Wet Screens

Characterization of physical properties of screens and Quantification of their effect on greenhouse energy use

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KAS ALS ENERGIEBRON

Referaat
De toepassing van Het Nieuwe Telen in Nederlandse kassen is sterk afhankelijk van het gebruik van één of meerdere beweegbare schermen. Schermen beïnvloeden ook de beheersing van het kasklimaat door effecten op uitstraling en lucht- en vochtuitwisseling onder en boven het scherm. Dit heeft direct invloed op de energiebesparing. De doelstellingen van het project waren het kwantificeren van de schermeigenschappen door gestandaardiseerde metingen: thermische eigenschappen zoals emissie, aerodynamische eigenschappen zoals luchtdoorlatendheid en vochttransport. Uit de gemeten schermeigenschappen kan vervolgens de totale potentiële energiebesparing worden berekend onder vooraf gedefinieerde omstandigheden. Hiermee wordt een objectieve vergelijking van schermmaterialen onder droge en natte omstandigheden mogelijk. Hierdoor krijgen telers meer inzicht in schermeigenschappen en kunnen ze een weloverwogen keuze maken voor hun investeringen en gebruik in de praktijk. De resultaten laten zien dat schermen met een lage permeabiliteit en een lage emissie de grootste energiebesparing opleveren.

Abstract
The application of new cultivation techniques (Het Nieuwe Telen) in Dutch greenhouses heavily relies on using one or more movable screens. Screens also affect the control of the greenhouse climate by radiation exchanges and air and humidity exchanges between the lower and upper part of the screens. This directly influences energy saving. The objectives of the project were the quantification of the screen properties by standardised measurements: thermal properties such as emissivity, aerodynamic properties such as air permeability and humidity transport characteristics. From the measured properties the overall potential energy saving can then be calculated under defined conditions for an objective comparison of the performance of different screen materials in dry and wet conditions. This helps growers to understand more about screen properties and allows them to make an informed choice of investment and practical usage. The results show that screens low permeability and low emissivity give highest energy saving.

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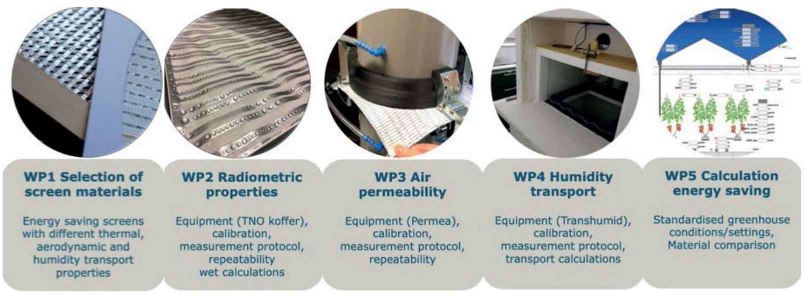
Summary

The application of new cultivation techniques (Het Nieuwe Telen) in Dutch greenhouses in recent years heavily relies on using one or more movable screens. Screens also affect the control of the greenhouse climate, which is highly dependent on the air and humidity exchange between the upper and lower compartments of the greenhouse, as they are separated by the screens. This air and humidity exchange is partly controlled by additional equipment (e.g. mechanical dehumidification) or other control actions (e.g. screen gaps), but experiments have shown that a significant part of this energy flow occurs through the screens, even when they are fully closed (Hemming *et al.* 2017). This means that part of the air exchange through the screens is not controllable, and this uncontrollable amount should be considered as one of the discriminating properties of a screen.

In the current project, new standardised protocols for the determination of the thermal, aerodynamic and humidity transport properties have been developed for screen materials, also under wet conditions. Suitable measurement equipment has been developed and calibrated, standardised and repeatable measurement protocols have been developed and screen properties have been measured of different types of energy saving screens. Besides, where needed, modifications have been made to the dynamic greenhouse climate simulation model Kaspro (de Zwart, 1996) were applied to better describe the energy and mass exchange through a screen in wet and dry conditions. With the re-established measurements of screen properties and an improved simulation model energy saving calculations have then been carried out for different screen samples. An analysis and sensitivity exploration has been made to give insights for suppliers and growers.



In workpackage 1 different energy saving screen materials have been selected with expected different material properties (§2.1).

In workpackage 2 the **thermal properties** of the different screens have been determined (§2.3). A measurement equipment was already in place to determine the thermal properties of screen materials, the TNO emissivity device. The results show that we can measure the thermal properties of dry materials with high repeatability on a randomly selected spot on the materials on the TNO emissivity device. We are not able to measure thermal properties of wet materials, instead we calculate them in the KASPRO model: the measured emissivity dry is used as input, the emissivity is changed gradually depending on the humidity transport characteristics and the dewpoint, complete wet materials have an 0.9 emissivity. Results show further that investigated materials differ is thermal properties. A **low emissivity** and a **high reflectivity** for thermal infrared radiation of a screen is correlated to low radiative energy loss. The measured permeability characteristics are input to the KASPRO model to calculate the overall potential energy saving.

In workpackage 3 the **aerodynamic properties** of the different screens have been determined (§2.4 §3.3). A new measurement equipment is developed in the form of a small wind tunnel, which can determine the air permeability of screen materials, the Permea device. The results show that we can measure air permeability properties of dry and wet materials with high repeatability on a randomly selected spot on the materials on the Permea device. Results show further that investigated materials differ is their air permeability properties. Some materials show higher permeability if wet, others show a lower permeability if wet. A **low air permeability** of a screen is correlated to a low loss of sensible (and latent) heat. The measured permeability characteristics are input to the KASPRO model to calculate the overall potential energy saving.

In workpackage 4 the **humidity transport properties** of the different screens have been determined (§2.2 §3.1). A new measurement device is developed to determine the humidity transport through screen materials, the TransHumid box. Results show that we can measure humidity transfer properties of dry and wet materials with good repeatability on a randomly selected spot on the TransHumid box. Results further show that investigated materials differ in their humidity transport properties. A **low humidity transport** of a screen is correlated to a low loss of latent heat. Humidity transfer is high for materials with high air permeability, on materials with low air permeability the fraction of humidity transported by hygroscopy becomes more important. The measured humidity transport characteristics are input to the KASPRO model to calculate the overall potential energy saving.

The measurements of all properties are essential to give insights for manufacturers for further material development.

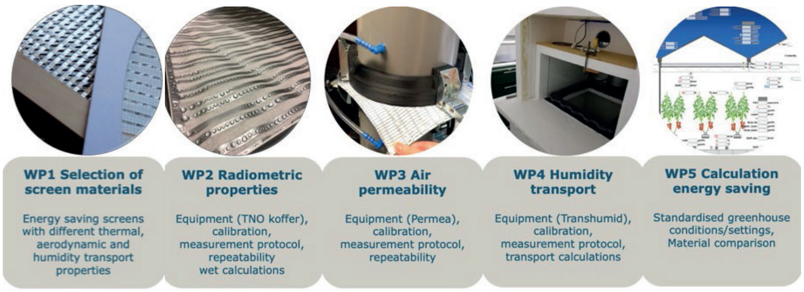
Finally, in workpackage 5 an analysis of the **overall potential energy saving** is given. Simulation results show that the lowest energy use can be achieved if the screens have a **low air permeability**. To avoid the hours with a too high **humidity**, **screen gaps** can be used. An alternative for screen gaps, which may lead to an unwanted horizontal homogeneity, are the **screen fans**. Just like screen gaps, screen fans deliberately increase the air exchange between the top and bottom compartment of the greenhouse. As the intended effect is equal, the enlarged energy consumption by using screen fans to reduce humidity is almost equal to using screen gaps. Using **mechanical dehumidification** is a completely different technique to control the humidity as it aims at reduction of the sensible and latent heat losses from humidity control. Although it increases the heat demand to some extent, it largely reduces the energy demand as the major part of the heat demand can be provided with the sensible and latent heat that is captured during the dehumidification process.

Screen manufacturers should focus on the development of screens with low air permeability combined with high reflectivity for thermal infrared radiation (low emissivity) for highest energy saving. Information on different screen properties and calculations of standardised energy saving potentials help **growers** in their choice of screen types and the energy saving usage in daily practice.

Samenvatting

De toepassing van nieuwe teelttechnieken (Het Nieuwe Telen) in de Nederlandse kassen in de afgelopen jaren leunt sterk op het gebruik van één of meerdere beweegbare schermen. Schermen hebben ook invloed op de regeling van het kasklimaat, dat sterk afhankelijk is van de lucht- en vochtuitwisseling tussen het bovenste en onderste compartiment van de kas, gescheiden door de schermen. Deze lucht- en vochtuitwisseling wordt deels geregeld door extra apparatuur (bijv. mechanische ontvochtiging) of andere regelacties (bijv. schermkieren), maar experimenten hebben aangetoond dat een aanzienlijk deel van deze energiestroom door de schermdoeken zelf plaatsvindt, ook wanneer deze volledig gesloten zijn (Hemming *et al.* 2017). Dit betekent dat een deel van de luchtuitwisseling door de schermen niet controleerbaar is, en deze oncontroleerbare hoeveelheid luchtuitwisseling moet worden beschouwd als een belangrijke schermeigenschap.

In het huidige project zijn nieuwe gestandaardiseerde protocollen ontwikkeld voor het bepalen van de thermische, aerodynamische en vochttransport eigenschappen voor schermmaterialen, ook onder natte omstandigheden. Er is geschikte meetapparatuur ontwikkeld en gekalibreerd, er zijn gestandaardiseerde en herhaalbare meetprotocollen ontwikkeld en schermeigenschappen van verschillende typen energiebesparende schermen zijn gemeten. Daarnaast zijn waar nodig aanpassingen gedaan aan het dynamische kasklimaat simulatiemodel Kaspro (de Zwart, 1996) om de energie- en massa-uitwisseling door een scherm in natte en droge omstandigheden beter te beschrijven. Met de opnieuw vastgestelde metingen van schermeigenschappen en een verbeterd simulatiemodel zijn vervolgens energiebesparingsberekeningen uitgevoerd voor verschillende schermmaterialen. Er is een analyse gemaakt om leveranciers en telers inzicht te geven in het effect van schermeigenschappen op de energiebesparing.



In werkpakket 1 zijn verschillende energiebesparende schermmaterialen geselecteerd met verschillende materiaaleigenschappen (§2.1).

In werkpakket 2 zijn de **thermische eigenschappen** van de verschillende schermen bepaald (§2.3, §3.2). Er was al een meetapparaat aanwezig om de thermische eigenschappen van schermmaterialen te bepalen, het TNO-emissiviteitsapparaat. De resultaten laten zien dat we de thermische eigenschappen van droge materialen met hoge herhaalbaarheid kunnen meten op een willekeurig geselecteerde plek op de materialen met het TNO-emissiviteitsapparaat. We kunnen de thermische eigenschappen van natte materialen niet meten, in plaats daarvan berekenen we ze in het KASPRO-model: de gemeten emissiviteit droog van een scherm wordt gebruikt als input van het model, de emissiviteit wordt geleidelijk veranderd, afhankelijk van de gemeten vochttransportkarakteristieken en het dauwpunt van het scherm, volledig natte schermen hebben een emissiviteit van 0,9. De resultaten tonen verder aan dat de onderzochte materialen verschillen in thermische eigenschappen. Een **lage emissiviteit** en een **hoge reflectiviteit voor thermische infraroodstraling** van een scherm is gecorreleerd aan een laag stralingsenergieverlies. De gemeten permeabiliteitskenmerken worden ingevoerd in het KASPRO-model om de totale potentiële energiebesparing te berekenen.

In werkpakket 3 zijn de **aerodynamische eigenschappen** van de verschillende schermen bepaald (§2.4, §3.3). Er is een nieuwe meetapparatuur ontwikkeld in de vorm van een kleine windtunnel, die de luchtdoorlatendheid van schermmaterialen kan meten, het Permea-apparaat. De resultaten laten zien dat we de luchtdoorlatendheid eigenschappen van droge en natte materialen kunnen meten met een hoge herhaalbaarheid op een willekeurig geselecteerde plek op de materialen op het Permea-apparaat. De resultaten tonen verder aan dat de onderzochte materialen verschillen in hun luchtdoorlatende eigenschappen. Sommige materialen vertonen een hogere doorlatendheid als ze nat zijn, andere vertonen een lagere doorlatendheid als ze nat zijn. Een **lage luchtdoorlatendheid** van een scherm hangt samen met een laag verlies aan voelbare (en latente) warmte. De gemeten permeabiliteitskenmerken worden ingevoerd in het KASPRO-model om de totale potentiële energiebesparing te berekenen.

In werkpakket 4 zijn de **vochttransport eigenschappen** van de verschillende schermen bepaald (§2.2, §3.1). Voor het bepalen van het vochttransport door schermmaterialen is een nieuw meetinstrument ontwikkeld, de TransHumid box. De resultaten laten zien dat we de vochtdoorlatendheid eigenschappen van droge en natte materialen kunnen meten met een goede herhaalbaarheid op een willekeurig geselecteerde plek op de TransHumid-box. De resultaten tonen verder aan dat de onderzochte materialen verschillen in hun vochttransport eigenschappen. Een **laag vochttransport** van een scherm hangt samen met een laag verlies aan latente warmte. Het vochttransport is hoog voor materialen met een hoge luchtdoorlatendheid, op materialen met een lage luchtdoorlatendheid wordt de vochtfractie die door hygroscopie wordt getransporteerd belangrijker. De gemeten vochttransport karakteristieken worden ingevoerd in het KASPRO-model om de totale potentiële energiebesparing te berekenen.

De metingen van alle eigenschappen zijn essentieel om fabrikanten inzichten te geven voor verdere materiaalontwikkeling.

Tot slot wordt in werkpakket 5 een analyse gegeven van de **totale potentiële energiebesparing**. Simulatieresultaten laten zien dat het laagste energieverbruik kan worden bereikt als de schermen een lage luchtdoorlatendheid hebben. Om uren met een te **hoge luchtvochtigheid** te vermijden, kunnen **schermkieren** worden gebruikt. Een alternatief voor schermkieren, die mogelijk tot een ongewenste horizontale homogeniteit kunnen leiden, zijn de **schermventilatoren**. Net als schermkieren vergroten schermventilatoren bewust de luchtuitwisseling tussen het boven- en ondercompartiment van de kas. Omdat het beoogde effect gelijk is, is het verhoogde energieverbruik door schermventilatoren bijna gelijk aan het gebruik van schermkieren om de luchtvochtigheid te verlagen. Het gebruik van **mechanische ontvochtiging** is een heel andere techniek om de vochtigheid te regelen, aangezien het erop gericht is de voelbare en latente warmteverliezen door vochtregeling te verminderen. Hoewel het de warmtevraag in eerste instantie verhoogt, vermindert het de totale energievraag in hoge mate, omdat het grootste deel van de energievraag kan worden ingevuld door de voelbare en latente warmte die wordt opgevangen tijdens het ontvochtigingsproces.

Schermfabrikanten zouden zich moeten concentreren op de ontwikkeling van schermen met een lage luchtdoorlatendheid gecombineerd met een hoge reflectiviteit voor thermische infraroodstraling (lage emissiviteit) voor de hoogste energiebesparing. Informatie over verschillende schermeigenschappen en berekeningen van gestandaardiseerde energiebesparing mogelijkheden helpen **telers** bij de keuze van schermtypes en het verlagen van het energiegebruik in de dagelijkse praktijk.

1 Introduction

The application of new cultivation techniques (Het Nieuwe Telen) in Dutch greenhouses in recent years heavily relies on using one or more movable screens. Screens also affect the control of the greenhouse climate, which is highly dependent on the air and humidity exchange between the upper and lower compartments of the greenhouse, as they are separated by the screens. This air and humidity exchange is partly controlled by additional equipment (e.g. mechanical dehumidification) or other control actions (e.g. screen gaps), but experiments have shown that a significant part of this energy flow occurs through the screens, even when they are fully closed (Hemming *et al.* 2017). This means that part of the air exchange through the screens is not controllable, and this uncontrollable amount should be considered as one of the discriminating properties of a screen.

In a former project “Energy saving screen materials” a methodology was developed to determine the overall energy saving of commercial screens under a set of standard defined conditions and based on the measured physical properties of energy saving screens relevant in greenhouses: thermal properties (radiative energy losses), aerodynamic properties (air permeability, convective energy losses of sensible and latent heat) and humidity transport properties. This allowed for the comparison of the performance of different screens materials of different suppliers with each other. This has helped growers to understand more about screen properties and allowed them to make an informed choice of investment. However, all protocols to measure the relevant physical properties of the energy saving screen materials in the lab, were earlier developed and applied to dry materials. In greenhouse practice, energy saving screens are wet for a large proportion of the time during the growing cycle. The reason is that the screen, when closed, divides the greenhouse volume in two compartments with different temperature and humidity conditions. The top compartment, in contact with the roof cover and with some leakage to the outside air is cold and relatively dry, whereas the main greenhouse air compartment is warm and humid, thanks to the heating system and crop transpiration. The cold top compartment cools down the screen to temperatures below the dewpoint of the greenhouse air. With this temperature below dew point, condensation occurs on the bottom face of the screen. As it is likely that the physical properties of the screen will change when it becomes wet, the actual energy saving of a screen might be significantly different than the computed energy saving based on the screen properties in dry conditions. Especially the radiative properties (emissivity, transmissivity and reflectivity of thermal infrared (TIR) radiation) are likely to change and maybe also the aerodynamic properties (air permeability). And if aerodynamic properties change under wet conditions, also the humidity transport capacity will change and finally the overall energy saving properties.

In the current project, new protocols for the determination of the thermal, aerodynamic and humidity transport properties have been developed for wet screen materials. Suitable measurement equipment has been developed and calibrated, standardised and repeatable measurement protocols have been developed and screen properties have been measured of different types of energy saving screens. Besides, where needed, modifications have been made to the dynamic greenhouse climate simulation model Kaspro (de Zwart, 1996) were applied to better describe the energy and mass exchange through a screen in wet and dry conditions. With the re-established measurements of screen properties and an improved simulation model energy saving calculations have then been carried out for different screen samples. An analysis and sensitivity exploration has been made to give insights for suppliers and growers.

2 Material and methods

2.1 Selection energy saving screen materials

In the same approach as deployed in the former screen-project, a wide range of energy screens with different properties (transparent, aluminized, different porosities, black-out screens, etc.) made by different producers have been selected. This includes some screens which were used in the former “Energy saving screen materials” project and a group of new screens. The screens were provided by the companies participating in the present project. The reason to use again some screen samples of the former project is to use the dry measurements already done in these samples to verify the changes under wet conditions for a larger range of screens and to cover a wide range of screen types.
In total, 14 screens have been used for the measurements (Figure 1).

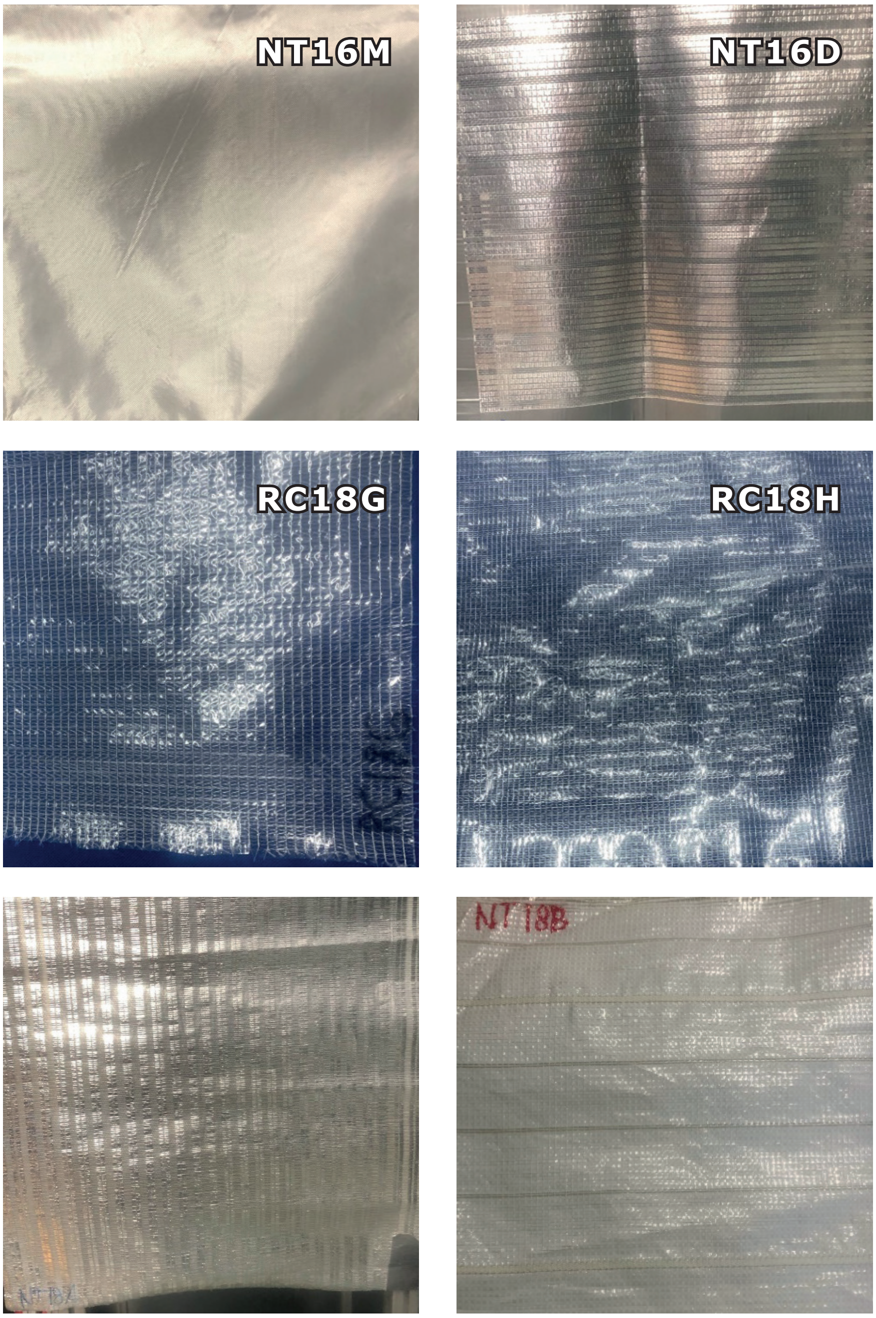


Figure 1 *Screen samples used in the project.*

2.2 Humidity transport measurements

2.2.1 Design and assembly of a new humidity transport device (TransHumid device)

If humidity is transferred through a screen material, latent heat is lost from the greenhouse. The goal of this workpackage is to quantify the amount of humidity transfer and therefore latent heat loss through different types of screens.

During the former project, screen samples have been sent to Sweden to be measured at Swerea Institute. As the sending and measurement was elaborative and time consuming it was agreed with the participating companies that a new device for the measurement of humidity transport properties would be designed and built. Having such a device at hand enables to study the moisture transport under various conditions. This was in particular needed in this project since the air exchange and humidity transport was supposed to be determined for a dry and a wet screen. The Swerea institute had a protocol only developed for wet screen conditions.

The new humidity transport device was designed as two air spaces separated by the screen sample of interest. The temperature and humidity settings can be specified for each of the spaces separately. Figure 2 shows a sketch of the principle and Figure 3 shows a picture of the realized device.

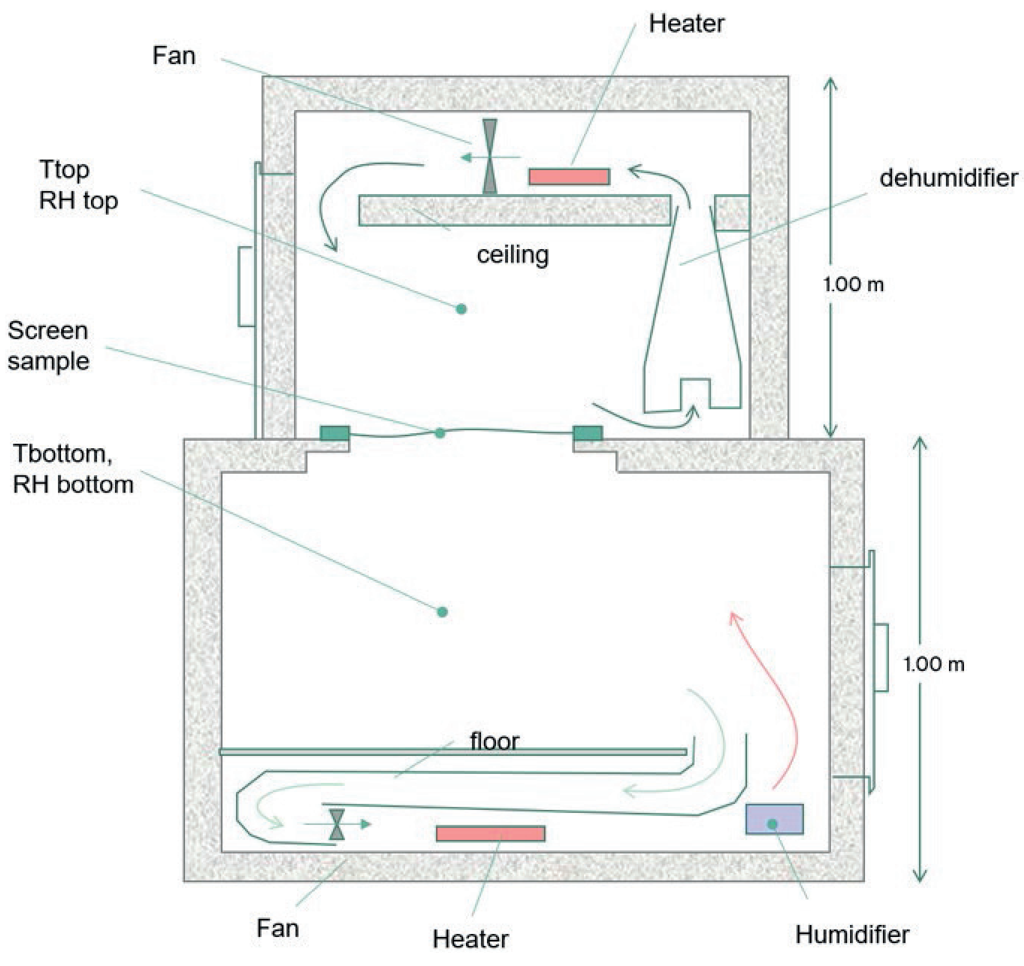


Figure 2 *Principle sketch of the TransHumid device where moisture is transported through the screen sample from the bottom to the top-compartment due to a temperature and humidity gradient.*

The lower box mimics the climate conditions in the main compartment of a greenhouse in which an energy saving screen is used, that is the warm and humid volume. The upper box mimics the temperature and humidity conditions above the screen in customary winter-time conditions.

Figure 3 *Picture of the TransHumid device as it is placed in a climatized room in one of the WUR laboratories.*

To realize a warm and humid bottom compartment, the compartment is equipped with
- A heating element (resistor-wire), to rise temperature to the desired value.
  The power to the heating element is controlled by an industrial PID-controller comparing the measured temperature in the bottom compartment with the set point. Based on the observation of the temperature being too low or too high, a smaller or bigger fraction of full AC-power cycles is applied to the heating element. In this way a linear controllable heating power of 0 to 64 W can be applied.
- A humidifier, to rise the absolute humidity to the desired value.
  The humidifier consists of an ultrasonic vibrating element that produces very small droplets of water that evaporate in the air. As the vibration is a mechanical process it adds energy to the system. The amount of moisture added to the bottom compartment is controlled by a short periods of on/off duty cycles of ultrasonic evaporators.
- A small fan to gently homogenise the climate in the box.

The pictures in Figure 4 show details of the bottom box.

The upper box mimics the climate conditions in the top compartment of a greenhouse in which an energy saving screen is used. It is a cold and drier volume.
To achieve these conditions the top compartment is fitted with:
- A cooler/condenser, in which cold water (0-5°C) is circulating,
- A heater to adjust the sensible/latent ration of the cooling and dehumidification process.
- A fan to gently homogenise the climate.

Pictures on details of the upper compartment are shown in Figure 6.

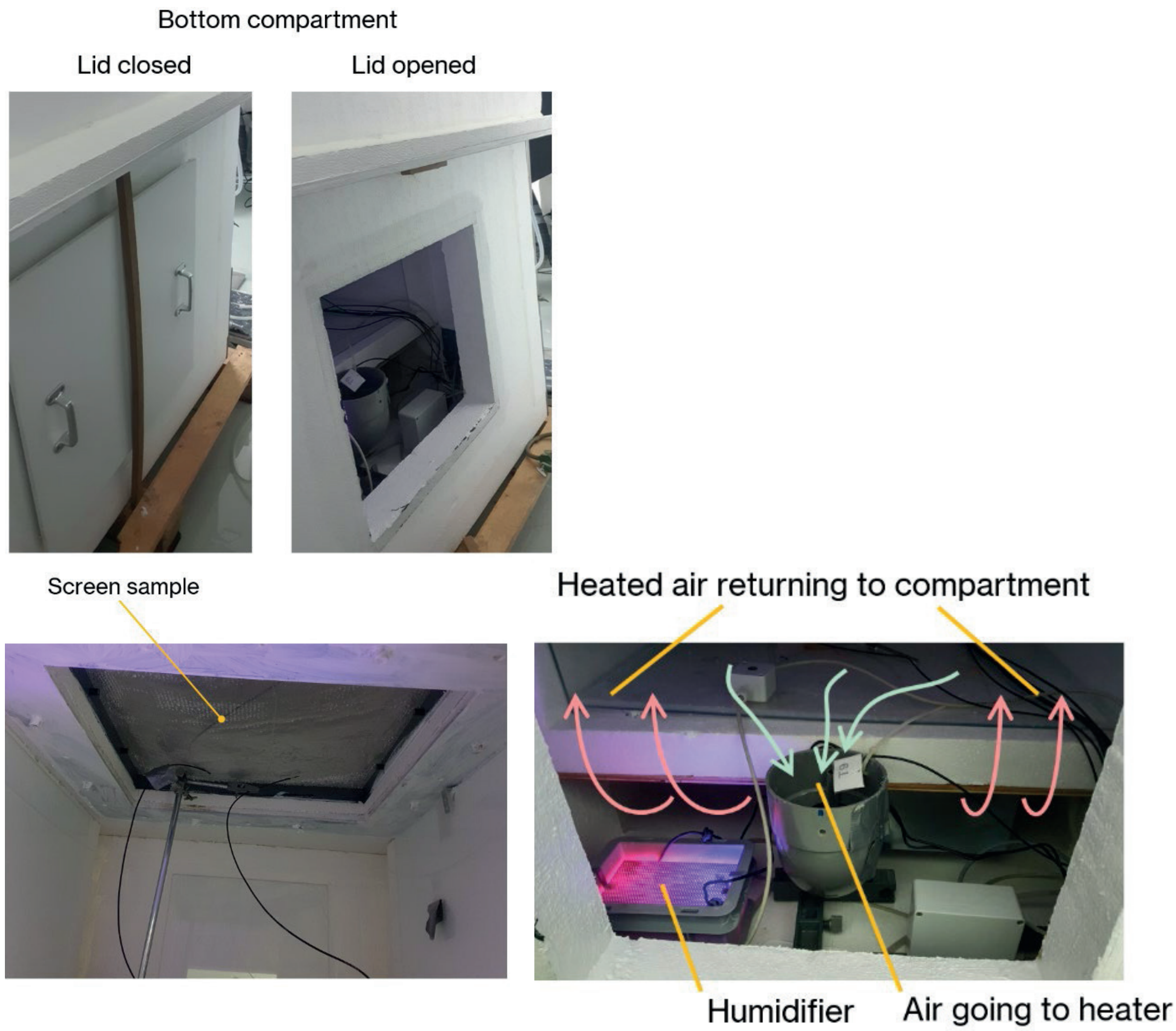


Figure 4 *Detailed pictures of the inner of the bottom compartment.*

The rate at which water evaporates is determined by keeping track of the weight reduction of a tank that replenishes the water level in the small container with the ultrasonic humidifiers (plural as for highly permeable screens 2 or even 3 humidifiers are used in parallel). Figure 5 shows this weighing scale.

Figure 5 *Tank from which water flows to the humidifier on a scale.*

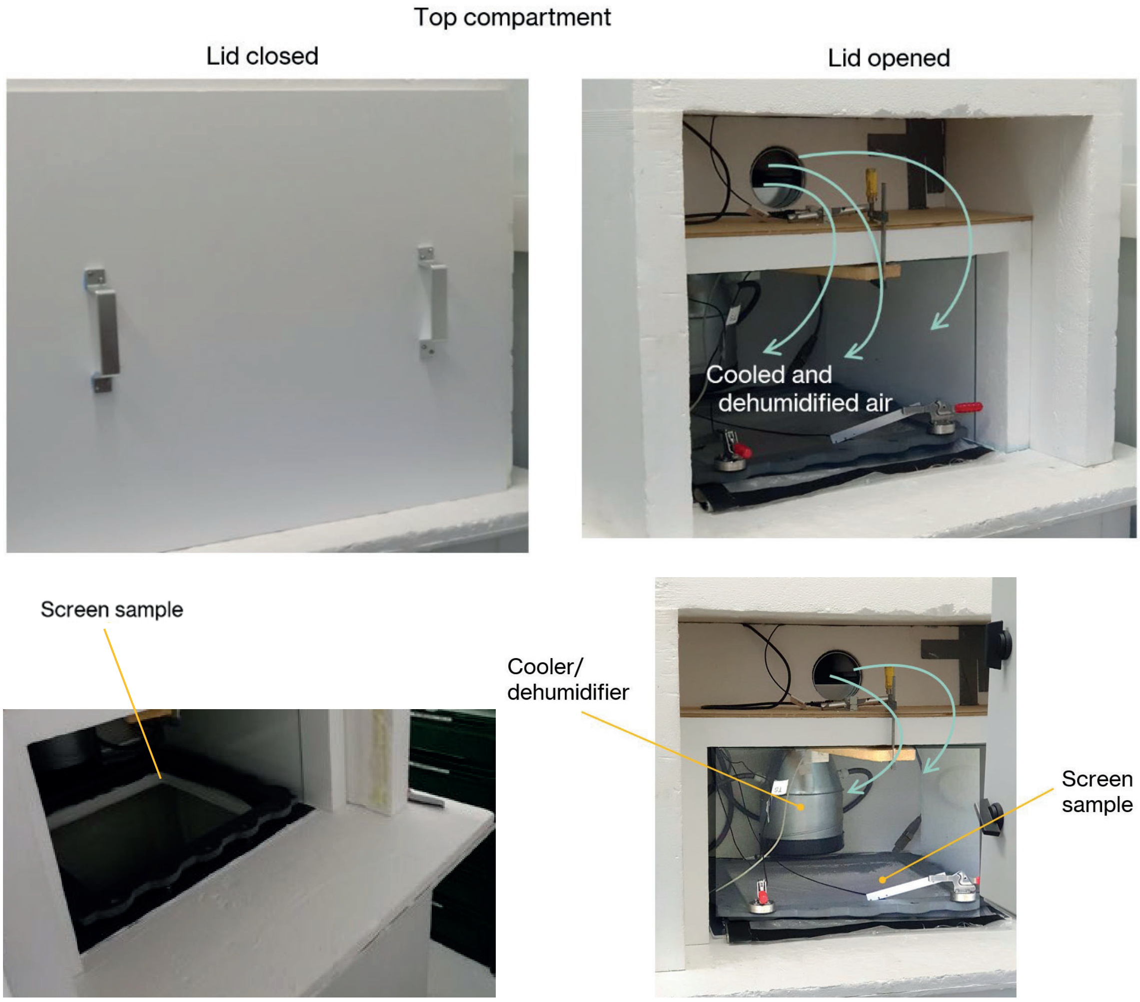


Figure 6 *Detail pictures of the inner of the upper compartment.*

The water that condenses at the dehumidifier is caught and directed to another scale. This water can come from nowhere else than by transfer through the screen. Indeed, when the screen sample is replaced by glass or foil the cooler remains dry and the water collection scale doesn't gain weight.
However, even when non-permeable samples are placed, some evaporation can occur in the bottom box. This is because of condensation at the bottom side of the sample. At a certain moment this water drips off. Dripping water is collected and weighed on a third scale.

The controller keeps track of the temperatures and humidity in the upper part. If the humidity becomes higher than the setpoint, the temperature of the cooling water flowing through the dehumidifier is lowered by adjusting a mixing valve. It can well be that, due to this, the temperature becomes too low. Then a heater will reheat the air somewhat in order to get both temperature and humidity at the desired level.
Figure 7 shows the mixing valve, together with the complete set of scales.

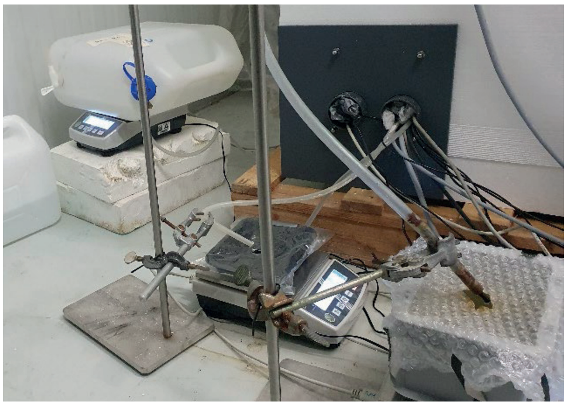



Figure 7 *Mixing valve to control the cooling and dehumidification and the scales that measure the water balance.*

The TransHumid device was equipped with a large number of sensors, both for monitoring the conditions accompanying the air and humidity transport as for the control itself. The sensors are listed in Table 1. Data were sampled with a 60 second frequency.

Table 1
List of data channels stored.

Channel register	Details
date/time	-
$T_{up_}$chamber [°C]	Temperature of upper chamber
$T_{low_}$chamber [°C]	Temperature of lower chamber
Humidity up [%]	Relative humidity of upper chamber
Humidity_low [%]	Relative humidity of lower chamber
scale humidifier [g]	Weight of evaporated water
scale dehum coil [g]	Weight of condensed water on upper compartment
scale dropplets screen [g]	Weight of dripping water from screen
Tset_up [°C]	Temperature set point in the upper chamber
Tset_low [°C]	Temperature set point in the lower chamber
Rhset_up [%]	Relative humidity set point in the upper chamber
Rhset_low [%]	Relative humidity set point in the lower chamber
Fan speed Set_Up [%]	Set point fan of upper chamber
Fan speed Set_Low [%]	Set point fan of lower chamber
Fan speed_Up [%]	Fan speed on upper compartment
Heater_up [%]	Heater power in the upper compartment
Dehumidifier_Up [%]	Dehumidifier power in the upper compartment
Fan speed_Low [%]	Fan speed in the lower compartment
Heater_Low [%]	Heater power in the lower compartment
Humidifier_Low [%]	Humidifier level in the lower compartment

After the assembly of the different parts, the first tests were made with the device to verify its proper functioning and possible design/assembly failures. The most important issues that were identified and corrected were:

1. Humidifiers got clogged;
   This was solved by using demineralized water.
2. Water balance could not be closed; a certain amount of water was evaporated but not caught as condensate from the cooler or drop off from the screen;
   This was solved by using a water and damp tight coating on the inside surfaces, careful sealing of joints and cable conduits and use of larger diameter drain hoses to assure undisrupted flow of condensate from the condensing surfaces to the scales.
3. Difficult access to replace screen samples;
   This was solved by making a well closing front entrance to the sample.
4. Screen temperature readings not accurate;
   This issue could not be solved, but the problem is circumvented by processing the measuring results with the help of the greenhouse climate model.

2.2.2 Set up and calibration of the humidity transport device

A large number of pre-test runs were made with different samples placed on the device in order to ensure:

- The sensor reading was correctly functioning and registering of data was successful
- The controller settings were fine-tuned to ensure sufficiently stable conditions around the setpoints.
- The water balance was correct (water evaporated by humidifier=water condensed by dehumidifier+ dripping water collected + water condensed on the screen)

Typically, a measuring sequence consists of two stages. First a period of 8-12 hours in which the temperature and humidity conditions generated on both compartments are such that the screen remains dry. In this period the humidifier and dehumidifier work. And moisture can be transported from the bottom to the top compartment, but the screen temperature remains above dewpoint temperature. Such conditions can be realized by a temperature gradient of 8 to 10°C across the screen with a lower compartment humidity of 70%. In the second stage, the temperature gradient is kept the same, but the humidity in the lower compartment is increased to 90%.

Figure 8 shows the measured temperature and humidity in such a two-stage measurement sequence. The data come from a measurement-procedure in screen samle RC18H.

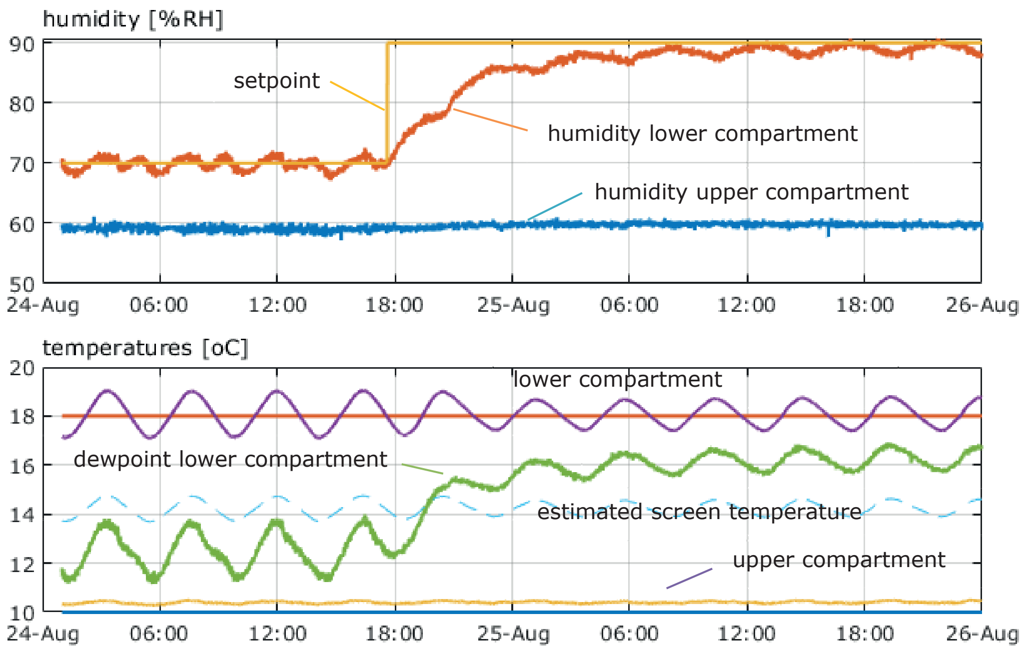


Figure 8 *Temperatures and humidity during the two stages of a measuring sequence.*

Figure 8 shows that the conditions in the upper compartment are very stable, but that the temperature and humidity in the lower compartment are fluctuating around the setpoint. However, as the measuring period is long and the fluctuations are very regular around the setpoints, these oscillations are considered not to be a problem. In the measuring protocol, the whole period is observed, and two stable periods are selected. In the case showed, the conditions typical for the dry screen phase are the 16 hours from 1:00, August 24th till 17:00. The typical conditions for the wet screen phase are stated from 06:00 on the 25th till the end of the day.
The first period is considered to have a dry screen as the estimated screen temperature is always above dewpoint of the air in the lower compartment (and certainly above dewpoint of the cold and dry air of the upper compartment). In the second phase, the estimated screen temperature is well below dewpoint. It is called 'estimated screen temperature' because, despite many attempts to measure the screen temperature correctly, it appeared not to be possible to do this in a stable, repeatable manner. However, as the heat exchange at the upper and lower side of the screen is very much comparable, the screen temperature cannot be very different from the average between the upper and lower compartment. This arithmetic average between lower and upper compartment is shown by the dashed line in Figure 8.

The major reason for the development of the TransHumid device is to determine the humidity transport through the screen sample. Figure 9 shows the total amount of moisture evaporated in the bottom compartment and the total amount of water collected from the dehumidifier in the top-compartment.

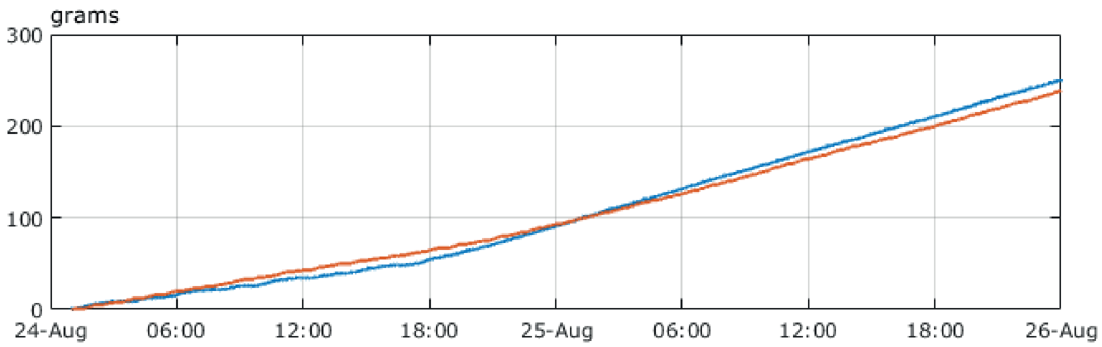


Figure 9 *Amount of water evaporated in the lower compartment by the humidifier (blue) and condensed at the dehumidifier in the upper compartment (red).*

Especially in the blue line of Figure 9, showing the amount of water that flowed out of the tank connected to the humidifier (Figure 5), there are clearly two slopes. A lower slope in the first 16 hours and a steeper slope in the second part. In the first 16 hours, 49 grams of water flowed from the tank to the humidifier, meaning an evaporation rate of 3 gram/h. In the second part of the graph, from 06:00 on 25th of August till the end of the day, 250-130=120 grams of water were drawn out of the tank, meaning a transpiration rate of 120/18=6.7 g/h. When doing the same exercise on the weight gained by the scale that catches the condensate from the dehumidifier, the weight gained in the first 16 hours is 60 gram and the weight gained in the last 18 hours is 112 gram. So, based on the other scale, the moisture transport in the dry screen conditions would be 3.8 gram/hour and in the wet screen conditions is 112/18 = 6.2 g/h.

As the water transport from the tank to the humidifier is based on communicating vessels at very small height differences, the measurement of the water collected by the dehumidifier is considered to be more accurate than the weight loss of the tank connected to the evaporators. Also, the water supply to the lower box can be a little more as it includes the water that wets the screen. Therefore, all measurements of humidity transport reported from the TransHumid device measurements are based on the water collected from the dehumidifier.

As the screen sample measures 0.25 m², all numbers on measured humidity transport are multiplied by 4 to get the moisture transport per m² per hour.

The significant difference between the humidity transport in the dry conditions phase compared to the wet screen phase are largely related to the larger temperature and humidity gradient across the screen. If screens are permeable, a larger temperature difference leads to a higher air exchange rate which, by itself already increases humidity transport. The higher humidity gradient is a multiplicative factor on top of this. The more or less doubled moisture exchange in the wet screen conditions that follows from the measurements shown in Figure 8 and Figure 9 are therefore not because of the fact that the screen has become wet.

This can easily be seen when the humidity transport capacity is expressed in terms of moisture transport per gram/m³ humidity gradient. In the dry screen conditions, the absolute humidity of the lower compartment is 10.8 g/m³ and the absolute humidity of the upper compartment is 5.8 g/m³. Thus, the moisture transport per g/m³ humidity gradient in the dry screen condition is 3.0 g/(m² h) per g/m³. In the wet screen condition, the absolute humidity of the upper compartment remains the same, but the lower compartment is at 13.7 g/m³. Therefore, for the wet screen condition, the humidity transport capacity of the screen is 3.15 g/(m² h) per g/m³. In general, the wet screen moisture transport capacity will be higher as there can be some hydroscopic exchange as well (see section 2.3.3).

2.2.3 Standardised measurement protocol and repeatability

A standardised measurement protocol for the Humidity transport device is established in order to reach maximum possible repeatability and to minimize the measurement errors. In order to investigate whether the humidity transport only takes place through the sample area, the (absent of) humidity transport with glass sheet in between the two compartments was measured.

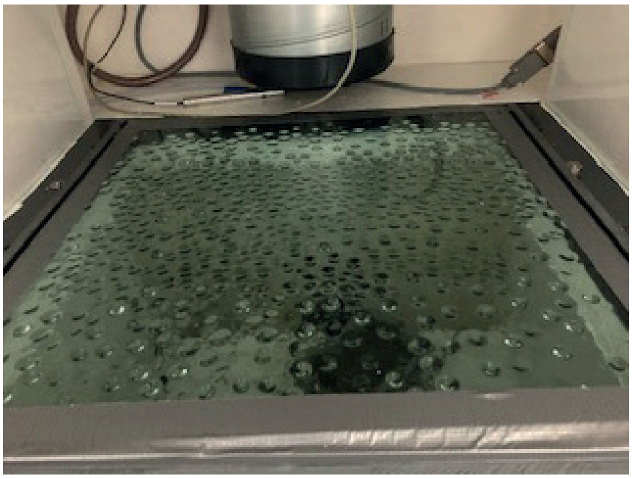


Figure 10 *Glass plate with condensed water on lower part of the surface.*

Indeed, in case a glass pane is placed between the compartments, water is evaporated in the bottom compartment, but no water ends up in the top compartment. The water evaporated comes back on the scale that measures the drip off.

shows for a number of screens and a number of repetitions the measured moisture transport through the screens (marked by transp (g/(m² h)) and the moisture transport per unit humidity gradient (trnspCap, g/(m² h) per g/m³). As can be seen, there is variation in the measured transport capacity, but when a number of measurements are averaged, there is a clear distinction between the one and the other screen material.

Table 2 shows for a number of screens and a number of repetitions the measured moisture transport through the screens (marked by transp (g/(m² h)) and the moisture transport per unit humidity gradient (trnspCap, g/(m² h) per g/m³). As can be seen, there is variation in the measured transport capacity, but when a number of measurements are averaged, there is a clear distinction between the one and the other screen material.

Table 2

Table showing moisture transmission measurements with a good repeatability (green marked results), moderate repeatability (yellow marked results) and poor repeatability (red marked results). At the left side results for dry conditions are shown and the results at the right side refer to wet samples.

dry perm	DT	DX	trnsCap	transp		wet perm	DT	DX	trnsCap	transp
3.3	7.7	5.1	4.3	22.1	NT16M	3.3	7.7	7.0	4.5	31.2
3.3	7.8	5.3	3.3	17.2	NT16M	3.3	7.6	7.1	4.7	33.3
3.3	7.6	5.1	4.3	22.0	NT16M	3.3	7.6	7.1	4.7	33.2
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
					LS19A	0.6	12.4	11.0	4.1	44.8
					LS19A	0.6	10.8	10.0	4.2	42.0
					LS19A	0.6	9.0	10.1	3.3	33.6
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
					LS19C	0.7	10.7	10.5	3.2	33.6
					LS19C	0.7	10.7	10.5	3.5	37.3
					LS19C	0.7	10.5	10.3	2.8	28.7
					LS19C	0.7	12.2	10.8	5.0	54.0
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
0.4	7.7	5.2	2.3	12.0	LS19B	0.7	10.5	10.3	3.6	37.2
0.4	7.7	5.2	2.6	13.6	LS19B	0.7	7.8	7.7	2.5	19.2
					LS19B	0.7	7.8	8.0	2.6	20.4
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
					RC18G	0.8	10.8	11.5	4.1	47.2
					RC18G	0.8	10.9	11.4	4.0	45.2
					RC18G	0.8	11.4	10.2	4.2	42.9
					RC18G	0.8	10.8	11.5	4.1	47.2
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
0.5	7.6	5.2	2.2	11.6	RC18H	0.5	10.7	11.5	3.9	44.5
0.5	7.6	5.2	3.0	15.6	RC18H	0.5	10.7	10.5	3.1	32.8
					RC18H	0.5	7.7	8.2	2.8	23.2
					RC18H	0.5	7.6	8.1	3.1	24.8
					RC18H	0.5	7.7	8.0	3.1	24.4
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
					RC18F	0.9	12.5	11.0	4.8	52.8
					RC18F	0.9	11.9	10.5	4.5	46.8
					RC18F	0.9	11.0	11.8	3.7	44.0
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
1.6	7.7	5.2	2.2	11.6	NT16K	2.0	7.6	8.1	3.1	25.2
					NT16K	2.0	7.7	8.3	3.0	24.9
perm	DT	DX	trnsCap	transp		perm	DT	DX	trnsCap	transp
0.5	7.7	5.5	0.9	5.1	NT18B	0.5	7.8	8.5	2.3	19.6
0.5	7.7	5.5	1.0	5.6	NT18B	0.5	7.9	8.5	2.2	18.4
0.5	7.8	5.5	1.4	7.6	NT18B	0.5	7.7	8.3	2.1	17.6

Part of the variation comes from the fact that the different measurements come from different settings for temperature and humidity gradient. Originally, measurements were taken by large temperature differences between top and bottom compartment (10 -12°C), but as the measuring-protocol developed, the measurements were taken at an equilibrium temperature difference around 8°C. This because a larger than 8°C temperature difference between greenhouse temperature and top temperature is rare in everyday greenhouse horticulture. By expressing the moisture transport by the moisture transport capacity (defined as g/(m² h) per g/m³ humidity difference) rather than the actual moisture transport largely eliminates the differences in measuring conditions, but due to the non-linearities still some variation remains. Therefore, for the sake of comparability, the measurement protocol will stick to the 8°C temperature difference as the standardized measuring conditions.

When the data in the table are translated in an overview that relates the moisture transport capacity to the permeability the following graph is obtained.

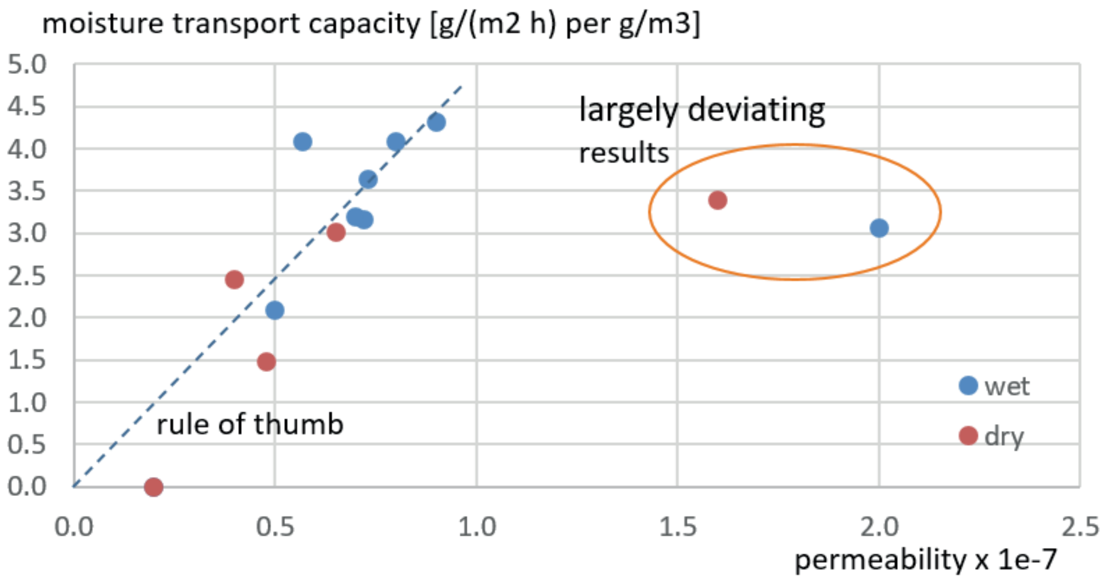


Figure 11 *Correlation moisture transport and screen permeability.*

For most screens there is a fair relation between permeability and moisture transport capacity. Also, this relation does not seem to be strongly affected by the fact if a screen is dry or wet. As a rule of thumb, one can say that the moisture transport capacity of a screen equals 5 times the permeability x1e^{7}. For this rule of thumb, the moisture exchange capacity is expressed in g/(m² h) per g/m³ humidity gradient.
However, especially when screens are manufactured notably different from the 'average' energy screen, the relation between permeability and humidity transport can deviate a lot from this 'rule of thumb'. The screen material shown in the right side of the graph has a much lower moisture transport than expected from its permeability. This deviation is not likely to be caused by a faulty measurement as Table 2 shows that repetitions of measurements on this screen show pretty much the same results. Therefore, we conclude that humidity transport characteristics of a screen must always be measured.

2.3 Thermal properties measurements

2.3.1 Use of thermal properties device (TNO emissivity meter)

If thermal infrared radiation is transferred through a screen material, radiative energy is lost from the greenhouse. The goal of this work package is to quantify the amount of thermal infrared radiation and therefore radiative energy loss through different types of screens.

Thermal infrared radiation (TIR) is heat radiation in the range of 2500-100000 nm (which is equal to 2.5-100 mm). When thermal infrared radiation encounters a material, part is transmitted (τ_{TIR}), a part is reflected (ρ_{TIR}) and a part is absorbed ($\alpha_{TIR}=\varepsilon$) by the material. This energy exchange process can be formulated as follows:
$\tau_{TIR} + \alpha_{TIR} + \rho_{TIR} = 1$

This means that when thermal infrared radiations coming from the greenhouse encounters a screen material, its TIR transmissivity (τ_{TIR}), TIR reflectivity (ρ_{TIR}) and the emissivity (ε) determine the height of the barrier the screen forms for radiative heat loss.

The device (Figure 12) to measure thermal properties of screen materials has been developed in the past by TNO. The device consists of two radiative half spheres kept on different temperatures. One half sphere has the room temperature and the other one is heated. The temperature difference is about 25 to 30 degrees Celsius. Both half spheres have a built-in infrared sensor. The sensor consists of a large number of thermo-couples which are integrated on an IC. Herewith any increase or decrease in surface temperature is compared with the sensor temperature. The sensor is able to measure its own temperature and has a response time less than 0.1s. Emissivity (ε), thermal infrared reflectivity (ρ_{TIR}) and thermal infrared transmissivity (τ_{TIR}) are determined based on the known properties of glass and gold which are measured during calibration, as well as the reading of the empty device.

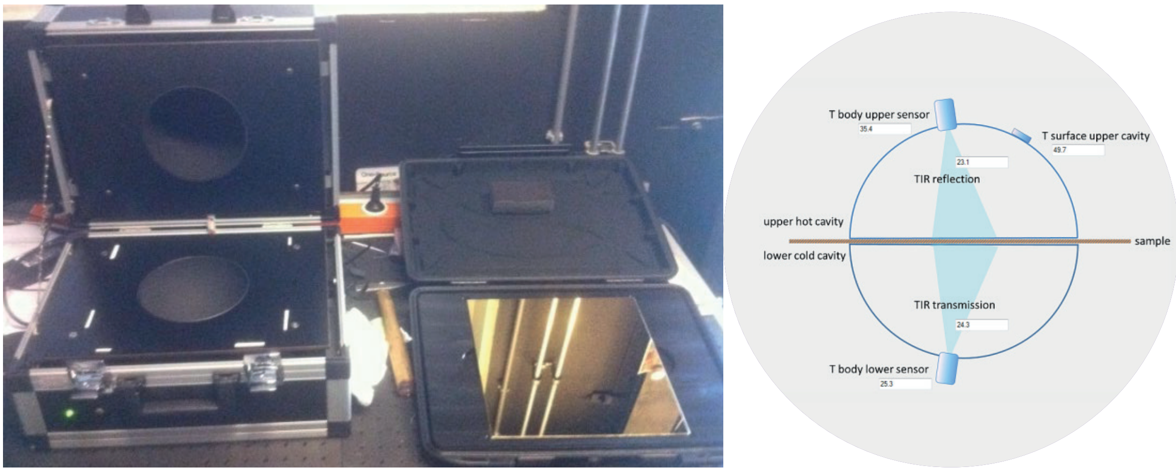


Figure 12 *Picture and schematic drawing of the emissivity measurement device (TNO emissivity meter).*

The device measures in between hemispherical and near normal values. By default, hemispherical values are used.

For flat materials, like screens, with an TIR reflectivity of around 0.5, the measuring error of the TIR reflection is at is largest and becomes about 2%. Bot lower and higher reflection coefficient yields a mor accurate measurement.

The following specifications are given on the device:
- The device measures in between hemispherical and near normal values. By default, hemispherical values are used. The error depends on the material properties of the measured sample and is largest for smooth flat materials, around 2% for samples with TIR reflectivity around 50%. For screens the error is estimated to be smaller.
- For highly transparent samples (>50% TIR Transmissivity) the TIR reflectivity of the spheres should be taken into account. The TIR reflectivity of the spheres is estimated to be around 10%. A different algorithm is needed to measure highly transparent samples. In that case TNO has to be contacted.
- The Melexis sensors (Figure 13) have a sensitivity for different thermal infrared wavelengths as in the following figure. The sensitivity of the sensors covers the range of 4-14μm. Results can therefore differ from other devices such as an FTIR spectrophotometer.

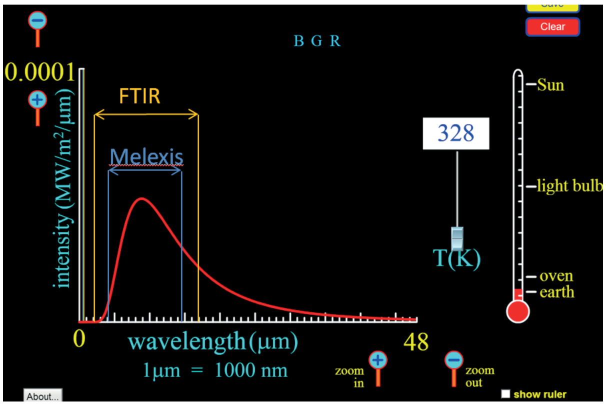


Figure 13 *The Melexis sensors window.*

However, this device cannot be used with wet samples, as dripping water could damage it. During the project we also found no reliable method to measure the thermal properties of wet screens in another way. Therefore, the project group agreed to simply state that a wet screen will get the know optical properties of a water film, being that it is almost not transmitting and highly emitting TIR radiation (τ_{TIR}=0.05, ε_{TIR}=0.9), leading to a high TIR reflection.

2.3.2 Standardised measurement protocol and repeatability

A detailed description of the standardised measurement protocol to measure dry samples can be found in the report of former project (Hemming *et al.* 2016).

Measurements of a standard reference samples give insight in the repeatability of the device. We use a ETFE film as standard reference material.
Each time when the emissivity value of ETFE film was deviating too much from the expected value, the calibration is repeated. According to our observations, the more variations in the climate conditions of surrounding area, the more often new calibrations are needed. The results of measurements of ETFE film during different sessions are shown in the Table 3. Regular measurements of the standard reference material (ETFE) show the repeatability of the equipment.

Table 3
Thermal properties of ETFE measured with the TNO emissivity device.

ETFE	ρ_{TIR}	τ_{TIR}	ε	ε abs. stdev
M1	14	29	57	
M2	17	31	52	
M3	16	31	52	
M4	15	29	56	
M5	15	30	56	2.38
M6	17	33	50	
M7	16	32	52	
M8	17	31	53	
M9	16	29	55	
M10	15	29	56	

The obtained absolute standard deviation of repeated measurement of is about 2.38%. It is important to notice that ETFE film is a homogeneous sample and displacement of this sample has no effect on the measurements. In practice, many of energy screens are a combination of different materials with different patterns which may affect the homogeneity of the measurements results.

2.3.3 Screen properties in relation to simulations with the KASPRO simulation model

The parameters describing the thermal and moisture transport capabilities can be used to predict the energy saving properties of the screens when applied in a practical greenhouse. This is carried out when feeding the screen parameters to the Kaspro simulation model. This model is explained in more detail in section 2.5.
The simulation model can be used to mimic the conditions in the TransHumid device. Ideally, when the parameters of the screens are set correctly, the humidity transport calculated for the conditions applied in the TransHumid device are in agreement with the water condensing at the dehumidifier of the top section of this measuring device.
In order to mimic the conditions in the TransHumid device, the simulation model is calculating a ‘greenhouse’ without a crop. The air of the bottom compartment is heated by an air heater instead of heating pipes and a misting system supplies such an amount of moisture that the calculated humidity in the simulated box equals the humidity measured in the TransHumid device.
Just like in the TransHumid device, there is no heat loss at the floor of the greenhouse and also no heat loss at the ‘roof’. It is only the cooled and dehumidified air of the top-compartment that removes heat and moisture.
Once the major screen parameters are known by the determination of the permeability and the radiative properties, a simulation of a stabilized condition in the TransHumid device can be performed by just setting the temperatures and humidity of the upper and lower compartment equal to the measuring conditions and selecting the screen of interest.
Figure 14 shows the simulation of the dry screen conditions as they were earlier shown in Figure 8.

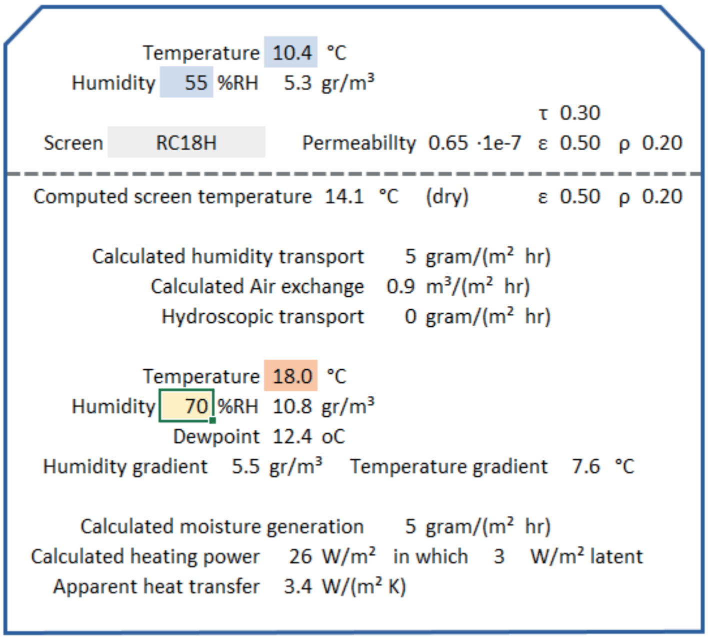


Figure 14 *Input (highlighted fields) and results of the simulation of the TransHumid device with Kaspro.*

The simulation model shows that the equilibrium screen temperature is calculated to be 14°C, which is a little lower than the arithmetic mean between the upper and lower compartment. This is caused by the higher emission coefficient of the upper face of the screen compared to the emission coefficient of the bottom side of the screen.

As the screen temperature is still well above the dewpoint temperature of the warm and humid air, the screen will stay dry.

Based on the permeability, which was determined to be 0.65·10^{-7} m, the model computes an air exchange rate of 0.9 m³/(m² h). As the humidity gradient is 5.5 g/m³, the moisture exchange across the screen equals 0.9 * 5.5 = 4.8 g/(m² h).
As the screen remains dry, no additional moisture will be transferred by condensation and re-evaporation from the screen surface.
The computed amount of water vapour transferred is somewhat higher than the 3 grams per m²/h calculated from the weight gain of the scale that catches the condensate (Figure 9), but in absolute terms the 1.8 gram/m² per hour over estimation is a small amount.
Due to the low permeability, the low emission and low transmission coefficients of the screen and the relatively dry air conditions, the calculated energy consumption in the bottom part is quite low, 26 W/m².

In the second phase of the measuring cycle earlier shown in Figure 8, the humidity in the lower compartment is increased to 89%. When these air conditions are entered in the model that mimics the TransHumid device, the screen is calculated to be wet and the computed humidity transfer increases to 24 g/(m² h). More details can be seen in Figure 15.

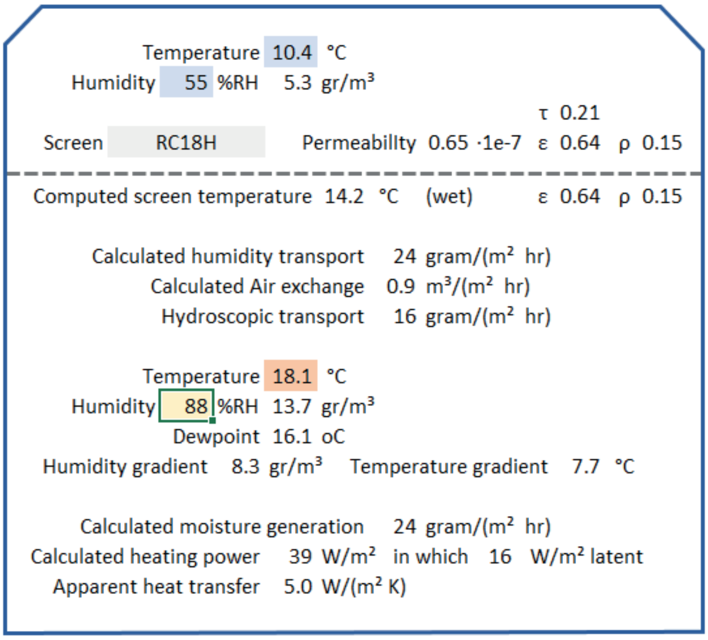


Figure 15 *Input (highlighted fields) and results of the simulation of the TransHumid device with Kaspro for the wet screen case in the second part of the measurement cycle shown in figure 8.*

As the temperature difference stayed (almost) equal, and this particular screen did not show a change in permeability when the screen becomes wet, the calculated air exchange rate remains to be 0.9 m³/(m² h). But, as the humidity gradient is now 8.3 g/m³, the amount of vapour exchanged with the air has grown to 8.3*0.9 = 7.5 g/(m² h) (not shown in the figure).

However, the model calculates 24 g/(m² h). This computed amount is very close to the 24.4 g/(m² h) measured from the slope of the weight of the scale that catches the water from the dehumidifier (Figure 9). The difference is coming from the hydroscopic transport, which means that water is condensing at the bottom side of the screen, then transported through the fabric to the top side where it re-evaporates. As can be seen from the numbers, this hydroscopic transport is more than twice the amount of moisture exchanged along with the air.
Due to the wetness of the screen, the emission coefficients of both sides of the screen have become equally high (0.9) and the infrared transmission dropped to 0.05.

The enlarged latent heat associated with the humidification of the air in the lower compartment has increased the heat demand of the lower compartment to 39 W/m². With a temperature difference equal, the heat transfer through the screen has grown from 3.4 W/(m² K) to 5.1 W/(m² K). This is an example of the heat exchange coefficient being directly influenced by the humidity differences across the screen.

The two examples above show that the greenhouse climate simulation model shows a good resemblance between measured and calculated humidity transport based on the screen properties measured with the Permea device and the radiative properties measured at the TNO emissivity device.

The procedure as described above (copying the measurement conditions and screen type in the simulation model and compare the calculated moisture transport with the measured values) was carried out for 10 different screen samples and for different wet and dry cases and different temperature and humidity gradients.
When plotting the calculated humidity transport against the measured values, the following scatter plot was obtained.

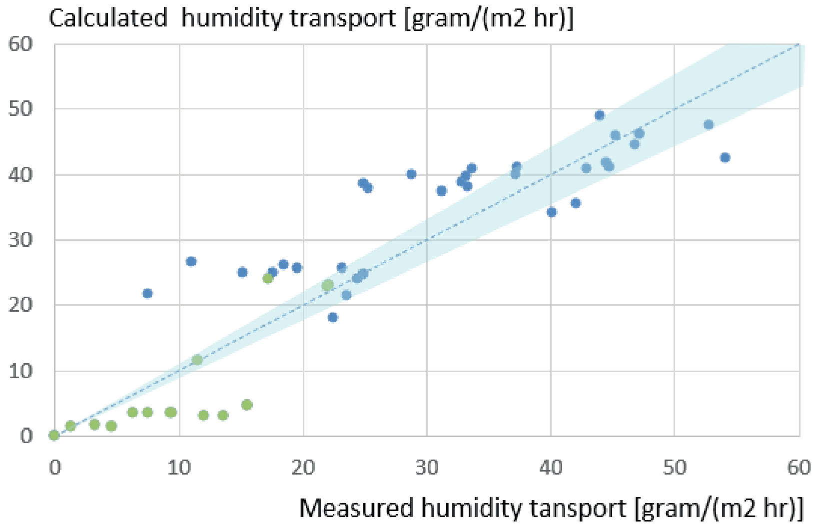


Figure 16 *Measured humidity transport on the x-axis and calculated humidity transport by the Kaspro model. The model is fed with the equilibrium average conditions and the permeability and longwave radiation properties are taken from the measurements on the Permea-device and the TNO emissivity device respectively. The hydroscopy is set to 1. Note that the TNO emissivity device measurements are only relevant for the dry screen conditions (green points). Points in the marked area are less than 10% off.*

For a number of measurements the simulated moisture transport is in good agreement with measurements, but there are also quite some measurements where the simulated moisture exchange is substantially more than the measured amount. As the Permea-device is giving very stable measurements, such deviations are not likely to be caused by a permeability too high. The only parameter left for tuning is then the hydroscopy, which accounts for the capability of a screen to transport liquid water condensing at the bottom side to the top side.
By decreasing the hydroscopy-factor for screens that showed a too high moisture exchange in Figure 16 the graph shown in Figure 17 was obtained.

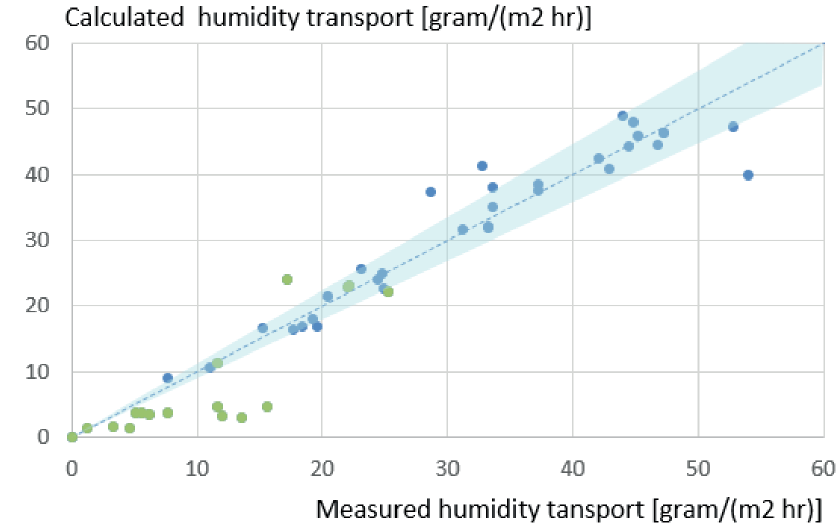


Figure 17 *Measured humidity transport on the x-axis and calculated humidity transport by the Kaspro model, fed with the equilibrium average conditions, after tuning the hydroscopy-factor in order to bring simulations closer to measurements. The permeability is taken from the Permea-device and the infrared properties are taken form the TNO emissivity device, but are only relevant for the dry screen conditions (green points). Points in the marked area are less than 10% off.*

When comparing Figure 16 with Figure 17 it is clearly seen that tuning of the hydroscopy-factor brings the calculated transport close to the measured transport. Almost all points are within a 10% error which, in absolute terms means that the calculated moisture transport capability of the screen is calculated with ± 5 g/(m² h) error in most cases.

Of course, tuning of the hydroscopy-factor does not improve the dry-screen measurements as in this case moisture is only exchanged along with the air flow.

2.4 Air permeability measurements

2.4.1 Design and assembly of a new wind tunnel device (Permea device)

In the former "Energy saving screen materials" project, the aerodynamic properties (permeability and inertial factor) were determined in small dry samples of the screen using an air suction device developed by Miguel (1997, 1998). A detailed description of this device, its measurement principle and measurement protocols can be found in the report of the former project (Hemming *et al.* 2016).

One of the limitations of this device was the small size of the screen samples that were required for the measurement (40 mm of diameter), which could limit the representativeness of the screen samples. In addition, the samples were measured in vertical position, which of course, hampers the measurement of wet samples, as this would cause the sliding and dripping of the condensed humidity.

Therefore, a new device was designed, assembled and calibrated to do measurements of aerodynamic properties of both dry and wet screen samples, of almost 14 times the surface of those measured in the old air suction device (150 mm compared to 40 mm diameter). Because of the much larger flow induced by the new device, the air flow could no longer be based on a slowly emptying water tank. It was therefore decided to design from scratch a simple and accurate small and portable vertical wind tunnel (Figure 18).

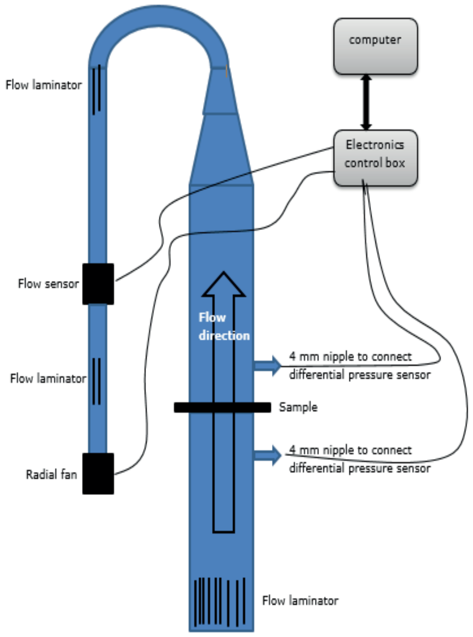


Figure 18 *Scheme of the new small wind tunnel device for the measurement of aerodynamic properties of dry/ wet screen samples.*

The main reason for the former design was that at the time this device was designed, there were hardly any sensitive pressure difference sensors, hardly any sensitive and accurate flow sensors and it was difficult to automatically control the air flow. Given the circumstances, creating a constant air flow by the under-pressure achieved by emptying a high placed tank of water provided a good solution.
In recent years however, the quality and ranges of affordable sensors and actuators have improved a lot. Therefore, this newly designed vertical wind tunnel could be based on a stable low-volume controllable fan (Nidec Copal Electronics TF037E-2000-F), an accurate low volume flow sensor (Sensirion) and an accurate pressure transducer. They are marked in Figure 19.

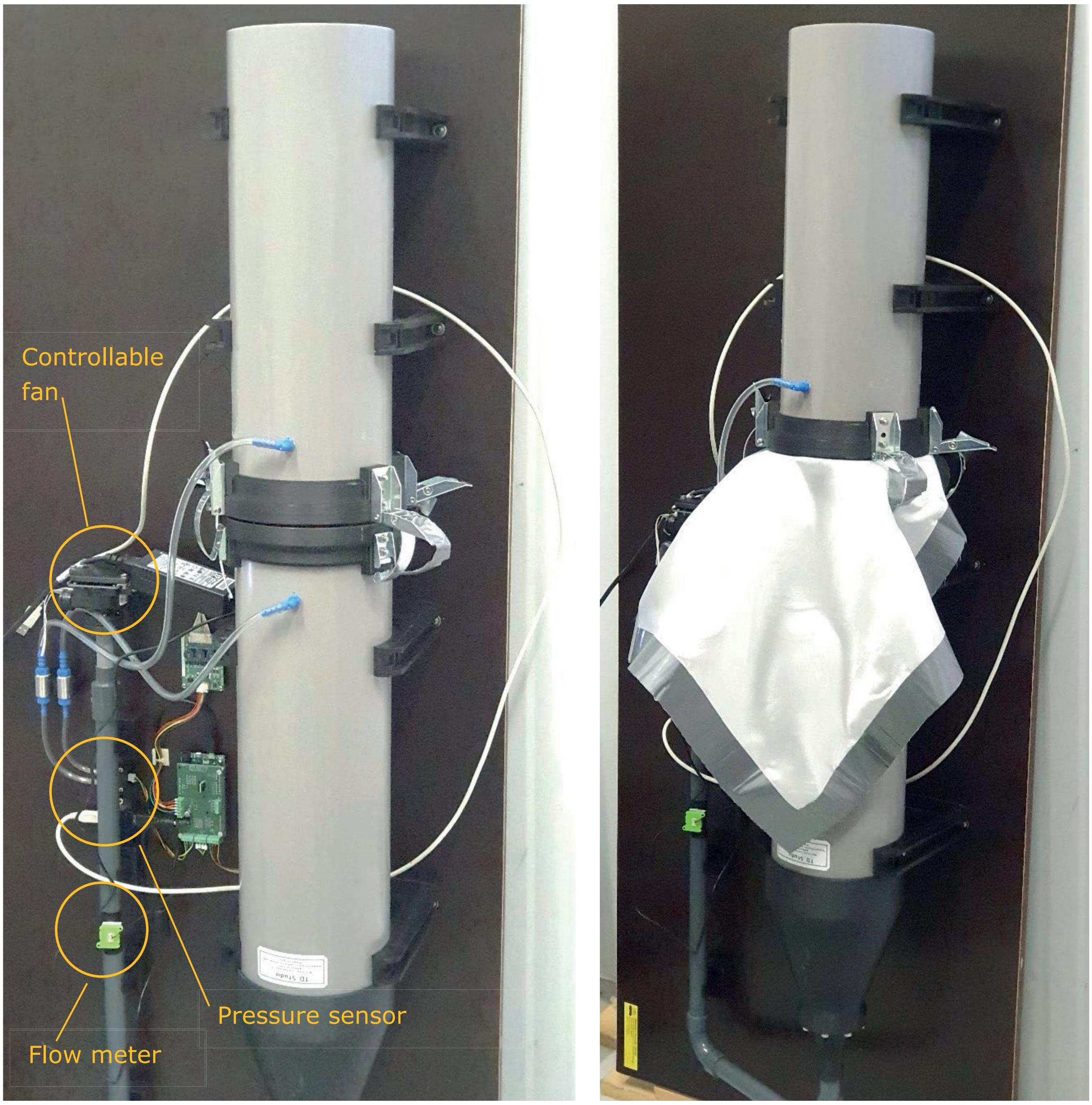


Figure 19 *Detailed pictures of the new device for measuring aerodynamic properties of dry and wet samples.*

2.4.2 Setup and calibration of the new wind tunnel device

After the Permea device was assembled, a large number of measurements were performed to determine the standard deviation of the measurements and the repeatability. Variations of measured results can be caused by
a. Inherent in the device itself
b. Caused by sample placement
c. Caused by sample inhomogeneity

In order to determine the repeatability of the measurements in the wind tunnel, first a certain sample (LS19C) was measured 11 times, without taking the sample in and out.
The permeability was measured by speeding up the fan with small steps. At each step of the fan, the pressure difference and the air flow was registered. One such a series of points is shown in the below graph (Figure 20).

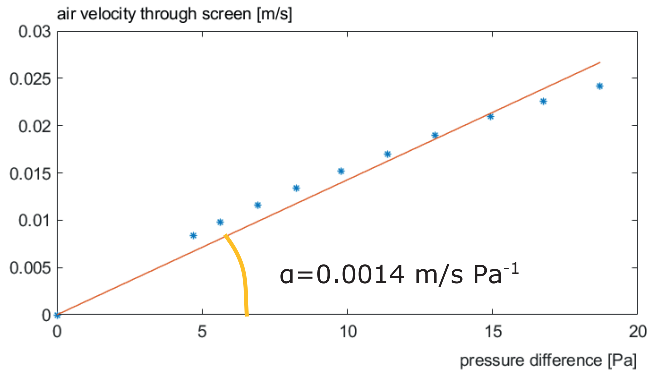


Figure 20 *Measurements of air velocity through screen under difference pressure differences on the Permea device with one of the screen samples (LS19C).*

A best linear fit between pressure difference and air velocity shows an angle α, which is 0.0014 m/s of air movement through the screen per Pa pressure difference.
By definition, the air velocity is 0 without a pressure difference, so therefore the line is forced to start at (0,0). One measurement-session consists of a series of increasing fan speeds until either the pressure difference exceeds 20 Pa or the air speed exceeds 0.03 m/s. These boundaries are chosen because in an actual greenhouse, higher pressure differences or higher air-flows across a screen will definitely not occur.
The picture shows that the linear representation of the relation between pressure difference and air velocity is a little deviating from the measured points. Still, the linear representation is considered to be good enough as it gives a simple relation between pressure difference and air flow.

The slope multiplied by the viscosity is the permeability. The viscosity is dependent on the air temperature and is 1.789e-5 [Pa s] for air of 15°C. This 15°C is the temperature of the room where the Permea-device is normally used, but when the device is used at other temperatures, the viscosity is adapted by 0.005 (Pa s)/K (a higher temperature gives a higher viscosity).
The permeability of the screen from which the characteristics are shown is therefore 0.0014 * 1.789e-5 = 0.25e-7. Given the unit of the slope (m/s Pa^{-1}) and the unit of viscosity (Pa s), the unit of the permeability is m.

Table 4
Measurement of the repeatability of the Permea device without sample removal and re-placement on one of the screen samples (LS19C).

Measurement Name	Permeability x10^{-7}
LS19C_5	0.245
LS19C_6	0.243
LS19C_7	0.243
LS19C_8	0.244
LS19C_9	0.244
LS19C_10	0.243
LS19C_11	0.244
LS19C_12	0.244
LS19C_13	0.244
LS19C_14	0.244
LS19C_15	0.244
Average	0.244
Standard deviation	0.0004

When the above described procedure was repeated 11 times without re-mounting the sample, the computed permeability showed an absolute standard deviation of 0.2% compared to the average of the 11 samples. Therefore, it was concluded that the measurement procedure is very stable.

The next check on variability is to see the differences in computed permeability when a sample is put in and out several times and when different spots of a larger piece of screen are used
To test the effect of repeated sample placement and of homogeneity, the same LS19C sample was measured on all 4 corners at least 3 times. LS19C_#_# the first # indicates number of full rotations and the second # indicates the corner itself (Table 5).

Table 5
Measurement of the repeatability of the Permea device with sample removal and re-placement on one of the screen samples (LS19C)

Measurement Name	Permeability x10^{-7}
LS19C_1_1	0.242
LS19C_2_1	0.215
LS19C_3_1	0.235
LS19C_4_1	0.242
LS19C_1_2	0.215
LS19C_2_2	0.220
LS19C_3_2	0.208
LS19C_1_3	0.234
LS19C_2_3	0.307
LS19C_3_3	0.234
LS19C_1_4	0.242
LS19C_2_4	0.248
LS19C_3_4	0.240
Average _#_1	0.233
Average _#_2	0.214
Average _#_3	0.258
Average _#_4	0.244
Std [%] _#_1	3%
Std [%] _#_2	3%
Std [%] _#_3	16%
Std [%] _#_4	2%
Overall average	0.239
Overall std [%]	10%

The summary of the standard deviations indicate, that when sample is replaced and when other areas a chosen to do the measurements the standard deviation is much higher than the standard deviation from the measurement equipment itself. In the repetition on a replaced screen sample in the 3rd corner, one quite odd measurement was done, showing a permeability of $0.307 \cdot 10^{-7}$. It is this measurement that pulls the standard deviation really up, but also when this measurement is discarded, there seems to be quite some variation in permeability in the screen material itself, depending on which corner of the screen is clamped into the device.

Table 6
Summary of the standard deviations in the Permea measurements.

	permeability
Standard deviation of the measurement	0.2%
Standard deviation of sample replacement	~6%
Standard deviation of sample replacement and sample inhomogeneity	10%

The Permea device is also suitable to take measurements of wet screens. This is done by placing the wet screen samples on the device immediately after a humidity transport measurement in the TransHumid device. In this way the wetness of the screen is created in condensation conditions as close as possible to those in the greenhouse.

2.4.3 Standardised measurement protocol and repeatability

Every time before a measurement on the Permea device is taken, a control measurement of a defined standard material is taken. In case of the Permea device this standard materials consist of a metal plate with fixed holes. By measuring this standard material regularly, the repeatability of measurement results can be obtained (Table 7). Next to that, these measurements serve as performance control of the equipment during daily operation.
The obtained absolute standard deviation of repeated measurements of the standard reference material (metal plate with fixed holes) is 0.19%.

Table 7
Air permeability measurements of a defined standard materials (metal plate with fixed holes) to determine the repeatability of the equipment.

Reference WR21P1	Permeability (x1e^{-7})	Mean value (x1e^{-7})	abs.stdev (x1e^{-7})
M1	4.65	4.46	0.19
M2	4.80		
M3	4.31		
M4	4.34		
M5	4.37		
M6	4.28		
M7	4.75		
M8	4.76		
M9	4.81		
M10	4.69		
M11	4.40		
M12	4.21		
M13	4.36		
M14	4.37		
M15	4.42		
M16	4.42		
M17	4.34		
M18	4.46		
M19	4.37		
M20	4.36		

2.5 Calculation of overall energy saving

In this section, the procedure for the standardized way of calculating the energy saving of a screen is described. Basically, it applies the screen properties in combination with a defined set of greenhouse climate control settings to a simulation model for the calculation of the year-round energy consumption. The year-round calculation is made with and without a screen and the difference shows the energy saving obtained. Next to the effect on energy use, a screen also influences the climate in terms of humidity. Also, this effect is shown as a standardised assessment of a particular screen.

The results largely depend on the simulation model and therefore first a concise description of the model is provided.

2.5.1 General description of energy model KASPRO

The greenhouse process model (KASPRO) is a dynamic model for calculating greenhouse climate and energy consumption. The model is constructed from modules describing the physics of mass and energy transport in the greenhouse enclosure, and a large number of modules that simulate the customary greenhouse climate controllers. Thus, the model takes full account of mutual dependencies between greenhouse characteristics and its climate control. The state variables and boundary conditions in the KASPRO model are shown in Fig. 21. Full details of the model can be found in "Analysing energy-saving options in greenhouse cultivation using a simulation model" (de Zwart, 1996) and a more comprehensive description of the main components of the model can be found in the 'De Uitstralingsmonitor' (de Zwart *et.al.*, 2017, https://edepot.wur.nl/421065).

The simulation of the greenhouse physical processes comprises the energy and mass fluxes in the enclosure. These fluxes result in a transient course of temperature, humidity and CO_2 concentration.
All processes are parameterized according to their physical characteristics like optical parameters in the visible and infrared wavelengths, their inertia and physical limitations (*e.g.* maximum ventilation capacities, leakage, maximum heating or cooling power etc.).
The climate controller of the KASPRO simulation model mimics the behaviour of commercial greenhouse climate computers controlling by means of heating, cooling, ventilation, dehumidification, misting, shading, artificial illumination, and carbon dioxide supply. The model also describes the behaviour of the boiler, short-term and seasonal heat storage facilities, co-generation of heat and electricity and heat pumps.
The interface with these controllers is similar to the interface that growers are familiar with; the definition of time-varying setpoints for heating, ventilation, dehumidification and CO_2-supply.
The inner climate in terms of PAR-radiation and temperature results in crop biomass production according to the well-known photosynthesis model of Farquhar (Farquhar, 1980). Periods of unfavourable temperatures are taken into account, resulting in a decrement of actual photosynthesis in comparison to maximal photosynthesis under the given light and CO_2-conditions. And if unfavourable conditions prolong for a few days, also it's impact on slow processes like fruit set an quality loss are taken into account.
The model has shown to be helpful in understanding the phenomena observed in greenhouses and has a high predictive value for the energy consumption, inside humidity and temperature conditions under given outside climate conditions and greenhouse parameters.

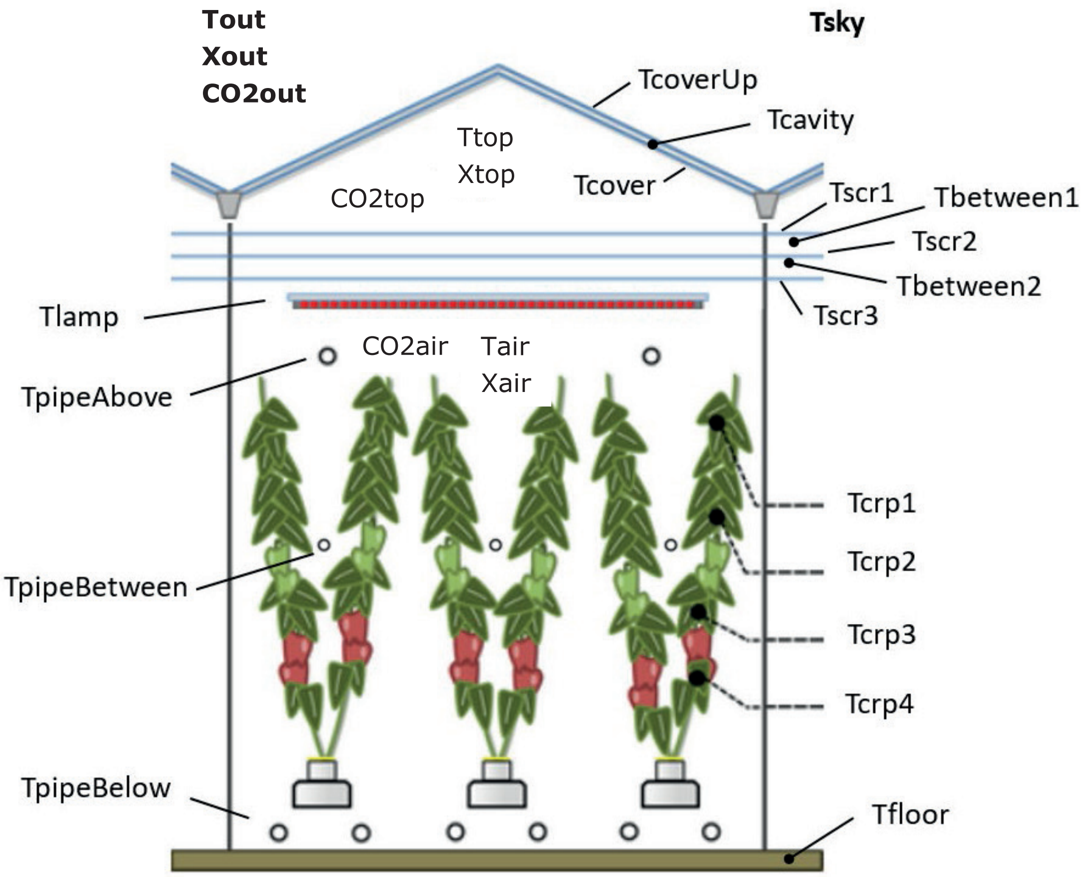


Figure 21 *State variables and external state variables (bold face) in the Kaspro simulation model.*

In this particular project, the model is used to get a more detailed insight in the energy and mass fluxes across screens.

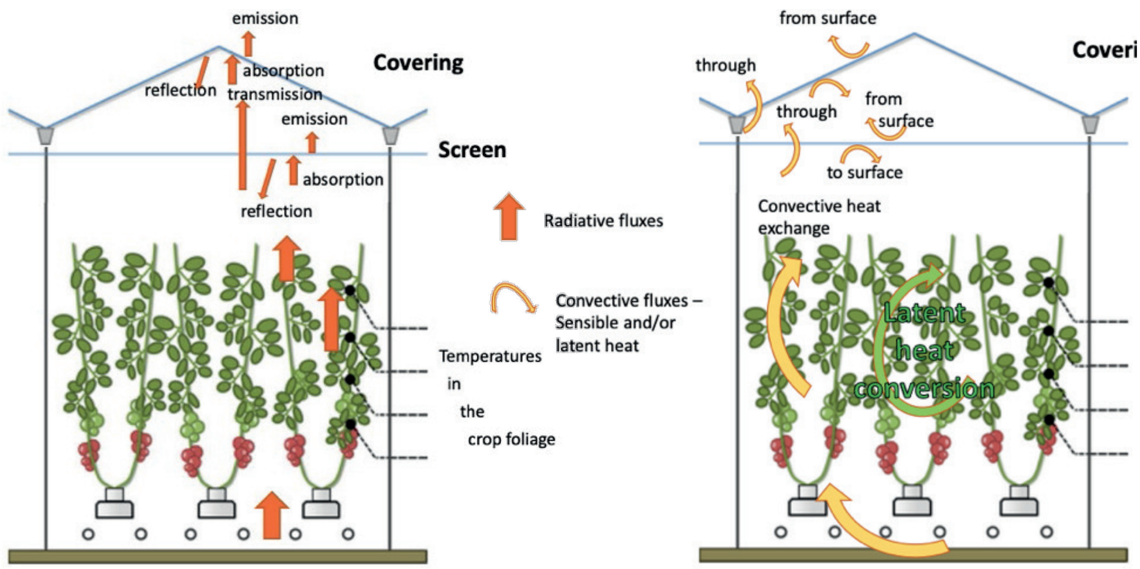


Figure 22 *The major exchange processes in the model, here shown with only one screen.*

When zooming in on the processes around the screen, the model distinguishes between air exchange through the screen, sensible and latent heat exchange at the screen and radiative heat exchange trough the screen. These different energy fluxes are shown in the sketch in Figure 23.

The graph shows that the parameters that are required to be able to calculate the properties are determined with the three tools available at the Wageningen UR LightLab. The TNO emissivity device is an instrument which is already available for many years and it is well capable of measuring the radiative properties in dry conditions. The TNO emissivity device cannot be used with wet screens, but as it is well known that material that gets wet on the surface inherits the radiative properties of water, it is assumed by the model that when the screen becomes wet, the emission coefficient goes to 0.9 and the transmission coefficient for infra-red radiation becomes 0.05. The remaining 0.05 is the absorption coefficient for infrared radiation.

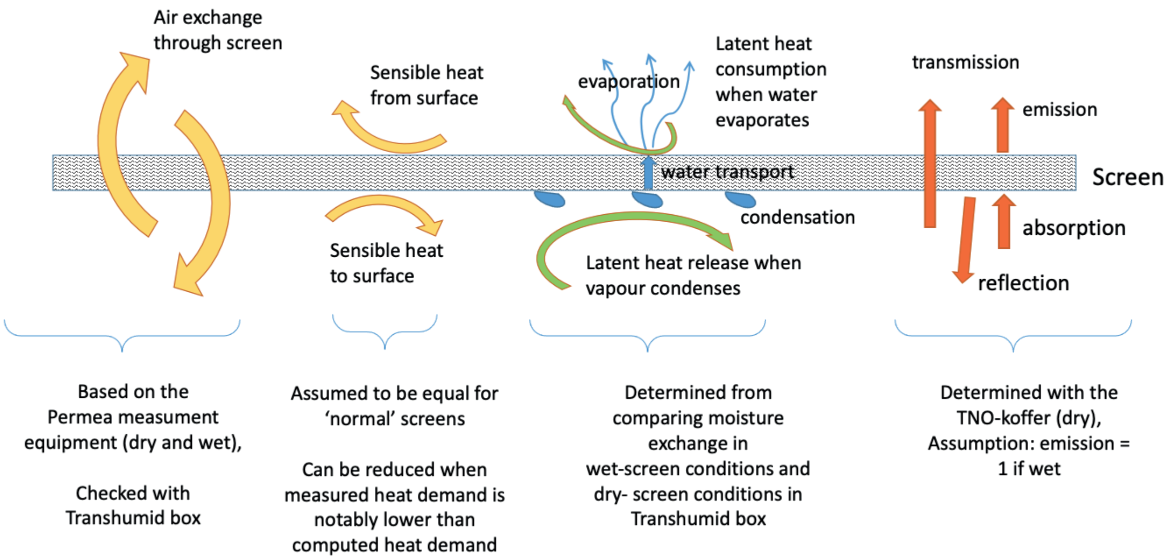


Figure 23 *The exchange processes distinguished around a screen.*

The air exchange through the screen is a function of pressure difference and the relation between these can be accurately measured with the new Permea-device. After multiplication with the dynamic viscosity, the Premea-device gives the permeability.
In the greenhouse, the pressure difference that drives the air exchange through the screen is generated by the density difference, which, in its turn, is generated by a temperature difference. Already in the eighties, Balemans defined a relation between temperature-driven air exchange through a screen as a function of permeability. In his work he found the air exchange proportional to the permeability and the temperature difference powered 0.66.

Therefore, the current KAPRO-model uses the formula

flowThroughScreen = 1000 * dT066 * permeability [$m^3/(m^2\ s)$]

in which dT066 is the temperature difference with a power 0.66 and the permeability is the value measured with the permea-device. As the temperature difference across a screen is typically around 8°C and the permeability of typical energy screens is around $1e^{-7}$ m, a typical flowrate through an energy screen is $3.9e^{-4}$ $m^3/(m^2\ s)$, which is 1.4 $m^3/(m^2\ h)$.

With the Permea-device both wet and dry samples can be measured and if these differ, the simulation model is provided with both values. During the simulation, the model computes the wetness of the screen and when it transforms from dry to wet, the radiative and permeability parameters gradually change from the dry screen to the wet screen values. Fully wet means that the amount of water on the screen is equal to its maximal water holding capacity. When fully wet, additional condensation will result in a drip-off of water. Water dripping off from the screen is assumed to fall on the floor where it will be re-evaporated.

Water that condensates at the screen adds latent heat to the screen surface, which is accounted for in the energy balance of the screen. Water condensed at the lower face can be transported hydroscopically to the top side of the screen and depending on the pressure difference between the saturated vapour of the screen and the vapour pressure in the top compartment, water can be evaporated at the top-side. The evaporation process consumes latent heat, which is also taken into account in the simulation model.
Hydroscopic moisture exchange from the lower compartment to the top-compartment is considered a separate exchange process that may add additional moisture transport between the two compartments on top of the moisture transport through the permeability of the screen. For such hydroscopic moisture transport, the screen has of course to be wet (= below dewpoint of the lower compartment), and it needs to be able to transfer liquid water from the bottom face to the top face. The first precondition is dynamically calculated by the simulation model. The second precondition is a parameter between 0 (not capable to transport water) to 1 (all water condensing at the bottom can be transported to the top). However, the rate at which water can be evaporated from the top of the screen depends on the humidity of the air in the top compartment. If this humidity is high, even from a screen with hydroscopy 1, water will drip off from the bottom side as the rate of condensation will be higher than the rate of evaporation from the top.
Most woven-like screens will be capable to transport water from the bottom to the top. Foils, even when they are perforated will typically not be able to transfer liquid wate upwards. These will allow for moisture exchange by air exchange through the screen, but do not have this additive hydroscopic transport.

2.5.2 Description of calculation assumptions

In order to quantify the energy saving of the screens, a realistic simulation of a typical tomato crop growing cycle following Het Nieuwe Telen has been carried out. In order to account for a representative outside climate, a typical meteorological year (SEL2000), which was built using a large number of yearly weather datasets for a location (de Bilt) in The Netherlands, has been used as input.
Next to the weather data, a standardized set of greenhouse parameters (size, covering material, etc.), equipment (heating system, screen, etc.) and the set points used to define the inner climate has to be described. The computations are made for a non-illuminated tomato crop with the settings as shown below.

Table 8
Crop and cropping period.

Crop:	tomato
Plant date:	15-12
End of crop cycle:	20-11

This crop is supposed to be grown in a well-built state of the art Venlo-type greenhouse with the following properties.

Table 9

Greenhouse system.

Area:	40000	m^2
Gutter height:	6	m
Roof slope:	22	degree
Span width:	4	m
Section size:	5	m
Cover:	Standard glass	
Leakage:	$1e^{-4}$	$m^3/(m^2\ s)/(m/s)$
Window length:	2.5	m
Window height:	1.2	m
Nr of windows:	0.05	per m^2

The greenhouse is heated with a standard heating system, consisting of a pipe-rail system together with a crop heating system. The pipe-rail system is the primary heating system. The heating power of the boiler is supposed to be non-limiting, but the maximal temperature of the heating pipes is set to 70°C (supply side temperature).

Table 10

Heating system.

Primary heating network:	Low
Low pipes diameter:	51 mm
Number low heating pipes per span:	5
Maximum supply temperature pipe-rail	70°C
Crop heating system diameter:	32 mm
Number of Crop heating pipes per span:	2.5
Maximum supply temperature grow pipe	55°C

In order to perform simulations which are close to nowadays horticultural practice, a typical set of climate control and screen settings are based on the outline of Het Nieuwe Telen. However, as daytime usage of screens, which is common practice on cold and dull days in Het Nieuwe Telen, is much dependent on the light transmittance properties of the screen, only the night-time energy saving properties are used to benchmark the screens.
As in practice, growers will keep a (highly) transparent screen also deployed during dull and/or cold days, the practical energy saving perspective of a highly transparent screen may be somewhat higher than calculated with this standardized method.

Another difference between the standardised procedure and daily horticultural practice is that in the standardized procedure screens are always fully opened (daytime) or fully closed (night time when outside temperature is below 10 to 14°C, see below). For the benchmark computations, no screen gaps or screen ventilators (explained in more detail later on) are made to carry off humidity during too high humidity conditions.
The table below shows the screen controller settings applied for the standardised benchmark calculations.

Table 11

Screening setpoints.

Screen system:	dd-mm	Setting	
Max Tout screen:	01-10	14°C	If outside temperature is below this value, the screen will be closed during the night
"	01-05	10°C	
Close Screen below:		10 W/m²	Screen only used when solar radiation is below this value
Gap on temp. excess:		0 %	Percentage of gap opening of the screen when temperature exceeds the set point
Gap On humidity excess:		0 %	Percentage of gap opening of the screen when humidity exceeds the set point
Leakage of screen system		1.6 $m^3/(m^2h)$	Even if the screen itself is air tight (e.g. a foil), the screen installation is not. The provided figure (1.6) is the air exchange rate, at 4°C temperature difference between top and bottom, but is enlarged or decreased at other temperature differences with power 0.66

Of course, the heating temperature setpoint is of great importance for the energy saving perspective of a screen. The higher the temperature, the more effect a screen will have on the energy saving.
Below there is a list of typical temperature settings for a non-illuminated tomato-crop throughout the year.

Table 12

Temperature setpoints for heating and ventilation and humidity.

	Date	Value	
Heating temperature (°C):	15-12	18	Day and night at 18°C
"	26-12	19 17	Day 19°C, night 17°C
"	01-02	20 17 18	Make a large difference between day and evening
"	20-04	20 16 18	Steeper temperature drop in the evening
"	10-09	20 17 18	In autumn heating will become more important
"	20-11	5	Stop heating when growing cycle is finished
Radiation influence		200 400 2	The heating setpoint is increased with 2 degrees if the solar radiation increases from 200 to 400 W/m²
Dead zone (°C):	15-12	4	Excess of temperature compared to the setpoint in order to start opening the vents. High in winter
"	01-03	3	
"	01-04	2	More tight on the heating setpoint to avoid too high temperatures in the greenhouse
Humidity threshold		88 % RH	When the humidity in the greenhouse exceeds this value, vents are opened (but no screen gaps are applied)

With the settings above, bench-mark runs are performed for all screens measured in this report. The benchmark show the energy saving of the described greenhouse with the particular screen or without this screen.

3 Results

3.1 Humidity transport properties

In Table 2 (section 2.2.3) a large number of measured humidity transport figures are given. However, as these conditions in which these data were obtained is not equal in all cases, a better insight in humidity transport capacity can be provided by the calculated humidity transport under standardized conditions.
This can be done with the methodology explained in section 2.3 after the physical properties of the screen are determined with the Permea-device and the TransHumid box.
Setting the conditions below the screen at 18°C and 88 %RH and the conditions above the screen at 10°C and 60 % RH, the moisture transport capacity of the screens that are observed in this study are the following.

Table 13
Moisture transport capacity for different screens at standard conditions (Top compartment at 10°C, 60% RH and bottom at 18°C, 88% RH).

	Wet Permeability x 1e^{-7}	Humidity Transport g/m^2/h
2016		
BP16A	0.04	17.7*
CU18O	42.32	276.0*
NT16D	0.04	4.9*
NT16H	3.13	34.5
NT16K	2.00	22.2
NT16M	3.43	38.3
2018		
RC18F	0.88	26.7
RC18G	0.83	28.6
RC18H	0.52	23.3
NT18A	*	*
NT18B	0.51	15.8
LS19A	0.57	21.5
LS19B	0.72	23.7
LS19C	0.75	25.5

* only based on Permea measurement.

Table 13 shows that, of course, the moisture transport is related to the permeability, but as hydroscopic transport plays a role as well, the relation is not 1-to-1. Most screens with a low permeability are still capable to transport quite some moisture. The role of hydroscopy is relatively getting more important on screens with low permeability.

Almost all screens transport more than 20 grams per m² per hour, which means that as long as the temperature difference between greenhouse and top-compartment is larger than 8°C, and the top-compartment is relatively dry, the transport capacity is larger than the moisture production of a non-illuminated tomato crop.
A low humidity transport is correlated to a low loss of latent heat energy and is therefore correlated to a high energy saving. The overall potential energy saving of a material is (§3.4), however, also determined by the other materials properties measured (§3.2, §3.3).

3.2 Thermal properties

Measurement results of the thermal properties of 14 different screens are shown in Table 14. Reflection of thermal infrared radiation (TIR) (ρ_{TIR}), transmissivity of TIR (τ_{TIR}) and emissivity (ε) in % including the absolute standard deviation are given. All measurements are carried out on dry materials. We can conclude from the results that materials NT16D (top), NT18A (top) and LS19A (top) show the highest TIR reflectivity on a dry material
However, as screens will be wet very often, the majority of differences in radiative properties will be blurred by the equal properties that the screens obtain when they get wet. The properties of wet materials are dynamically calculated with Kaspro (§2.3.3). Then the TIR emission coefficient goes to 0.9 and the TIR transmissivity goes to 0.05.
A low TIR emissivity (high TIR reflectivity) is correlated to a low loss of radiative energy and is therefore correlated to a high energy saving. The overall potential energy saving of a material is, however, also determined by the other materials properties measured (§3.1, §3.2).

Table 14
Results of the measurements of thermal properties of different screens, reflection of TIR (ρ^{TIR}), transmissivity of TIR (ρ^{TIR}) and emissivity (ε) including the absolute standard deviation as measured on the TNO emissivity device.

	ρ_{TIR}	τ_{TIR}	ε	ε abs. stdev
2016				
BP16A	23	74	3	1.00
CU18O	17	28	54	4.77
NT16D_top	68	23	10	2.19
NT16D_bot	23	23	53	3.65
NT16H	24	9	67	0
NT16K	18	50	32	3.24
NT16M	15	7	78	3.13
2018				
RC18F	16	9	75	3.11
RC18G	20	32	48	3.51
RC18H	19	30	51	3.11
NT18A_top	58	34	8	1.22
NT18A_bot	29	34	37	2.17
NT18B	19	36	45	1.14
LS19A_top	68	6	26	4.50
LA19A_bot	22	7	71	3.16
LS19B	20	16	64	2.00
LS19C	20	33	47	1.53

3.3 Aerodynamic properties

Measurement results of the aerodynamic properties of 14 different screens are shown in Table 15. All measurements are carried out on dry and wet materials. We can conclude from the results that several materials who substantial differences in their aerodynamic properties if dry or wet. Some materials become more permeable if wet (e.g. NT16K, NT16M, LS18B, LS18C), other become less permeable if wet (e.g. BP18A, RC18G). Materials BP18A and NT16D show the lowest air permeability. A low permeability for air is correlated to a high loss of sensible (and latent) heat energy and is therefore correlated to a higher energy saving. The overall potential energy saving of a material (§0) is, however, also determined by the other materials properties measured (§3.1, §3.2).

Table 15
Results of the measurements of aerodynamic properties of different screens, in dry and wet condition including the absolute standard deviation as measured on the Permea device.

	Permeability x $1e^{-7}$			
	Dry	abs. stdev	Wet	abs. stdev
2016				
BP16A	0.19	0.04	0.04	0.07
CU18O	36.86	0.08	42.32	0.97
NT16D	0.02	0.00	0.04	0.00
NT16H	5.28	0.07	3.13	2.87
NT16K	1.64	0.17	2.00	0.32
NT16M	3.28	0.20	3.43	0.03
2018				
RC18F	0.76	0.00	0.88	0.07
RC18G	1.07	0.11	0.83	0.00
RC18H	0.53	0.09	0.52	0.03
NT18A	0.10	0.00	*	*
NT18B	0.48	0.00	0.51	0.07
LS19A	0.59	0.02	0.57	0.03
LS19B	0.44	0.18	0.72	0.07
LS19C	0.57	0.17	0.75	0.03

* aerodynamic parameters of material could not be measured due to low permeability.

3.4 Overall energy saving

3.4.1 Standardised overall potential energy saving

With the climate settings described in chapter §0 and the measured screen characteristics, simulations with the Kaspro model, fully equipped to describe the processes around wet screen), were carried out. Results show an average of ± 25% saving on the heating demand (expressed in m^3 of natural gas equivalents) (Table 16). We observe that a screen with a very high air permeability (CU16O) shows the lowest energy saving potential and a screen with a very low permeability (NT16D) has the highest energy saving potential.

Table 16
Overview of the yearly gas use, the gas use during the night, the saving percentage compared to no screens, the average saving percentage during the night, the maximum saving per day and the maximum saving percentage during one night, for 13 screen types.

	heating		saving		maximum saving
	total	night	year	night	
	$m^3/(m^2 \cdot y)$	$m^3/(m^2 \cdot y)$	%	%	$m^3/(m^2 \cdot day)$
BP16A	31.0	19.7	27	36	0.10
CU16O	37.1	26.4	12	14	0.06
LS19A	29.1	17.9	31	42	0.13
LS19B	31.1	20.1	26	35	0.11
LS19C	30.7	19.4	27	37	0.11
NT16D	27.5	15.9	35	48	0.14
NT16H	33.0	22.1	22	28	0.10
NT16K	31.0	19.6	27	37	0.10
NT16M	33.1	21.9	22	29	0.10
NT18B	30.7	19.3	27	38	0.10
RC18F	31.8	20.6	25	33	0.11
RC18G	30.8	19.6	27	36	0.10
RC18H	30.8	19.6	27	37	0.10
reference	42.2	42.2			

As the greenhouse climate settings are equal for all simulations, the differences in energy saving obtained are fully determined by the physical properties of the screens. As these properties are determined with some uncertainty, a sensitivity-analyses has been made on the computed energy saving in case the measured properties deviate one standard deviation from their average value. This means that for each screen the following changes in the parameters have been applied.

- The average measurements, so all parameters unchanged.
- The average measurements, but with one standard deviation lower air permeability.
- The average measurements, but with one standard deviation higher air permeability.
- The average measurements, but with one standard deviation lower TIR transmissivity.
- The average measurements, but with one standard deviation higher TIR transmissivity.
- The average measurements, but with one standard deviation lower emissivity.
- The average measurements, but with one standard deviation higher emissivity.

The results are shown in the graph below.

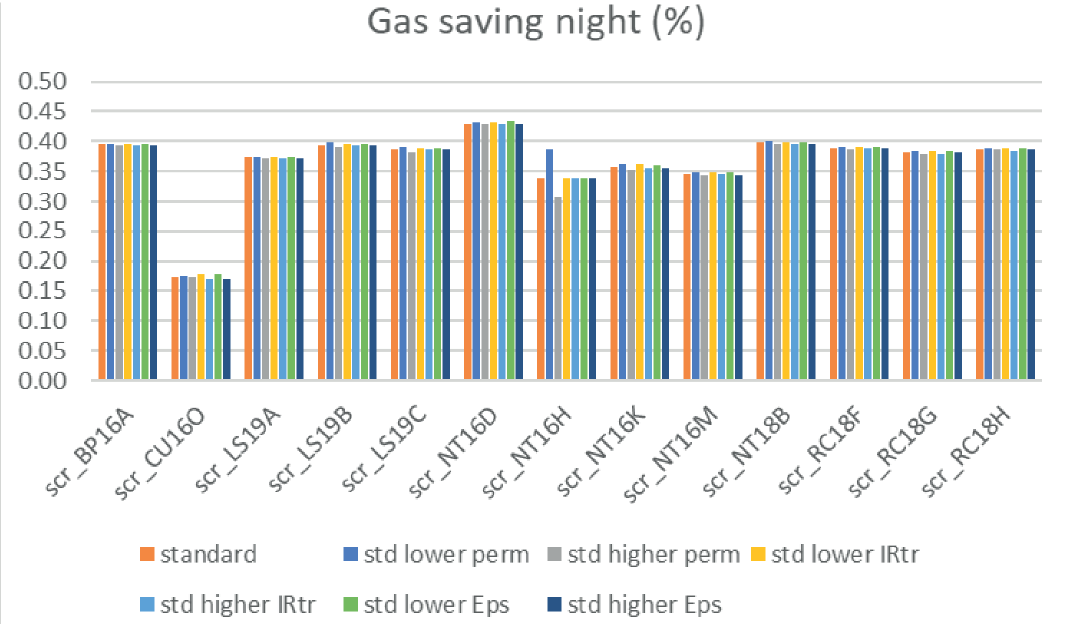


Figure 2. *The average gas saving percentage during the night for different screens with their average measured properties compared to the cases if the air permeability, the TIR transmissivity or the emissivity would be the standard deviation lower or higher.*

As can be seen, due to the small standard deviation in the measurements, the effect of uncertainty in the measured parameters is very small. There is only one exception and that is the effect of uncertainty in the permeability of NT16H. Indeed, according to

Table 15, the standard deviation of the measurement of the wet permeability for this screen was exceptionally large.

In general we can conclude that the small measurement errors (small standaraddeviation) does not lead to large differences in the total calculated energy consumption.

In Annex 1 the different energy components (fluxes) through a screen and their absolute and relative contribution to the total energy flux is given at a standardised situation for different screens with different properties in dry and wet conditions.

3.4.2 Effect of humidity control on potential energy saving

Screens with low permeability lead to the highest energy saving potential. However, in case no additional actions to lower the humidity other that opening the vents are taken, the increased insulation caused by the screen leads to a higher humidity of the greenhouse air. When the crop is just planted, the increased humidity will be appreciated by growers, but for a mature crop, adversive crop development may occur when the humidity becomes too high (a too vegetative growth, higher fungal disease pressure).

To lower the humidity, measures can be taken to promote the introduction of dryer air to the greenhouse. A commonly applied way is to open small screen gaps.

In recent years, more and more growers are using screen fans in order to have a better controllable air exchange between greenhouse air and the air in the top-compartment, but essentially, also in this option humidity is lowered by deliberately increasing the air exchange between the bottom and top compartment.
A novel and advanced way of reducing the humidity of the greenhouse air is the mechanical dehumidification, where the excess humidity is condensed on a condenser inside the greenhouse. In this way sensible and latent heat can be better kept inside the greenhouse system, reducing the energy losses to the environment.
In the graph below, first the cumulative frequency duration curve of humidity during the hours with a deployed screen is shown in case no additional humidity control is applied.

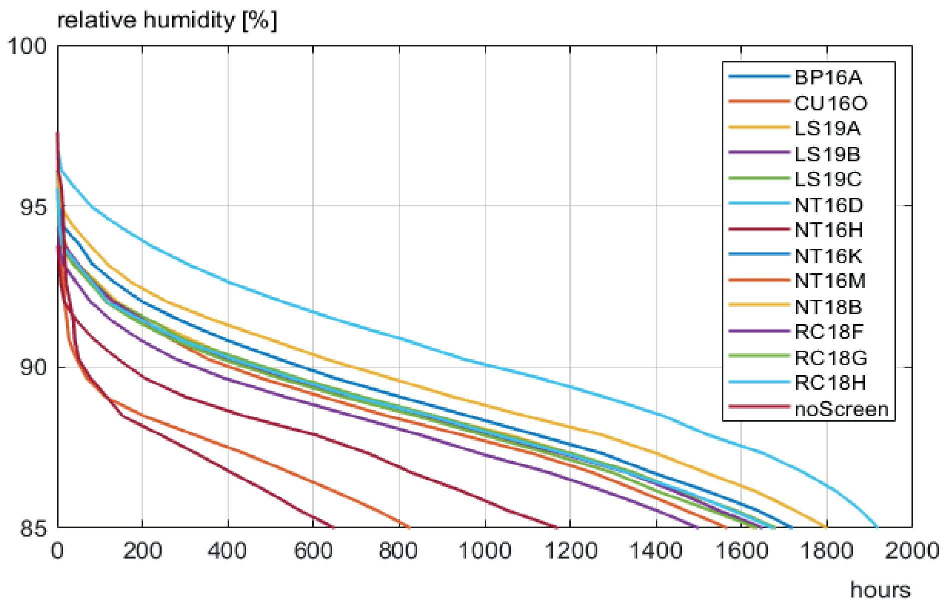


***Figure 25** Duration curves of the relative humidity (%) of the greenhouse during the hours that screens are deployed for 13 screen types and in case no screen is available.*

In the simulations applied to generate the figure above (Figure 25), no other action is applied than **opening the vents** when the greenhouse humidity exceeds the threshold of 88% RH.

It can clearly be seen that the highly permeable screen CU16O has hardly any impact on greenhouse air humidity as the humidity is only some 50 hours more above the threshold than in the simulation without a screen. On the other side of the spectrum, the almost non-permeable screen NT16D results in 1400 hours with a humidity above the threshold.

When taking action in the form of making **screen gaps** whenever the humidity exceeds the threshold, the cumulative frequency curve of humidity changes like shown below (Figure 26). For these calculations, a screen gap of 0 to 5% was made when the humidity exceeds the threshold with 0 to 5% RH-points. So, giving a threshold of 88%, a humidity of 90% inside the greenhouse would lead to a 2% screen gap, which is a 10 cm opening in the screen.

It is clear that applying screen gaps is an effective way to reduce the humidity below a screen as it can restore the air exchange between the greenhouse air to the outside air and/or the condensing cold greenhouse cover.

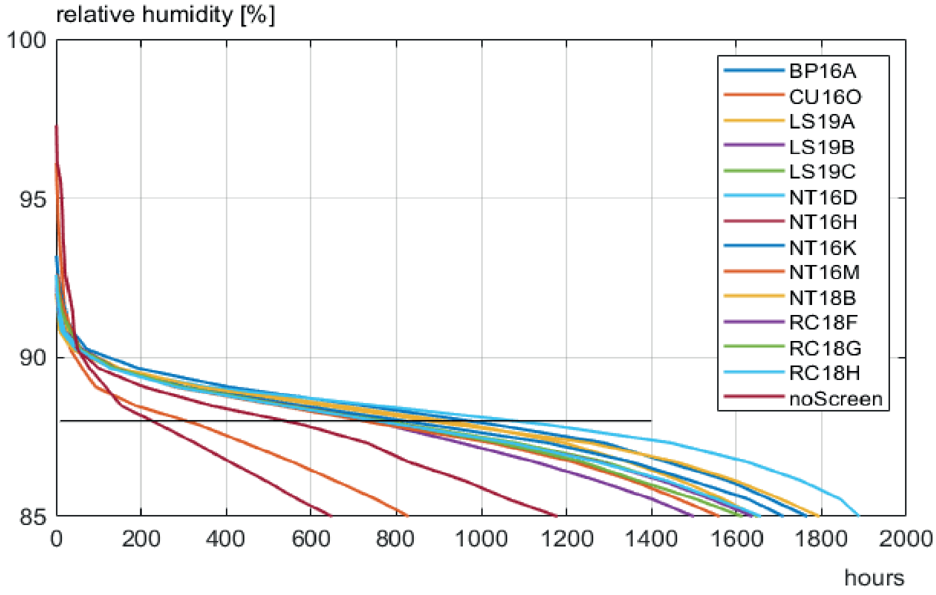


Figure 26 *Duration curves of the relative humidity (%) of the greenhouse during the hours that screens are deployed for 13 screen types when using screen gaps in case the humidity exceeds the threshold.*

The downside of using screen gaps is that it may lead to large temperature in-homogeneities. This negative point is largely solved by using **screen ventilators**. The result in terms of humidity in the greenhouse below the deployed screen is shown in the graph below (Figure 27).

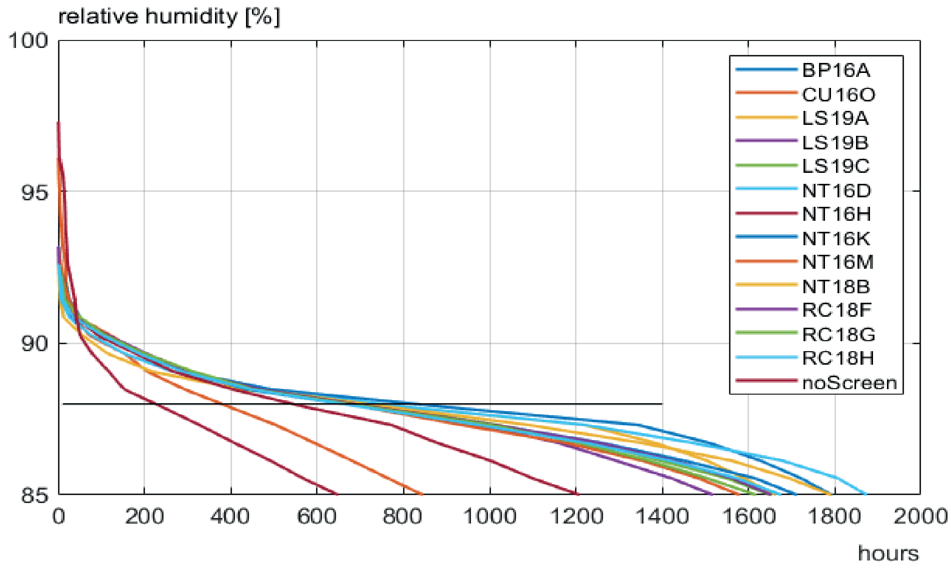


Figure 27 *Duration curves of the relative humidity (%) of the greenhouse air during the hours that screens are deployed for 13 screen types when using ventilators to mix the air below and above the screen in order to reduce the humidity.*

The increased mixing of greenhouse air with the air above the screen comes of course at the price of an increased energy consumption.

Table 17 shows the night-time energy use and the night time and year round energy saving by the different screens for both the additional humidity control measures. And for reference, the numbers from Table 16 are repeated.

Table 17

Night-time, and yearly energy use in m³ of natural gas per m² for the different screen materials when no additional action is taken on humidity excess and when either screen gaps or a screen ventilator is used. The energy saving figures give the saving percentage, relative to the reference without screen, where the yearly heating demand is 42.2 m³ of natural gas equivalents, from which 30.9 is used during the night-time.

	No additional humidity control				Screen gaps				Screen ventilator			
	Night		Year		Night		Year		Night		Year	
	Use [$m^3/m^2/y$]	Saving [%]	Use [$m^3/m^2/y$]	Saving [%]	Use [$m^3/m^2/y$]	Saving [%]	Use [$m^3/m^2/y$]	Saving [%]	Use [$m^3/m^2/y$]	Saving [%]	Use [$m^3/m^2/y$]	Saving [%]
BP16A	19.7	36	31.0	27	20.4	34	31.7	25	20.6	33	31.8	25
CU16O	26.4	14	37.1	12	26.4	14	37.1	12	26.3	15	36.9	13
LS19A	17.9	42	29.1	31	18.2	41	29.4	30	18.0	42	29.2	31
LS19B	20.1	35	31.1	26	20.4	34	31.5	26	20.3	34	31.4	26
LS19C	19.4	37	30.7	27	19.8	36	31.0	27	19.7	36	30.9	27
NT16D	15.9	48	27.5	35	16.6	46	28.0	34	16.5	46	27.8	34
NT16H	22.1	28	33.0	22	22.3	28	33.2	21	22.2	28	33.0	22
NT16K	19.6	37	31.0	27	19.8	36	31.2	26	19.6	36	30.9	27
NT16M	21.9	29	33.1	22	22.1	28	33.3	21	21.8	29	32.9	22
NT18B	19.3	38	30.7	27	19.7	36	31.0	27	19.5	37	30.8	27
RC18F	20.6	33	31.8	25	20.9	32	32.1	24	20.8	33	31.9	24
RC18G	19.6	36	30.8	27	20.0	35	31.2	26	20.0	35	31.1	26
RC18H	19.6	37	30.8	27	19.9	35	31.1	26	19.8	36	31.0	27

As next to the hours in which the greenhouse will get a too high humidity when the screen is deployed there are also many hours where the humidity is not a problem (or even more favourable), the more actively controlled humidity has a limited effect on the energy saving potential. Another reason for the small effect of using screen gaps or ventilators on total heat demand is the fact that it is predominantly the mild weather condition in which humidity excess plays a role. In cold nights, which have a high leverage on the energy consumption, humidity tends to be low anyway.

However, for all simulations shown above, humidity control is based on carrying off moisture by exchange with the outside air, and/or by condensing moisture at the greenhouse cover. In all cases, this means that sensible and latent heat is exchanged with the outside air.

This loss of energy can be prevented by keeping the vents closed during periods of humidity excess and let the excess of moisture condensate on a **mechanically cooled surface**. In this way, the latent heat is not lost to the environment, but transferred to the cooling fluid. After elevation the temperature of this latent heat to 40 to 45°C by means of a heat pump, this latent energy can be used as a sustainable heat source for greenhouse heating.

Table 18 shows the energy demand for heating for all different cases and the gas and electricity consumption associated to the generation of the required amount of heating.

Table 18
Heat demand and energy consumption of a greenhouse equipped with a dehumidification system based on recapturing of latent heat from humidity excesses in order to be used for heating. It is assumed that the regenerated latent heat is used first and where not sufficient the remaining demand is produced by burning natural gas. Total energy costs are computed assuming gas at 30 cents per m³ and electricity at 10 cents per kWh.

	heating	gas	electricity
	m^3 gas equivalent/y	$m^3/m^2/y$	$kWh/m^2/y$
BP16A	32.8	18.4	36
CU16O	37.9	25.1	32
LS19A	30.5	16.6	35
LS19B	32.5	18.9	34
LS19C	32.1	18.3	35
NT16D	29.2	14.8	36
NT16H	34.0	20.9	33
NT16K	32.3	18.4	35
NT16M	34.3	20.4	35
NT18B	32.1	18.0	36
RC18F	33.2	19.2	35
RC18G	32.2	18.5	34
RC18H	32.2	18.4	35
reference	42.2	42.2	0

When comparing the amount of gas equivalents for heating in Table 18 with the heat demands mentioned in the first column of Table 16 it might be surprising to see an increment of the heat demand. This is caused by the fact that condensing moisture at a cold surface dehumidifies the air, but also cools the air. So, at first sight, sensible heat is lost just as good as when the greenhouse is dehumidified by exchanging air with outside. The even sensible-to-latent heat loss ratio for dehumidification with a cooler is most of the time even worse than when dehumidifying with outside air. This explains the higher heat demand.

The big difference however, is when the greenhouse air is dehumidified (and collaterally cooled), the sensible and latent heat is not lost, but recoverable by using a heat pump. Using this recoverable heat seriously reduces the amount of gas needed for heating, shown in the second column of Table 18. However, using the heat pump (and air circulation fans) comes at the cost of electricity, which is shown in the third column.
The most straightforward way to combine gas and electricity into one number is to multiply each with a cost price. This is shown in Figure 28 and leads to the conclusion that, especially when using an active dehumidification system, the lowest permeable screen leads to the lowest gas consumption and the lowest energy costs.

If we compare the different humidity control strategies (no additional humidity control, screen gaps, screen fans, mechanical dehumidification) of all different screens (with different combined properties) we obtain the result in Figure 29. We can conclude that the lowest energy costs can be obtained by a grower using a screen with low permeability combined with low emissivity (high TIR reflectivity) and controlling humidity with a mechanical dehumidification system. From the same figure a grower also learns that a higher humidity setpoint (here 88%) can substantial save energy costs compared to a lower humidity setpoint (here 85%). Important aspects within the "Het Nieuwe Telen" growing strategies.

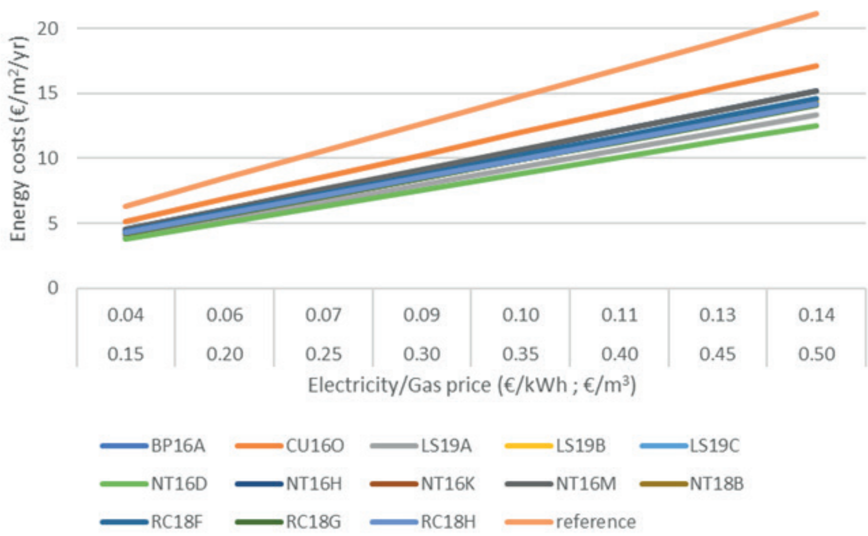


Figure 28 *Energy costs of a greenhouse equipped with a dehumidification system based on recapturing of latent heat from humidity excesses in order to be used for heating. It is assumed that the regenerated latent heat is used first and where not sufficient the remaining demand is produced by burning natural gas. Total energy costs are computed depending on different gas and electricity prices for all different screens.*

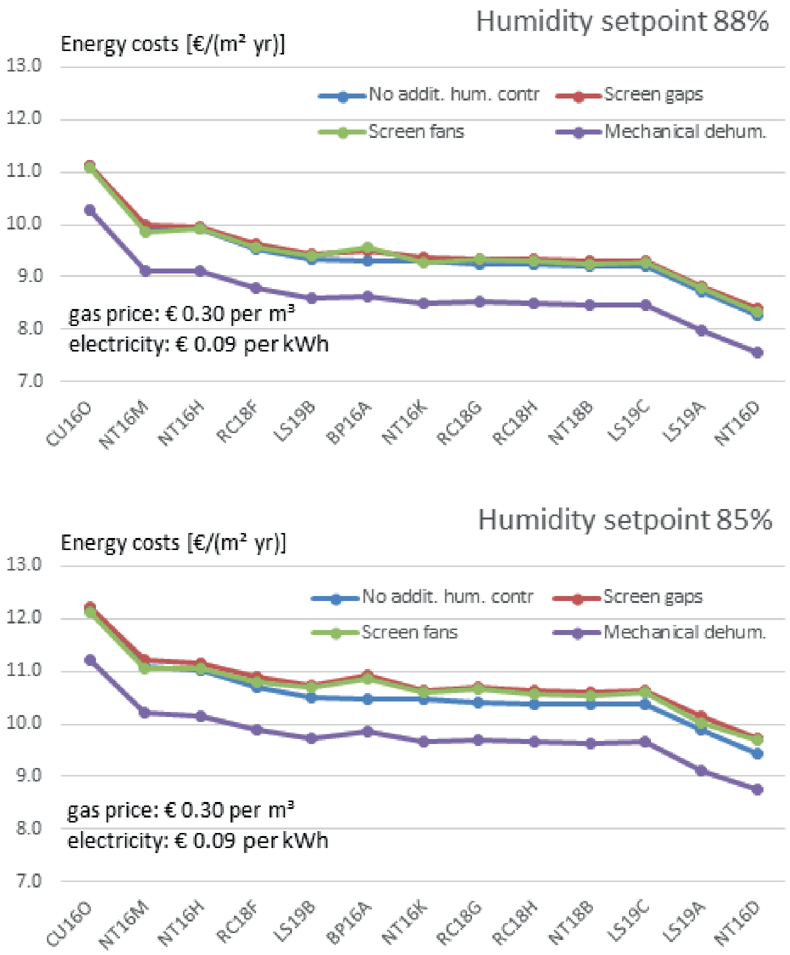


Figure 29 *Energy costs of different humidity control strategies (no additional humidity control, screen gaps, screen fans, mechanical dehumidification) of all different screens (with different combined properties). The upper figure shows the energy costs at a humidity setpoint of 88%, the lower figure at 85%.*

4 Conclusions

In this study, different equipment, methods and standardized measurement procedures for determining screen material properties (dry and wet) have been developed. We recommend screen producers to obtain the following material properties for their materials and provide this information to growers. Growers can use this information to make a choice for a screen material depending on crop and requirements.

- Thermal properties: thermal infrared reflectivity, thermal infrared transmissivity, emissivity of screens.
- Aerodynamic properties: air permeability of screens.
- Humidity transport properties.
- Calculation of standardised overall energy saving key figures for objective comparison of screen materials.

Thermal properties:

- A measurement equipment was already in place to determine the thermal properties of screen materials, the TNO emissivity device.
- The TNO emissivity device can measure thermal properties of dry materials with high repeatability on a randomly selected spot.
- Materials investigated differ is thermal properties. A low emissivity and a high reflectivity for thermal infrared radiation of a screen is correlated to low radiative energy loss.
- We did not succeed to measure thermal properties of wet materials. However, it also showed out that the thermal properties play a relatively small role in the energy balance around a screen. Air permeability and convective exchange processes, especially due to condensation are of much more importance.
- Measured thermal radiative properties are input to the KASPRO model to calculate the overall potential energy saving.

Aerodynamic properties:

- A new measurement equipment is developed in the form of a small wind tunnel, which can determine the air permeability of screen materials, the Permea device.
- The Permea device determines the permeability with high repeatability on a randomly selected spot.
- Materials investigated differ in their air permeability properties. Some materials show higher permeability if wet, others show a lower permeability if wet. A low air permeability of a screen is correlated to a low loss of sensible (and latent) heat.
- Measured permeability characteristics are input to the KASPRO model to calculate the overall potential energy saving.

Humidity transport properties:

- A new measurement device is developed to determine the humidity transport through screen materials, the TransHumid device.
- It can measure humidity transfer properties of dry and wet materials with good repeatability.
- Materials investigated differ is their humidity transport properties. A low humidity transport of a screen is correlated to a low loss of latent heat.
- Humidity transfer is high for materials with high air permeability, but also low permeable screens can pass quite some moisture due to condensation at the bottom and evaporation from the top. This process is called the hydroscopic moisture exchange.
- Measured humidity transport characteristics are input to the KASPRO model to calculate the overall potential energy saving.

From these measured properties the overall potential energy saving can be calculated in a standardised way and reported to growers to facilitate objective comparison of screen materials.

Overall potential energy saving:
- Overall potential energy saving simulation results show that the lowest energy use can be achieved if the screens have a low air permeability.
- Among the investigated screens energy savings differ between 17% (low permeability) and 43% (high permeability) during night-time usage compared to a situation without a screen.
- Screens with low air permeability will cause higher humidity levels. These can well be avoided by deliberately increasing the air exchange rate, either by screen gaps or by screen ventilators. The latter might be of preference for growers as screen gaps might result in quite an inhomogeneity of the temperature in the greenhouse.
- Mechanical dehumidification can seriously lower the energy demand of a greenhouse as it allows to recuperate latent energy. This comes at the costs of an increased electricity demand, but at the current ratio between gas and electricity costs, the combined heating costs will notably go down.
- In order to have the most profit from mechanical dehumidification, a low-permeable screen is even more important.
- Screens with low permeability should also simultaneously a low emissivity (high reflectivity for thermal infrared radiation) to result in highest energy saving.

Screen manufacturers should focus on the development of screens with a low air permeability which show the highest energy saving. If this is combined with a high reflectivity for thermal infrared radiation (low emissivity) a high energy saving (in our study 43% during night-time hours) can be realized.

For a **grower** the results mean that a low permeable screen may lead to many hours with a too high humidity but if in those cases the air exchange between upper and lower compartment is deliberately enlarged by making screen gaps or by using fans that exchange air between the top and main greenhouse compartment too high humidity can be avoided. Of course, this way of reducing the humidity leads to an increment of energy consumption, as growing at lower humidity will always results in higher heat demand. However, as increasing the air exchange across the screen is used most on the less cold periods, the additional heat demand of screen gaps or screen ventilators is in no case more than 0.9 m^3/m^2 year. For a number of screens, the additional heat demand is hardly measurable. Growing at high humidity should be an accepted principle according to “Het Nieuwe Telen” growing. If humidity is controlled at a lower humidity, e.g. 85% RH instead of 88%, energy consumption will notably increase.

If mechanical dehumidification is used with sensible and latent heat recovery, the importance of a low-permeable screen is only increasing further. The working principle of mechanical dehumidification is the avoidance of latent heat losses to the environment, so a better closing screen will be important.

The project has resulted in better insight in the importance of (limiting) unwanted air exchange through screens and in tools for suppliers and growers to show the processes around screens and the importance of limiting the air exchange.

5 Conclusies

In dit onderzoek zijn verschillende apparatuur, methoden en gestandaardiseerde meetprocedures ontwikkeld voor het bepalen van de eigenschappen van schermmaterialen (droog en nat). We raden schermproducenten aan om de volgende materiaaleigenschappen voor hun materialen te meten en deze informatie aan telers te verstrekken. Met deze informatie kunnen telers afhankelijk van het gewas en de wensen een keuze maken voor een schermmateriaal.

- Thermische eigenschappen: thermische infraroodreflectiviteit, thermische infrarood transmissiviteit, emissiviteit van schermen.
- Aerodynamische eigenschappen: luchtdoorlatendheid van schermen.
- Vochttransport eigenschappen.
- Berekening van gestandaardiseerde algemene energiebesparingskengetallen voor objectieve vergelijking van schermmaterialen.

Thermische eigenschappen:

- Er was al meetapparatuur aanwezig om de thermische eigenschappen van schermmaterialen te bepalen, het TNO emissiviteitsapparaat.
- Het TNO-emissiviteitsapparaat kan thermische eigenschappen van droge materialen meten met een hoge herhaalbaarheid op een willekeurig gekozen plek.
- De onderzochte materialen verschillen qua thermische eigenschappen. Een lage emissiviteit en een hoge reflectiviteit voor thermische infraroodstraling van een scherm is gecorreleerd aan een laag stralingsenergieverlies.
- Het is ons niet gelukt om de thermische eigenschappen van natte materialen te meten. Het onderzoek toonde echter ook aan dat de thermische eigenschappen een relatief kleine rol spelen in de energiebalans rond een scherm. Luchtdoorlatendheid en convectieve uitwisselingsprocessen, vooral door condensatie, zijn belangrijker.
- Gemeten thermische stralingseigenschappen worden ingevoerd in het KASPRO-model om de totale potentiële energiebesparing te berekenen.

Aerodynamische eigenschappen:

- Er wordt een nieuwe meetapparatuur ontwikkeld in de vorm van een kleine windtunnel, die de luchtdoorlatendheid van schermmaterialen kan bepalen, het Permea-apparaat.
- Het Permea-apparaat bepaalt de doorlatendheid met hoge herhaalbaarheid op een willekeurig gekozen plek.
- De onderzochte materialen verschillen in hun luchtdoorlatende eigenschappen. Sommige materialen vertonen een hogere doorlaatendheid als ze nat zijn, andere vertonen een lagere doorlatendheid als ze nat zijn. Een lage luchtdoorlatendheid van een scherm hangt samen met een laag verlies aan voelbare (en latente) warmte.
- Gemeten permeabiliteitskenmerken worden ingevoerd in het KASPRO-model om de totale potentiële energiebesparing te berekenen.

Vochttransport eigenschappen:

- Er is een nieuw meetapparaat ontwikkeld om het vochttransport door schermmaterialen te bepalen, het TransHumid-apparaat.
- Het kan de vochttransport eigenschappen van droge en natte materialen meten met een goede herhaalbaarheid.
- De onderzochte materialen verschillen in hun vochttransport eigenschappen. Een laag vochttransport van een scherm hangt samen met een laag verlies aan latente warmte.
- Het vochttransport is hoog bij materialen met een hoge luchtdoorlatendheid, maar ook weinig doorlatende schermen kunnen behoorlijk wat vocht doorlaten door condensatie aan de onderkant en verdamping aan de bovenkant. Dit proces wordt de hydroscopische vochtuitwisseling genoemd.
- Gemeten vochttransportkarakteristieken worden ingevoerd in het KASPRO-model om de totale potentiële energiebesparing te berekenen.

Op basis van deze gemeten eigenschappen kan de totale potentiële energiebesparing op een gestandaardiseerde manier worden berekend en aan telers worden gerapporteerd om objectieve vergelijking van schermmaterialen te vergemakkelijken.

Totale potentiële energiebesparing:

- Simulatieresultaten van de totale potentiële energiebesparing laten zien dat het laagste energieverbruik kan worden bereikt als schermen een lage luchtdoorlatendheid hebben.
- Bij de onderzochte schermen verschilt de energiebesparing tussen 17% (hoge luchtdoorlatendheid) en 43% (lage luchtdoorlatendheid) in de nacht in vergelijking met een situatie zonder scherm.
- Schermen met een lage luchtdoorlatendheid veroorzaken een hogere luchtvochtigheid. Deze is goed te vermijden door bewust de luchtuitwisseling te verhogen, hetzij door schermkieren of door schermventilatoren. Dit laatste kan voor telers de voorkeur hebben, omdat schermkieren mogelijk kunnen leiden tot inhomogeniteit van de temperatuurverdeling in de kas.
- Mechanische ontvochtiging kan de energiebehoefte van een kas aanzienlijk verlagen omdat latente energie geregenereerd kan worden. Dit gaat ten koste van een grotere elektriciteitsvraag, maar bij de huidige verhouding tussen gas- en elektriciteitskosten zullen de gecombineerde energiekosten aanzienlijk dalen.
- Om het meeste profijt te hebben van mechanische ontvochtiging, is een scherm met een zeer lagen luchtdoorlatendheid nog belangrijker.
- Schermen met een lage luchtdoorlatendheid en gelijktijdig een lage emissiviteit (hoge reflectiviteit van warmtestraling) zorgen voor de hoogste energiebesparing.

Schermfabrikanten zouden zich moeten richten op de ontwikkeling van schermen met een lage luchtdoorlatendheid en gelijktijdig een lage emissiviteit, deze zorgen voor de hoogste energiebesparing (in ons onderzoek tot 43% tijdens de nacht uren).

Voor een **teler** betekenen de resultaten dat een laag doorlatend scherm kan leiden tot meer uren met een te hoge luchtvochtigheid. Echter, als in die gevallen de luchtuitwisseling tussen boven- en ondercompartiment bewust wordt vergroot, bijvoorbeeld door schermkieren of door schermventilatoren te gebruiken die lucht tussen boven en onder het scherm verversen, kan zo een te hoge luchtvochtigheid worden vermeden. Natuurlijk leidt deze manier van verlaging van de luchtvochtigheid tot een toename van het energieverbruik, omdat telen bij een lagere luchtvochtigheid altijd zal resulteren in een hogere warmtevraag. Omdat het verhogen van de luchtuitwisseling over het scherm echter het meest wordt toegepast tijdens minder koude periodes, is de extra warmtevraag van schermkieren of schermventilatoren in geen geval meer dan 0,9 m^3/m^2 jaar. Voor een aantal schermen is de extra warmtevraag nauwelijks meetbaar. Telen bij een hoge luchtvochtigheid zou volgens “Het Nieuwe Telen” een geaccepteerd principe moeten zijn. Als de luchtvochtigheid bij een lagere luchtvochtigheid wordt geregeld, bijvoorbeeld 85% RV i.p.v. 88% RV, zal het energieverbruik aanzienlijk toenemen. Als mechanische ontvochtiging wordt toegepast met voelbare en latente warmteterugwinning, wordt het belang van een weinig doorlatend scherm alleen maar groter. Het werkingsprincipe van mechanische ontvochtiging is het vermijden van latente warmteverliezen naar de omgeving, dus een beter gesloten scherm zal belangrijk zijn.

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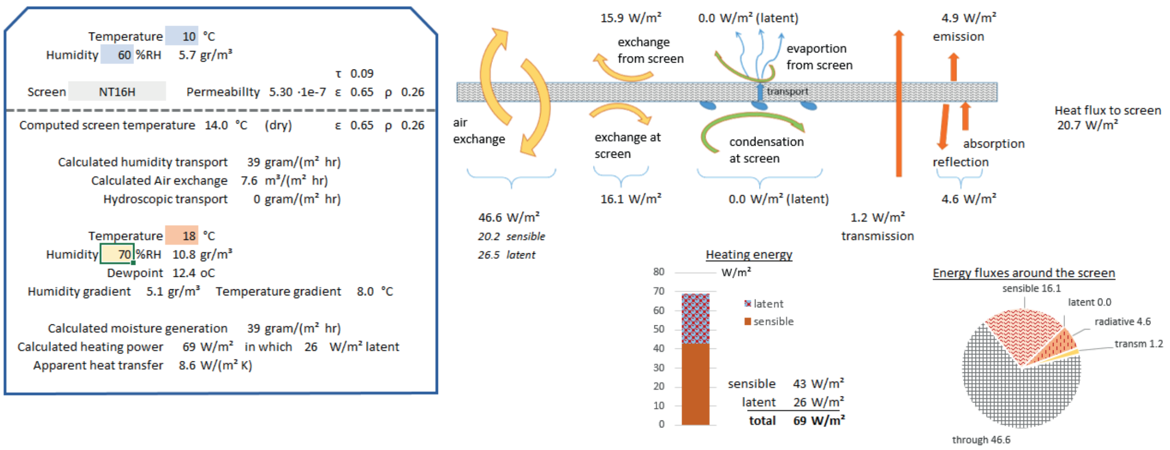
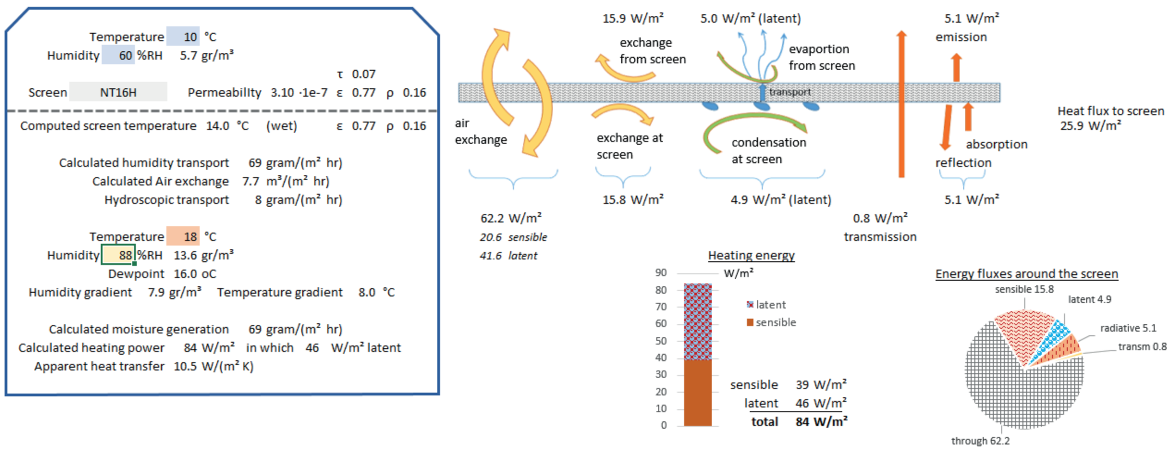
Annex1 Energy fluxes through screens

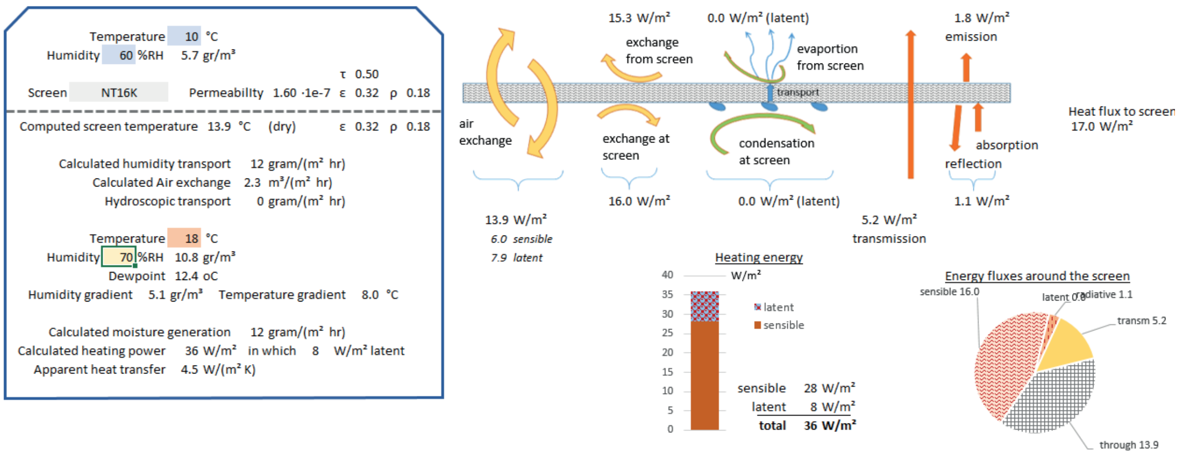
Contribution of the different components



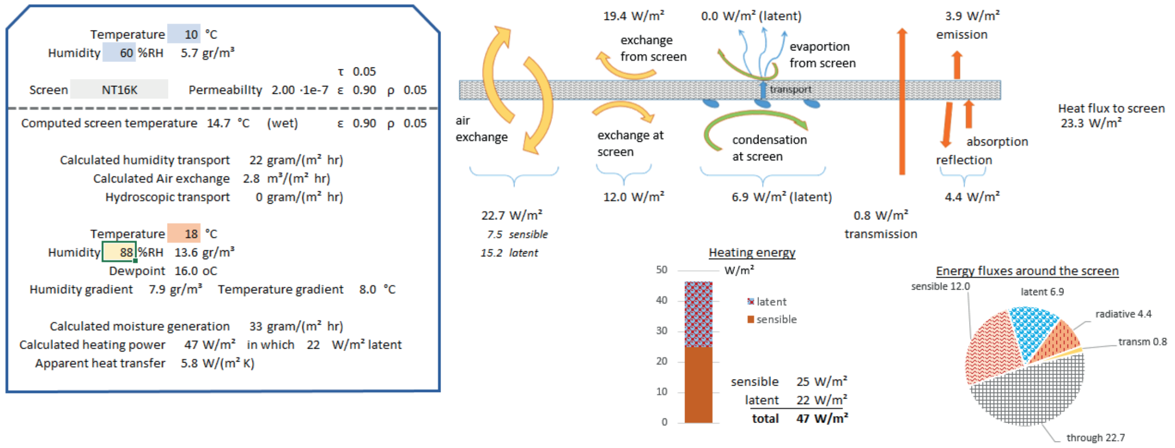
Screen with very high permeability, dry conditions.



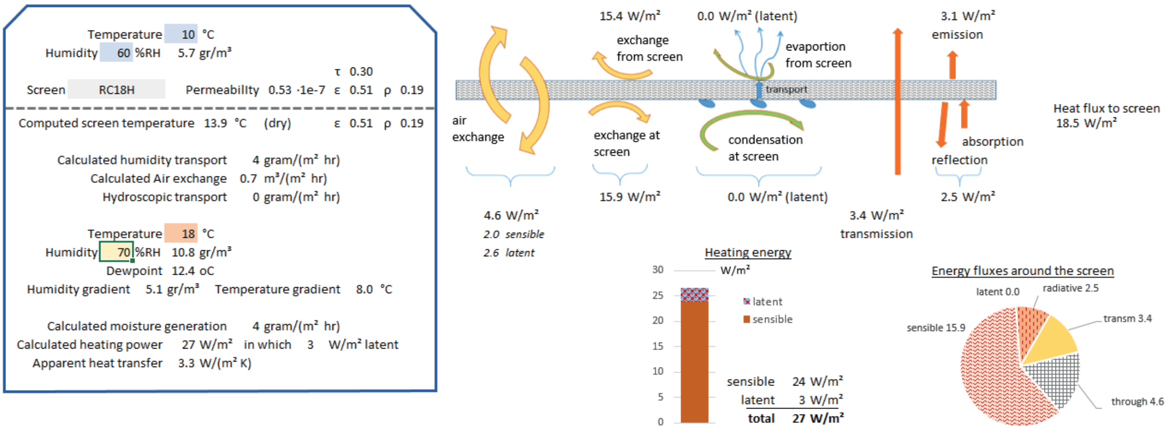
Screen with very high permeability, wet conditions.



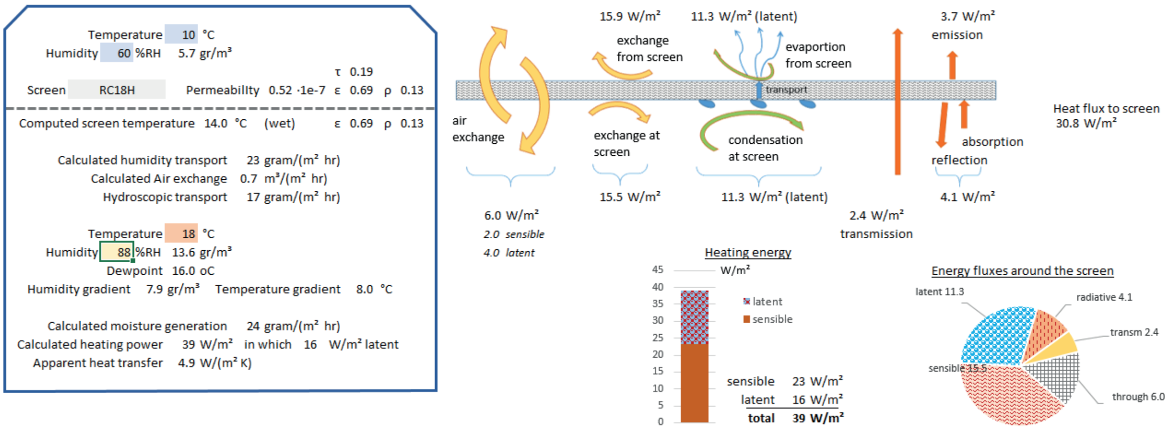
Screen with high permeability, dry conditions.



Screen with high permeability, wet conditions.

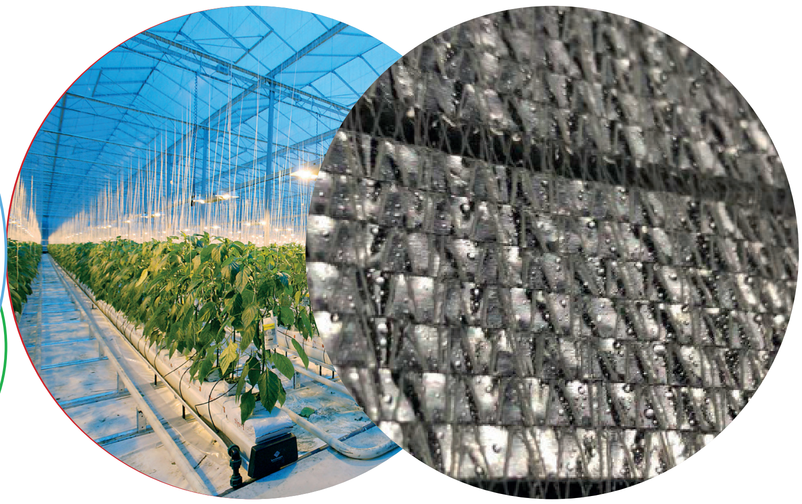


Screen with low permeability, dry conditions.



Screen with low permeability, wet conditions.

To explore the potential of nature to improve the quality of life



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The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 6,800 employees (6,000 fte) and 12,900 students, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.