Energy efficiency regulation of the light source's luminous flux

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Abstract: Based on the analysis and generalization of the obtained and published experimental data the analytical dependencies were established, necessary for the determination of the energy efficiency regulation of the light source's luminous flux. The analysis of the energy efficiency was carried out by determining the specific costs of the light energy unit produced within the average duration of the lighting by cheap, low-efficient, but still very popular thermal, and expensive, highly energy efficient semiconductor light sources.

Keywords: light source, energy efficiency, regulation, luminous flux

1. Introduction

The lack of energy resources and the unceasing growth of the Earth's population stipulated by the global demographic transition are the main factors determining the necessity of the intensive implementation of energy saving technologies in all spheres of human activity. In the first place, it concerns the spheres where the energy resources consumption is the highest. Lighting is one of these spheres as every fifth kWh of electricity is consumed by lighting units of different purposes.

Current analysis of the latest research papers and publications proved insufficiency of the „set and forget" principle [1–6]. The main factor leading to a radical increase of lighting energy efficiency is not only the decrease of general capacity of the installed lighting units at the expense of transition to the use of highly efficient light sources, but also general electricity consumption reduction [7–10]. This can be achieved solely through the introduction of intelligent lighting control systems. Lighting units or their components should be activated only when it is really necessary. Herewith they should provide a required level of light (brightness) taking into account the influence of the spectral composition of light sources on the individual's activity in twilight and night vision (S/P-factor) [11]. Nowadays it is common knowledge that the regulation (decrease) of the light source's luminous flux leads automatically to the increase of energy efficiency of lighting units. The question is if it is really so. On one hand, it is true because the value of the active power consumption decreases, though being nonlinear. On the other hand, there are a number of hidden parameters that can negate any efforts if the optimal boundaries of the regulation of luminous flux are not determined.

Therefore, the purpose of this paper is to investigate the energy efficiency regulation (decrease) of the luminous-flux (LF) of a light source (LS) on the basis of the cheapest and least energy efficient thermal light sources (TLS) still popular with the population and the most energy efficient, perspective and expensive semiconductor light sources (SLS).

2. Experiments and research results

Electrical, lighting and operational characteristics of thermal and semiconductor light sources were previously tested to achieve the above mentioned goal. To ensure the reproducibility of the experiments the number of light sources of each of the above mentioned groups, according to the statistical G-Kohren criterion, was set to be equal six [12]. Before the experiment, the light sources had been activated in the electrical network with nominal parameters for 100 hours. The investigation of electrical and photometric characteristics was carried out in a photometric sphere of «Everfine Spectron Coating Integration Sphere» type.

In consequence of the experimental research, the normalized dependencies were obtained of power and luminous flux of the current flowing through them fig. 1 and the average duration of glow (ADG) of TLS from normalized values of voltage U_N on them and SLS from normalized values of current flowing through them fig. 2. The dependencies of normalized values of ADG of thermal ($\tau_{TLS.N}$) and semiconductor ($\tau_{SLS.N}$) LS were obtained by the authors of the article based on the published data analysis [13] and our own experimental research regarding the impact of TLS magnitudes of active values of voltage network on ADG and temperature p-n junction (t_N) on SLS, expressed, for convenience of calculations, through the active value of current (I_N) $t_N = 0.58I_N + 0.418$ based on extrapolation of the data of short-term (six thousand hours) tests about the degradation of luminous flux in time, depending on the temperature of the p-n junction. These graphical dependencies can be analytically described by the following equations:

$$\tau_{TLS.N} = -186.11\, U_N^3 + 546.24\, U_N^2 - 538.34\, U_N + 178, \tag{1}$$

$$\tau_{SLS.N} = 0.998\left(0.58\, I_N + 0.418\right)^{-3.22}, \tag{2}$$

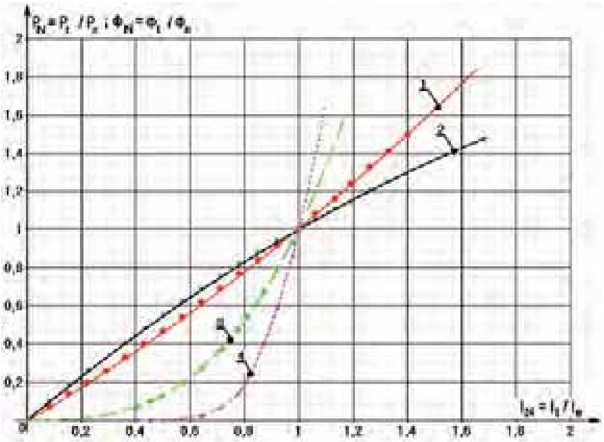

Fig. 1. Dependencies of normalized values of SLS and TLS from normalized values of the current flowing through them: 1, 3 – power (P_N) and 2, 4 – luminous flux (Φ_N), accordingly

Rys. 1. Zależności wartości znormalizowanych wielkości SLS i TLS od wartości znormalizowanych prądu przepływającego przez nich: 1, 3 – moc (P_N) i 2, 4 – strumień świetlny (Φ_N), odpowiednio

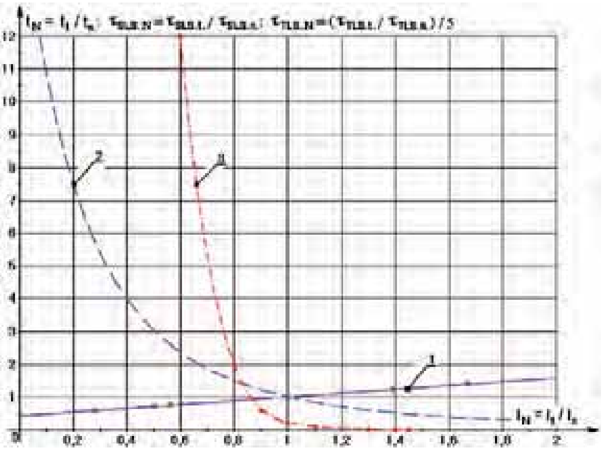

Fig. 2. Dependencies of normalized values of quantities: 1 – temperature of p-n junction (t_N) and 2 – ADG of SLS (τ_{SLS}) from normalized values of the current, 3 – AFG of TLS(τ_{SLS}) from normalized values of voltage U_N

Rys. 2. Zależności znormalizowanych wartości wielkości: 1 – temperatura złącza p-n (t_N) i 2 – ADG SLS (τ_{SLS}) od znormalizowanych wartości prądu, 3 – AFG TLS (τ_{SLS}) od znormalizowanych wartości napięcia U_N

$$\Phi_{TLS.N} = 9.28\, I_N^3 - 14.54\, I_N^2 + 7.55\, I_N - 1.29, \tag{3}$$

$$\Phi_{SLS.N} = -0.18\, I_N^2 + 1.18\, I_N, \tag{4}$$

$$P_{TLS.N} = I_N^{2.95}, \tag{5}$$

$$P_{SLS.N} = 0.16\, I_N^2 + 0.85\, I_N - 0.005, \tag{6}$$

where:

$\tau_{TLS.N} = \tau_{TLS.t} \cdot \tau_{TLS.n}^{-1}$ – normalized values of ADG of thermal LS;

$\tau_{SLS.N} = \tau_{SLS.t} \cdot \tau_{SLS.n}^{-1}$ – normalized values of ADG of semiconductor LS;

$\Phi_{TLS.N} = \Phi_{TLS.t} \cdot \Phi_{TLS.n}^{-1}$ – normalized values of the luminous flux of thermal LS;

$\Phi_{SLS.N} = \Phi_{SLS.t} \cdot \Phi_{SLS.n}^{-1}$ – normalized values of the luminous flux of semiconductor LS;

$P_{TLS.N} = P_{TLS.t} \cdot P_{TLS.n}^{-1}$ – normalized values of power of thermal LS;

$P_{SLS.N} = P_{SLS.t} \cdot P_{SLS.n}^{-1}$ – normalized values of power of semiconductor LS;

$\tau_{TLS.t}$, $\tau_{SLS.t}$, $\tau_{TLS.n}$, $\tau_{SLS.n}$ – running and nominal values of ADG of thermal and semiconductor LS respectively. For incandescent lamp (IL) PILA 60 $\tau_{TLS.n}$ = 1000 hours, for halogen lamps (HL) – 2000 hours; and for SLS $\tau_{TLS.n}$ = 25 000 hours;

$U_N = U_t \cdot U_n^{-1}$, $I_N = I_t \cdot I_n^{-1}$ – normalized values of voltage on thermal LS and current through semiconductor LS respectively;

U_t, U_n, I_t, I_n – running and nominal values of voltage on thermal LS and current through semiconductor LS respectively;

$\Phi_{TLS.t}$, $\Phi_{SLS.t}$, $\Phi_{TLS.n}$, $\Phi_{SLS.n}$, $P_{TLS.t}$, $P_{SLS.t}$, $P_{TLS.n}$, $P_{SLS.n}$ – running and nominal values of luminous flux and power of thermal and semiconductor LS respectively.

The normalization of the above mentioned dependencies has allowed us to transfer the equations (1)–(6) to the rank of universal – valid for the calculations of the veritable values of ADG, luminous flux, power, current and voltage of the existing gamma of thermal and semiconductor LS. Herewith it is quite easy to move from the normalized values to the veritable values of the corresponding quantities by multiplying the normalized values by the nominal ones.

The analysis of the acquired dependencies shows that the decrease of the TLS light flux always leads to the decrease of their light output. This linearity change of luminous efficacy is observed only in the range of 0.9 to 1.1 of the normalized values of current.

The regulation of the SLS luminous flux is accompanied by antithetic processes. With the decrease of the current through the SLS in regard to the nominal value (the point with coordinates (1, 1) in fig. 1), the luminous output increases and reaches its maximum in the area. With the current increase, it decreases. This proves the expediency of the SLS use at low, relative to the nominal values, currents.

Irrespective of the principle of their functioning, the ADG of light sources increases with the decrease of the luminous flux and falls with its increase (curves 2 and 3 in fig. 2). This is due to the corresponding changes in the rate of evaporation of tungsten in TLS and of the p-n junction temperature in SLS. Thus, the speed of changes of normalized values of a luminous flux, power and ADG in TLS is significantly higher than those in SLS.

Based on the acquired experimental data (expressions (1-6)) calculations were made concerning the quantity of normalized light energy (Qi) produced by thermal and semiconductor LS fig. (3) within ADG by the following formula:

$$Q_N = Q_t \ Q_n^{-1} = {}_t \quad {}_t \left({}_n \quad {}_n \right)^{-1} \tag{7}$$

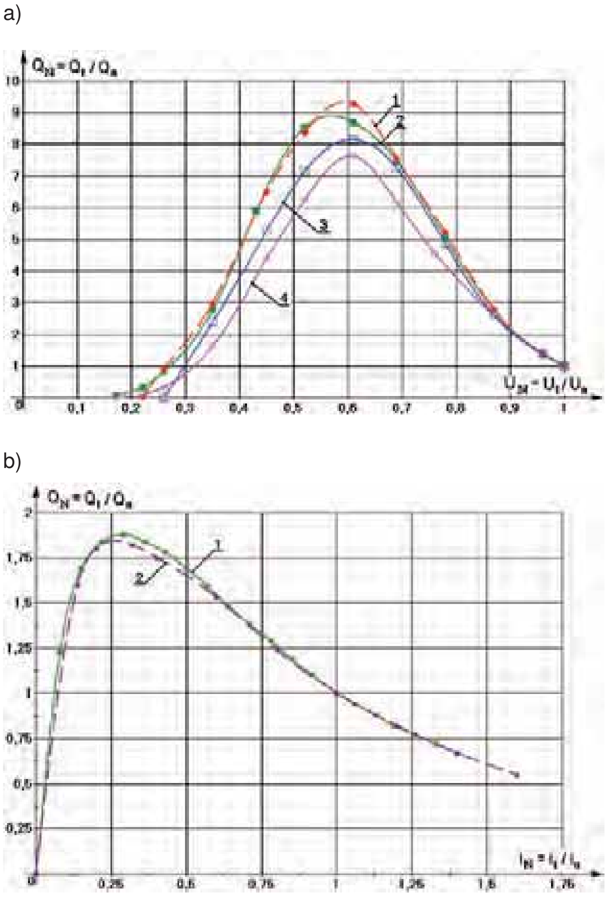

Fig. 3. Dependencies of the normalized quantity of luminous energy produced by TLS and SLS within ADG in the process of regulation of a luminous flux: a) TLS: 1 – HL 42 = 35 W; 2 – HL XENON 42 = 60 W; 3 – HL 28 = 35 W; 4 – IL PILA 60 W; b) SLS: 1 – luminarie with 42 LED total power 15.5 W; 2 – PARATHOM CLASSIC GLOBE 10.5 W

Rys. 3. Zależności znormalizowanej ilości energii świetlnej wytworzonej przez TLS i SLS w ciągu ADG w procesie regulacji strumienia świetlnego: a) TLS: 1 – HL 42 = 35 W, 2 – HL XENON 42 = 60 W, 3 – HL 28 = 35 W, 4 – IL PILA 60 W, b) SLS: 1 – oprawa oświetleniowa z 42 diodami LED o mocy całkowitej 15,5 W, 2 – PARATHOM CLASSIC GLOBE 10,5 W

The analysis of fig. 3 shows that the amount of luminous energy produced in the process of voltage reduction on TLS and the current through SLS at first increases gradually and then decreases, passing through its maximum at some values of voltage network for TLS, and at certain values of the current through SLS. For TLS, the maximum is located in the area $U_N = 0.6$, and for SLS – in the area $I_N = 0.25$. In this connection, the maximum amount of normalized luminous energy produced by thermal LS PILA 60 W exceeds (approximately by (7.65/1.86) = 4.1 times) the appropriate amount of luminous energy produced by SLS. This is due to the lower values of nominal ADG (in TLS nominal ADG is 25 times smaller than that in SLS) and more intensive growth of normalized values of ADG of thermal LS in the process of regulation of the luminous flux in comparison with SLS $\tau_{TLS.N} \cdot \tau^{-1}_{SLS.N} = 12 \cdot 2.35^{-1} = 5.1$. In absolute terms, there is practically no value difference between them.

Thus, at $U_N = 0.6$ for TLS $\tau_{TLS.t} = \tau_{TLS.N} \cdot 5 \cdot \tau_{TLS.n} = 12 \cdot 5 \cdot 1000 = 60\ 000$ hours, and at $I_N = 0.6$ for SLS $\tau_{SLS.t} = \tau_{SLS.N} \cdot \tau_{SLS.n} = 2.35 \cdot 25\ 000 = 58\ 750$ hours.

The data obtained makes it possible to determine values of arguments for which the amount of light energy produced by LS will reach its maximum. It is important, at the stage of their selection, but not enough to determine the energy efficiency of LS in the operation process of both stationary and dynamic modes of glow. Therefore, to calculate the LS energy efficiency we suggest using an integrated approach to the determination of the light sources energy efficiency as described in [13]. It is based on establishing the specific cost of a luminous energy unit produced by LS

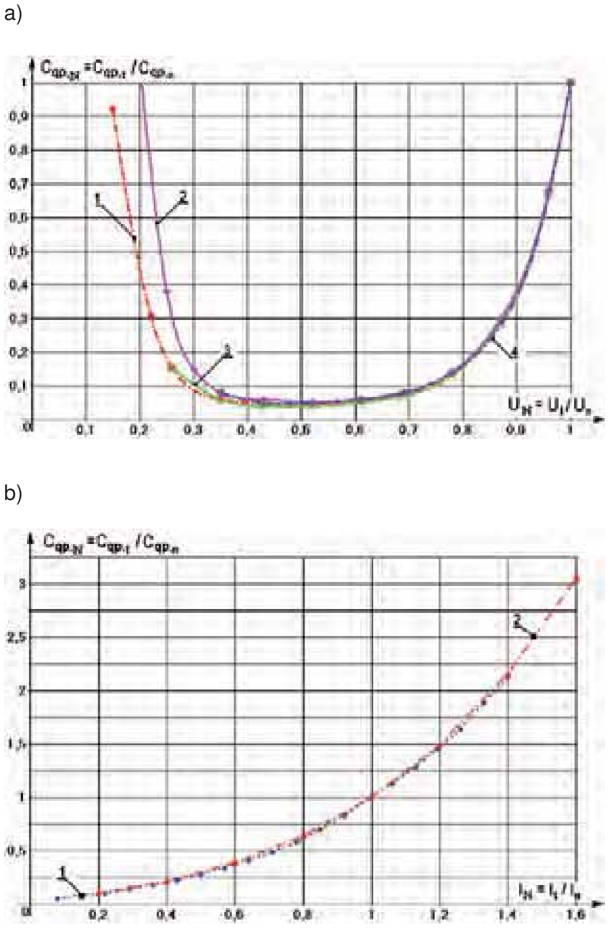

Fig. 4. Dependencies of the energy efficiency of the luminous flux regulation from the standpoint of the normalized specific cost of unit of luminous energy produced by LS within ADG: a) TLS: 1 – HL XENON 42 = 60 W; 2 – IL PILA 60 W; 3 – HL 42 = 55 W; 4 – HL 28 = 35 W; b) SLS: 1 – luminarie with 42 LEDs DURIS E5 of the total power 15.5 W; 2 – PARATHOM CLASSIC GLOBE 10.5 W

Rys. 4. Zależności efektywności energetycznej regulacji strumienia świetlnego z punktu widzenia znormalizowanych kosztów właściwych jednostki energii świetlnej wytwarzanej przez LS w ciągu ADG: a) TLS: 1 – HL XENON 42 = 60 W; 2 – IL PILA 60 W; 3 – HL 42 = 55 W; 4 – HL 28 = 35 W; b) SLS: 1 – oprawa oświetleniowa z 42 diodami LED DURIS E5 o mocy całkowitej 15,5 W, 2 – PARATHOM CLASSIC GLOBE 10,5 W

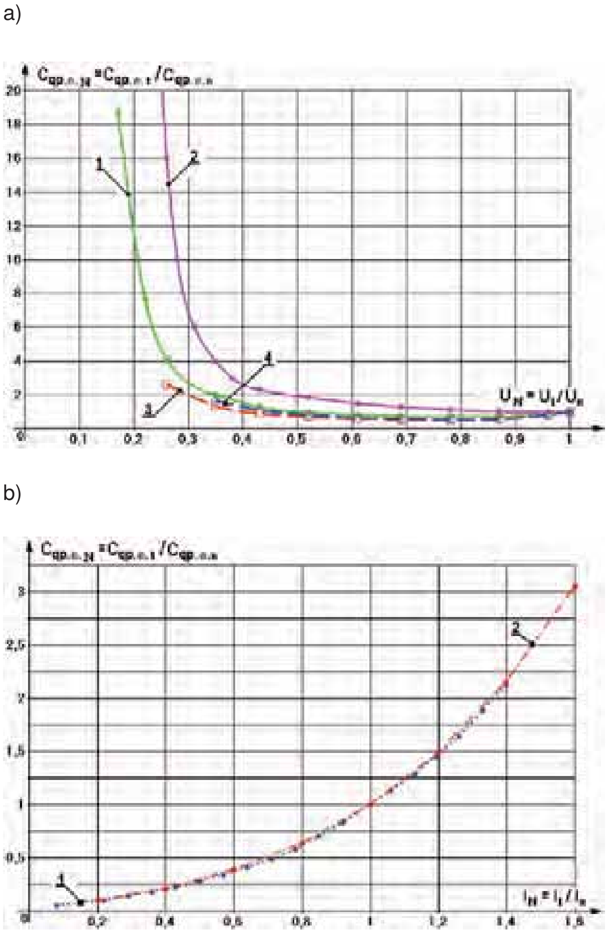

Fig. 5. Dependencies of the energy efficiency of the luminous flux regulation from the standpoint of the normalized specific cost of unit of luminous energy produced by TLS and SLS within ADG including power losses in CG, electricity costs consumed by a LS + CG set, and the downturn of the LS luminous flux in the exploitation process: a) TLS: 1 – HL XENON 42 = 60 W; 2 – IL PILA 60 W; 3 – HL 42 = 55 W; 4 – HL 28 = 35 W; b) SLS: 1 – luminarie with 42 LEDs DURIS E5 of the total power 15.5 W; 2 – PARATHOM CLASSIC GLOBE 10.5 W

Rys. 5. Zależności efektywności energetycznej regulacji strumienia świetlnego z punktu widzenia znormalizowanych kosztów właściwych jednostki energii świetlnej wytwarzanej przez TLS i SLS w ciągu ADG z uwzględnieniem strat w stateczniku CG, kosztów energii elektrycznej zużytej przez komplet LS + statecznik CG i spadku strumienia świetlnego LS w trakcie eksploatacji: a) TLS: 1 – HL XENON 42 = 60 W; 2 – IL PILA 60 W; 3 – HL 42 = 55 W; 4 – HL 28 = 35 W; b) SLS: 1 – oprawa oświetleniowa z 42 diodami LED DURIS E5 o mocy całkowitej 15,5 W; 2 – PARATHOM CLASSIC GLOBE 10,5 W

within ADG, both at the stage of its choice and in service, taking into account the cost of LS, the electricity pricing, the decrease of the LS luminous flux in service, and the minimum required value for the normal functioning of LS, and control gears (CG) (electrical ballast) by the following formulas

$$C_{qP} = \left(C_{LS} + C_{CG}\right) \cdot P_{LS} \cdot \left(\Phi_n \cdot \tau_{LS}\right)^{-1}, \tag{8}$$

$$C_{qP.e} = \frac{\left(\left(C_{LS} + C_{CG}\right) + \left(P_{LS.t} + \Delta P_{CG.t}\right) \cdot \tau_{LS.t} \cdot q\right)\left(P_{LS.t} + \Delta P_{CG.t}\right)}{\int_0^{\tau_{LS.t}} \Phi(t)\, dt}, \tag{9}$$

where C_{qP}, $C_{qP.e}$ is the cost of specific of the unit of luminous energy produced by LS within ADG at the stage of LS selection (without the power losses in CG, the cost of electricity consumed by the (LS + CG) set and the downturn of the LS luminous flux ($\Phi(t)$ in the exploitation process) and at their considering, (EUR kW)/(Mlm·hours); C_{LS}, C_{CG} – the cost of LS and CG, EUR; q – the tariff for electricity, EUR/(kW·hours); $\Delta P_{CG.t}$ – power losses in the CG, kW.

According to the obtained results based on (8), (9) the corresponding graphs have been constructed fig. 4 and 5.

The analysis of the obtained graphic dependencies has shown that while evaluating energy efficiency regulations of the LS luminous flux from the standpoint of the normalized specific cost of the luminous energy unit produced by LS within ADG by the expression (8), the character of the dependencies is defined by the type of LS. In dependencies for TLS fig. 4a, three specific areas may be singled out:

1 – a sharp increase of energy efficiency (decrease of normalized cost of specific light energy units) within the limits of $U_N = (1–0.70)$,
2 – high energy efficiency within the limits of $U_N = (0.70–0.40)$,
3 – a sharp fall of energy efficiency within the limits of $U_N = (0.40–0.15)$.

The second area is the most energy efficient.

Semiconductor light sources are characterized by a constant, close to the exponential law, increase of energy efficiency of their exploitation under the growth of the multiplicity of the luminous flux regulation up to its complete fading fig. 4b.

The losses in the CG, the cost of the electric energy consumed by a LS + CG set, and the decline of the LS luminous flux in the exploitation process affect only the dependences significantly for TDS fig. 5a. The first section of a sharp increase in energy efficiency of the luminous flux regulation process ($U_N = (1–0.70)$) disappears, at the expense of which the second section expands and covers the range of normalized voltages from $U_N = (1–0.40)$. The dependence of the energy efficiency regulation of the SLS luminous flux remains practically unchanged fig. 5b.

3. Conclusions

1. Each type of light source, depending on the physical principles of its work (thermal, semiconductor, low and high intensity discharge, fluorescent etc.), has its own areas, characteristic only for itself, within which the regulation of the luminous flux is really cost-effective. For thermal light sources, it is limited by the normalized value of voltage $U_N = 0.40$, whereas there are no such restrictions for semiconductor LS.
2. The larger the value of the light source, the smaller is the impact of adverse factors (power losses in CG, the

cost of electric energy consumed by a LS + CG set, the downturn of the LS luminous flux in the exploitation process) on the luminous flux energy efficiency regulation.

3. The best in terms of the energy efficiency regulation of the LS luminous flux is the value of the argument for the surrounding area typical of which are not only the smallest values of the normalized cost of specific light energy units, but the maximum number of their production. For LS – it is $U_N = 0.60$, and for SLS – $I_N = 0.27$.

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Efektywność energetyczna regulacji strumienia świetlnego źródeł światła

Streszczenie: Na podstawie analizy i uogólnienia opublikowanych rezultatów badań i eksperymentalnych danych otrzymanych przez autorów ustalono zależności analityczne niezbędne do określenia efektywności energetycznej regulacji strumienia świetlnego źródeł światła. Analizę efektywności energetycznej przeprowadzono w oparciu o wyznaczanie kosztów właściwych jednostki energii świetlnej wytwarzanej w ciągu średniego czasu świecenia przez termiczne źródła światła, tanie i o niskiej efektywności energetycznej, ale nadal bardzo popularne, oraz półprzewodnikowe źródła światła, kosztowne i o wysokiej energoefektywności. Stwierdzono, że dla każdego rodzaju źródeł światła, w zależności od zasad fizycznych ich działania (termicznych, półprzewodnikowych, wyładowczych niskiego i wysokiego ciśnienia itp.) są swoje, wyłącznie tylko dla nich charakterystyczne zakresy, w których regulacja strumienia świetlnego jest rzeczywiście opłacalna ekonomicznie. Dla termicznych źródeł światła przedział ten ograniczony jest znormalizowanymi wartościami napięcia na lampie od 1 do 0,4, natomiast dla półprzewodnikowych źródeł światła takiego ograniczenia nie ma. Tak więc im większa cena źródła światła, tym mniejszy wpływ na przebieg zależności efektywności energetycznej regulacji strumienia świetlnego mają takie uboczne czynniki jak straty mocy w układach stabilizacyjno-zapłonowych, koszt energii elektrycznej zużytej przez zestaw „źródło światła – statecznik” i spadek strumienia świetlnego źródeł światła w trakcie eksploatacji. Optymalnymi pod względem efektywności energetycznej regulacji strumienia świetlnego źródeł światła są takie wartości okolic argumentu, dla których charakterystyczne są nie tylko najmniejsze wartości znormalizowanych kosztów właściwych jednostki energii świetlnej, ale również wytwarzano maksymalną jej ilość.

Słowa kluczowe: źródło światła, efektywność energetyczna, regulacja, strumień świetlny

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