Energy-saving Lighting Installations and Equipment for Multi-tier Narrow-bench Greenhouse Technologies

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Abstract. Enterprises of the protected ground or greenhouse horticulture centres must have facilities for the necessary supply of heat, water, electric power, natural and artificial optical radiation. The long-term practice of plant cultivation has shown that in autumn, winter and spring, the basic limiting factor in transparent greenhouses is light.

The radiating mode of the greenhouses is one of the major and power-intensive factors of a microclimate. Therefore, in case of artificial irradiation, it is necessary to pay special attention to the minimization of power consumption, which is associated with the selection of a source, type of irradiation device, reflector configuration and location of the lighting fixtures.

The specific consumption (Sharupich et al., 2005) of power resources in the most common greenhouses in the world, which have one fructifying plant layer in the greenhouse volume, constitutes 40-55 mega-calories per 1kg of the product, which is by 40-45% higher than in the case of the technology of intensive cultivation of the culture, using the method of drop watering. The more productive and more power saving technology, i.e. the so-called Dutch technology is not advantageous in the environmental conditions of Estonia.

The latest research works of scientists have revealed that for the protected ground in the second heat-affected zone, including Estonia, multi-tier narrow-bench hydroponics is a more preferable technology. It allows to make more effective use of the greenhouse volume to ensure a simultaneous fructification of 5 layers, to increase the production yield per area unit by 3.0-4.0 times in comparison with the traditional technology, and to reduce the specific power expenses by approximately 70%.

However, the lighting maintenance of the cutting-edge technology which has a specific arrangement of the plant layers on inclined planes has not been sufficiently elaborated as yet. In particular, there are no technical decisions on the special lighting fixtures ensuring the increase of power efficiency of additional artificial irradiation. Therefore, it is essential to enhance the efficiency of one of the high energy consumption processes of artificial irradiation of the plants considering the spatial specificity of the promising multi-tier narrow-bench hydroponics technology.

Key words: multi-tier narrow-bench greenhouse technologies, irradiator, power efficiency

JUSTIFICATION OF THE MAIN PARAMETERS OF SYSTEM FOR ADDITIONAL ARTIFICIAL IRRADIATION IN GREENHOUSE WITH MULTI -TIER NARROW-BENCH HYDROPONICS

The main objective is to increase the energy efficiency of the additional artificial irradiation in greenhouses with multi-tier narrow-bench hydroponics through the use of lighting which is adapted to multi-tier narrow bench hydroponics (MNH) technology.

In 2009, a new Energy Efficiency Target Program was adopted, which takes into account the results of the previous Energy Efficiency Target Program in Estonia for 8 years, the requirements of EU directives 93/76 (SAVE) and many other international acts relating to energy efficiency (Energy Charter Treaty, the Kyoto Protocol, Agenda Baltic 21 for the Baltic Sea Region, etc.). The main requirement of the Program is to grant the application of energy-saving technologies.

The basis of all popular technologies widely used both in Estonian and international practice of frame area agriculture follows one and the same technological principle – only one fructifying plant tier in the volume of one greenhouse. Realization of a new structure-forming principle resulted in principal changes in the technology of growing plants in greenhouses. The principle is (Sharupich et al., 2005) the following: to increase the amount of fructifying layers in the limits of the same greenhouse, i.e. transition to multi-tier narrow-bench hydroponics (developed by Giproniselprom institute) (scheme in Fig. 1).

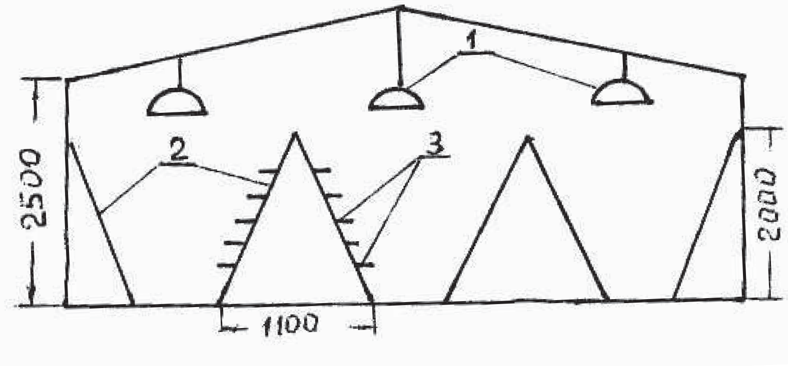

Fig. 1. Layout of equipment according to MNH-technology: 1 – Illuminators; 2 - Dispositions of MNH; 3 – Layers.

A vertical shift of the MNH layers resulted in a significant reduction of costs in the overall energy consumption (Karpov et al., 2005). The power costs when using technology of agronomical physics with horizontal photo culture constitute 70-90 Mcal per 1 kg of product, with the traditional soil technology – 50-55 Mcal kg^{-1}. The value of the same marker in Holland is 25-30 Mcal kg^{-1}. The power costs when using multi-tier narrow-bench technology in translucent greenhouses constitute 8-12 Mcal kg^{-1}.

The multi-tier narrow-bench hydroponics technology is a vegetative cenosis having five simultaneously fructifying layers. An analysis of the used irradiation systems shows that there are no special irradiation sets that will meet the requirements of this technology applicably to the spatial distribution of the flow.

The certain bulk of works presented by several organizations (VNIIS, Giproniselprom, SZNIIMESH, etc.) as well as by many independent authors has been devoted to finding solutions that will help improve the efficiency of irradiation of plants in greenhouses.

The main attention of this research is focused on one of the problems connected with the peculiarities of greenhouse production, such as: promoting energy efficiency by improving the spatial distribution of flow in multi-tier narrow-bench technologies.

It should be noted that the wide scale of power of sufficiently effective discharge lamps can solve the abovementioned problem using a spatial distribution of electric energy (before it is transformed into a stream). However, both SPbGAU and Giproniselprom institute have a negative experience with the development and durable demonstration of multi-tier narrow-bench greenhouses with tubular fluorescent lamps in each tier. This solution obviously seems simple and effective. However, this set attracted the attention of neither scientists nor manufacturers. The main reasons are: a huge number of low-power lamps (hence - increasing complexity of operation and the number of servicers), shading of growing plants from natural light, and additional inconveniences while handling plants. Taking into account the fact that high-pressure gas discharge lamps can have a light output 2-3 times longer than that of fluorescent lamps and that these are preferred in a large-scale greenhouse production, the given study takes them as sources of light.

When selecting the types of radiation sources, preference should be given to those with a higher $\acute{\eta}_{\Phi AP}$ (not less than 20%). Modern high-intensity gas-discharge lamps for greenhouses (metal halide lamps, high pressure sodium lamps) are produced in a wide range of power ranges all over the world (from 125 W to 6.0 kW) and have $\acute{\eta}_{\Phi AP}$=0.25-0.30. As a rule, lamps with a high power range have a higher $\acute{\eta}_{\Phi AP}$ than those with a low power range.

Inclined plane, where the tiers are fixed, has set new lighting tasks concerning the distribution of flow fixtures. The peculiarities of the process are in special requirements for the spatial distribution of the flow source, that do not allow choosing a lamp according to its power like it is traditionally done, and to guarantee the uniformity by calculating the distance to the neighbouring lamp. We analyzed 7 variants of optical schemes (Kabanen 2008), corresponding to the traditional placement of the lamp above the passage between pyramids (Fig. 2, a - g).

The analysis was conducted in accordance with 4 criteria: the scheme of the rays from the reflector, the need for special irradiation devices for the extreme (in front), inclined surfaces, the efficiency of the flow source, the presence or absence of shading cenosis.

The results of calculations and graphical analysis are given in Table 1.

It turned out that none of the variants meets all the four quality criteria. A preliminary analysis of light optical schemes gave reason to assume that the illumination of the lower trays will be substantially lower than that of the upper ones. To make the final decision on the possibility of using the traditional method of irradiation in the MHN-technologies, the needed spatial distribution of the flow of the lamp (light intensity curve) was calculated when horizontal surface turns to a sloping one, and assuming the irradiance level in the characteristic points of the respective tiers.

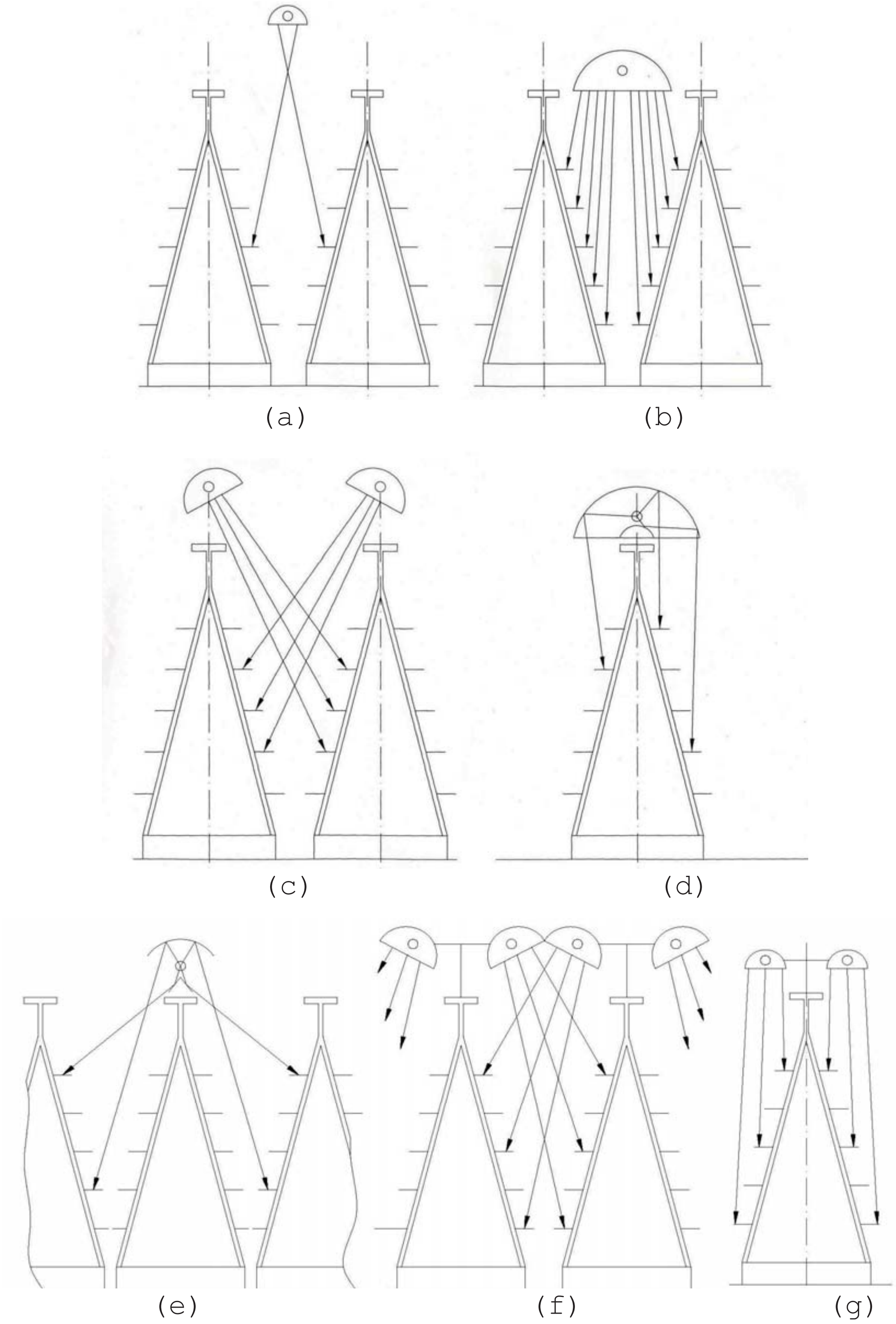
(a) (b) (c) (d) (e) (f) (g)

Fig. 2. Layout of irradiating sets (a) between the tiers, variant 1, (b) between the tiers, variant 2, (c) above the tiers, variant 3, (d) above the tiers, variant 4, (e) above tiers, variant 5, (f) removing the axis between the tiers, variant 6, (g) axis between the tiers, variant 7.

Table 1. The results of the analysis of options for optical schemes of upper artificial irradiation for MNH

Criterion	Variant						
	B1	B2	B3	B4	B5	B6	B7
1 – pattern of the reflected rays	+	–	+	–	–	+	+
2 – need for special irradiation sets for additional artificial irradiation of outer MNHs	–	–	–	+	–	+	+
3 – rationality of use of the flow produced by the irradiation sources	+	+	–	+	–	–	+
4 – absence of trays shading each other	–	–	+	–	+	+	–

\+ – efficient variant, according to given criterion
– – inefficient variant, according to given criterion

Fig. 3 gives the results of calculations for the lighting of one side of the pyramid with five numbered points, which correspond to the five tiers. It also shows the cross-section of the horizontal surface with preservation of five points' relative positions. The location of the source is determined by the height index H_1 as to the first tier defining the distance index ℓ_1. Since it is important to determine the difference of spatial distribution of the flow for the horizontal and inclined surfaces, the calculations were made for conditional distances of the pyramid and for the illumination index E=100 standard units. The dependence of radiant intensity on angle α was calculated by the formula $I=\ell^{2}\cdot 100\,(\cos\alpha)^{-1}$. Luminous intensity distribution curves (LIDC) for the inclined (upper one) and horizontal (lower one) surfaces shown in Fig. 3 indicate to fundamentally different requirements for the lamps. In particular, the greatest flow by the horizontal surface corresponds to the direction to point 5, the one by the inclined surface – to point 1. This is due to varying regularity of the distance ℓ change while moving from point 5 to point 1 (decreases in the case of an inclined surface, increases in the case of a horizontal surface). It is important not only because the distance index ℓ squared is included in the rating formula but also due to the fact that in the case of inclined surface, index ℓ_1 (first tier) is not high enough. This means that the determining factor is the direct flow from the source of light but not the not yet formed reflected one, which in turn means that the given illumination index E for the first tier actually determines the main fraction power of the source for the first tier. The estimated LIDS also indicate that the luminous intensity that corresponds to the subsequent tiers should grow. This growth requires an increase in the source's intensity, i.e. excess of energy at upper tiers.

The analysis confirmed the assumption that any biological object (plant) contributes significantly to the specificity of the power supply of the production in APK (compared to abiotic production). Modelling of the inclined plane (Fig. 3) was done by turning the horizontal one. The creation of normalized lighting in a minor area does not cause any new problems. However, it is impossible to place the same number of plants in this area and get equal crops. One of the reasons is growing cenosis. Therefore, the specific (per m^2) source intensity in the MNH-technologies should be higher than the one in the projective area. In addition, there appear new relations of the spatial distribution of the flow. Fig. 3 shows $l_{\min}$ (the shortest distance) and ℓ_1 (distance to a definite point in the first tier). Angle β_1 is introduced together with the height index of the first tier H_1. In general, we can conclude the following:

$$l_i = \frac{H_i}{\cos\alpha}, \tag{1}$$

Since $\ell_i = l_{\min} (\cos\beta_i)^{-1}$, the expression for the irradiance of the horizontal surface of any tier (instead of $E_i = I_\alpha \cdot \cos^3\alpha_I H_i^{-2}$) through $\ell_{\min}$ and β is the form of:

$$E_i \frac{I_\alpha \cdot \cos\alpha_i \cdot \cos^2\beta_i}{l_{\min}^2}. \tag{2}$$

Hence, the expression for I_α at distinguished value E_i=const:

$$I_\alpha = \frac{E_i \cdot l_{\min}^2}{\cos\alpha \cdot \cos^2\beta}. \tag{3}$$

We got a mathematical model that relates luminous intensity with parameters characterizing the position of a tier on an inclined surface (angle β with a known value of $l_{\min}$). The results of calculations of luminous intensity necessary for the angle $(\alpha + \beta) = 60^\circ$ (which corresponds to the construction of MNH) are given in Table 2 ($E_i \cdot l_{\min}$ is accepted as 1.0).

Table 2. The luminous intensity needed for the construction of MNH with the angle $(\alpha + \beta) = 60^\circ$, with $E_i \cdot \ell_{\min} = 1.0$

β	50°	40°	30°	20°	10°
I_α	2.55	1.8	1.53	1.47	1.62

The calculation results confirm the requirement for an increase in luminous intensity directed towards the lower tiers. They also show the advisability of ensuring equal irradiance to the tiers by one lamp because the illumination of the upper tiers at small angles β and at relatively short distance ℓ is sufficiently large, specifying the power of the lamp. The illumination of the lower tiers should be brought to norm with the help of a special 'bottom' light source which is placed inside the pyramid.

Calculations of the four set variants for the reflectors of metalized films of different thickness were performed under the programme that has been worked out by Giproniselprom institute.

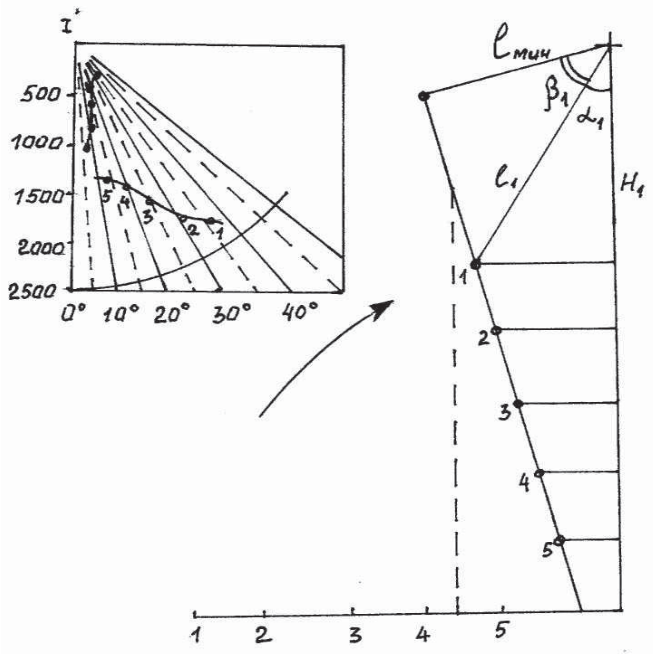

Fig. 3. Analytic model and luminous intensity distribution curves.

As a result of studies, a rational design of irradiator with an HPS-lamp was chosen and a control sample was produced (Fig. 4). A distinctive feature of this sample is the use of polyethylene terephthalate (polyester) films such as PET with an aluminium deposition thickness of 200 microns for the reflective surfaces of the irradiator. The efficiency factor of the irradiator is up to 95%.

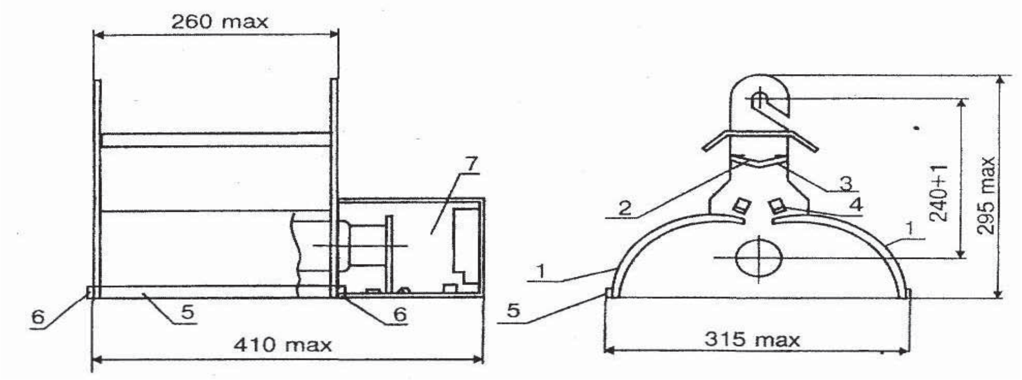

Fig. 4. Irradiator. Items: 1 - Reflector; 2 - Corner; 3 - Corner reflector; 4 - Retainer bar; 5 - Retainer bar; 6 - Takedown screw for the retainer bar; 7 - Box.

CONCLUSIONS

1. A laboratory test of an industrial sample of the designed irradiator with an efficient HPS-lamp confirmed its working capacity under conditions of high temperatures produced by the lamp. It also proved the conformity of lighting parameters to the calculated ones as well as confirmed the possibility of providing the racks of MNH with the specified value of power – 0.8–1.0 kW m^{-2}.

2. Performance tests in a real greenhouse revealed that the lighting parameters correspond to normal requirements, reliability indices of the lighting set are contained within the existing rules, and analysis of the plants during the long growing season revealed no significant differences by levels with a two-tiered system of irradiation.

3. The estimates obtained in economical testing confirmed that due to a more efficient use of light flow, the technological scheme of artificial irradiation of plants ´upper + lower´ compared to ´upper´ option allows to increase the productivity of plants by 52.7%, to reduce the costs of electricity by 1.53-fold per unit of output and to increase the outcome by 1.5-fold in the conditions of the same installed capacity of light sources.

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