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Heat Transfer Coefficients of Layers of Greenhouse Thermal Screens

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Abstract **-** The total energy saving effect of different types of greenhouse thermal/shade screens was determined by measuring and calculating the overall heat transfer coefficients (*U*-values) for single and several layers of screens. The measurements were carried out using the hot box method and the calculations were performed according to the ISO Standard 15099. The goal was to examine different types of materials with a wide range of thermal radiation properties using for thermal screens in combinations with a dehumidification system in order to improve greenhouse insulation. The experimental results were in good agreement with the calculated heat transfer coefficients. It was shown that a high amount of infra-red (IR) radiation can be blocked by the greenhouse covering material in combination with moveable thermal screens. Aluminum foil screen could be replaced by transparent screens, depending on shading requirements. The results indicated that using a single layer, the *U*-value was reduced by approximately 70% compared to covering material alone, while the contributions of additional screen layers containing aluminum foil strips could reduce the *U*-value by approximately 90%. It was shown that three screen layers are sufficient for effective insulation.

Keywords**:** *U*-value; Thermal screens; Heat loss; Greenhouse insulation.

1. Introduction

Minimizing energy consumption for heating or cooling a greenhouse has been a major topic in the food industry in recent decades. Usually, a greenhouse is heated with hot air distributed by inflatable tubes or with hot water distributed by pipes and cooled using evaporative systems such as high-pressure fog system for naturally ventilated greenhouses, pad and fan cooling for mechanical ventilation systems, or active dehumidification systems for closed greenhouses ([1]-[8]). It is common to install horizontal airflow fans for additional air circulation in order to improve the uniformity conditions, release air stuck in the corners, and remove excess moisture from the crop canopy.

As a substitute approach, moveable energy-saving screens, or thermal screens, are commonly used in greenhouses. These screens deploy and retract easily in order to provide stable climatic conditions, such as internal shading and insulation. Previous studies showing that such systems are capable of approximately 30% energy savings with a single layer of low-cost film or woven screens and up to 60% savings with thermally opaque screens ([9]-[17]).

A closed greenhouse that incorporates heating and cooling along with dehumidification using the proper combination of thermal screens can provide both uniform indoor conditions as well as energy conservation. Heating is used only to compensate for heat loss through the covering materials, while ventilation, used to remove excess humidity and avoid vapor condensation, is completely excluded using a dehumidification system. In this way, the system provides a simplified and efficient infrastructure that is much easier to install and maintain. Moreover, the use of such a system eliminates the need for anti-drip treatment of the cover material due to the absence of condensation. Therefore, cost efficiency of dehumidification system with thermal screens could be higher compared to traditional greenhouse control systems with high operating cost including extensive ventilation, heating or cooling, etc.

In general, the energy saving properties of thermal screens are related to thermal buoyancy; diffusion and convection heat transfer; air permeability; and humidity transport ([18], [19], [13]). However, using a dehumidification system eliminates the risk of condensation due to excess humidity and therefore eliminates the need for air permeability of screens and extensive ventilation ([14]-[16]). In this case, it is possible to use films that are much cheaper and easier to manufacture. Thus, the material's emissivity becomes the main factor that determines the energy loss of a thermal screen. The energy losses are dependent on the radiation heat exchange among crop, dehumidification system, greenhouse screens, covering material, and the sky [20]. Depending on the time of day and weather conditions, screen layers with a sun/sky reflecting outer layer (on the top) provide efficient insulation, keeping the growing area cool on summer days and warm on winter nights. At the same time, using an IR reflecting bottom layer, part of the thermal radiation from inside the warm greenhouse can be absorbed and re-emitted by the screen material, reducing heating costs.

To maintain steady state conditions inside the greenhouse, the heat loss through the cover surfaces can be substantially reduced by using multilayer thermal screens. They can be effective when there is no sun, including at night, and may contribute to insulating the greenhouse during the heating in the afternoon or early morning. Different amounts of climate control in the greenhouse are needed for different climate zones. For colder regions, heating and dehumidification are required overnight, and natural ventilation during the daytime may be sufficient throughout the year. For Mediterranean climates, there are two energy-intensive periods: winter nighttime (heating and dehumidification) and summer daytime (ventilation and cooling). During winter daytime and summer nighttime, ventilation may require with or without dehumidification. In tropical regions with a hot and humid climate, a ventilation or cooling (with dehumidification) regime is required throughout the entire year. In addition, the thermal transparent covering materials (without thermal screens) are useful for transmitting photosynthetically active radiation and for allowing the excess heat to escape the greenhouse. Thus, using a combination of different screens depending on the external weather conditions affords proper control of light, temperature, and humidity, thus maintaining optimal levels for growing, preventing condensation on the covering material due to low outside temperatures, and saving significantly in energy costs.

The main objective of this paper was to evaluate the properties of multilayer thermal screens, in terms of resistance to infrared radiation, and to determine the total energy savings under defined conditions. In order to compare the performance of a system that incorporates dehumidification with different combinations of screens, the heat transfer coefficient of various commercial screens was investigated using the hot box method and validated via calculations of one dimensional heat transfer model described in ISO Standard 15099 [21]. This is a detailed calculation standard to predict the glazing system (or windows) thermal performance.

The next section describes the energy saving screen materials used in this study with a specific focus on infra-red radiation (IR) opaque materials and their combinations, and the measurement and calculation procedure for the overall heat transfer coefficient is presented. Section 3 presents the overall heat transfer coefficient (U-value) for different combinations of commercial thermal screens, and the conclusions are presented in Section 4.

2. Materials and Methods

Different types of commercial screens were tested individually and in combination as part of this study. The screens were made of ultra-violet (UV) stabilised polyethylene film (PE-UV) of approximately 60 microns thick, both: top covering materials and screens. In order to reduce the passage of thermal radiation, screen materials usually contain infrared reflecting additives (IR) or are comprised of polyester film strips alternated with strips of aluminum foil. Aluminum foil (AlFo) reflects over 90% of the solar radiation. The number and width of aluminum strips determine the shading percentage. For example, commercial thermal screens such as Aluminet IC-100, IC-30, and IC-0 have shading percentages of 99%, 30%, and 0% respectively. Thus, using different types of covering materials in combination with thermal screens allowed for the control of the shading percentage required for desirable plant development. Furthermore, using several layers of the aluminised film provided almost 99% insulation during the winter, while substantially reducing solar gain during the summer.

2.1. Calculation method

The calculation of the overall heat transfer coefficient through layers of screens were obtained by adoption of the well documented comprehensive algorithm, described in ISO 15099 standard [21] for calculation of one-dimension heat transfer trough a glazing system to evaluate thermal performance of windows in building. In following, the key statements are presented in accordance with the ISO standard mathematical model. The overall heat transfer coefficient is defined as inverse value of the total system thermal resistance including indoor, multi-layer inner and outdoor resistances:

$$U = 1/\left(R_{out} + \sum_{i=1}^{n} R_{gl,i} + \sum_{i=1}^{n} R_{gap,i} + R_{in}\right) \tag{1}$$

where R_{out} is the thermal resistance on the outdoor side of the glazing system involving radiative heat transfer between the system and environment, G_{out}, and convective heat transfer modelled using correlations for heat transfer coefficient, h_{out}, representing natural or forced convection over a flat plate:

$$R_{out} = (T_{f,1} - T_{amb})/\left(h_{out}(T_{f,1} - T_{out}) + J_{f,1} - G_{out}\right) \tag{2}$$

$R_{gl,i}$ is conductive heat transfer through each screen of thickness $t_{gl,i}$, having thermal conductivity coefficient $k_{gl,i}$, and n is total number of screens:

$$R_{gl,i} = t_{gl,i}/k_{gl,i} \tag{3}$$

$R_{gap,i}$ includes radiative and convective heat exchange within each gap between the layers:

$$R_{gap,i} = (T_{f,i} - T_{b,i-1})/\left(h_i(T_{f,i} - T_{b,i-1}) + J_{f,i} - J_{b,i-1}\right) \tag{4}$$

and R_{in} includes the radiative, G_{in}, and natural convection heat transfer with convection heat transfer coefficient, h_{in}, in a rectangular enclosure:

$$R_{in} = (T_{room} - T_{b,n})/\left(h_{in}(T_{room} - T_{b,n}) + G_{in} - J_{b,n}\right) \tag{3}$$

These expressions are obtained from the energy balance for each layer of the system, addressing the $T_{f,i}$ and $T_{b,i}$ are front and back surface temperatures of the each i-layer; $J_{f,i}$ and $J_{b,i}$ are radiosities from front and back surface of each screen:

$$J_{f,i} = \varepsilon_{f,i}\sigma T_{f,i}^4 + \tau_i J_{f,i+1} + \rho_{f,i} J_{f,i-1} \tag{4}$$

$$J_{b,i} = \varepsilon_{b,i}\sigma T_{b,i}^4 + \tau_i J_{b,i-1} + \rho_{b,i} J_{f,i+1} \tag{5}$$

where ε, τ and ρ are the surface optical characteristics: emissivity, transmittance and reflectance, respectively; $\sigma = 5.6704 \times 10^{-8}\,\mathrm{W/m^2K^4}$ is Stefan-Boltzmann constant.

Finally, the non-linearized system can be represented in the matrix form and solved using an iterative solution algorithm given in [21].

2.2. Measurement method

Thermal properties of insulation materials intended for use as thermal screens in greenhouses have been evaluated by measuring the total heat flux passing through several layers of materials using the hot-box methodology. This method is commonly used to determine the thermal properties of insulation materials for general building design, but it has also been proven less suitable for greenhouses that are more affected by unstable outside conditions. For example, the overall heat transfer coefficient is increasing with increasing wind velocity and deep-sky temperature. It can be reduced due to condensation phenomena ([17], [22], [23]). The hot box method assumes thermal equilibrium and homogeneous thermal properties. This method does not consider the dynamic behaviour of ambient conditions, low sky temperatures, or the effect of condensation. However, even with these limitations, the method can be efficiently utilized to determine the steady-state thermal properties of screens and to validate and compare the performances under different conditions.

The measurement procedure is described in detail in [24]; here, the method is outlined briefly. To evaluate heat transfer through different combinations of several layers of screens, two insulated hot-boxes apparatuses with a volume of 1 m^3 each were installed under a shelter to reduce the influence of unstable external conditions. The layers of screens of 1m^2 were installed on the top of each box with a 5 cm gap, while the bottom of each box has been exposed to uniform controlled heating. The overall heat transfer coefficients, U-value (W m^{-2} $^{o}C^{-1}$), were obtained by measuring the temperature difference between the box's internal volume, T_{in} (°C), and outside the box, T_{out} (°C). These temperatures were monitored by T-type thermocouples for two days for each tested set. The U-value integrates the thermal resistance of the material tested, including the convective fluxes from the interior of the box toward the room, including the air between the layers; the radiative fluxes of longwave radiation through the different layers of materials and any other components of the box; and the airflow outside the box. By assuming a stationary regime and uniform radiation properties of all surfaces, the heat transfer passing through the screens can be calculated as follow:

$$U = \frac{(Q - Q_l)}{S(T_{in} - T_{out})} \quad (1)$$

where S is the area of the screen surface (m^2), Q is energy provided by resistance heater (W), Q_l is sidewall heat loss (W). Heat losses through the box walls were obtained from the separate case measurements with a polyurethane plate at the top of each box. Figure 1 illustrates the measurement results of inside and outside temperature difference in two boxes and calculated U-value during one hours after the system stabilization. It was shown that the results obtained remained stable and uniform. The time-averaged U-value for the case of the complete insulated box was obtained as 0.4 W m^{-2} ºC with a 0.03 standard deviation value.

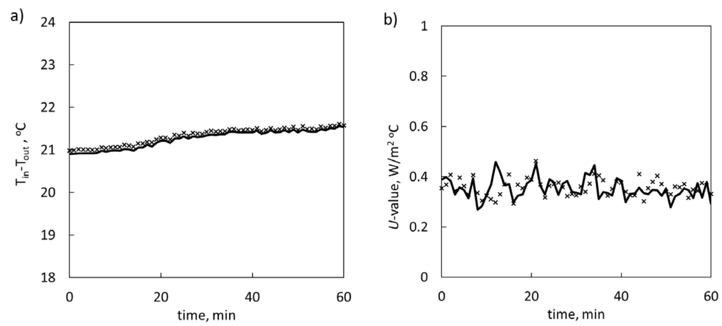

Fig. 1: Time variations of a) inside and outside temperature difference, and b) overall heat transfer coefficient for the case of an insulated system with polystyrene cover on the top of each box. Lines and crosses correspond to measurements in each hot-box.

2.3. Results and discussion

Table 1 presents calculated U-values for systems consisting glasses (for validation with published results) and insulated materials used in present study. The calculations for glazing system were in good agreement with ASHRAE data [24]. Optical characteristics of the screen materials were measured using standard procedure (e.g., [25])

Table 1: Calculation of U-value corresponding winter conditions: inside temperature air is 295K, external air temperature is 259K, 24 km/h winds outdoors, zero solar flux [24].

	ε	τ	U, W/m²K
Glass screens			
Single glazing, 3 mm	0.900	0.100	6.30
Double glazing, 64 mm air space			3.24
Double glazing, 12.7 mm air space			2.79
Thermal screens			
PE-UV	0.310	0.690	9.31
IR	0.640	0.330	7.32
IC-100	0.092	0.104	2.02
AlFo	0.056	0.002	1.98

The overall heat transfer coefficients as a function of the number of thermal screens are presented in Figure 2. The results correspond to experiments using a polyethylene film with a UV inhibition (PE-UV) as a cover with additional layers of thermal screens: infra-red radiation reflecting (IR) screens; thermal screens of type IC-100, IC-30, IC-0 (IC-100 consisted of the maximum number of aluminum foil strips; IC-30 gave 30% shading; IC-0 was a clear screen); and aluminum foil (AlFo) 50 micron thick screen (that is a film in contrast to IC-100 is knitted material). The figure shows that the heat transfer coefficient decreased rapidly for all types of screens. The reduction of the overall heat transfer coefficient can reach 30% by the addition of a single clear screen, such as IR and IC-0, and up to 70% for aluminum-containing screens, such as IC-100 and AlFo. With following an additional screen, the coefficient decreased by approximately 10%. The data trends could be described by the power law $U(n)=8n^{-m}$, while the values of the decay index, m, ranged from 0.6 to 1.4 depending on the properties of the tested materials. These results were in good agreement agreement with results obtained by [22] for three IC-100 screens (representing strong insulation). According to our results, results, the overall heat transfer coefficients decreased approximately by 90% when five layers of AlFo film are used.

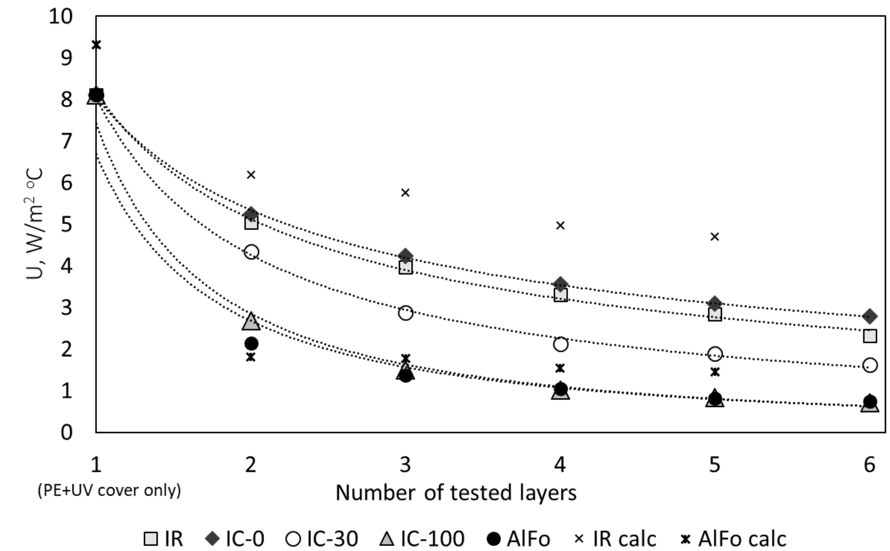

Fig. 2: Crosses represent calculated values (averaged over five values calculated in the range T_{in}= 313-323 K, T_{iout}=295-303K, no wind) and symbols represent measured overall heat transfer coefficients and trade lines (dashed lines) for a PE-UV (polyethylene with UV inhibition) covering and additional thermal screens of type IR (m=0.70, R^2=0.99), IC-0 (m=0.61, R^2=0.99), IC-30 (m=0.93, R^2=0.99), IC-100 (m=1.32, R^2=0.99), and AlFo (m=1.38, R^2=0.97); m represents the decay index of the power law trend lines $U(n)=8n^{-m}$. The correlation coefficients, R^2, were close to 1 for all trend lines.

Figure 3 shows that the most effective insulation is provided by a set of three to five AlFo layers, as expected, while the normalised U-value for four IC-100 layers (containing the maximum amounts of aluminum strips) is higher by about 30%. Regardless of the steady decline of the U-values, there were three sets of material combinations having close to equal values. These sets are highlighted by rectangles along the x-axis. We observed that one AlFo layer gave the same results as two IC-100 layers or four IC-30s, or five IR layers.

We also observed that even for transparent screen materials (first ten columns on Figure 3), the reduction of the overall heat transfer coefficient decreases from 60% to 40%. This conclusion is relevant if both insulation and transmittance properties are important simultaneously, for example, heat conservation during the daytime on a cold winter day.

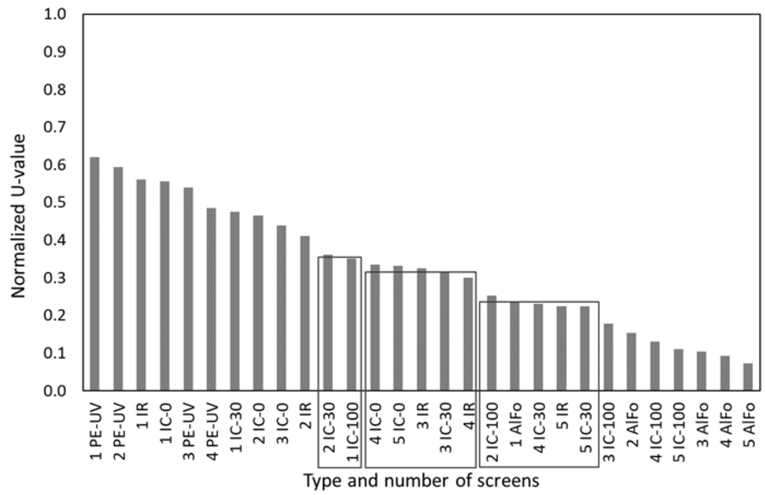

Fig. 3: Measured overall heat transfer coefficients for the IR blocking covering polyethylene in combination with one to five layers of different types of thermal screens (PE-UV, IR, IC-0, IC-30, IC-100, AlFo). The values were normalised using the value for IR cover without screens ($U_{\text{IR cover}}$= 7.44 W m^{-2} ºC^{-1}, σ=0.39). Rectangles showing along with x-axis denote screening combination with similar normalised *U*-values.

Considering the above observations, we examined the effects of insulating properties and reflectance on the temperature underneath the covering layer. Figure 4 shows the variation of the temperature measured underneath the covering material, T_{top}, as a function of the difference between the inside and outside temperatures for two types of covering materials, PE-UV and IR. Figure 4 shows that in the absence of thermal screens, the temperature below the covering increases linearly with the temperature differences, while it remains more or less constant when thermal screens are installed. Similar behaviour was observed for both types of covering materials. Similar tendency was obtained using calculation method.

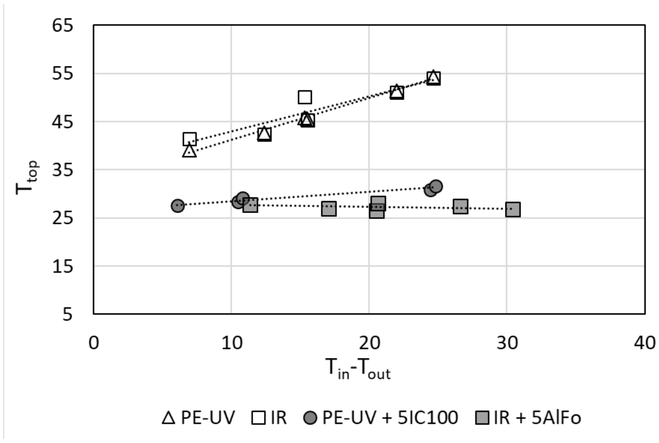

Fig. 4: The temperature of the air underneath a cover material installed at the top of the hot box.

4. Conclusion

The ISO standard calculation algorithm supported by measurements using hot-box method was used to examine the overall heat transfer coefficient of the combination of covering materials and thermal screens. These cross-validated methods allowed for the evaluation of thermal insulation performance of the multi-layer thermal screen system which could be further extended to developing a technology to provide improved greenhouse insulation.

The use of thermal screens can reduce the overall heat transfer coefficient by 40% (for one layer) and up to 90% (for multi-layer screens), thus reducing energy consumption in the greenhouse, and improving growing conditions. Our results showed that the best insulation performance was provided by a set of three to five AlFo screens. However, practically, up to three screen layers (reduction of U-value by 90% using IC100 or AlFo thermal screens, see Figure 4) are enough for effective insulation. The deployment of additional layers does not have a significant additional effect on insulation. We also showed that various sets of screen materials can be replaced by other sets with similar overall U-values. Thus, growers can select materials depending on the availability of materials and/or shading requirements.

The results showed that using low-emissivity materials installed under the cover can reduce the heat transfer coefficient by 30%, while the direction of the reflective side had no effect on the *U*-value. These results were in accordance with theoretical predictions and thereby validate the presented measurement method. The presented data can also be used for the validation of theoretical and numerical (Computational Fluid Dynamics) models, which allow for the comprehensive comparison of various thermal screen combinations under different environmental conditions in order to improve the performance of the cooling/heating and dehumidification systems. And by significantly reducing year-round energy consumption, reducing the heat transfer coefficients contributes to sustainability as well.

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