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Low energy greenhouse – method to analyse heat flux and PAR transmittance

The main task of the German joined research project “Future Initiative Low Energy Greenhouse”, ZINEG is to develop low energy greenhouses. Within this research project four concepts of low energy greenhouse have been developed. The experimental greenhouses have been built in Berlin, Hannover, Osnabrück and Neustadt/Weinstraße. In Hannover the experimental greenhouse is situated at the horticultural research station in Hannover-Ahlem (LVG). For energy saving the roof is covered with double glazing with AR-coating. Additionally three thermal screens are installed in order to get a maximum insulation. In order to evaluate this concept measurements of heat consumption and PAR transmittance (photosynthetic active radiation) are carried out. In comparison with a single glazed greenhouse 84% of energy can be saved during night, when all screens are closed. With the method described in this paper the heat flux inside the roof can be analysed. Especially the portion of latent heat flux by condensation can be calculated. Furthermore the influence of evapotranspiration of the crop and the latent heat flux on the overall heat consumption can be determined.

Keywords
Low energy greenhouse, thermal screen, black out system, energy balance, PAR transmittance, diffuse radiation

Abstract
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Greenhouses are mostly used for a year-round production of horticultural crops. Depending on the crop, certain requirements concerning the air conditioning have to be met. From an energy perspective, especially in the winter months, the temperature standards are of importance because they are directly correlated with high energy costs. The light transmittance of greenhouse roofing is of particular importance during winter time. Light as minimizing factor often limits the plant growth. That is why single glazed greenhouses are often used, since double or triple glazing reduce the light transmittance. The use of single glazing in the winter months leads to a relatively high energy consumption for the greenhouse heating and consequently to high energy costs. Since greenhouses are still predominantly heated with fossil fuels such as fuel oil and natural gas, the finite nature of those resources and the reduction of fossil CO_2 emissions have to be taken into consideration. This is the backdrop against which the future initiative low energy greenhouse (ZINEG) has been created [1]. This joint research project aims at reducing the energy consumption of the greenhouses of low energy level. In Berlin, Hanover, Neustadt at the Weinstrasse, and Osnabrück, different concepts for low energy greenhouses were developed and experimental greenhouses realized [1]. These greenhouses are currently being investigated.

The concept of the low energy greenhouse in Hannover-Ahlem will also be presented, and the approaches to energy savings from an energy perspective will be analyzed.

Material und Methods

The low energy greenhouse at the horticultural research station in Hannover-Ahlem (LVG) has a floor area of 960 m^2 (length: 40 m, width: 24 m) and is divided into two compartments. The heating and ventilating systems are regulated separately. In order to save energy, the greenhouse roof is covered with double glazing (4-12-4 mm) and equipped with a day screen, a thermal screen, and a blackout system. The glazing is anti-reflex coated so that its light transmittance is slightly better than a conventional single glazing with float glass. The day screen is a lightweight fabric with approximately 20 % shading effect. This screen can be kept closed in the daytime at very low ambient temperatures and a high heating demand. In summer the thermal screen is used as shading. Therefore a material with 50 % shading effect was selected. All three systems can be closed horizontally in the longitudinal direction of the greenhouse from truss to truss. For the blackout system the side walls and gables are screened with a roll down twin system. The outer side walls and gable are covered with PMMA-quadruple sheets (32 mm), whereas the wall between the two compartments is covered with PMMA double layer plates (Alltop, 16 mm). Solar energy provides an alternative energy source by using fan-coil heat exchangers as low temperature heating system in the night and as a cooling system during the daytime. In each compartment eight devices are installed on the outer side wall. The fan-coil units are divided into two groups so that four devices are controlled separately. The air is blown out at the top so that a horizontal air recirculation is achieved in the longitudinal direction.

Heat consumption

The heat consumption is measured by magnetic inductive water flow meters (MID) from Krohne, type Optiflux 1 000 C, DN 15 that are installed in front of each compartment. The accuracy of repeated measurements is ±0.1 % (1 mm/s) and the long term stability is ±0.1 %. The operation temperature ranges from -25 to +120 °C. Thermocouples NiCr-Ni are used for the measurement of inlet and outlet temperatures, accuracy ±0.1 K. The air temperature and humidity are determined with Sensirion SHT 75, accuracy ±0.3 °C, ±1.8 % RH. The installation of all measuring devices was performed according to the "Bericht zur Bestimmung und Bewertung des Energiebedarfes von Gewächshäusern"[2]. Thus five sensors were installed at the height of 1 m in each compartment. An additional sensor was placed in the roof area above the screens. Two sensors were installed outside in a meteorological hut. Additional sensors (NiCr-Ni) were used to measure the surface temperature inside and outside the side walls, the gables, and the double glazing of the roof. Two sensors were placed onto the surface of the concrete floor and in 10 cm depth. The measurements were carried out at an interval of 15 seconds. They were stored on a hard disc and later transferred into a SQL-database. All further calculations were performed with Excel 2010.

Over all heat consumption coefficient

For the evaluation of the heat consumption, the heat consumption coefficient U_{cs} can be calculated:

$$U_{cs} = \Phi_{cs}/(A_s\,(\vartheta_i - \vartheta_e)) \qquad [\mathrm{W\,m^{-2}\,K^{-1}}] \qquad \text{(Eq. 1)}$$

The heat energy input Φ_{cs} can be determined by the water flux as well as the inlet and outlet temperatures:

$$\Phi_{cs} = V_w\,\rho_w\,c_{pw}\,(\vartheta_{in} - \vartheta_{out}) \qquad [\mathrm{W}] \qquad \text{(Eq. 2)}$$

The density and heat capacity of water can be calculated as a function of the water temperature ϑ_w using a fourth degree polynomial:

$$\rho_w\,c_{pw} = 8{,}797E^{-10}\,\vartheta_w^4 - 2{,}0118E^{-7}\,\vartheta_w^3 + 1{,}4532\,E^{-5}\,\vartheta_w^2 - 0{,}0008114\,\vartheta_w + 1{,}1714 \qquad [\mathrm{Wh\,L^{-1}\,K^{-1}}] \qquad \text{(Eq. 3)}$$

A problem occurs when taking into consideration that the surface areas of the roof, the side walls, and gables are covered with different materials. In large production greenhouses with a size of e.g. 1 to 2 ha, the portion of the sidewalls and gables in comparison to the whole surface area is small. Thus the portion of heat transfer through the roof is of most importance. It is hence necessary to estimate the heat transfer through the roof in order to be able to transfer the results to larger greenhouse areas. This is possible when the heat fluxes through the side walls and gables are calculated and subtracted from the measured heat consumption.

The heat flux through the side walls can be calculated:

$$\Phi_{sw} = \Lambda_{sw}\,A_{sw}\,(\vartheta_{swi} - \vartheta_{swe}) \qquad [\mathrm{W}] \qquad \text{(Eq. 4)}$$

and similarly for the gables:

$$\Phi_{ga} = \Lambda_{ga}\,A_{ga}\,(\vartheta_{gai} - \vartheta_{gae}) \qquad [\mathrm{W}] \qquad \text{(Eq. 5)}$$

The calculation of the heat flux through the roof follows:

$$\Phi_{ro} = \Phi_{cs} - \Phi_{sw} - \Phi_{ga} \qquad [\mathrm{W}] \qquad \text{(Eq. 6)}$$

and finally the heat consumption coefficient of the roof U_{ro} can be calculated:

$$U_{ro} = \Phi_{ro}/(A_{ro}\,(\vartheta_i - \vartheta_e)) \qquad [\mathrm{W\,m^{-2}\,K^{-1}}] \qquad \text{(Eq. 7)}$$

With a quick test [3], the efficiency of thermal screens can be evaluated without measurements of heat consumption. Using the measured air temperatures ϑ_o, ϑ_i and ϑ_a, a ratio P_{air}-value can be defined:

$$P_{air} = (\vartheta_o - \vartheta_a)/(\vartheta_i - \vartheta_a) \qquad [°\mathrm{C}] \qquad \text{(Eq. 8)}$$

Analysis of the heat transfer inside the roof

For the analysis of the heat transfer inside the roof, the heat transfer coefficient h_i can be calculated:

$$h_i = \Phi_{ro}/(A_{ro}\,(\vartheta_i - \vartheta_{roi})) \qquad [\mathrm{W\,m^{-2}\,K^{-1}}] \qquad \text{(Eq. 9)}$$

Inside the roof heat is transported by convection, long wave thermal radiation and condensation of water vapour. The heat transfer by condensation and thus the latent heat transfer Φ_{cd} is important for the heat consumption of a greenhouse.

$$\Phi_{cd} = h_{cv} / c_{pa} A_{ro} r_0 (x_a - x_{sat}) \quad [W] \quad (Eq. 10)$$

Similar to the heat transfer by convection, the heat transfer coefficient h_{cd} for condensation can be calculated:

$$h_{cd} = \Phi_{cd}/(A_{ro} (\vartheta_i - \vartheta_{roi})) \quad [W\ m^{-2}\ K^{-1}] \quad (Eq. 11)$$

If the heat transfer coefficient for condensation h_{cd} is related to the heat transfer inside the roof h_i the portion of the latent heat can be estimated:

$$p_{lat} = h_{cd} / h_i \quad [-] \quad (Eq. 12)$$

Heat transfer by air exchange

The overall heat consumption coefficient U_{cs} includes the heat transfer through the covering material as well as the heat transfer by air exchange:

$$U_{cs} = U_T + U_{air} \quad [W\ m^{-2}\ K^{-1}] \quad (Eq. 13)$$

The heat transfer by air exchange Φ_{air} includes the sensible and latent heat of the air:

$$\Phi_{air} = V_{air}\, \rho_a\, (c_{pa} (\vartheta_i - \vartheta_e) + r_0 (x_i - x_e)) \quad [W] \quad (Eq. 14)$$

A direct measurement of the heat transfer by air exchange is difficult. Thus the heat transfer through the different surfaces Q_T must be calculated:

$$\Phi_T = \Phi_{roT} + \Phi_{sw} + \Phi_{ga} \quad [W] \quad (Eq. 15)$$

The heat transfer through the roof Φ_{roT} is as follows:

$$\Phi_{roT} = \Lambda_{gl} A_{ro} (\vartheta_{roi} - \vartheta_{roe}) \quad [W] \quad (Eq. 16)$$

The heat transfer by air exchange Φ_{air} is the difference between the measured heat consumption and the heat transfer through the covering materials Φ_T:

$$\Phi_{air} = \Phi_{cs} - \Phi_T \quad [W] \quad (Eq. 17)$$

According to Equation 14, the heat transfer by air exchange can be divided into a sensible (An_{sen}) and a latent part (An_{lat}).

$$An_{sen} = c_{pa} (\vartheta_i - \vartheta_e) \quad [kJ/kg] \quad (Eq. 18)$$

$$An_{lat} = r_0 (x_i - x_e) \quad [kJ/kg] \quad (Eq. 19)$$

The latent portion p_{lat} of heat transfer can be calculated.

$$p_{lat} = An_{lat} / (An_{lat} + An_{sen}) \quad [-] \quad (Eq. 20)$$

PAR and solar transmittance

Incoming solar radiation was quantified with solarimeters (CMP 6 by Kipp and Zonen, measuring range 310–2 800 nm, zero offset < 12 W/m², temperature error (-10 °C to +40 °C) < 4 %) that were installed in each compartment at the height to eaves above the screens. An additional solarimeter was placed outside on the ridge of the greenhouse. The solar transmittance of the covering material can be estimated with this arrangement. For the measurement of the photosynthetic active radiation (PAR) three Quantum sensors (LI-190 by LI-COR Environmental, measuring range 400–700 nm, error < ±5 %) were installed in each compartment at the height of the crop canopy. An additional PAR sensor was placed outside just beside the solarimeter.

All sensors were sampled every 15 seconds. The measured values were integrated during the day from 8 AM to 5 PM. The transmittance is the ratio of the integral of inside PAR to the integral of outside PAR:

$$\tau_{PAR} = \frac{\int_{08}^{17} PARi}{\int_{08}^{17} PARe} * 100 \quad [\%] \quad (Eq. 21)$$

$$\tau_{sol} = \frac{\int_{08}^{17} soli}{\int_{08}^{17} sole} * 100 \quad [\%] \quad (Eq. 22)$$

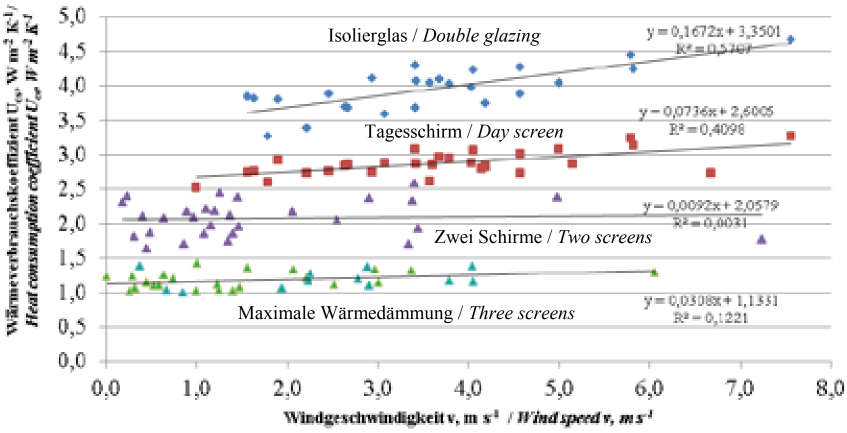
Results

In order to evaluate the heat consumption all measurements were carried out every 15 seconds and mean values were calculated for each night from 22 PM to 5 AM. The use of mean values reduces the interference caused by fluctuating weather conditions and the influence of storage capacities in the greenhouse.

Overall heat consumption coefficient

In **Figure 1**, the calculated heat consumption coefficients are shown as a function of the wind speed. As expected, there are clear differences between the double glazing with or without the addition of the different screens. Regarding the dependence on the wind speed, the heat consumption coefficients of double glazing without screens clearly increase with increasing wind speeds, whereas on the wind speed with closed screens the dependence is reduced. The slope of the regression lines is not significant. Using the measured heat consumption coefficients values for the energy saving potential of the different saving methods can be calculated. In **Table 4**, the calculated mean U_{cs}-values are shown in comparison to single glazing, using a value of U_{cs} = 7.6 W m^{-2} K^{-1} [4], as well as in comparison to single glazing and one thermal screen (U_{cs} = 4.6 W m^{-2} K^{-1}) (standard in production greenhouses). Thus the energy saving of double glazing and day screen, thermal screen and blackout system is compared to single glazing 84 %, compared to double glazing 70 % and compared to single glazing with thermal screen (standard) 74 %. With double glazing and/or two screens an en-

Fig. 1



Heat consumption coefficients U_{cs} as a function of wind speed (mean values from 22 pm to 5 am)

Table 1

List of abbreviations

Symbol *Symbol*	**Beschreibung** *Description*	**Dimension** *Dimension*
A	Fläche/*area*	m²
An	Anteil/*part*	-
cp	Wärmekapazität/*heat capacity*	J kg⁻¹ K⁻¹
d	Dicke einer Schicht/*thickness of the layer*	m
h	Wärmeübergangskoeffizient/*heat transfer coefficient*	W m⁻² K⁻¹
P	Teil/*part*	-
p	relative Anteil/*portion*	-
PAR	photosynthetisch aktive Strahlung/ *photosynthetic active radiation*	µmol m⁻² s⁻¹
R	Wärmewiderstand/*resistance of heat transfer*	m² K W⁻¹
r0	Verdampfungswärme *enthalpy of evaporation of water*	J kg⁻¹
sol	Solarstrahlung/solar radiation	W m⁻²
V	Luftwechselvolumen/*volume of air exchange*	m³ s⁻¹
V	Wasser-Durchfluss/*water flux*	m³ h⁻¹
v	Windgeschwindigkeit/*wind speed*	M s⁻¹
x	Wassergehalt der Luft/*water content of the air*	kg kg⁻¹
Δh	Enthalpie-Differenz *enthalpy difference of exchanged air*	kJ kg⁻¹
$\Delta\vartheta$	Temperaturdifferenz *temperature difference within a layer*	K
ϑ	Temperatur/*temperature*	°C
λ	Wärmeleitfähigkeit/*heat conduction coefficient*	W m⁻¹ K⁻¹
ρ	Dichte/*density*	kg m⁻³
Φ	Wärmestrom/*energy flux*	W
Λ	Wärmedurchlasskoeffizient *internal heat transfer coefficient of covering material*	W m⁻² K⁻¹
τ	Durchlässigkeit/*transmittance*	-

Table 2

List of indices

Indizes *Indices*	**Beschreibung** *Description*
a	Luft/*air*
air	Luftwechsel/*air exchange*
cd	Kondensation/*condensation*
cs	Verbrauch/*consumption*
cv	Konvektion/*convection*
e	außen, extern/*external*
ga	Giebel/*gable*
gl	Glas/*glass*
i	innen/*inside*
in	Vorlauf/*inlet*
L	Undichtigkeit/*leakage*
lat	latent/*latent*
o	oberhalb der Schirme/*above the screens*
out	Rücklauf/*outlet*
p	Druck/*pressure*
PAR	Photosynthetisch aktive Strahlung *photosynthetic active radiation (400-700 nm)*
r	Strahlung/*radiation*
ro	Dach/*roof*
s	Oberfläche/*surface*
sat	gesättigt/*saturation*
sen	sensible/*sensible*
sol	Solar/*solar*
sw	Stehwand/*side wall*
T	Transfer/*transmittance*
v	Wasserdampf/*vapour*
w	Wind/*wind*
w	Wasser/*water*

Table 3

Data for calculation

Gewächshausabmessungen (pro Abteilung)/*Greenhouse dimensions (1 compartment)*			
Grundfläche/*Greenhouse ground area*	A_{gr}	432,0	m^2
Dachfläche/*Roof area*	A_{ro}	464,4	m^2
Stehwand/*Side wall*	A_{sw}	180,0	m^2
Giebel/*Gable*	A_{ga}	62,4	m^2
Hüllfläche/*Surface area*	A_s	732,0	m^2
Konstante/*Constant*			
Spezifische Wärme der Luft/*Heat capacity of air*	c_{pa}	1,0056	$kJ\ kg^{-1}\ K^{-1}$
Verdampfungswärme von Wasser/*Energy of vaporisation of water*	r0	2257	$kJ\ kg^{-1}$
Dichte der Luft/*Density of air*	ρ_a	$-0{,}0043\ \vartheta + 1{,}2912$	$kg\ m^{-3}$
Wärmedurchlasskoeffizient von Isolierglas/*Internal heat transfer coefficient of double glass*	Λ	4,87	$W\ m^{-2}\ K^{-1}$
Wärmedurchlasskoeffizient einer Stegvierfachplatte/*Internal heat transfer coefficient of 4-layer PMMA*	Λ	2,04	$W\ m^{-2}\ K^{-2}$

Table 4

Wärmeverbrauchskoeffizienten und Einsparungen des Niedrigenergiegewächshauses
Table 4: Heat consumption coefficient U_{cs} and energy saving of the low energy greenhouse

Maßnahme zur Wärmedämmung ***Methods for energy saving***	**Gemessen** ***Measured*** **U_{cs}-Wert** **U_{cs}-value** **$W\ m^{-2}\ K^{-1}$**	**Einsparung** ***Saving*** **Isolierglas** ***double glazing*** **U_{cs} = 4,0** **%**	**Einsparung** ***Saving*** **Einfachglas** ***single glazing*** **U_{cs} = 7,6** **%**	**Einsparung** ***Saving*** **Einfachglas + Energieschirm** ***single glass + thermal screen*** **U_{cs} = 4,6** **%**
Isolierglas *Double glazing*	4,0	0	48	14
Isolierglas + Tagesschirm *Double glas + day screen*	3,0	27	62	38
Isolierglas + zwei Schirme *Double glass + double screens*	2,1	47	72	54
Isolierglas + drei Schirme *Double glass + three screens*	1,2	70	84	74

ergy saving of 72 and 54 % is achieved. With the day screen the energy saving is 62 and 38 %. Double glazing without screens has an energy saving of 48 and 14 %.

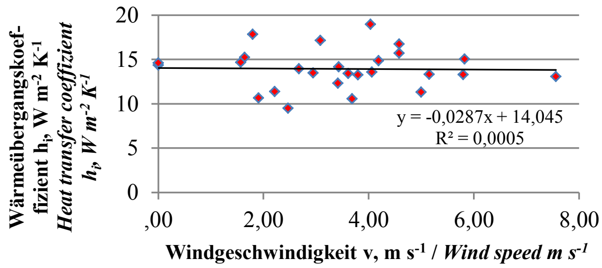
Heat transfer inside the roof

Using Equation 9 a heat transfer coefficient can be calculated for the heat transfer h_i inside the roof. **Figure 2** shows an example for the calculated heat transfer coefficients as a function of wind speed. As expected the heat transfer coefficient is not influenced by wind speed. The slope of the regression line is not significant. In the time from December 17th 2011 to January 12th, 2012 the mean value was $h_i = 14.0\ W\ m^{-2}\ K^{-1}$. According to literature [4] the heat transfer coefficient depends on the heating system and the evapotranspiration of the crop in addition to the latent heat transfer to the covering material. As the fans of the heat exchangers are controlled by the climate computer, the internal air speed and air movement are not constant. This might have an influence on the convective heat transfer. With all screens closed this influence is very small and could not be detected by the measurements.

Heat transfer by condensation inside the roof.

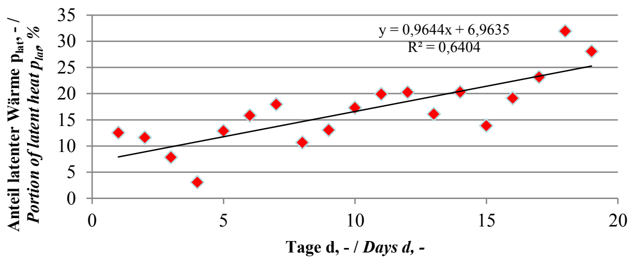
Besides convection the heat transfer by condensation inside the roof is important and will mainly be influenced by the evapotranspiration of the crop. The latent portion can be estimated using equations 10 through 12. In **Figure 3** one can see the relative portion of latent heat transfer as a function of time. At day 1 the greenhouse was empty. At day 5 a new crop had been potted and put into the greenhouse. During crop growth, the portion of latent heat increased again. A dependency on the leave area index or irrigation cycles could not be detected because the condensation is also influenced by outside air temperature.

Fig. 2



Heat transfer coefficient inside the roof (hi) (mean values from 22 pm to 5 am)

Fig. 3



Portion of latent heat at the heat transfer (plat) inside the roof (mean values from 22 pm to 5 am) (days 1 to 4 without a crop, from day 5 with new potted plants)

Influence of condensation on the heat consumption coefficient

In order to evaluate the influence of the evapotranspiration on the heat consumption it is necessary to look into the heat transfer through the roof more thoroughly. On its way from the inside to outside the heat has to pass different resistances. These resistances can be calculated as the invers of the heat transfer coefficients. In **Table 5** these values are shown. For the applied energy saving methods the U_{cs}–values were used to calculate the resistance $1/U_{cs}$. Since these resistances are series-connected, single resistances can be calculated (**Table 5**, third column). For the heat transfer inside the roof a heat transfer coefficient h_i = 14 W m^{-2} was measured. As a simplification the heat transfer coefficient can be determined without condensation as h_i = 8 W m^{-2} [4]. Under these assumptions it is possible to calculate the increase of heat transfer by condensation (**Table 5**, fifth column). This example demonstrates that by using double glazing the condensation increases the heat transfer by 18 % and by closing all three screens only 6 %. In this calculation the heat transfer by air exchange was neglected.

Heat transfer by air exchange

All greenhouses have leakages. These leakages may be located at the ventilators or at the glazing bars. A quantitative evaluation is difficult. Using equations 13 through 17 the heat flux by air exchange can be calculated. In **Figure 4** the heat consumption coefficient for air exchange is shown as a function of the wind speed. The slope of the regression line is significant. The values are valid for double glazing without screens. When the screens are closed no heat consumption by air exchange can be detected. The result is shown in **Figure 5**. The values do not depend on wind speed. There is only a scattering of the heat consumption coefficients around the zero line. According to Equations 14-16 the heat flux by air exchange was calculated as a remaining heat flux. All errors calculating the heat flux through the roof, the side walls and gables are included in the result. Closing the three screens will not only reduce the heat transfer through the covering material but also the heat transfer by air exchange significantly.

Portion of latent heat at the heat flux by air exchange

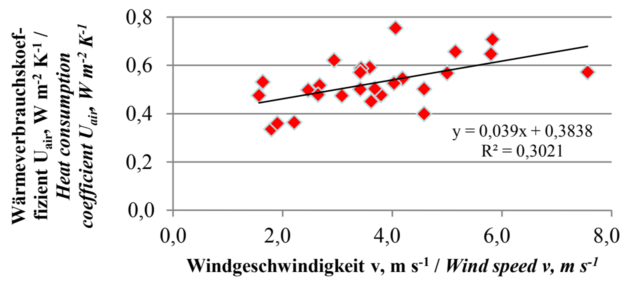
According to Equation 14 sensible and latent heat are transferred by air exchange. Again the portion of latent heat depends

Table 5

Influence of condensation (latent heat transfer) on the heat consumption (assumption: without condensation hi = 8; with condensation hi = 14 W m^{-2} K^{-1})

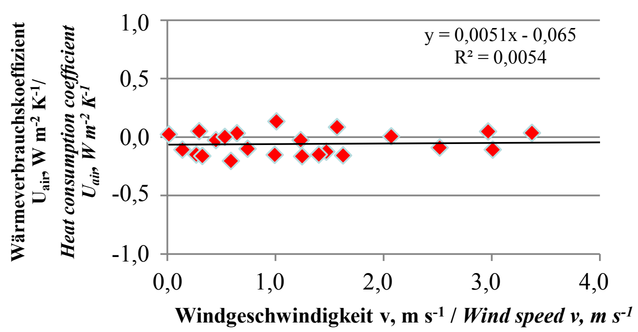
	U_{cs} gemessen *measured* W m^{-2} K^{-1}	Widerstände *Heat resistance* $1/U_{cs}$ hi = 14	Widerstände *Heat resistance* einzeln *single*	Widerstände *Heat resistance* $1/U_{cs}$ hi = 8	U_{cs} berechnet *calculated* W m^{-2} K^{-1}	Einfluss Kondensation *increase by latent heat* %
Isolierglas *Double glazing*	4,0	0,25	0,18	0,30	3,3	17,7
Isolierglas + Tagesschirm *Double glazing + day screen*	3,0	0,33	0,08	0,39	2,6	13,8
Isolierglas + zwei Schirme *Double glazing + double screens*	2,1	0,48	0,14	0,53	1,9	10,1
Isolierglas + drei Schirme *Double glazing + three screens*	1,2	0,83	0,36	0,89	1,1	6,0
Wärmeübergangskoeffizient innen h_i *Heat transfer coefficient inside*	14,0	0,07	0,07	0,13	8,0	

Fig. 4



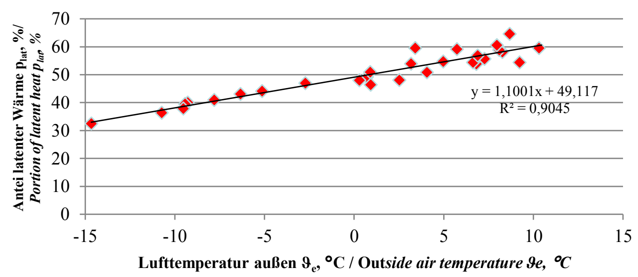
Heat consumption coefficient for air exchange (U_{air}) through leakages as a function of wind speed, double glazing (screens open) (15.12.2011 - 12.01.2012)

Fig. 5



Heat consumption coefficient for air exchange through leakages (U_{air}) as a function of wind speed, double glazing and three thermal screens (mean values from 22 pm to 5 am)

Fig. 6



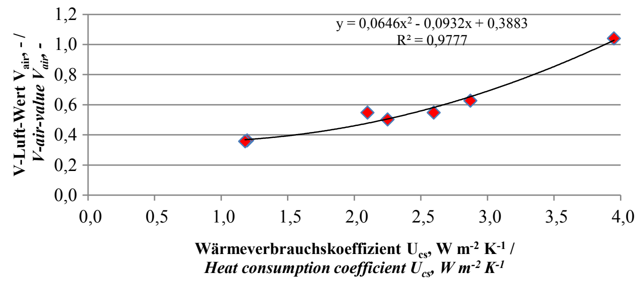
Portion of latent heat at the heat consumption (p_{lat}) by air exchange as a function of outside air temperature (mean values from 22 pm to 5 am, 26.01. – 13.03.2012)

on the evapotranspiration of the crop. In **Figure 6** the portion of latent heat flux by air exchange is shown as a function of outside air temperature. There is a clear dependence of outside air temperature. The slope of the regression line is significant. At outside air temperatures above 0 °C the scattering around the regression line is increased.

V_{air}-value to estimate the efficiency of thermal screens

As the measurement of heat consumption is expensive and reliable results are only possible under constant climate conditions

Fig. 7



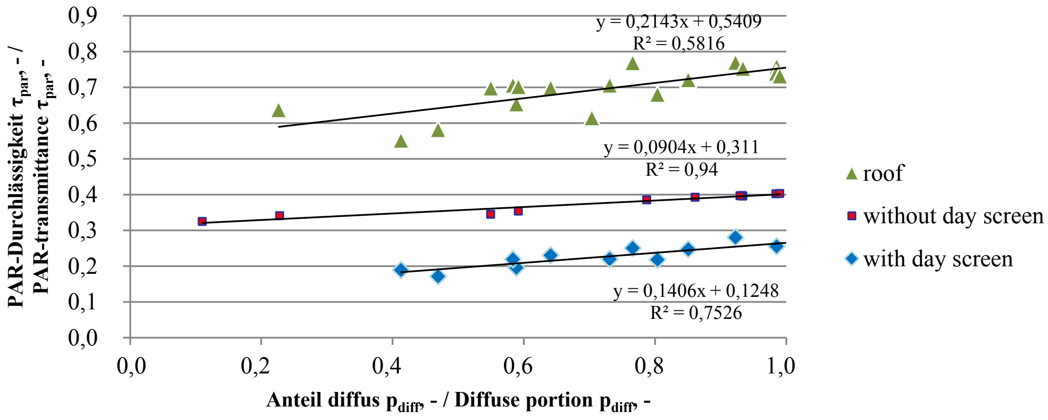
V-air-value (V_{air}) as a function of the heat consumption coefficient (U_{cs}), mean values of measurements with double glazing, double glazing with day screen, double glazing with two screens and double glazing with three screens

the calculation of the V_{air}-value using Equation 8 was tested. The results are shown in **Figure 7** as a function of the heat consumption value U_{cs}. The results can be connected using a second polynomial degree. The slope of the regression line is larger at larger U_{cs}–values, indicating a better accuracy compared to low U_{cs}–values. Thus this method is suitable for one thermal screen. For two or three screens the differences of the V_{air}-value decrease. With U_{cs}–values below 2.5 this method is too inaccurate.

PAR transmittance

The results of the heat consumption measurements show that with double glazing and three thermal screens a significant reduction of energy consumption is possible. It is important to determine how the applied saving methods reduce the PAR transmittance especially in wintertime. **Figure 8** shows the results of PAR transmittance in the time from February 2nd to March 3rd 2012 as a function of the diffuse portion of solar radiation. The results demonstrates that for a north-south-orientated greenhouse the PAR transmittance depends on the portion of diffuse radiation. In winter time at a low solar incident angle the angle of inclination for direct radiation is unfavourable. Therefore the transmittance (of the roof) measured above the screens is only 60 %. For diffuse radiation the transmittance is 75 %. This difference is even larger in January. Here, the transmittance for direct radiation is around 45 %. **Figure 8** shows that the PAR transmittance in the height of the crop canopy is reduced to 40 % for diffuse radiation and 30 % for direct radiation. This very low transmittance is caused by the packages of folded screens. The package size is about 0.4 m at 4 m truss distance. Furthermore the greenhouse has been constructed for full snow load. The construction is therefore heavier than for a common production greenhouse. The heavier construction causes more shading. Additionally the installed artificial lighting system is reducing the PAR transmittance too. If the day screen is closed during day time there is an additional reduction of the transmittance by 35 %.

Fig. 8



AR-transmittance (par) of a greenhouse north-south orientated, roof (above the screens), at the height of plant canopy with and without day screen (08.02.–03.03.2012)

Conclusions

The investigations of the low energy greenhouses in LVG Hannover-Ahlem have shown that with the taken heat insulation measures the energy consumption can be significantly lowered. In comparison to a single-glazed greenhouse the determined savings are over 80 %, compared to a greenhouse with single glazing and thermal screen the energy saving is still 70 %. With the methodological approach presented, it is possible to analyze the heat flows more accurately. The inner heat transfer coefficient can be determined and the amount of latent heat in the heat transfer calculated. The value of latent heat obtained, however, depends on the evapotranspiration of the crop and therefore cannot be generalized. The calculation example in Table 4 shows that with increasing thermal insulation the influence of the latent heat transfer on the heat consumption decreases. The determination of the heat flow by air exchange through leakages as remainder of the individual transmitted heat flows is inaccurate and provides zero values for double glazing and three thermal screens.

The calculated energy savings are valid under constant conditions with temperature differences inside - outside greater than 10 K. With fluctuating day-night temperatures, heat storage capacities of the greenhouse play a greater role. When lowered night temperatures were used under normal operation, U_{cs}-values of 0.6 W m^{-2} K^{-1} were obtained. This hints to possible energy savings by dynamic control strategies that are currently being investigated. As a result of energy-saving methods a higher humidity occurs caused by a reduced rate of condensation at the greenhouse cover due to double glazing and thermal screens. At night, humidity values of over 95 % R.H. were sometimes measured. So far, no negative impact on the crop has been observed. But it must be clarified in further experiments at which humidity level the risk of infection by fungal diseases will increase.

The measured PAR transmittance is too low for potted plants in wintertime, so that the implementation of the low energy greenhouses in practice requires a higher PAR transmittance. Several improvements are necessary. The greenhouse roof must consist of narrow constructional parts and larger dimensions of glazing sheets. The thermal screens and the blackout system must be constructed as a wire supported push-pull system using racks and pinions. These systems have smaller packages when opened, causing less shadow. The side walls should be screened with roll tube screens. The blackout system has been changed accordingly. The orientation of the greenhouse should be east-west to achieve a higher PAR transmittance during wintertime.

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