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THE AIR LAYER THICKNESS INFLUENCE ON GREENHOUSES MEMBRANE COVER HEAT TRANSMISSION

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SUMMARY:

Heating constitutes the major energy requirement for greenhouses. Measures that minimize heating requirement include designs that minimize surface area and cover heat losses, maximize the penetration of solar radiation, use heat conserving covering materials, and features that store day time solar energy for release into the greenhouse at night. As well as protecting plants against adverse climate and pests, a greenhouse provides an elevated temperature during the day.

Energy efficiency improvement is currently one of the mayor concerns in greenhouses design development. Plastic membrane covered greenhouses thermal losses are larger comparing to the glass covered, due to cover low thermal properties and thickness. In order to decrease energy losses, heat transfer through the two layer foil cover with air layer inside, has been investigated, particularly heat transfer coefficient dependence on Nu and Ra number and natural convection onset in air layer within two plastic foils.

KEYWORDS:

greenhouses, natural convection, heat transfer coefficient, air layer, temperature, foil, energy losses

INTRODUCTION

Designing a system for saving environmental conditions in agricultural objects, especially in greenhouses, is a complex process, due to large number of influential factors and inter-dependence: environmental hydro-meteorological parameters, plant species growth and yield parameters, as well as agricultural economic income restrictions /1/.

In plant-growing structures, it is necessary to coordinate expenses of the system for keeping environmental controlled conditions, and find necessary environmental control degree in production, i.e. permitted level of deviation from ideal conditions, which will not endanger product quality.

Since dominant expenses during greenhouse exploitation are the ones for energy used to compensate closed space heat loss, the main objective of the energetic optimization of these structures is to reduce coefficients of covered areas heat transmission. Usual covers nowadays are single or double-layered constructions made of glass or plastic materials. Plastic covers are thin, light foils, and put over cheap and light constructions, using minimal effort and material. Due to inferior thermal characteristics, plastic covers' heat losses are considerably bigger than with glass covers (with similar interior temperature conditions).

Cover materials have to provide best possible permeability of such solar radiance wavelengths which are most favorable for growth of certain plants, while permeability coefficient of infrared heat radiance of the interior soil and plants is as low as possible. Lowering coefficient of heat transmission through greenhouse walls, heat loss should be provided, and energy efficiency increased, with a simple construction and price level.

This paper examines conditions of instability, and establishment of natural convection in the air layer between two foils, and their influence on heat transmission through double-layered cover /1/.

PAPER SUBJECT AND OBJECTIVE

In order to minimize heat transmission coefficient in greenhouse's double-layered cover, an analyses of the influence of greenhouse's double-layered cover's air-layer thickness on the establishment of natural convection has been performed /1/, as well as the analysis of its dependence on air-layers temperature varieties /1/.

In order to cover a greenhouse with two plastic foils of certain thickness with an air-layer (according to the given sketch of cross-section at Figure 1), it is necessary to determine:

- thermal resistance to heat transmission dependence on calm air-layer thickness.
- characteristic, i.e. optimal air-layer thickness at certain foil layers' temperature varieties, which causes instability in an air-layer – convective cells appear.
- dependence of effective thermal resistance to heat transmission in an air-layer, with convective instability, i.e. convective effect, depending on an air-layer thickness.
- dependence of cover's heat transmission coefficient on an air-layer's thickness and characteristic temperature varieties.

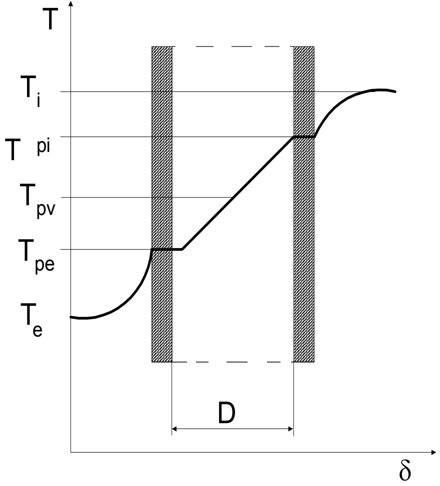

Figure 1. Characteristic foil temperature in stationary overall heat transfer trough two later greenhouse foil

ADEQUATE GREENHOUSE COVERING MATERIAL CHARACTERISTICS

Material characteristics adequate for its use as greenhouse cover are as follows:

- Light permeability (total; min, max, %)
- Thermal effect - permeability of long-wave infrared radiation (%)
- Coefficient of cover's heat transmission ($Wm^{-2}K^{-1}$)
- Aging in regard to external factors - durability (years)
- Condensation factor
- Steam porosity
- Inflammability

The paper's subject is thermal resistance, i.e. cover's heat transmission coefficient.

ANALYSES

Specific heat transfer losses are in the range of 0 and 120 W/m^2 /1/, what correspond to heat flux through plastic foil with overall heat transfer coefficient of 4 W/m^2K inside greenhouse air temperature of 20°C, and outside air temperature of -10°C:

$$q = k \cdot (T_e - T_i) = 4 \cdot [20 - (-10)] = 120 W/m^2 K \qquad (1)$$

Assuming that foil thickness are small and there is not temperature gradient in them, inside and outside foil temperature difference are adopted with following values: 5°C, 10°C, 15°C.

Heat transfer coefficient from foil outside on the outside air at mean velocity is 25 W/m^2K, and from foil inside to greenhouse air is 8 W/m^2K.

At stationary regime of heat transmission through a cover, characteristic temperature profile is formed (Figure 2). At internal temperate T_i heat is transmitted through convection to internal cover surface of T_{pi} temperature, and then conducted through a double cover, and from cover's outer surface of T_{pe} temperature through convection transmitted to external air /1/.

Resistance to heat transmission through double cover is a sum of plastic foil's layers' resistance and air-layer's resistance /1/:

$$R_p = 2 \cdot \frac{\delta_{pf}}{\lambda_{pf}} + \frac{D}{\lambda_v} \qquad (2)$$

where are:

δ_{pf}	[m]	plastic foil thickness
λ_{pf}	[W/mK]	heat conductivity coefficient
λ_v	[W/mK]	air heat conductivity coefficient
D	[m]	air layer thickness

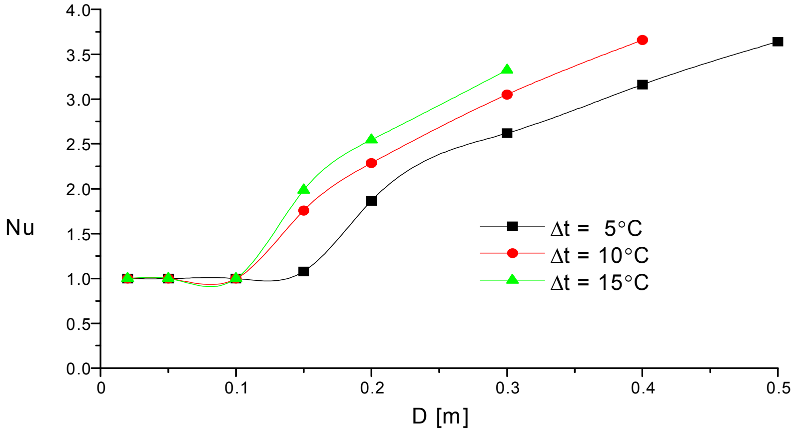

Figure 2. Dependence of Nusselt number on from air layer thickness and layer temperature difference for T_v = 283K

At certain foil layers' thickness, such resistance depends on air-layer's thickness and the condition whether it is calm, or in state of its natural convective movement, caused by established temperature field and adequate field of specific thickness under the influence of earth's gravitation force.

Increase of air-layer's D thickness causes resistance of air-layer determined by D/λ_v. However, at certain air-layer's thickness and certain two foils' temperature varieties, $\Delta T = T_{pi}-T_{pe}$, i.e. at certain temperature grade in air-layer hydraulic instability is caused, as well as convective fluid movement. From that moment, air-layer is no longer calm, increasing so heat transmission intensity, i.e. reducing thermal resistance /1/.

This occurrence is defined by dependence of Nuselt's Nu number criterion, which is determined in certain inclination angles of examined fluid layer by the following method /1/:

- for inclination angles domain $0 \le \theta \le 75^\circ C$ and $0 \le Ra \le 10^5$

$$Nu = 1 + 1.44\left(1 - \frac{1708}{Ra\cdot\cos\theta}\right)^{\bullet} + \left(1 - \frac{1708\cdot(\sin 1.8\theta)^{1.6}}{Ra\cdot\cos\theta}\right)^{\bullet} + \left[\left(\frac{Ra\cdot\cos\theta}{5830}\right)^{0.33} - 1\right]^{\bullet} \tag{3}$$

where is

$$[x]^{\bullet} = \frac{(|x| + x)}{2} \tag{4}$$

- for inclination angles domain $75^\circ C \le \theta \le 90^\circ C$

$$Nu = \left(1\cdot 0.039\,(Ra\cdot\sin\theta)^{0.33}\right)_{\max} \tag{5}$$

where is Rayleigh number determined with expression:

$$Ra = \frac{g \cdot \beta \left(T_{pi} - T_{pe}\right) \cdot D^3}{\nu_v \cdot \lambda_v} \tag{6}$$

where are

β	[1/K]	thermal expansion coefficient
v_v	[m^2/s]	kinematic viscosity coefficient

According to certain dependence and parameter analysis of Nu numbers for characteristic values of adequate parameters, the following dependences are subsequently similarly determined:

- effective coefficient of air-layer heat transmission followed by convective instability on air-layer thickness - α_{ef} (Wm^{-2}K^{-1}):

$$\alpha_{ef} = \frac{Nu \cdot \lambda_v}{D} \tag{7}$$

- thermal resistance to air-layer heat transmission by convective instability on air-layer thickness - R_v (m^{2}KW^{-1}):

$$R_v = \frac{1}{\alpha_{ef}} = \frac{D}{Nu \cdot \lambda_v} \tag{8}$$

- total coefficient of heat transmission by effective transmission / convection of air-layer, and radiation between foil layers air-layer thickness - α_{up} (Wm^{-2}K^{-1})

$$\alpha_{up} = \alpha_{ef} + \frac{\varepsilon \cdot 5.77}{\Delta T \left(2 - \varepsilon\right)} \cdot \left[\left(\frac{T_{pi}}{100}\right)^4 - \left(\frac{T_{pe}}{100}\right)^4\right] \tag{9}$$

- thermal resistance to cover heat transmission on air-layer thickness - R_p (m^{2}KW^{-1})

$$R_p = \frac{2 \cdot \delta_{pf}}{\lambda_{pf}} + \frac{1}{\alpha_{up}} \tag{10}$$

where are

ε		plastic foil emission coefficient
δ_{pf}	[m]	plastic foil thickness

Finally, similar parameters analysis was performed for dependence of cover heat transmission coefficient - K (Wm^{-2}K^{-1})

$$K = \frac{1}{\frac{1}{\alpha_e} + R_p \frac{1}{\alpha_i}} \tag{11}$$

RESULTS OF THE ANALYSES

Figure 3. shows dependence of Ra criterion, i.e. Rayleigh number, determined by equation (6) on air-layer thickness and parameters of layers both sides' temperature varieties ΔT /1/.

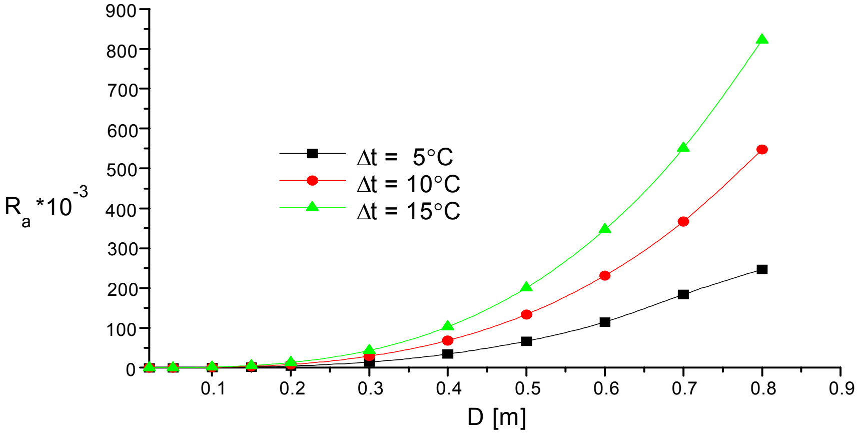

Figure 3. Rayleigh number dependence on the air layer thickness and temperature difference for T_{pv}=283K

Figure 2. shows dependence of criterion Nu, i.e. Nuselt's number, determined by equation (4) on air-layer thickness for three values of parameter of layers (or plastic foils') both sides' temperature varieties (ΔT) /1/.

Curves on Figure 2. show certain temperature varieties, and are interrupted at certain points of more intensive values of layer's thickness, where at certain temperature varieties ΔT criteria of Ra numbers reach Limiting values of equations (4) and (5). Extra-polishing these curves, for thicker air-layers from 500mm up to 800mm /1/.

Diagram on Figure 2 clearly shows critical regimes of natural convection at air-layer thickness lower than 130 mm, for all the three examined temperature varieties ΔT. Zone with determined critical regimes may be better analyzed at Figure 4. showing the same zone, but magnified. It is obvious that at air-layer thickness lesser than 80 mm at all parameter values, all temperature varieties ΔT have Nuselt's number values equal to one, showing that the air of such thickness is calm. Points where the curve deviates from the horizontal line (Nu=1) for ΔT=15°C start at air-layer thickness of app. D≈87 mm. So, at such thickness, Nuselt's criterion is Nu>1, showing hydro-dynamical instability. With the increased thickness at the same temperature variety ΔT further development of natural convection continues, with further increase of Nu number. At ΔT=10 the same occurs with somewhat thicker layer (D≈96 mm), and at ΔT=5°C the same instability occurs with a bit thicker layer of D≈128 mm /1/.

Considering the bigger temperature varieties ΔT characterize higher specific heat flows, i.e. losses, the same should be adequate when choosing optimal air-layer thickness. Therefore, optimal thickness is the air-layer thickness of 80-90 mm, and when using greenhouses in cold months, December and January, it could me less thick than 80 mm /1/.

Figure 4. shows dependence of effective coefficient of air-layer heat transmission on layer's thickness. It is obvious that the increase of the calm air-layers thickness leads to heat reduction of its values, and afterwards to sudden growth during instability, followed by stagnating values as layers' thickness increase /1/.

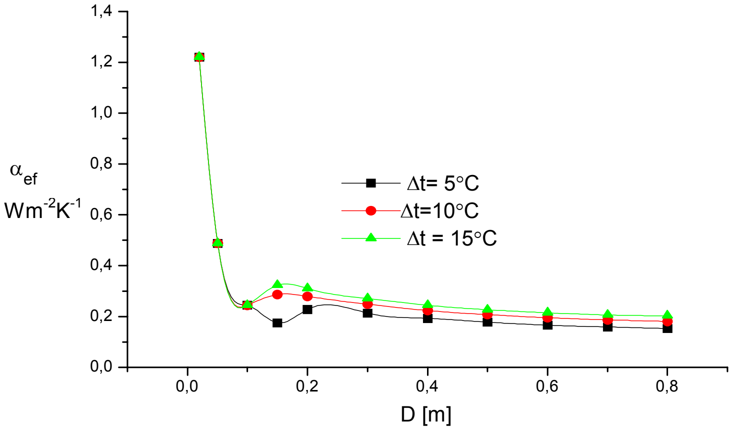

Figure 4. Air layer effective overall heat transfer coefficient dependence on layer thickness for T_{pv}=283K

Figure 5 shows dependence of thermal resistance to heat transmission on air-layer thickness. These curves are in an inverse proportion to curves shown at diagram on Figure 4. Figure 6 shows dependence of total effective thermal resistance to heat transmission of double-layered cover with an inter air-layer /1/.

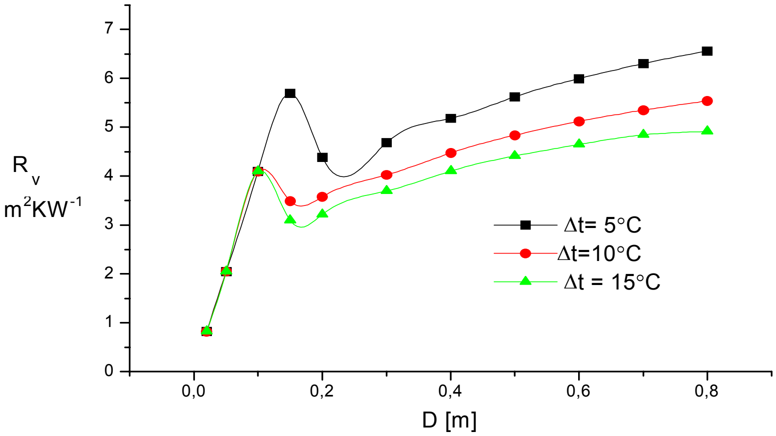

Figure 5. Overall thermal resistance dependence on air layer thickness for T_{pv}=283K

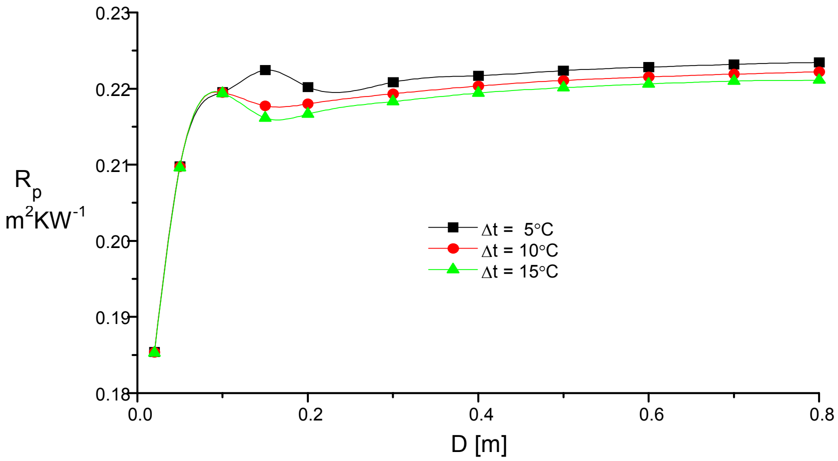

Figure 6 Total effective convective thermal resistance on air layer thickness (T_{pv}=283K, δ_{pf}=180μ, ε=o,94).

The last diagram on Figure 7. shows dependence of calculated theoretical value of cover's transmission coefficient on an air-layer's thickness and characteristic temperature varieties. Form of the shown curves is the same as of theoretical curves showing air-layer's thermal resistance, as well as that of the whole cover, absolutely identical with similar dependences, that is laws determined during experimental measurements, while absolute values of the real heat transmission effective coefficients determined by measurements are higher, considering the real values include other effects additionally increasing heat transmission coefficient, and respective specific heat losses (heat bridges, infiltration. etc) /1/.

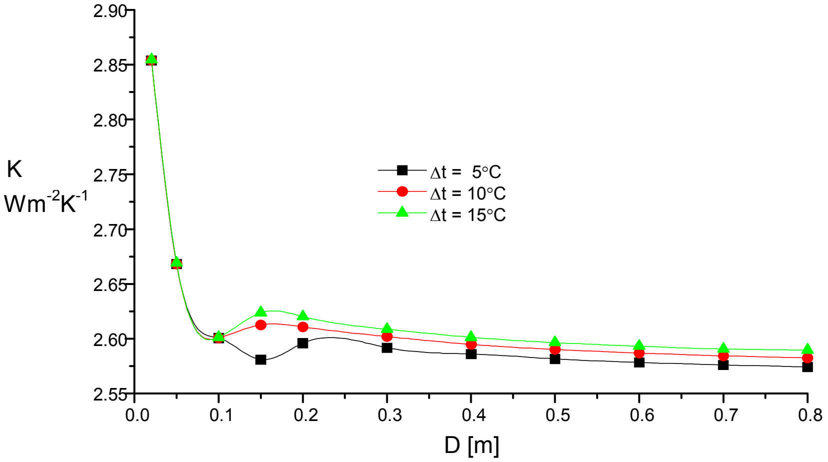

Figure 7. Calculated theoretical overall heat transfer coefficient dependence on air layer thickness (T_{pv}=283K, δ_{pf}=180μ, ε=o,94, α_e=25$Wm^{-2}K^{-1}$, α_i=725$Wm^{-2}K^{-1}$,).

CONCLUSION

Nature of changes of characteristic and adequate values in the analysis of heat transmission through a cover absolutely shows physical nature of examined occurrences and processes. All analyses, in regard to determining optimal air-layer thickness, may be considered adequate for practical determination and dimensioning of air-layer thickness of double-layered covers made of plastic foils with air-filled cavities. We should also have in mind determined zones where dependence criteria apply, for certain temperature varieties ΔT, and air-layer thickness.

Finally, it is of great importance to conclude that, in order to reduce greenhouse heat loss, and increase its energetic efficiency, apart from the right choice of air-layer thickness of double-layered plastic cover, heat transmission should be done in the most unfavorable regime of heat extension, without convective movement, i.e. reduction of heat extension to heat transmission, and radiation through air-layer. The air should be dry, so that may play the role of thermo-insulating layer. Besides, dry air reduces occurrence of condensation in air-layer, which could have multiple negative influence.

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