including capacitive, resistive, hygrometric, gravimetric and optical ones, was made by Rittersma (2002).

There are two types of humidity sensors that are frequently used for controlling the climate in greenhouses – psychrometers (dry and wet bulb instruments) and capacitive sensors. The working principle of psychrometers consists in the measurement of two different temperatures: a dry bulb temperature (T_{db}) and a wet bulb temperature (T_{wb}) (Figure 3). In case of capacitive sensors it is a thin film, made of either polymer or metal oxide, which reacts to changes in relative humidity (Rittersma, 2002; Schurer & Visscher, 1998).

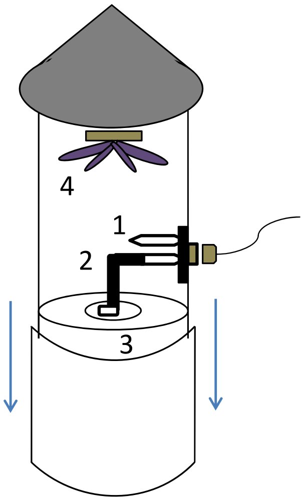

Figure 3. A psychrometer set-up: 1 – dry bulb thermometer, 2 – wet bulb thermometer, 3 – reservoir for water for a wet bulb thermometer, and 4 – fan (adapted from Nederhoff, 1997).

3.4 Humidity control

In practice, it may be required to either reduce or to increase the level of humidity in the greenhouse. The most common way to decrease humidity is to use combined ventilation and heating. In order to increase the humidity, evaporative cooling (fan-pad, fog/mist or roof cooling) can be employed. A review of different methods used for ventilation and cooling was written by Sethi and Sharma (2007). They described two types of ventilation, i.e. natural and forced ventilation systems, as well as various evaporative cooling methods, shadings and composite systems (earth-to-air heat exchanger installations and aquifer coupled cavity flow heat exchanger systems). A review and evaluation of various heating technologies, which are based, among others, on the storage of thermal energy in water, in rock beds and in phase change materials, or which involve the use of earth-to-air heat exchangers or ground air collectors was performed by Sethi and Sharma (2008).

Ventilation can be either natural, as it is most commonly practiced, or forced, where the movement of air is induced mechanically – typically by means of fans (Sethi & Sharma, 2007). Both types of ventilation have to fulfil three main conditions, namely to enable the sufficient exchange between the greenhouse and the ambient air, to allow for a good distribution of the incoming air (so that the air coming from outside could be effectively mixed with the greenhouse air) and to induce such a movement of air inside the greenhouse that the heat and mass exchange could be guaranteed (Bailey, 2000). The distribution of the air inside the greenhouse is affected by the characteristics of the ventilation openings – by their size, design and location (von Elsner *et al.*, 2000). Typically, the openings are located along the longitudinal axis of the greenhouse span, in the roof, in walls or both in the roof and walls (Bournet & Boulard, 2010). There are two main types of ventilation openings – the roll-up and the pivoting ones. Furthermore, greenhouses can be equipped with either continuous or discontinuous vents.

3.4.1 Natural ventilation

In the case of natural ventilation the flow of air through the openings in the greenhouse structure is induced by the pressure difference. The pressure difference, in turn, is caused by the wind forces and by the buoyancy forces (stack or chimney effect), i.e. the temperature difference between the outdoor and the indoor air (de Jong, 1990). Many studies aiming at the determination of the ventilation rate in naturally ventilated greenhouses have been performed. Both indirect methods, including the tracer gas techniques (Baptista *et al.*, 1999; Campen & Bot, 2003; de Jong, 1990; Kittas *et al.* 1997; Ould Khaoua *et al.*, 2006) and the energy balance models (Demrati *et al.* 2001), and direct methods, e.g. differential pressure measurements over the vent opening (Boulard *et al.*, 1998) may be used.

Wind effect

The wind affecting the greenhouse generates different pressures around the structure – positive on the side that is exposed to the wind (windward) and negative above the roof and on the side that is not directly affected by the wind (leeward) (Castilla, 2013). As described by Boulard and Baille (1995) the wind effect consists of two components – the steady effect and the turbulent one. The steady effect is related to the mean wind speed through the average wind pressure coefficient whose value depends on the directions of the wind. The turbulent effect is characterized by the fluctuating pressure coefficient that is independent of the wind speed. If the wind speed is low, below 2 m s^{-1}, its contribution to the ventilation is negligible – in such a case it is the stack effect that dominates (Castilla, 2013).

The influence of the wind speed on the natural ventilation of a greenhouse located in the province of Almería, Spain, was investigated by Molina-Aiz *et* *al.* (2004). The analysed greenhouse had both roof and side openings. The importance of the roof openings for the efficient ventilation was emphasized.

Stack effect

If the greenhouse air is warmer (has a lower density) than the outdoor air, it rises to the vents located in the upper part of the greenhouse. The outdoor air that is colder (and therefore has higher density) settles down. The problem appears during the warm season, when the temperature difference is not high enough to enable the sufficient air movement.

3.4.2 Mechanical ventilation

Forced ventilation systems are indispensable when the rate at which heat is generated inside the greenhouse is higher than the rate of heat removal through natural ventilation. In this case, in order to increase the rate of air exchange, a mechanical device has to be used (e.g. a fan or a blower). The advantage is that this kind of ventilation works independently of the wind speed outside the greenhouse. The drawback, as pointed out by Seemann (1974), is that the airflow induced over the canopy may be too intensive, thus having a negative impact on the plants. To obtain a more favourable airflow and air distribution a number of fans of low speed and large diameter have to be installed.

3.5 Temperature and humidity gradients

Typically, the climatic conditions inside the greenhouse are not uniform and both horizontal and vertical differences in the distribution of the temperature and the relative humidity can be observed. The distribution of both temperature and humidity affects the homogeneity of the crop (Zhao *et al.*, 2001). The non-uniform distribution of the temperature influences the heat losses (may increase them) and makes it difficult to efficiently control and optimize the climate in the greenhouse.

As to the horizontal gradients, the temperature can be higher next to the south-facing wall and lower close to the north-facing wall. Moreover, the temperature usually tends to be lower close to the wall that is exposed to the wind. The vertical temperature and humidity gradients are affected by the location of the heating system – if heating pipes with hot water are located close to the ground the air temperature is higher while relative humidity is lower in this area than in the upper parts of the greenhouse space.

For precise detection and registering of the temperature and relative humidity gradients a large number of sensors are required. A promising solution involving the application of wireless sensors was developed by the research institute of Wageningen UR Greenhouse Horticulture in the frame of the Greenhouse as a Source of Energy programme (Dutch: Kas als Energiebron) (Balendonck *et al.*, 2010; Balendonck *et al.*, 2014). In the autumn/winter season 2008-2009 the system was tested in Dutch greenhouses in which tomatoes, cucumbers, Gerbera and Matricaria were cultivated. Sensors formed a dense network (58-128 sensors ha^{-1}), enabling the continuous and accurate measurements of temperature and humidity. It was concluded that 9 sensors per hectare are necessary in order to identify all wet and cold spots. In general, increasing the number of sensors improves the accuracy of humidity estimation.

4 Materials and methods

4.1 Studied greenhouse facilities

Data used in this study were collected in three commercial greenhouses, Greenhouse A housing tomato crops, Greenhouse B housing tomatoes and some melons and Greenhouse C dedicated to ornamental plants. The greenhouses were located in the south of Sweden, in the province of Scania (latitude 55-56°N). In Paper I, all greenhouses were studied, whereas in Papers II and III solely Greenhouse A was investigated.

4.1.1 Greenhouse A (Papers I, II and III)

The greenhouse consisted of eight equally sized compartments having the total area of 80 000 m^2 (Figure 4). The height of the greenhouse was 5.0 m to the gutter and the roof slope was 26°. The cover material used for the walls and for the roof was single glass. Additionally, all walls up to the height of 1.5 m were insulated and the southern wall was sprayed with lime up to the height of 3.0 m. Each compartment was equipped with thermal screens.

Natural gas was burned in order to provide thermal energy to the greenhouse. The water based heating systems included two independent circuits – one delivered water to compartments no. 2, 4, 6 and 8 and another one to compartments no. 1, 3, 5 and 7. Heating pipes were located at two levels – below the plant beds and above the crop canopy.

The indoor climate conditions were controlled by a Priva Intégro system (version 724). Two pairs of Priva sensors (thermistors and aspirated psychrometers) registering the air temperature and the relative humidity were installed in each compartment, except for two compartments where four sensor pairs were located.

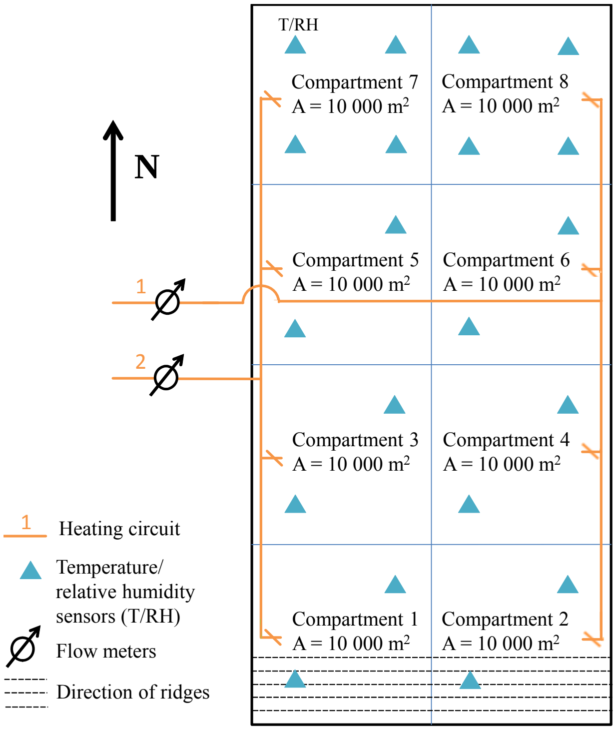

Figure 4. The layout of Greenhouse A, depicting the distribution of compartments, heating circuits, temperature and relative humidity sensors and flow meters.

4.1.2 Greenhouse B (Paper I)

The greenhouse consisted of six different compartments with the total area of 13 700 m^2 (Figure 5). The greenhouse was 3.75 m high with the exception of one compartment having the height of 4.20 m to the gutter. Single glass was used as a covering material for the walls and the roof in all compartments apart from one where double-wall acrylic sheets were used for the walls. Thermal screens were installed in two compartments.

The energy source used for heating was natural gas and woodchips (with the contribution of 50%). Heating pipes were generally located at two levels – below the plant benches and above the crops, at the gutter height. In some compartments, pipes were also installed at a third level, inside the plant canopy.

The indoor climate was controlled by a Priva Intégro system (version 724). In each compartment one pair of temperature/humidity sensors (thermistors and aspirated psychrometers) was installed.

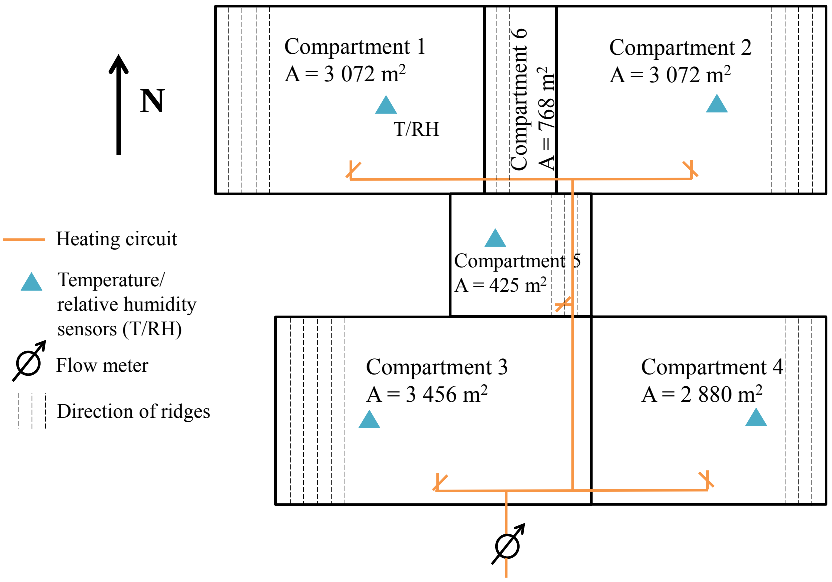

Figure 5. The layout of Greenhouse B, depicting the distribution of compartments, the heating circuit, temperature and relative humidity sensors and the flow meter.

4.1.3 Greenhouse C (Paper I)

The greenhouse consisted of eight compartments having the total area of 6 500 m^2 (Figure 6). Between weeks 12 and 42, the plants were cultivated in all compartments, while between weeks 43 and 11 compartment no. 1 was not used. The compartments differed in height, from 2.5 to 4.5 m to the gutter. The cover materials used for the walls were single glass, double-wall polycarbonate and acrylic panels. In one of the compartments the walls consisted of two air-inflated layers of polyethylene film. The roof, depending on the compartment, was covered by single glass, double-wall polycarbonate and acrylic panels. Thermal screens were installed in seven compartments.

Thermal energy was supplied by three groundwater heat pumps backed up by three boilers – one electric and two oil-driven. Further, in one of the compartments an air-heating system with fan coils was employed. There were three different levels where heating pipes were installed – below the tables with plants, along the greenhouse walls and below the roof at the gutter height.

Environmental conditions were controlled by a Priva Intégro system (version 724). Priva sensors (thermistors and aspirated psychrometers) registering the temperature and humidity, respectively, were located in all compartments.

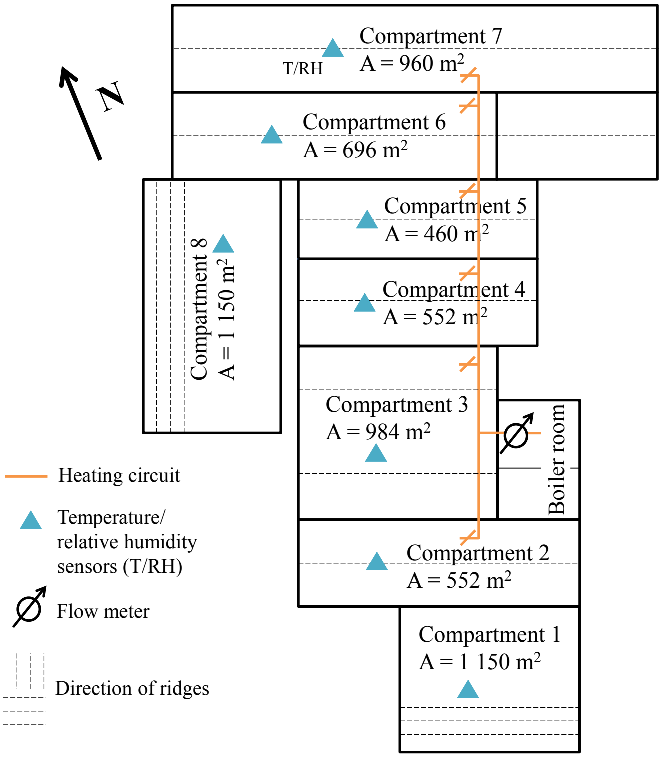

Figure 6. The layout of Greenhouse C, depicting the distribution of compartments, the heating circuit, temperature and relative humidity sensors and the flow meter.

4.2 Collection of climate data and thermal energy use calculations

The external climate parameters (air temperature, solar radiation and wind speed), data on the internal climate conditions (air temperature and relative humidity) and on the heating system (temperature of inlet/return water from/to the boiler and the flowmeter pulses) were registered for each of the greenhouses and stored at the interval of one hour. The outdoor air temperature and the wind speed were measured by means of the sensors included in the Priva meteorological station placed at the roof of each greenhouse. Solar radiation was registered by Kipp & Zonen solarimeters. The values of the outdoor relative humidity for the Malmö station were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The indoor temperature and the relative humidity were measured by the Priva sensors placed in the measuring boxes. The temperature of the heating water was registered by SVM TCF Pt100 sensors and the flow was measured by the flow meters Hydrometer WP-XKA with the pulse rates of 250, 100 and 25 pulses/litre for Greenhouse A, B and C, respectively. The total use of thermal energy during each hour (Q_t, kJ) was computed using the measured temperatures of heating water leaving and returning to the boiler and the pulses registered by the flow meters. The total monthly and yearly use of thermal energy (MJ m^{-2}) was calculated for Greenhouses B and C. For Greenhouse A, the use of thermal energy (MJ m^{-2}) in the months April-October was computed. The investigated periods were chosen based on the availability of data. The following formula was used for thermal energy use calculations:

$$Q_t = V_w \cdot \Delta T_w \cdot \rho_w \cdot C_{p\ av},$$

where V_w (m^3) denotes the volume of heating water calculated using the flow meter pulses, ΔT_w (°C) is the temperature difference between the inlet and return water, i.e. water leaving/returning to the boiler, ρ_w (kg m^{-3}) is the density of water on the side of the flow meter and $C_{p\ av}$ (kJ kg^{-1} $°C^{-1}$) is the average value of specific heat of inlet and return water.

4.3 Thermal energy use at different outdoor temperatures and under no-sunlight conditions (Paper I)

With the aim of eliminating the impact of disturbing factors, the influence of the wind speed on the use of thermal energy at different outdoor temperatures was studied under no-sunlight conditions. Out of the primary data sets, including 5136 hourly values (April-October) for Greenhouse A and 7296 hourly values (January-October) for Greenhouses B and C, the temperature, wind speed and energy use values for the hours with the average solar radiation (q_{solar}) lower than 5 W m^{-2} were selected for further analyses. The new data sets consisted of 2075, 3390 and 3501 hourly values for Greenhouses A, B and C, respectively. Subsequently, the acquired values were grouped according to the outdoor temperature (T_{out}). Seven different outdoor temperature ranges were studied: $T_{out}<0°C$, $0 \leq T_{out}<5°C$, $5 \leq T_{out}<10°C$, $10 \leq T_{out}<15°C$, $15 \leq T_{out}<20°C$, $20 \leq T_{out}<25°C$ and $T_{out} \geq 25°C$. Finally, the use of thermal energy (MJ m^{-2}) in each temperature range was computed and the number of hours within each temperature interval was determined.

4.3.1 The influence of wind speed and outdoor temperature

In order to analyze the influence of wind speed on the use of thermal energy a statistical software Minitab version 16.2.4 was employed. In Minitab analyses, values of thermal energy use per square meter of heated greenhouse floor area (MJ m^{-2}_{heated}) were used. Pearson correlations were done to study how the wind speed affected the use of thermal energy in three greenhouses and to find out the degree of linear relationship between these two factors. Regression analyses with the use of thermal energy being a response variable and the wind speed and the outdoor temperature being two predictor values were performed. The resulting regression equations were employed to calculate the potential for thermal energy savings due to decreased wind speed. The measured values of the wind speed were reduced in each hour by 5%, 10%, 15%, 25%, 50% and 75% and those new values were substituted into the equations. The obtained new values of thermal energy used in each greenhouse were compared with the originally measured uses in the period of April-October for Greenhouse A and January-October for Greenhouses B and C.

4.4 Powersim model (Papers II and III)

A model created in Powersim software was employed for simulations of thermal energy use in a greenhouse. The model made it possible to determine both the energy and the humidity balances in a greenhouse. The output of the model was the amount of heat that is generated by the boiler. Further, the energy balance included the heat added due to solar radiation incident on the greenhouse and due to the process of transpiration (where sensible heat is converted to latent heat) as well as heat losses because of ventilation, condensation, heat transmission through the greenhouse cover and air-leakage through the gaps in the greenhouse structure. As to the moisture balance, the positive contribution of transpiration and evaporation and the negative effect of ventilation, condensation and air-leakage through the greenhouse cover were included in the model.

The Powersim software was employed to model the use of thermal energy in Greenhouse A in the months of April-September. The obtained values were further compared with the measured data on the use of energy.

In the first step of modelling, the excessive moisture in the greenhouse air was being removed by natural ventilation, i.e. by opening vents when necessary. In the next step, dehumidification was done by mechanical ventilation and by a heat exchanger. The moisture and temperature efficiencies of the heat exchanger used in the model were determined experimentally as described in chapter 4.5. In the simulations, two values of leaf area index (LAI), i.e. LAI = 3.5 m^2 m^{-2} and LAI = 4.0 m^2 m^{-2}, affecting a process of transpiration and therefore also a need for dehumidification, were used. The use of thermal energy for dehumidification of Greenhouse A in the period of April-September was modelled for both values of LAI. Finally, it was calculated how much energy is necessary for dehumidification under sunlight and no-sunlight conditions ($q_{solar} < 5$ W m^{-2}).

4.5 Heat exchanger measurements (Paper III)

A rotary air-to-air heat exchanger VVVA Swegon (Figure 7) was used during the in situ measurements performed at the Swedish University of Agricultural Sciences, Alnarp. An AAC-216 (Analog ASCII Converter) PC logger was employed to record the data. The purpose was to experimentally determine the temperature and moisture efficiencies of the heat exchanger operating at higher humidity levels and subsequently to use the obtained efficiency values in the Powersim model to estimate the potential for thermal energy savings (for energy required for dehumidification).

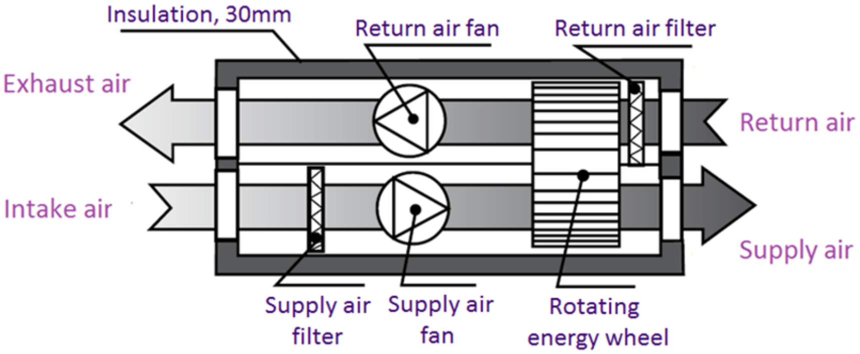

Figure 7. A schematic of a rotary heat exchanger used for the measurements (adapted from Swegon, 2012).

During the measurements, the temperatures of the outdoor air, of the supply air, of the return air and of the exhaust air as well as the values of humidity of the intake, supply and return air were registered. Rotronic Hygrometers C94 and thermocouples (type T) were used for humidity and temperature measurements, correspondingly.

Using the values of saturation pressure of water vapour at a given temperature (e_s, Pa) and the values of actual water vapour pressure (e_a, Pa) the moisture content (x, kg_{water}/kg_{air}) in the air streams was computed. Finally, the temperature and moisture efficiencies (η_t and η_x, respectively) were calculated according to the following formulas:

$$\eta_t = \frac{t_{supply} - t_{intake}}{t_{return} - t_{intake}} \cdot 100\%,$$

$$\eta_x = \frac{x_{supply} - x_{intake}}{x_{return} - x_{intake}} \cdot 100\%,$$

where t_{supply}, t_{intake} and t_{return} (°C) and x_{supply}, x_{intake} and x_{return} (kg_{water}/kg_{air}) denote the temperatures and the humidity contents of different streams of air (Figure 7).

5 Results

5.1 Measured thermal energy use in greenhouses

The amount of thermal energy used in Greenhouse A in the months of April-October was 793 MJ m^{-2}. The yearly use of energy in Greenhouses B and C equalled to 1 529 MJ m^{-2} and 873 MJ m^{-2}, respectively.

5.2 Thermal energy use at different outdoor temperatures (Paper I)

The cumulative use of thermal energy (MJ m^{-2}) at different outdoor temperatures and the cumulative number of hours when the outdoor temperature was within a given interval is presented in Figure 8. Data collected under no-sunlight conditions ($q_{solar} < 5$ W m^{-2}) for the months April-October (Greenhouse A) and January-October (Greenhouses B and C) were used.

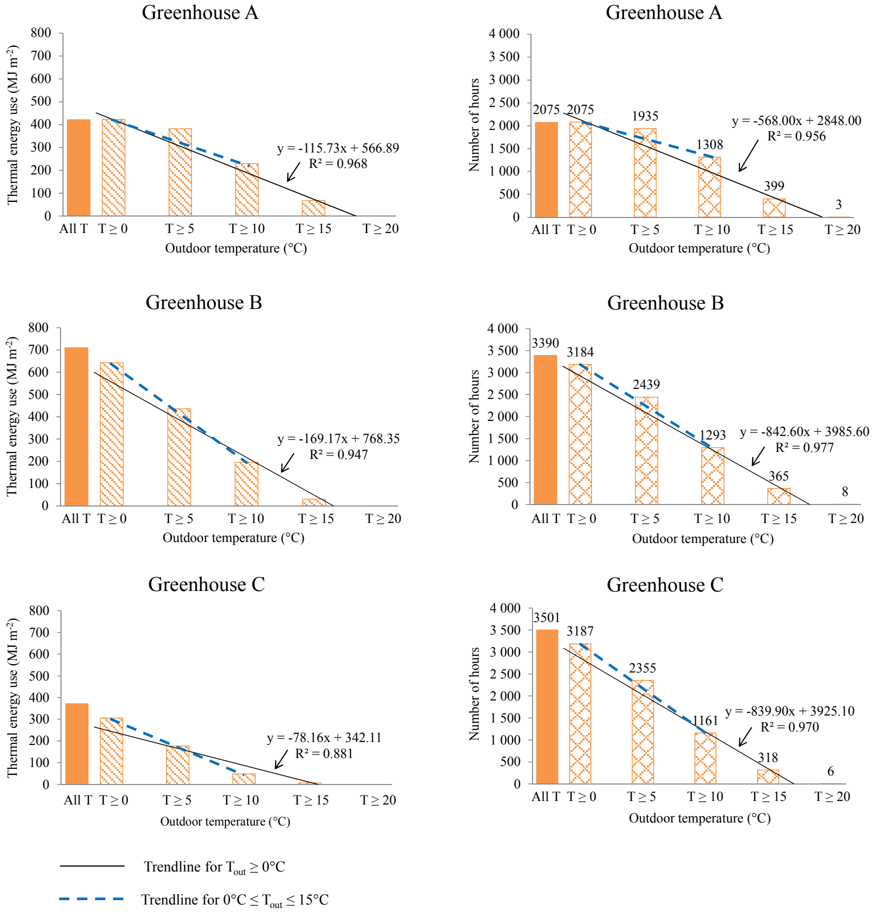

Figure 8. Cumulative use of thermal energy per square meter of greenhouse floor area in different outdoor temperature ranges under no-sunlight conditions ($q_{solar} < 5$ W m^{-2}) and the cumulative number of hours with temperatures within a given interval for Greenhouse A (April-October) and Greenhouses B and C (January-October).

5.3 The influence of wind speed and outdoor temperatures on the use of thermal energy (Paper I)

In case of all investigated greenhouses and in all outdoor temperature ranges Pearson correlation coefficients for the use of thermal energy and the wind speed were positive. Thus, the amount of energy used was increasing together with the growing wind speed. Depending on the outdoor temperature range, correlation coefficients in the range of 0.017-0.470 were obtained.

Under no-sunlight conditions, the average values of wind speed were 3.1, 2.7 and 1.8 m s^{-1}, for Greenhouses A, B and C, respectively. The results showed that the use of thermal energy decreased by 4-10% when the wind speed was reduced by 50%. If the wind speed could be reduced more, by 75%, the achievable savings of thermal energy were over 15% for Greenhouse B (Table 5).

Table 5. *Reduction of the thermal energy use in three greenhouses due to a decreased wind speed by 15, 50 and 75%.*

Wind speed reduction (%)	Thermal energy savings (%)		
	Greenhouse A	Greenhouse B	Greenhouse C
15	1.2	3.1	1.8
50	4.0	10.3	6.0
75	6.1	15.5	9.0

5.4 Modelled thermal energy use in a greenhouse (Papers II and III)

According to the Powersim simulations performed for Greenhouse A under the assumption that the leaf area index (LAI) is equal to 3.5 m^2 m^{-2}, the use of thermal energy per square meter of greenhouse area was 596 MJ m^{-2} (April-September). The obtained monthly uses of energy were 159, 125, 61, 69, 73 and 110 MJ m^{-2} for the months of April, May, June, July, August and September, respectively. When LAI was assumed to be 4.0 m^2 m^{-2}, the use of thermal energy in the same period amounted to 651 MJ m^{-2}. The monthly values were 168, 134, 66, 78, 83 and 122 MJ m^{-2} in April, May, June, July, August and September, respectively. The comparison between the measured and simulated (LAI = 4.0 m^2 m^{-2}) values of thermal energy use is shown in Figure 9.

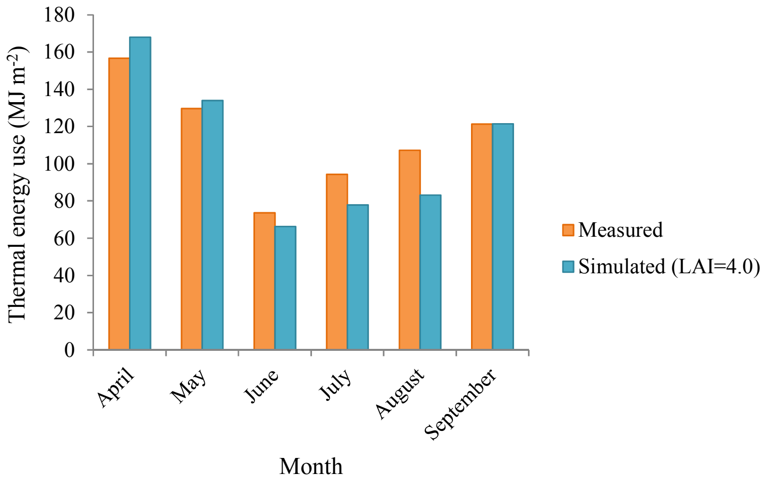

Figure 9. Measured and simulated (LAI = 4.0 m^2 m^{-2}) use of thermal energy in Greenhouse A in the months of April-September.

5.5 Modelled thermal energy use for greenhouse dehumidification by natural ventilation (Paper III)

The Powersim simulations done for Greenhouse A showed that 23% (for LAI = 3.5 m^2 m^{-2}) and 29% (for LAI = 4.0 m^2 m^{-2}) of thermal energy is used for dehumidification by ventilation. When just the use of energy under sunlight conditions was considered, the corresponding shares were 56 and 64%. In Table 6 the total monthly use of thermal energy in the period of April-September and the energy use for ventilation are presented.

Table 6. *Simulated total thermal energy use obtained for LAI = 4.0 m^2 m^{-2}, the energy necessary for ventilation for dehumidification and the percentage of energy used for ventilation under sunlight, no-sunlight and all conditions.*

		Simulated thermal energy use (MJ m^{-2}) for LAI = 4.0 m^2 m^{-2}						
		Apr.	May	June	July	Aug.	Sept.	SUM
No-sunlight conditions	Total use	98.9	78.0	36.9	39.4	37.0	62.6	353
	Ventilation	0.4	0.1	0.1	0.5	0.4	0.1	2
Sunlight conditions	Total use	69.1	56.0	29.3	38.4	46.1	58.9	298
	Ventilation	34.9	31.4	17.5	27.2	36.8	42.3	190
	% vent.	*51*	*56*	*60*	*71*	*80*	*72*	*64*
All conditions	Total use	168.0	134.0	66.2	77.9	83.2	121.5	651
	Ventilation	35.4	31.5	17.6	27.7	37.3	42.4	192
	% vent.	*21*	*24*	*27*	*36*	*45*	*35*	*29*

5.6 Modelled thermal energy use for dehumidification using mechanical ventilation and a heat exchanger (Paper III)

Based on the measurements performed at the Swedish University of Agricultural Sciences the temperature and moisture efficiencies of a rotary air-to-air heat exchanger were in the range 67-71% and 43-48%, respectively. The modelling indicated that the usage of a heat exchanger having a temperature efficiency of 70% and a moisture efficiency of 45% allowed for thermal energy savings of 15% (LAI = 3.5 m^2 m^{-2}) and 17% (LAI = 4.0 m^2 m^{-2}). Table 7 includes the values of thermal energy used in Greenhouse A in the period April-September obtained from the simulations, first when dehumidification was solely by natural ventilation and then by mechanical ventilation and a heat exchanger.

Table 7. *Simulated use of thermal energy (LAI = 4.0 m^2 m^{-2}) in Greenhouse A, first with ventilation for dehumidification and then with a mechanical ventilation system and a heat exchanger (HEX) and the percentage of achieved energy savings.*

	Simulated thermal energy use (MJ m^{-2}) for LAI = 4.0 m^2 m^{-2}					
	Apr.	May	June	July	Aug.	Sept.	SUM
Without HEX	168.0	134.0	66.2	77.9	83.2	121.5	651
With HEX	138.4	109.8	56.2	64.6	70.2	98.0	537
% savings	*18*	*18*	*15*	*17*	*16*	*19*	*17*

6 Discussion

The measured values of thermal energy used in three greenhouses (Paper I) are comparable with the values reported by the Swedish Board of Agriculture (Jordbruksverket, 2012). In general, the use of thermal energy per square meter was higher in Greenhouses A and B where tomatoes were cultivated than in Greenhouse C where ornamental plants were grown. Even though in case of Greenhouse C less heat was generated by the heating system, its average indoor temperature amounted to 20.8°C and thus was higher than the average temperatures in two other greenhouses being equal to 19.4°C (Greenhouse A) and 18.6°C (Greenhouse B). This likely depends on a larger use of supplemental lighting in a greenhouse with ornamental plants and to its structural design, mostly to the use of double-wall plastic panels having better insulating properties than single glass being predominantly employed in Greenhouses A and B. Further, the average value of relative humidity was lower in Greenhouse C (73% RH in the period of January-October) than in Greenhouses A (83% RH, April-October) and B (78% RH, January-October) which in combination with the lower energy use indicate a smaller need for dehumidification and thus a decreased heat loss due to opening the vents.

In the two greenhouses with tomatoes, a rather significant amount of thermal energy was used also at higher outdoor temperatures, i.e. when the rate of plant transpiration and therefore also the need for dehumidification were increased (Paper I). From Figure 8 it can be seen that in case of Greenhouse A similar amounts of thermal energy (per hour) were used in the two outdoor temperature ranges, 10-15°C and 15-20°C. Especially the use of energy in the higher outdoor temperature range (15-20°C) might be due to dehumidification by ventilation and due to the operation of a heating system when the vents were open.

In Paper III it has been shown that substantial amounts of thermal energy, in the range of 23-29%, may be required for greenhouse dehumidification. According to the simulations, less energy was used at lower values of leaf area index (LAI = 3.5 m^2 m^{-2}) when the contribution of transpiration was smaller as well. The use of thermal energy for greenhouse dehumidification increased when LAI was higher, amounting to 4.0 m^2 m^{-2}. As expected, the use of energy for dehumidification was significantly higher under sunlight conditions with only marginal energy demand for dehumidification under no-sunlight conditions.

The thermal energy use modelled for Greenhouse A (Papers II and III) showed a rather good agreement with the measured values. A larger discrepancy was observed in case of simulations performed for a lower value of leaf area index (LAI = 3.5 m^2 m^{-2}), likely due to an underestimated contribution of transpiration. Further, a constant value of LAI was used and no distinction between different stages of plant growth and thus between different sizes and quantities of leaves was made. According to the authors' knowledge and literature search, there are no studies investigating the changes of tomato leaves during various growth phases. It would be beneficial to perform such a study in order to be able to estimate the transpiration rate more precisely. Even though the output from the model was fairly precise, there is still more work that can be done, e.g. including the use of electricity for lighting and equipment, taking into account the influence of wind speed on heat losses from a greenhouse and including the heat storage in the greenhouse structure, floor and indoor components.

It has been showed that the use of thermal energy increases together with the increasing wind speed (Paper I). Bailey (1985), Bailey and Seginer (1989) and Zamir *et al.* (1984) pointed out that the rate of heat loss from a greenhouse is dependent on and increases with the wind speed. The Pearson correlation coefficients describing the relation between the use of thermal energy and the wind speed were rather low (0.017-0.470) demonstrating a large variation of measured data around the line of best fit. This can likely be attributed to the fact that there are more factors than just the wind speed which affect the use of energy. Nonetheless, it has been shown that the wind speed is of importance and that its reduction by 50% can lead to the energy savings of 4-10%. According to Sanford (2011), thanks to the application of windbreaks, the wind speed can be reduced by 50% and the related heat losses can be decreased by 5-10%. Paper I indicated that if the wind speed was reduced even more, by 75%, the achievable energy savings could amount to 15.5%. Under no-sunlight conditions, the reduction of the measured wind speed values by 75% would result in the values of 0.8, 0.7 and 0.4 m s^{-1}. The importance of both selecting an optimal greenhouse location assuring the protection from wind and of introducing windbreaks (e.g. a fence or several rows of trees/bushes) shielding the already existing greenhouse structures has been identified.

The rotary heat exchangers are used in ventilation systems in both residential and commercial buildings. However, according to literature research, there are no studies testing the performance of such a heat exchanger working at high humidity levels. The measurements including a VVVA rotary heat exchanger indicated that rather high thermal efficiencies in the range of 67-71% can be achieved at higher humidity levels of 81-86% (Paper III). According to the producer of a VVVA heat exchanger, the temperature efficiency of 78% can be expected (Swegon, 2012). Such a value was achieved when the measurements were carried out for lower humidity levels of 25-45% RH.

The simulations indicated that thanks to the use of mechanical ventilation combined with a heat exchanger, the use of thermal energy in a greenhouse could be reduced by 15-17% (Paper III). A significant amount of energy can be saved when mechanical ventilation is used for dehumidification (Coomans *et al.*, 2013). In their study, it has been reported that 12% of the energy used in a greenhouse in the period of January-November could be recuperated by a heat exchanger. The percentage of achievable savings obtained in our study is slightly higher, likely due to the fact that winter months, when the need for dehumidification is lower, were not included in the calculations.

7 General conclusions

Thermal energy use in greenhouses is affected by a large number of climate factors, which may influence also each other, and thus the role of a single parameter is difficult to determine in a straightforward way.

Based on the measurements and Powersim simulations the following conclusions can be drawn:

- The use of thermal energy was considerably higher in the two greenhouses with tomatoes than in the greenhouse with ornamental plants. A lower thermal energy use in the latter greenhouse can be attributed to the use of supplemental lighting, i.e. producing heat electric energy, and to the structural design (double-wall plastic cover). Further, a smaller need for humidity removal at higher temperatures may be of importance.
- It was shown that in the greenhouses with tomatoes significant amounts of energy were used at higher outdoor temperatures, most likely due to a higher transpiration rate and thus to an increased need for dehumidification.
- The use of thermal energy was found to increase together with the increasing wind speed. Therefore, choosing a greenhouse location with lower values of wind speed (when the greenhouse is to be built) or applying windbreaks may be a favourable solution. It was indicated by calculations that 4-10% of the thermal energy can be saved if the wind speed is reduced by 50%.
- The measured and modelled values of thermal energy showed a fairly good agreement, especially when the simulations were performed for a higher transpiration rate, i.e. for LAI = 4.0 m^2 m^{-2}. Further improvements of the model are necessary to increase its precision and to reduce the uncertainties.

- The Powersim modelling indicated that substantial amounts of thermal energy amounting to 23-29%, depending on the level of transpiration, may be used for greenhouse dehumidification.
- According to the measurements carried out for a non-hygroscopic air-to-air rotary heat exchanger working at higher indoor humidity levels, thermal efficiencies of about 70% and moisture efficiencies of about 45% were obtained.
- The Powersim modelling indicated that thermal energy savings of the order of 15-17% may be achieved in a greenhouse with mechanical ventilation and a rotary heat exchanger.

8 Future research

Further work is needed in order to improve the Powersim model, to remove the existing uncertainties related to the results of simulations and to eliminate the discrepancies between the modelled and the measured values of energy use. A goal should be to make the developed model a more precise tool that can be valuable for different users, both researchers and growers who should be able to use it for identifying the possible measures of how their greenhouses can be improved to decrease the use of thermal energy. Such a further work may include:

- Making the user interface friendlier and easier to work with.
- Introducing the possibility of studying greenhouses having various shapes and structures. Currently, the model enables simulations for greenhouses having a rectangular floor plan.
- Including different values of leaf index area, as they change during the growth of a plant, instead of one average value.
- Making it possible to calculate the consumption of electricity, e.g. for lighting, fans, etc.
- Taking into account the influence of wind speed on heat losses from a greenhouse.

Moreover, it would be interesting to test the performance of a heat exchanger, either rotary, as the one used in this study, or of different type, in a commercial greenhouse and to measure exactly how the use of energy is affected. Preferably, the measurements should be carried out both during the summer and winter season with varying needs for dehumidification.

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