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Multilayer Thermal Screens for Greenhouse Insulation

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Abstract**—**Greenhouse cultivation is an energy-intensive process due to the high demands on cooling or heating according to external climatic conditions, which could be extreme in the summer or winter seasons. The thermal radiation rate inside a greenhouse depends mainly on the type of covering material and greenhouse construction. Using additional thermal screens under a greenhouse covering combined with a dehumidification system improves the insulation and could be cost-effective. Greenhouse covering material usually contains protective ultraviolet (UV) radiation additives to prevent the film wear, insect harm, and crop diseases. This paper investigates the overall heat transfer coefficient, or *U-value*, for greenhouse polyethylene covering contains UV-additives and glass covering with or without a thermal screen supplement. The hot-box method was employed to evaluate overall heat transfer coefficients experimentally as a function of the type and number of the thermal screens. The results show that the overall heat transfer coefficient decreases with increasing the number of thermal screens as a hyperbolic function. The overall heat transfer coefficient highly depends on the ability of the material to reflect thermal radiation. Using a greenhouse covering, i.e., polyethylene films or glass, in combination with high reflective thermal screens, i.e., containing about 98% of aluminum stripes or aluminum foil, the *U-value* reduces by 61%-89% in the first case, whereas by 70%-92% in the second case, depending on the number of the thermal screen. Using thermal screens made from low reflective materials may reduce the *U-value* by 30%-57%. The heat transfer coefficient is an indicator of the thermal insulation properties of the materials, which allows farmers to make decisions on the use of appropriate thermal screens depending on the external and internal climate conditions in a greenhouse**.**

Keywords**—**Energy-saving thermal screen, greenhouse covering material, heat transfer coefficient, hot box.

I. INTRODUCTION

THE climatic conditions and the light quality inside a greenhouse depend mainly on the type and orientation of the structure and the cladding optical properties, such as light reflection, transmission, and absorption. Desired indoor climate conditions can be obtained by manipulating the properties of covering material. Thus, the reflection of infrared (IR) radiation (700-1400 nm) by the greenhouse covering significantly reduces the heating load. Thermal screens are often used to complement greenhouse cladding to improve thermal insulation when the greenhouse is not heated and diminishes energy consumption when a heating system is operated. Greenhouse covering films usually contain UV reflective additives to improve its strength properties. Besides, the UV-absorbing greenhouse covering creates an indoor environment unfavorable to harmful insects. For example, according to experiments [5] conducted in the greenhouse covered by the UV-absorbing polyethylene (PE) film, the UV-A and UV-B radiation transmittance ranges were 0.4% and 1.2%, respectively, during the first year and increased to 0.8% and 1.3% in the 2nd year. The corresponding values in the greenhouse covered by a PE film were 20.7% and 12.5% during the 1st year and 28.7% and 26.7% during the 2nd year.

The use and understanding of the physical properties of the covering materials are very important in the greenhouse industry. The overall heat transfer, i.e., *U-value* [2], determines the thermal insulation measure of the greenhouse cladding. For decades many researches have been devoted to evaluating the *U-value* for greenhouse cladding materials using the hot box method [1]-[4], [6]. Plastic and glass coverings with and without condensation were investigated [1]. It was shown that *U-value* reduced about by 30%-60% when highly reflective aluminized thermal screens AL IC (Aluminet 60% shade) were used in addition to covering film [3], [4]. More recent studies [6] reported results focused on combining a PE cover with 2-3 thermal screens made from materials, such as white polyester, in one or more layers. It was also shown that the presence of a canopy reduces the night sky radiation. According to the experiments described in [6], using a thermal screen reduced the *U-value* by 16-19% compared to the *U-value* for covering without thermal screens. In further experiments, the IR-covering insulation ability was tested with or without thermal screens. The experiment results show that *U-value* reduced by 70%-90% when up to five thermal screens with 0%, 30%, and 100% reflectivity in combination with IR-covering were installed [7].

Since maintaining optimal growing conditions is still a challenge, and the cost-efficiency of greenhouse production is an important factor, methods for improving the production processes need to be developed. Therefore, this study focuses on thermal insulation properties of PE films and glass, as the most common covering materials, and aluminized thermal screens (as a material with high thermal insulation properties).

The main objective of the study is to investigate the *U-value* range when only one covering, i.e., PE film or glass, is installed representing low insulation case and a covering in combination with different types of commercial thermal screens having low and high IR reflective properties, representing the best possible isolation case. To achieve this purpose, a series of experiments have been conducted using commercial PE and glass greenhouse covering combined with several layers of different IR reflective materials, to be used as thermal screens in a greenhouse. Overall heat transfer coefficient *U-value* is extensively measured by the hot box

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method that has already been successfully applied in previous experiments.

II. METHOD

The hot box method described in [6] is used for the measurements, whereas different combinations of samples are installed into the upper surface of the box. Two hot boxes were constructed for measuring the *U-value* to maintain the same external conditions for comparative measurements of different types and combinations of screens. Fig. 1 shows the snapshot and Fig. 2 shows a schematic illustration of the experimental setup. Fig. 2 schematically shows the hot box used for the laboratory experiment, including a description of the location of the thermocouples: 1, 2 on the heated plate, 3 in the center of the box volume, four under the samples, 5-10 between the samples and 11 on the roof. The room temperature was measured by an additional thermocouple 12 outside the box.

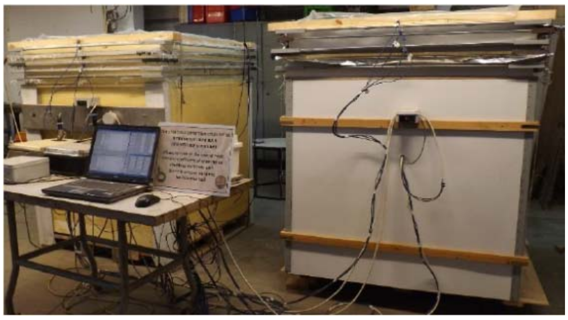
Fig. 1 Snapshot of two hot boxes for the laboratory experiment

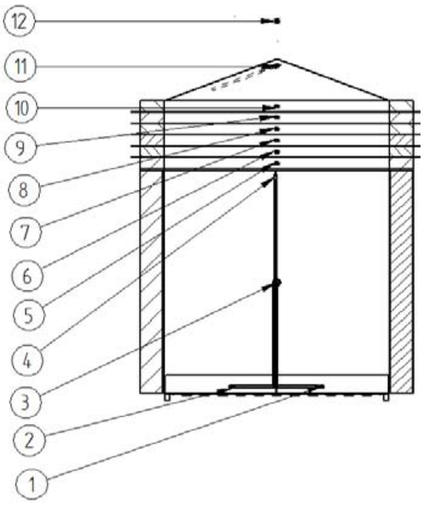

Fig. 2. Schematic diagram of the hot box with five samples on the top. The pointers correspond to the location of the thermocouples

Assuming that the system is in thermal equilibrium (steady-state), the overall heat transfer coefficient U (W/m^{2}C) of samples is given by:

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

where T_{in} (ºC) (thermocouple 3) and T_{out} (ºC) (thermocouple 12) are the air temperatures inside and outside of the hot box, respectively, S (m^2) is the sample area, aligned with the heat flow direction, Q (W) is heat power supplied to the bottom plate and Q_l (W) represents side wall heat losses. The wall heat losses were measured several times during the tests and were in the order of 0.4 W/m^2 in average for each box. Each test for the greenhouse coverings was carried out over two days and repeated about four-five times. The initial inside temperature was 40 ºC and was increased in increments of 3 degrees up to 55 ºC. It was found that in this range, the measurements were stable. Since the measurements of the overall heat transfer coefficient *U-value* require equilibrium, the boxes were heated for eight hours for each temperature. The measurements were scanned every second and averaged after every 1 minute via a data-logger. The typical temperature reading occurs similarly, as indicated in [7].

III. RESULTS

The overall heat transfer coefficients (*U-value*) are presented in Fig. 3, depending on the number of thermal screens complementing the coverage. Since the study aimed to determine the limit values of the *U-value* range, we used PE film with UV inhibition (P) and glass (G) coverings. These materials are most commonly used as greenhouse cladding. Aluminum foil films (AlFo), used in both cases as thermal screens, reflect over 99% of the solar radiation, representing the strongest insulation material. Aluminum foil streaks are commonly used in industry, for example, Aluminet IC-100 thermal screens (IC-100). Fig. 3 (a) presents the measurement results for a single PE film (representing a covering) with the addition of one to five samples installed under it. Two sets of samples are presented: PE films and AlFo films. The result shows that the overall heat transfer coefficient decreases with additional films in a hyperbolic dependence. The decay indexes of the power-law trend lines correspond to -0.605, -1.406, and -1.546 for the set of PE film samples, for the set of AlFo films with their reflective (glossy) surfaces facing outwards (AlFo_U), and the set of AlFo films facing inwards (AlFo_D) relative to the hot-box interior.

The overall heat transfer coefficient decreases by 37% when two samples were installed and decreases by 65% when five layers of samples were installed. Since five sample layers are not practical, we assume that 50%-60% is the range of reduction of *U-value* that can be achieved using PE films. The highest decrease of *U-value* is when the PE covering is installed together with AlFo films due to their higher reflectivity. For the case with a single AlFo film, the *U-value* decreases by 74-75%, and the coefficient decreases even more, by 91-92%, for the set of five AlFo films. The results show that the direction of the reflective surface of AlFo material has a negligible effect, it is only 2-3%. Fig. 3b represents the results of similar experiments but with a single glass covering. Similar to the previous results, the figure shows the hyperbolic decreasing of the overall heat transfer coefficient as more thermal screens are added. The decay index of the power-law trend lines corresponds to -0.395 and -1.482 for a glass covering with a set of PE films and AlFo films, respectively. The overall heat transfer coefficient decreases by 25% when one PE sample was installed as a supplement to glass covering and decreases by 48% when four layers of samples were installed. The *U-value* decreased by 93% when four or five AlFo films were installed.

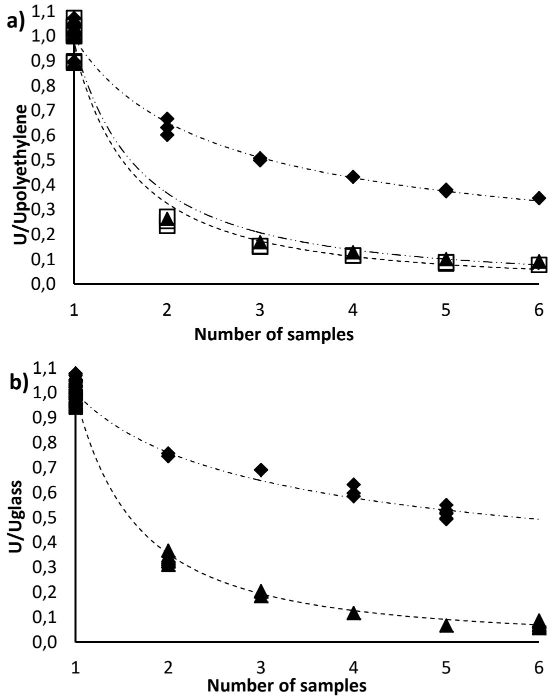

Fig. 3 Normalized overall heat transfer as a function of the number of thermal screens (samples). The values are normalized by the value measured for a single covering layer. Dashed and dashed-dotted lines represent trendlines. Symbols represent a covering in a combination of different types of thermal screens: (a) PE film covering: $U_{polyethylene}$ = 8.11 W/m^{2o}C; ♦ - PE films (dashed-dotted line); ▲ AlFo_D films with reflective surfaces facing inwards, (dashed line); □ correspond to the case with covering and AlFo_U facing outwards (dashed-double-dotted line); the trendline equations are: $y = 0.99x^{-0.61}$,$y = 0.97x^{-1.41}$, $y = 0.95x^{-1.55}$, and R-squared values are: 0.99, 0.99, 0.98, correspondently; (b) glass covering: U_{glass}= 5.45 W/m^{2o}C. ♦ PE films, (dashed-dotted line); ▲ AlFo_D films with reflective surfaces facing inwards (dashed line). The trendline equations are: $y = 1.0001x^{-0.39}$, $y = 0.97x^{-1.48}$And R-squared values are 0.97 and 0.99 correspondently

Fig. 4 (a) shows the comparison of different materials: PE film, glass, AlFo film, and commercial thermal screen Aluminet IC-100 (interwoven aluminum strips) in terms of the difference: $\Delta = U_{1sample}/U_{covering} - U_{5sample}/U_{covering}$, when AlFo or IC-100 are samples, and PE (P) or glass (G) are coverings. The figure presents the variations of the Δ-value by adding a set of five samples of each type. It is seen that the difference between *U-values*, when PE covering combined with a single thermal screen and with five thermal screens is 24% for Aluminet IC-100, and 17% for AlFo, i.e., an IC-100 single sample has slightly better insulation characteristics than an AlFo sample. The same results are obtained for glass covering: differences between *U-values* for glass combined with a single thermal screen and with five thermal screens are 30-31% for Aluminet IC-100 and 27% for AlFo. However, Fig. 4 (b) shows that the overall heat transfer coefficient decreases by about 75% for the PE covering with a single AlFo film, as shown in Fig. 3 (a), and decreases by 67% for the covering with a single Aluminet IC-100. In other words, a stronger reflectivity of a single AlFo film comparing to a single Aluminet IC-100 is observed. Besides, Fig. 4 (b) shows that the overall heat transfer coefficient decreases by 66% for the glass covering with a single AlFo film and decreases by 56-59% for glass covering with a single Aluminet IC-100.

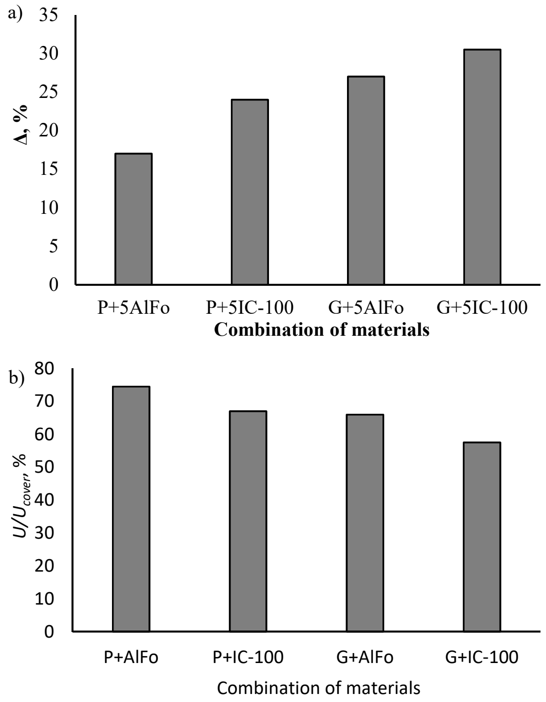

Fig. 4 Comparison of the overall heat transfer coefficient for different sample types: PE film, glass, AlFo film, and IC-100 thermal screen: (a) difference between *U-values*, for the case when the covering (PE film or glass) sample combined with a single sample and with five samples of each type; (b) the *U-value*, when the covering sample is combined with a single screen sample

IV. CONCLUSION

Using thermal screens as a supplement to conventional greenhouse cladding significantly improves the insulation of the greenhouse. The insulation level depends on the reflectivity of the thermal screen. In case when AlFo thermal screens, having the highest reflectivity, are applied, the insulation reaches from 75% to 91% in combination with PE film covering. In case when the AlFo thermal screens are involved, the overall heat transfer coefficient increases from

66% to 93% in combination with glass covering. In case when Aluminet IC-100 (higher reflective commercial thermal screens) is applied, the overall heat transfer coefficient increases from 67% to 91% for a PE covering and from 57% to 88% in combination with glass covering. Among the tested materials, the minimum insulation is provided by using PE film as thermal screens with PE covering. The same is found for a glass sample.

Using AlFo and Aluminet IC-100 samples, the transfer coefficient increases from 75% to 92% and 67% to 91%, respectively, in combination with PE covering, and from 66% to 93% and from 57% to 88% in combination with glass covering. That is, no significant differences between glass covering and PE film covering are found. The results also show higher reflectivity of AlFo film than an Aluminet IC-100 screen, and the difference between them is from 5% to 8%. The difference between *U-value*, when covering is combined with a single thermal screen and five thermal screens, is higher for Aluminet IC-100 than for AlFo, and it is from 3% to 5%. Such analysis allows to understand more about energy-saving screen properties and choose the appropriate materials depending on specific requirements.

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