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ANALYSIS OF SELECTED PARAMETERS OF COMPACT FLUORESCENT LAMPS DURING THEIR LONG-TERM OPERATION

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Abstract

This article is focused on considerations based on experimental studies concerning changes of selected parameters of identical compact fluorescent lamps (CFLs) intended for use in buildings during their operation. The studies constituted a long-term experiment whose goal was an evaluation of selected operating parameters of the CFLs in terms of meeting the requirements set out in the specified regulations as well as the issue of marking the lamps with the energy efficiency class. The measurements were performed with the authors' experimental setup consisting of original equipment designed and made especially for the purpose of the measurements. The studies covered registration of the luminous flux as well as selected electrical parameters such as active power, current and the power factor during the so-called "start-up time" and operation time equal to 100 h, 500 h, 1000 h, 2000 h, *etc*. with a 1000 h step. The studies were finished with the moment of natural burnout of the CFLs tested. The results showed that the biggest drawback of CFLs is lack of preservation of the required time to reach 60% of the stabilized luminous flux just after short time of lamp operation. Similarly when assessing the conformity of the parameters declared by the manufacturer that have been verified, it can be stated that they are true only at the initial stage of lamp operation.

Keywords: lighting technology, compact fluorescent lamp, energy efficiency, light source, luminous flux.

1. Introduction

For each technical device deterioration of its characteristic properties is observed during its exploitation [1–3]. This fact concerns also light sources of different types, intended for use both in buildings and outside [4–12]. However, it is not easy to assess the degree of reduction of lighting parameters within the lifetime of a given light source because such assessment requires long-term studies resulting from possibly long operation of a given source (above 10 000 hours). An important aspect is also the selection of parameters which should be assessed. The reason for this is that as each electrical device the light source is characterized by a series of different quantities and parameters which are the base for determination of its application range. The operation time of a given lamp as well as maintaining its characteristic parameters seem to be extremely important from the point of view of the end user. However, the issue of energy efficiency of buildings where the lamps are installed also has a special meaning [4, 5, 10]. In both cases the expectations are such that the parameters specified by the manufacturer (luminous flux Φ, luminous efficiency, time needed to reach 60% of stabilized total luminous flux) need to be kept during the whole period of exploitation of a light source, not only during the first several hundred hours of operation.

Unfortunately, the requirements included in the specific regulations [13] which define functionality of non-directional household lamps relate only to the assessment of the parameters within the initial stage of operation. There are no requirements which allow for assessment of the lamps during whole life cycle. In such case the assessment may be conducted only experimentally based on indication which parameters characterizing light sources remain unchanged in time, which parameters change in time, but remain at a level consistent with the guidelines for new light sources and which parameters do not meet the requirements after a specific period of operation.

The *compact fluorescent lamps* (CFLs) have been the light sources available on lighting market for many years and have been tested in recent years from different points of view [4–8, 14–22]. However, there are no literature data concerning long-term experiments focused on evaluation of selected operating parameters of CFLs changing during exploitation time. For example, in [4] the authors proposed a way to quantify the emissions of mercury (Hg) and CO_2 associated with the manufacture and operation of CFLs as well as cost per unit of operation time. They found that both quantities depend linearly on the number of times per unit of time it is turned on and the time of continuous operation. Simultaneously, they noticed that there are intervals when a lamp is turned off during which emissions of pollutants and costs are identical regardless of how often the lamp is turned on or the time it remains on. In [5] the CFLs were, however, analysed from the point of view of impact on environment. The results obtained by the authors have shown that the energy consumption during use dominates the total environmental impact by 93% on the average, while manufacturing accounts for 7% and end-of-life for less than 1%. The problem of warming up the compact fluorescent lamps was highlighted in [6]. The results of measurements indicated that the stabilization of the luminous flux of CFLs may take up to dozens of minutes, which is important when carrying out photometric measurements. The measurements concerned, however, the T5 type fluorescent lamps but it is worth emphasizing that CFLs are the effect of miniaturization of linear fluorescent lamps, so the results may be applied also to them. In [7] the authors, examining CFLs, presented the results of measurements of illuminance, active power and apparent power. The tests were carried out after 100 hours of operation. Based on the results obtained, the luminous flux, luminous efficiency and power factor were calculated. The authors concluded in their research that the active power of the lamp as well as the luminous flux may be higher or lower than the values declared by the manufacturers. In turn, the factors affecting the time of stabilization of the luminous flux of CFLs and LED sources were discussed in [8]. Several fluorescent lamps and LED lamps were subjected to experimental measurements. In the case of CFLs, while analysing changes in the luminous flux when switching the lamp on, the impact of the following factors was taken into account: operation position, parameters in the electronic system supplying the fluorescent lamp and the operation time of the fluorescent lamps. In [14] the results of research on the light sources used to illuminate apartments were published including halogen lamps, CFLs and LED lamps. It was found by the authors that despite lower electricity consumption LEDs are inferior to CFLs and halogen lamps in terms of power quality. Based on the measurements, it was also noticed that in the case of LED lamps the luminous flux was 12.38% lower than the value declared by the manufacturer, when in the case of the CFLs the value of luminous flux was 1.23% higher. The authors drew attention to the fact that manufacturers do not properly provide the properties of their products which is why consumers do not know the actual parameters of lamps which, in turn, is crucial when choosing lighting equipment.

In numerous papers authors concentrate on measuring electrical parameters of energy-saving light sources. For example, in [15] the results of measurements of CFLs and LED lamps were presented, illustrating the influence of the supply voltage value on current harmonics generated by the lamps as well as the power factor and apparent power. An increase in the current harmonic level with an increase in voltage was indicated. It was noticed also that in the case of LEDs, current harmonics and *Total Harmonic Distortion* (THD) values of the current are higher than in the case of CFLs. The authors of the paper [16] also came to other conclusions. They examined CFLs and LED lamps and noticed that LED lamps generate a lower harmonic content than CFLs. Electrical and photometric measurements were made for new (previously unused) lamps and after 5000 hours of operation. After 5000 hours of operation the value of the luminous flux decreased by 15–33% (depending on the manufacturer of the lamp), while the active power of the lamps increased in average by 3%. In [17] the issue of generation of higher harmonics by CFLs was discussed. The measurement results were presented and a developed fluorescent lamp model enabling simulation of the impact of compact fluorescent lamps on the power quality was discussed. [18] contains the results of measurements of replacements of classic incandescent bulbs in terms of meeting the photometric and colorimetric parameters declared by the manufacturers. Based on the research conducted, it was noticed that the luminous efficiency of some LED sources is comparable to that of the CFLs tested. The technical parameters of CFLs and LED sources were compared in [19]. Additionally, some photometric quantities of lamps were analysed during their operation time. Measurements were carried out for 0, 1500, 3000 and 4000 h. In the case of fluorescent lamps, decreasing of luminous flux value was noticed after 4000 hours of operation time in the range from 15% to 28%. The authors of [20] observed, however, significant differences between the measured and declared parameters of CFLs [20]. After the operation time equal to 100 hours the photometric and electrical parameters of the lamps were measured. For all the lamps tested, the measured active power was not in accordance with the manufacturer's specifications. The differences between the declared and measured power varied from 25% to 63%. The differences were also observed in the luminous efficacy which was not in accordance with the manufacturer's specifications. Due to the fact that energy efficiency is an important criterion for modernizing external lighting, CFLs in park luminaires can be found in practical solutions. In the work [21], the authors conducted studies based on measurements which determined the luminous efficiency of an opal sphere type luminaire fitting various light sources including three CFLs. The obtained values of CFL luminous efficacy were in the range of 55 to 63 lm which is quite good compared to mercury lamps or induction lamps. The results of measurements of electric parameters with respect to one compact fluorescent lamp were presented in [22]. In this work, the impact of voltage supplying to a single CFL was analysed in terms of influence on active power, apparent power, the power factor and THD_i.

From the above, it is clearly seen that analysis of CFLs has been performed in a wide range. Nonetheless, the authors decided to perform the studies and to present their results in terms of assessment of selected operating parameters of the CFLs after long-term operation up to the end of the lamp life which is a new look on the problem of CFLs analysis.

2. Goal, objects and scope of the studies

As was mentioned above, the main goal of the studies was to evaluate selected operating parameters of the CFLs in terms of meeting the requirements set out in the specified regulations. Specifically, the evaluation made concerned the change of these parameters during long-term operation of the CFLs tested as an issue important from the point of view of the end user. The paper draws attention also to the issue of marking the lamps with the energy efficiency class which is an ambiguous matter when considering operation time of the lamps.

The reason for choosing the CFLs as the lamps used to be studied was quite complex. First, the fact of decision of withdrawing the conventional light sources from general use as a result of necessity of implementing the environmentally friendly policy had the impact on this decision. At the moment of commencement of the works described in the paper (second half of 2013), integrated compact fluorescent lamps were one of the most commonly used light sources that had replaced classic incandescent lamps. The process of withdrawing from the *European Union* (EU) market the light sources which were not environmentally friendly began in 2009 and proceeded in stages. Finally, as of September 1st 2012, a ban on all traditional light bulbs began to apply. At that time, CFLs had a well-established market position and were installed in many lighting applications including interior lighting. Hence, it seemed that a wide analysis performed during long-term operation of CFLs will bring new knowledge on the change of lamp parameters over the time of their operation. Second, CFLs remained available in various shapes. For research, the authors chose fluorescent lamps with the spiral shape of the discharge tube which the manufacturer additionally enclosed with an opal shade. This solution causes that their shape resembles traditional light bulbs to which users are accustomed. An additional advantage of CFLs considered in the studies were dimensions of the CFLs tested which are similar to those of classic light bulbs which allows to install CFLs almost in any luminaire. Third, to assess the CFLs, the authors decided that the experiment should be carried out through examination of lamps manufactured by one of the renowned manufacturers. It ensured the high quality and technical level of the lamps giving a guarantee of lack of influence of the low-quality factor. At the moment of beginning of the tests the LED sources, as an alternative to the CFLs, started to be available on the market. However, due to relatively high prices, their use in interior lighting was not very common. Anyway, the popularity of LED sources grew, especially as a result of marketing actions. However, in 2013 it was difficult to gain experience related to the use of these light sources as replacements for the classic light bulbs. The effect on the factors determining energy efficiency of these light sources had not yet been proven. Finally, it was decided to start work on relatively well-known light sources, bearing in mind that the experience gained during the assumed research program can be used in the future to analyse the LED sources when their position is well established.

The objects selected for experimental measurements were, as mentioned above, five identical compact fluorescent lamps. These lamps were of energy class A and were designed to be supplied from the 220–240 V network at frequency equal to 50/60 Hz. The data delivered by the manufacturer, the parameters of the tested light sources were as follows: active power 11 W, luminous flux 630 lm, warm white light colour, colour rendering index $\geq$ 80, time to reach 60% of luminous flux (run-up time) > 60 s, average lifetime 10 000 h. Each lamp was equipped with a E27 cap. The range of the studies covered registration of the luminous flux as well as selected electrical parameters (active power, current, power factor) during the so-called "start-up time" and after the operation time equal to 100 h, 500 h, 1000 h, 2000 h, *etc*. with a 1000 h step. The measurements were finished with the natural end of the lamp life. On the basis of the measurements performed, the time needed to reach 0.6 of the nominal luminous flux was determined individually for each lamp together with luminous efficacy calculated after a given operation time.

3. Methodology of measurements

Before the experiment began of, each CFL tested had been subjected to the initial measurements which were carried out in the system presented in Fig. 1. Due to the fact that the lamps considered were not previously exploited it was assumed that this measurement corresponds to zero operating hours and was marked as 0 h.

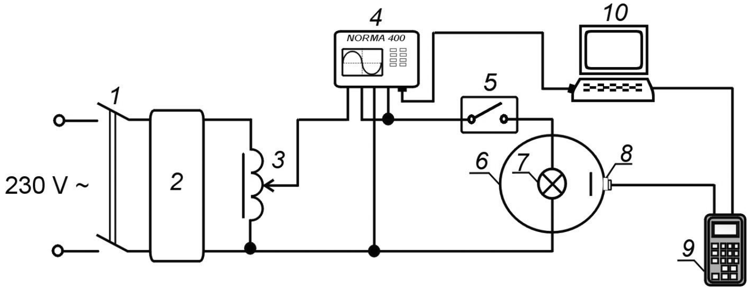

Fig. 1. System for lighting parameters measurement: 1 – power switch, 2 – voltage stabilizer, 3 – autotransformer, 4 – power analyser, 5 – time switch, 6 – integrating sphere (Ulbricht sphere), 7 – light source tested, 8 – photometric head, 9 – luxmeter, 10 – computer PC.

The measurement procedure consisted of the following steps. The voltage was supplied to the power switch (1) and after its closing to the voltage stabilizer ESN 2000 (2). It provided invariable rms voltage with 0.2% accuracy. The voltage was controlled by a Norma 4000 1PP42 power analyser (accuracy 0.2%) (4) and, if needed, it was adjusted with an autotransformer (3) to the value of 230 V. The electrical parameters were registered also by a power analyser. The distinctive lamps tested (7) were placed inside an integrating sphere (6) where was also located a photometric head (8) connected with the control unit of an L100 luxmeter (9) of accuracy class A according to the DIN 5032-7 [23]. After launching the measurement system, the time switch (5) closed the measurement circuit supplying the light source placed inside the integrating sphere. Reading the values of the distinctive quantities related to the tested lamps was carried out every 1 s for 60 minutes. The measurements in the integrating sphere were performed at the temperature equal to 25 ± 1°C. Each measuring instrument (power analyser, luxmeter, temperature meter) transferred the data registered in the on-line mode to a PC type computer (10).

After finishing the measurements performed in the circuit from Fig. 1, individual CFLs were installed in a specially designed setup which was used for conducting the assumed measuring process. This setup was prepared in a separate laboratory room and specially for the needs of the research described herein. The method of placing the lamps in the setup is presented in Fig. 2.

Fig. 2. The actual view of the setup for aging tests.

The supply circuit as well as the system of registration of lamp operation time corresponding to the setup from Fig. 1 are shown in Fig. 3.

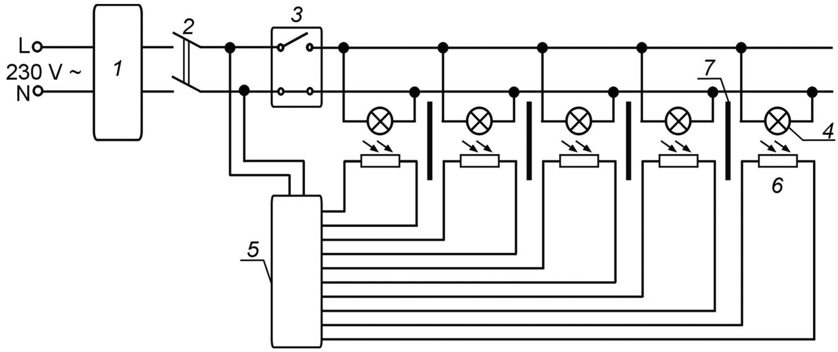

Fig. 3. Scheme of supply circuit for conducting the aging process: 1 – voltage stabilizer, 2 – power switch, 3 – time switch, 4 – tested light sources, 5 – time recorder, 6 – photoresistor, 7 – shutter.

As it is seen in the scheme, each lamp was supplied by an ESN 2000 voltage stabilizer. The network ensured an uninterruptible power supply, also in case of a mains failure. Relative humidity during the measurements was below 65% which is in accordance with the standard [24].

Verification of selected photometric parameters of CFLs tested is a long and time consuming process. Due to this fact, the authors decided to analyse only 5 identical CFLs (instead of a minimum of 20). The provision included in [13] for the lamps manufactured before 2013 refers to the assessment of changes in parameters only up to 2000 hours. At the same time the authors undertook to conduct a long-term experiment lasting up to the final damage of each lamp. Detailed guidelines concerning the conditions of conducting the measurements with regard to the lamps equipped with self-ballast and for general lighting purposes are contained in [24]. After an initial operation time of 100 hours, the lamps were turned off 8 times a day. The required shutdown time should have been between 10 and 15 minutes. In order to limit the trial time, the authors decided that the shutdown time was 11 minutes. What is also specified in [24] is the minimum burn time, which should be at least 10 minutes between the shutdowns. The authors adopted a lamp work cycle of 169 min / 11 min. This means that the lamps operated for 169 minutes and then were turned off for 11 minutes.

A very important element of the scheme from Fig. 3 is the photoresistor. It was placed near each lamp to determine individual operation time. The photoresistor used was the GL56390 model which was connected with a specially designed recorder. With the use of this device, the lamp life of each CFL was possible to be recorded. Lack of light emission from a given lamp resulted in decreasing the photoresistor resistance and this fact was captured by the recorder. It was possible because the recorder was equipped with an ATmega32 microcontroller together with an RTC DS1302 real-time clock. Thanks to this solution, the time of each event (date and hour) was registered in the EEPROM memory of the microcontroller. Fig. 4a presents the real view of the recorder made especially for the measurements described herein.

The use of the described recorder in the circuit from Fig. 3 also had an additional benefit. It allowed to determine whether a power supply interruption took place during the specified operation cycle of the lamps tested. In order to eliminate the influence of parasitic light emitted by the other lamps on the operation of the photoresistor assigned to a given lamp, the system was equipped with the shutters (no. 6 in Fig. 3) which were placed between individual CFLs.

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(a) The real view of the recorder registering the exact time of end of lamp lifetime.

(b) The timer controlling the lamp operation.

Fig. 4. The photos of the devices built.

As mentioned above, the goal of the studies was to determine how the operation time of the compact fluorescent lamps influences the time of stabilization of the luminous flux emitted by them. Thus, in order to achieve the assumed goal, it was necessary to apply in the measurement system also a solution that would allow for switching off the lamps after a predetermined operation time and then measuring their lighting parameters as per Fig. 1 (in the same way as it was made for the zero time of lamp operation). This necessity was forced by the fact that the end of assumed operation cycle for the light sources tested could have occurred during non-working hours. In such the situation fulfilling the assumptions of performing the measurements of lighting parameters after 100 h, 500 h, 1000 h, 2000 h, *etc*., would be very difficult. For this purpose the concept of the time switch was developed based on an 8-bit microcontroller (ATmega328). As in the case of recorder, the time switch was also equipped with a real-time clock (RTC DS1302) and, additionally, with a relay switching on/off the power supply for individual CFLs. The real view of the time switch is presented in Fig. 4b.

The software, specially designed for the microcontroller applied, made it possible to set the desired operation time (in the range between 1 minute and 10000 hours), after which automatic switching off of the fluorescent lamps took place. The time remaining to turning off the lamps was shown on the display of time switch. In general, the software gave the possibility both for continuous operation of the lamps tested and for operation in defined switch on/switch off cycles.

After the assumed operation time the lamps were switched off by the timer and then, using the integrating sphere and a group pattern of nominal luminous flux, one hour measurement was performed with the system from Fig. 1. The procedure was repeated as assumed and while it lasted next characteristic times were additionally extended by 1 hour resulting from the duration of measurements within the integrating sphere.

4. Results of the measurements and analysis

A graphic illustration of the change of the luminous flux in time, based on the measurements carried out for five CFLs (as average values), is given in Fig. 5. The first point on the graph refers to the luminous flux for the above-mentioned zero operation time. To facilitate the assessment of how much the luminous flux decreased during lamp operation, an additional vertical axis (in percentage) was introduced. Due to the fact that the initial luminous flux is given for luminous flux emitted after 100 hours of operation, for this value (second point on the chart) 100% was assumed. The results obtained, supported additionally by the minimum and maximum values and standard deviations for a given case, were also put in Table 1. Whereas there was a lot of measurement data and the lamps were of the same type, all the analyses were based on the average values from the five measurements. This assumption seemed to be correct looking at the standard deviations obtained which remained on the similar level during whole measurement cycle.

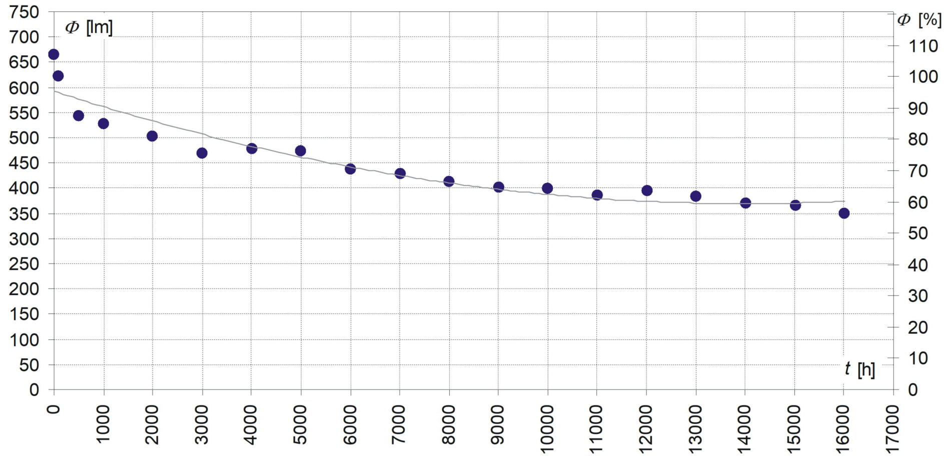

Fig. 5. The average values of the luminous flux as a function of operation time – $\Phi = f(t)$.

Table 1. The characteristic values of the luminous flux measured for specific operation times.

Operation time [h]	Luminous flux Φ_T (after 60 min from turning on) [lm]			
	MIN	MAX	AV	SD
0	651	677	665	11.0
101	603	639	620	19.0
502	518	572	545	23.1
1003	504	551	528	19.2
2004	486	526	504	16.5
3005	432	503	468	29.1
4006	459	499	478	19.7
5007	432	510	478	33.8
6008	414	448	437	15.8
7009	400	440	427	18.0
8010	394	423	410	12.2
9011	371	427	400	23.4
10012	372	424	398	21.3
11013	362	399	384	16.2
12015	380	417	396	15.5
14016	361	405	385	18.2
15017	353	403	372	22.0
16018	345	393	367	21.8

MIN – minimum value, MAX – maximum value, AV – average value, SD – standard deviation

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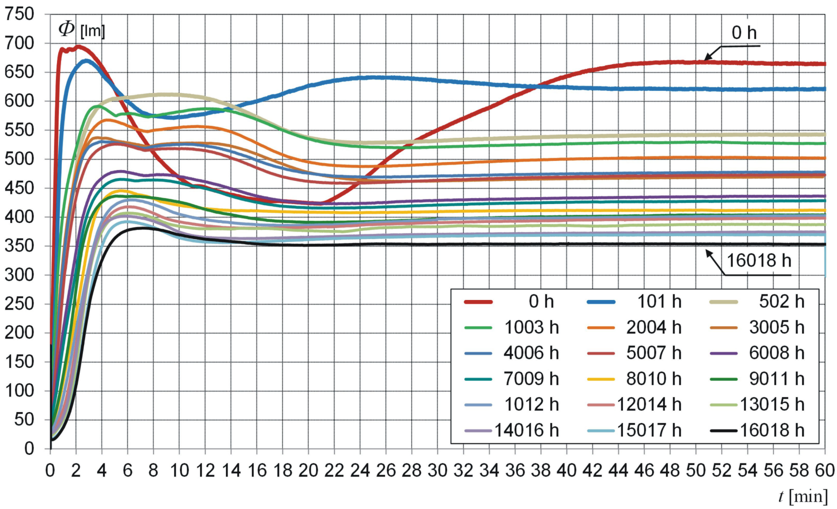
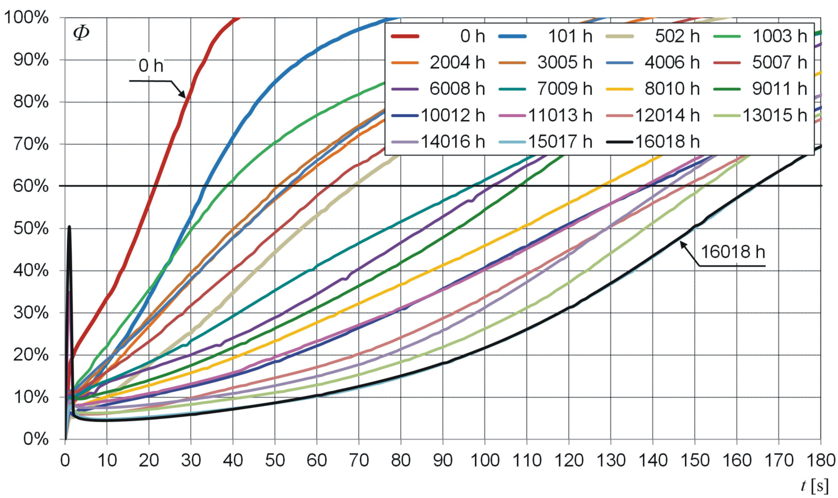
Figure 6 presents the characteristics of the CFLs tested illustrating changes of the luminous flux during one-hour of tests in the integrating sphere after subsequent operation times. Figure 6a shows the curves presenting changes of the luminous flux in the absolute values (in lumens). In order to determine the time (in seconds), after which the light source achieved the required percentage of stabilized luminous flux, the data from Fig. 6a were recalculated as relative values. The reference point was in this case the stabilized value of luminous flux that changes with the time of lamp exploitation. The results concerning the relative values in the first three minutes of operation of the lamps tested are presented in Fig. 6b.



(a) in absolute values during one-hour measurement in the integrating sphere



(b) in relative values

Fig. 6. The curves illustrating changes of the luminous flux in CFLs registered after different operation times.

Analysing the data from Fig. 6a, it is possible to investigate the change of emitted luminous flux in time. The observed phenomenon is obvious – the luminous flux decreases in time which is a natural process. The elements forming the light sources become older, which results in the decreasing luminous flux which is a fact well-known in lighting techniques [4, 6–9]. However, an interesting fact is the shape of luminous flux curve. Together with operation time, the time needed to reach the 60% of the stabilized value of the luminous flux lengthens. The data from Fig. 6b were used to determine the time after which the lamps achieved 60% of stabilized value of luminous flux. It is important to point out here that in accordance to [13] and with reference to lamps designed for use in buildings (domestic or office use), the time for reaching 60% of total luminous flux should be placed on the package of a given light source.

In this regulation, among the requirements concerning functionality of fluorescent lamps, it is given that for the 1st stage (binding from 1st September 2009) this time should be < 60 s, however for the 5th stage (binding from 1st September 2013) it should be < 40 s. The quoted values concern conventional CFLs *i.e.* lamps in which mercury occurs in the metallic form. It is, however, different is in the case of amalgam fluorescent lamps. The time to reach 60% of Φ is < 120 s (for the 1st stage) and < 100 s (for the 5th stage), respectively. In view of the fact that the tested fluorescent lamps were manufactured before year 2013 and contained mercury in the metallic state, the requirement of $t_{60\%\Phi} < 60$ s was applied. The results of the calculations including the assumptions presented above are shown graphically in Fig. 7.

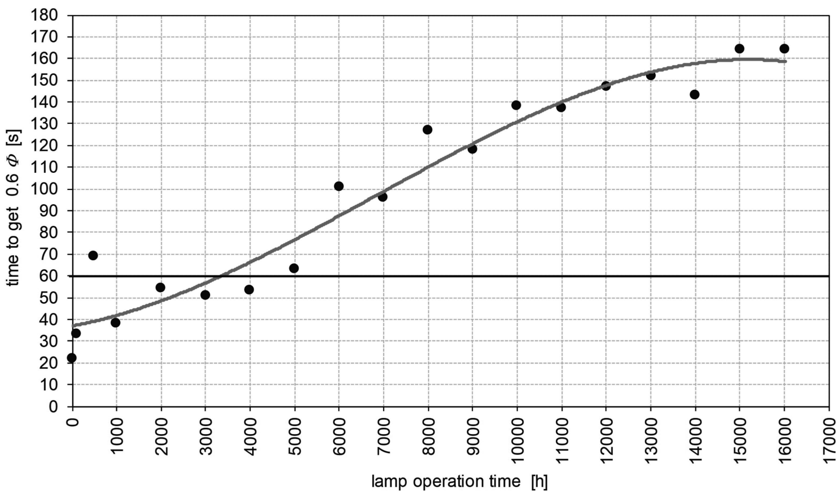


Fig. 7. Time after which the CFLs reach 60% of total luminous flux.

Similarly to the case of the luminous flux, the results were presented also in the tabular form (Table 2) including the minimum and maximum values as well as standard deviations.

Analysing the data presented above, it can be stated that the time needed to reach 60% of Φ is getting longer with the increase of the operation time of lamps. For new lamps (operation time $T = 0$ h) $t_{60\%\Phi} < 22$ s, while after $T = 5007$ h (which is approximately equal to half of the lamp life declared by manufacturer) $t_{60\%\Phi} < 63$ s, so the requirement for CFL functionality is no longer met.

Considering the fact that after 16 000 hours of operation individual CFLs have ceased to be technically efficient, the results of calculations for and after 16 000 h were presented in a separate drawing (Fig. 8) for each CFL separately.

In [13], in the paragraph focusing on the requirements concerning information about the product, a possibility is foreseen the of putting data on the declared power of an equivalent light

Table 2. The characteristic values of the time to get 0.6 of the stabilized luminous flux.

Operation time [h]	Time to get 0.6Φ [s]			
	MIN	MAX	AV	SD
0	18	33	21.8	6.5
101	27	40	32.4	5.0
502	49	78	67.4	11.8
1003	30	49	38.4	7.8
2004	36	74	52.8	14.4
3005	30	70	51	17.3
4006	30	82	55	22.0
5007	34	92	65.2	26.7
6008	38	135	88.6	44.3
7009	41	141	97.2	47.3
8010	55	168	123.6	48.5
9011	46	134	105	36.4
10012	66	207	139.8	58.5
11013	62	193	135.8	51.1
12015	95	189	147.4	41.6
14016	112	206	153.2	34.3
15017	113	191	143	32.7
16018	126	221	166.2	36.1

MIN – minimum value, MAX – maximum value, AV – average value, SD – standard deviation

Fig. 8. Time after which individual lamps reach 60% of the luminous flux after time of operation longer than 16 000 h (marks CFL 1 to CFL 5 are used only for distinction of a given Compact Fluorescence Lamp).

bulb on the package. This value (rounded to 1 W) is determined on the basis of the luminous flux of the lamp. Such approach allows for showing the potential customer what "intensity of lighting" can be expected from a lamp being a replacement of a classical light bulb. On the basis of the measured values of the CFL luminous flux, after the predetermined operation time T, the values of power of an equivalent light bulb P* were calculated. This calculation was made on the basis of linear interpolation. The results in this field were put in Table 3 in Column 3. Due to the decrease of the luminous flux Φ_T during operation of CFLs (Table 3, Column 2), the actual values of power of equivalent light bulb become lower too. In other words, together with longer operation time of CFLs, the luminous flux emitted by them corresponds to classical light bulbs of lower power.

Table 3. Selected parameters of CFLs determined after different operation time.

T [h]	Φ_T [lm]	P^* [W]	$LLMF$ [%]	$\cos\varphi$ [–]	P_{lamp} [W]	η_{lamp} [lm/W]	Energy class
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0	673	56	–	0.64	11.85	57	**A**
101	621	52	100	0.64	11.74	53	**A**
502	543	47	87	0.63	11.71	46	B
1003	527	46	85	0.63	11.66	45	B
2004	502	45	81	0.63	11.57	43	B
3005	470	42	76	0.64	11.39	41	B
4006	478	43	77	0.63	11.59	41	B
5007	473	43	76	0.63	11.64	41	B
6008	436	40	70	0.65	11.68	37	B
7009	428	40	69	0.63	11.73	37	B
8010	412	39	66	0.64	11.78	35	B
9011	402	38	65	0.62	11.78	34	B
10012	398	37	64	0.63	11.79	34	B
11013	385	37	62	0.61	11.66	33	B
12014	394	36	63	0.61	11.80	33	B
13015	383	36	62	0.63	11.73	33	B
14016	370	35	60	0.63	11.61	32	B
15017	366	35	59	0.63	11.76	31	B
16018	349	34	56	0.63	11.81	30	B

In the mentioned Commission Regulation [13] the term LLMF (*Lamp Lumen Maintenance Factor*) has been introduced. It is defined as a quotient of luminous flux produced in a defined life cycle of lamp Φ_T to the initial value $\Phi_T = 100$ (1) which is understood as the value reached after 100 h of lamp operation.

$$\text{LLMF} = \frac{\Phi_T}{\Phi_{T=100}} 100\% . \tag{1}$$

However, in relation to the CFLs with a second bulb, it is given that after 2000 h the luminous flux should reach the value ≥ 80%. The calculated values of LLMF for the individual operation times are quoted in Table 3 in Column 4. In the same document the required value of the power factor $\cos\varphi$ is also given. In the case of CFLs of active power lower than 25 W, it should not be lower than 0.5. The estimated values of this parameter are also put in Table 3 in Column 5. The key requirement for a light source is its energy efficiency which must be high. It is characterized by luminous efficacy (expressed in [lm/W]) which is the quotient of the emitted luminous flux Φ to the power of the lamp P_{lamp} (2).

$$\eta_{lamp} = \frac{\Phi}{P_{lamp}} . \tag{2}$$

This parameter determines the degree of energy efficiency of a light source and is closely related to the term of energy efficiency of lighting which has been permanently used in the lighting practice since the 1970s. The higher its value, the more efficient the light source is. Having the consumed power of the lamp and the luminous flux in the separate stages of light source operation, the luminous efficacy was calculated. The results are put in Table 3 in Column 7.

Analysing the data from Table 3 (Column 6). it can be stated, with some approximation, that the power of CFLs under test is on a similar level during the whole period of operation. Hence, taking into account that the luminous flux decreases with operation time, the conclusion is that the luminous efficacy will decrease too. In practice it means that the longer operation time of CFLs, the less energy efficient the CFLs become. Unfortunately, information in this field cannot be found on packages of light sources (lamps) because this parameter has not been specified as one important for consumers. According to the applicable rules information about energy efficiency of light sources should be delivered to the consumers using energy efficiency labels. However, it is important to point out that the classification of the lamp for a specific energy efficiency class is based on the value of the calculated energy efficiency index. With the data from the measurements (luminous flux and power of the lamps in separate stages of their operation) the energy efficiency classes of CFLs were determined. They are included in the last column of Table 3. From this column it is clearly visible that the CFLs tested can be classified as class A only at an early stage of their operation. After 502 h of operation their energy efficiency class changes to B.

In order to increase the attractiveness of the light sources, the manufacturers only show the term "energy saver" or similar one on the packages. This also took place in the case of the CFLs examined. According to the regulation [13], the inclusion of promotional wording regarding the effectiveness of the lamps can take place only when a particular requirement is met and this was put to test on the basis of specific calculations made. In the case of considered CFLs the maximum nominal power of light source for a given value of nominal luminous flux was defined. This value is determined on the basis of (3).

$$P_{\max} = 0.24\sqrt{\Phi} + 0.0103\Phi . \tag{3}$$

In view of the fact that the CFLs tested are opaque and equipped with additional bulb, in order to determine the maximum power of the lamp, the Pmax value in (3) should be divided by a correction factor of 0.95. When placing in (3) instead of Φ the value coming from the measurements (the values from Column 2 of Table 1), the active power of light source may be obtained as the value allowing for the use of the term "energy saver". The calculated values of maximum power ($P_{\max}/0.95$) together with actual power of the CFLs (P_{lamp}) for given operation time are presented graphically in Fig. 9.

It can be concluded from Fig. 9 that only at the early stage of CFLs operation (for $T = 0$ h, $T = 101$ h and $T = 502$ h) the active power of the lamps (P_{lamp}) is lower than the maximum power determined assuming the requirements included in [13]. Hence, just after 1003 h of operation using the term "energy saver" is no longer authorized.

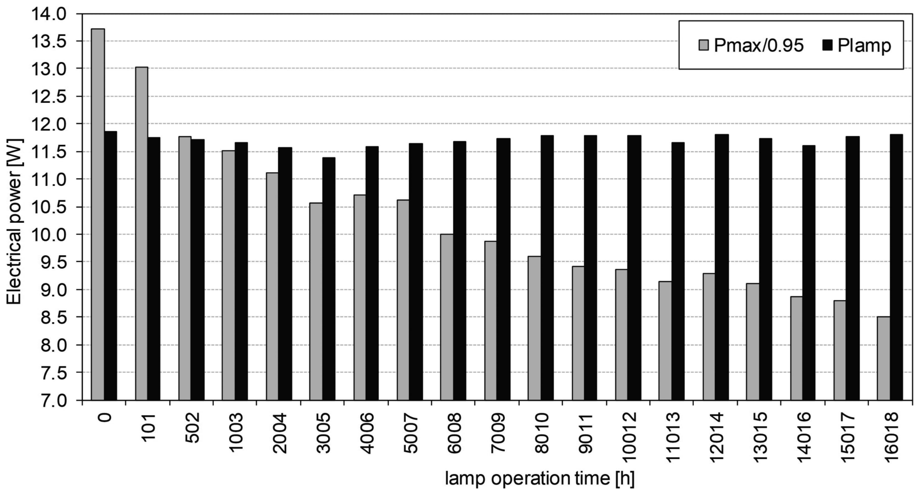


Fig. 9. Illustration of influence of operation time of CFLs on: a) maximum power of lamp to be marked as "energy saver" ($P_{\max}/0.95$), b) power of lamp (P_{lamp}).

Table 4 includes individual lamp life for each lamp separately. Additionally, the relationship T_i/T_d describing the relative lamp life was also quoted. When considering the issue of lamp life, it is also worth mentioning how it is defined. Very often it is identified as the number of hours after which lamp ceases to shine (*i.e.* it becomes technically inefficient). Due to the fact that CFLs consist of many elements, made with certain tolerance, in practice each lamp is characterized by a different lamp life (individual lamp life T_i). Thus, individual lamp life is determined by the least durable element. For this reason the manufacturers giving the lamp life usually use the concept of average life. In practice this average life is defined as the time after which the half of tested lamps ceases to be functional. With the average life criterion specified in this way, the number of tested lamps that the manufacturer subjects to the tests should be sufficiently large (depending on the number of lamps produced).

In Table 4 additional data were included which contain information on the active power of the lamps (P_{aging}) as well as the power factor ($\cos\varphi_{aging}$) after the lamps have ceased to be technically efficient (*i.e.* they no longer emit the luminous flux). As we can see, the

Table 4. Lamp life of individual CFLs and corresponding values of active power and power factor.

Lamp symbol	CFL1	CFL2	CFL3	CFL4	CFL5
Operation time	17515 h 19 min	23543 h 58 min	16437 h 56 min	25855 h 29 min	25193 h 47 min
T_i/T_d **[%]**	175.15	235.43	164.38	238.55	251.94
P_{aging} **[W]**	0.56	0.57	0.50	0.56	0.58
$\cos\varphi_{aging}$ **[–]**	0.39	0.38	0.38	0.38	0.37

T_i – lamp life of individual CFL, T_d – lamp life declared by manufacturer (10000 h)

Expiration of light sources is a natural process similar to the decrease in the luminous flux. It is caused by the wear of the electrodes, phosphor, elements in the electronic supply system, *etc*. In order to identify the reason of a lamp failure, their disassembly was performed. After separating the discharge pipes from the electronic supply system (placed in the plastic CFL housing), the

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technical condition of these two components was evaluated. It turned out that in all the five CFLs the electronic power supply system remained functional and the reason for the failure of the lamps was the burnout of one of the electrodes. In the case of one technical solution, (as presented in Fig. 10) the manufacturer offers the possibility of replacing not only the cap but also the discharge pipes and the stabilization-ignition system. In this way, when the user knows which of the elements is damaged, he/she can buy it and replace it without purchasing a new CFL.

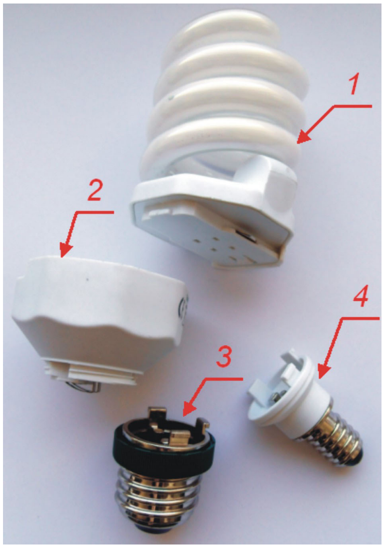

Fig. 10. CFL with interchangeable elements: 1 – discharge pipes, 2 – stabilization-ignition electronic system, 3 and 4 – E27 and E14 cap.

However, a next experiment was performed. Discharge pipes disassembled from a new, efficient (previously unused) CFL with the same parameters and from the same manufacturer were connected to the individual electronic circuits of the faulty lamps. Measurements for each of these systems (dismantled CFL electronics connected with new discharge pipes) were performed in the system shown in Fig. 1. The results of these measurements were presented in Table 5.

Table 5. Luminous flux Φ and time to achieve 0.6 Φ in the individual cycles of lamp operation.

Lamp symbol	CFL1	CFL2	CFL3	CFL4	CFL5
Results for new CFLs, operation time T = 0 h					
$\Phi_{T=0}$ [lm]	669	678	669	684	658
Time to get 0.6 Φ [s]	25	18	17	35	17
Results for CFLs reaching lamp life					
***T* [h]**	1719	23025	16018	23025	25027
$\Phi_{T=T_i}$ [lm]	350	346	359	341	340
Time to get 0.6 Φ [s]	143	172	148	129	133
Results for CFLs after replacement of damaged discharge pipes on new ones					
$\Phi_{T=0}$ [lm]	660	546	507	533	516
Time to get 0.6 Φ [s]	87	108	90	116	104

From Table 5 it can be inferred that the replacement of the discharge pipes with new ones improved properties of the lamps increasing their luminous flux. In the case of CFL1 and CFL2 the increase was high enough to bring the lamp back to class A of energy efficiency. In turn, the time to reach 0.6Φ was shortened, but still the standard requirements for this value were not met.

5. Conclusions

The results of the measurements carried out with regard to the integrated CFLs expanded the range of information on the change of their parameters during long-term operation. In general, it can be stated that, according to the assumptions made, increased operation time of the light sources tested causes a decrease in the luminous flux and the luminous efficacy.

Analysing the data quoted in Table 3 the clearly visible conclusion can be formed *i.e.* marking lamps with the energy efficiency class in order to determine the degree of their energy efficiency is not a precise approach. Both the lamps of luminous efficacy equal to 46 lm/W and 30 lm/W were classified for the same class of energy efficiency (class B), which may suggest that they are identical from the point of view of energy efficiency.

The time needed to reach 0.6 of the stabilized value of the luminous flux lengthens with increased operation time. Based on the measurements performed after 5007 h, it was noticed that the requirement of 60 s was not met.

The idea of manufacturing the lamp with exchangeable elements can be treated as an innovative approach, but from the authors' experience replacement of any used element (discharge pipes or electronic power supply system) does not guarantee meeting all the requirements for functioning of CFLs.

Additionally, it can also be stated that the biggest drawback of CFLs is lack of preservation of the time required to reach 60% of the stabilized luminous flux only after a short time of operation.

When assessing the conformity to the parameters declared by the manufacturer that have been verified, it can be said that these parameters are true only at the initial stage of lamp operation.

The tests were carried out on a sample consisting of five identical lamps. The light sources, like other mass production products, are characterized by a certain spread of parameters and, therefore, it cannot be excluded that the tests carried out on a sample with a larger number of randomly selected lamps from the same manufacturer would be more satisfactory.

The presented results of the studies have been the base for the authors' current studies by concerning LED sources. The authors are going to obtain a similar range of data hoping for equally interesting insights.

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