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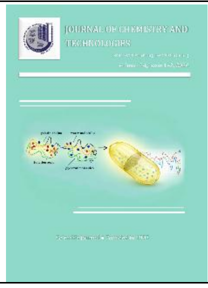

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COMPREHENSIVE EVALUATION OF ULTRAVIOLET DISINFECTION SYSTEMS CONSIDERING MAINTENANCE, SPECTRAL, AND OPERATIONAL COEFFICIENTS

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Abstract

The paper presents a comprehensive evaluation of ultraviolet (UV) disinfection systems by integrating maintenance, spectral, and operational coefficients into a unified analytical model. The study addresses the progressive decline in UV radiation efficiency caused by lamp aging, surface contamination, and changes in the reflective properties of operating environments. The proposed methodology extends the classical Maintenance Factor (MF) model defined in CIE standards by incorporating additional coefficients that account for spectral effectiveness (SEF), temperature influence (TCF), ballast performance (BF), irradiation geometry (UF), and dose compliance (DCF). Experimental data obtained for various UV systems (TUV15WG13, HNS15G13, TUV36WG13, ZW20D15Y, ZW20D15W) demonstrated that overall system efficiency decreases to 27–36 % of the initial level after 6,000 operating hours. The dominant loss factors were identified as UF (17–38 %), RFMF (20–35 %), and LMF (18–28 %), while RSMF, TCF, and BF contributed minor yet consistent effects. The developed integrated approach provides a more accurate prediction of degradation processes, allowing preventive maintenance scheduling, optimization of energy consumption, and stable disinfection efficiency throughout the service life of UV systems.

Keywords: ultraviolet disinfection; photobiological systems; maintenance factor; spectral efficiency; ballast factor; utilization coefficient; degradation modeling.

КОМПЛЕКСНЕ ОЦІНЮВАННЯ СИСТЕМ УЛЬТРАФІОЛЕТОВОГО ЗНЕЗАРАЖЕННЯ З УРАХУВАННЯМ КОЕФІЦІЄНТІВ ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ, СПЕКТРАЛЬНИХ ТА ЕКСПЛУАТАЦІЙНИХ ПАРАМЕТРІВ

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Анотація

У статті представлено комплексне оцінювання систем ультрафіолетового (УФ) знезараження шляхом інтегрування коефіцієнтів технічного обслуговування, спектральних та експлуатаційних коефіцієнтів у єдину аналітичну модель. Дослідження розглядає поступове зниження ефективності УФ-випромінювання, спричинене старінням ламп, забрудненням поверхонь і змінами відбивних властивостей робочого середовища. Запропонована методика розширює класичну модель коефіцієнта технічного обслуговування (MF), визначену в стандартах CIE, шляхом включення додаткових коефіцієнтів, що враховують спектральну ефективність (SEF), вплив температури (TCF), роботу баласту (BF), геометрію опромінення (UF) та відповідність дозі знезараження (DCF). Експериментальні дані, отримані для різних УФ-систем (TUV15WG13, HNS15G13, TUV36WG13, ZW20D15Y, ZW20D15W), показали, що загальна ефективність системи знижується до 27–36 % від початкового рівня після 6000 год роботи. Визначено, що домінувальними факторами втрат є UF (17–38 %), RFMF (20–35 %) та LMF (18–28 %), тоді як RSMF, TCF і BF мають незначний, але стабільний вплив. Розроблений інтегрований підхід забезпечує точніше прогнозування процесів деградації, що дає змогу планувати профілактичне обслуговування, оптимізувати енергоспоживання та підтримувати стабільну ефективність знезараження протягом усього строку служби УФ-систем.

Ключові слова: ультрафіолетова дезінфекція; фотобіологічні системи; коефіцієнт обслуговування; спектральна ефективність; баластний коефіцієнт; коефіцієнт використання; моделювання деградації.

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Introduction

The problem of effective air and surface disinfection using ultraviolet (UV) radiation has been actively studied over the past decades. UV rays in the wavelength range of 200–280 nm demonstrate a high ability to inactivate bacteria and viruses transmitted by airborne droplets [1–3]. Particular attention of researchers is focused on the effect of UV-C radiation on the SARS-CoV-2 virus, where rapid destruction of genetic material and high disinfection efficiency have been confirmed [2; 4].

Ultraviolet radiation is one of the key physical factors ensuring the inactivation of microorganisms, including pathogens hazardous to humans [1; 4]. Due to the high photochemical activity of nucleic acids, even short-term exposure to UV-C radiation leads to the destruction of DNA and RNA structures [5; 6], which makes this technology extremely effective. Therefore, modern photobiological electrical systems are widely used in medical institutions, public buildings, and the food industry for air [7–10] and surface [4; 7], and water treatment [11; 12], as well as in biological and agricultural technologies, including pre-sowing seed treatment [13].

The main component of photobiological electrical systems [8; 9] is the UV radiation source, most commonly low-pressure mercury discharge lamps or ultraviolet light-emitting diodes (UV-LEDs) [5; 14; 15]. The efficiency of such systems is determined by radiation intensity [11], spectral composition, exposure duration, and operational stability [16–18]. It is known that over time, lamp output gradually decreases because of lamp aging, electrode degradation, bulb blackening, changes in gas composition, and deterioration of optical materials [18–21]. In addition, dust and dirt accumulation on lamps, reflectors, protective surfaces, and treatment chambers significantly reduces the useful irradiance reaching the target object [22; 23]. Without regular maintenance, irradiance may drop below the level required for effective microorganism inactivation.

Another important aspect is the spectral and photobiological assessment of radiation sources. Since germicidal effectiveness depends not only on the total emitted power but also on the wavelength distribution, the spectral effectiveness of UV sources should be considered together with photobiological safety requirements [12; 16; 24]. In practical systems, ballast characteristics, thermal operating conditions, enclosure protection, and optical design may also influence the final disinfection performance [17; 21; 25]. Furthermore, the reflective properties of surrounding surfaces affect radiation redistribution in rooms and irradiation chambers, which may contribute both to improved dose formation and to additional losses under polluted operating conditions [23; 26].

For the quantitative evaluation of optical system efficiency, a set of coefficients is commonly used. Traditionally, the performance of such systems is assessed using the Maintenance Factor (MF), which accounts for the Radiant Flux Maintenance Factor (RFMF), Lamp Survival Factor (LSF), Luminaire Maintenance Factor (LMF), and Room Surface Maintenance Factor (RSMF) [22; 23]. This approach is well established in CIE recommendations for electric lighting systems [22; 23], but in UV disinfection practice it does not fully reflect the influence of spectral effectiveness, temperature conditions, ballast operation, irradiation geometry, and compliance with the required germicidal dose.

Considering these parameters and their respective coefficients by analogy with optical lighting systems allows a more accurate prediction of UV system performance under real operating conditions, optimization of maintenance schedules, reduction of energy consumption, and improvement of long-term disinfection reliability [20; 21; 25; 26]. Therefore, the development of an integrated approach to evaluating the efficiency of photobiological systems remains a relevant and important task. The aim of this study is to develop and experimentally validate a comprehensive analytical model for ultraviolet disinfection systems that combines maintenance, spectral, and operational coefficients in order to predict degradation processes and support stable disinfection efficiency throughout the service life of UV systems.

Materials and Methods

The study investigated the key factors determining the efficiency of electrotechnical UV systems, with particular emphasis on systems designed for air disinfection and surface treatment.

To evaluate the performance of UV technologies, international regulatory documents and technical recommendations were applied, including *LED modules for general lighting – Performance requirements* (IEC/PAS 62717:2011)

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[15], *Photobiological safety of lamps and lamp systems* (EN IEC 62471-7:2023) [16], *Guide on the Maintenance of Indoor Electric Lighting Systems* (CIE 97:2005) [22], *The Maintenance of Outdoor Lighting Systems* (CIE 154:2003) [23], and *Degrees of protection provided by enclosures* (IP Code) (EN IEC 60529) [25].

The proposed methodology for calculating the Maintenance Factor (MF) makes it possible to determine the overall operational efficiency of the system depending on its service life and the changing technical condition of the equipment. In addition to the classical CIE-based maintenance coefficients, the analytical framework considers spectral effectiveness, ballast operation, utilization geometry, temperature influence, and compliance with the required disinfection dose.

Statistical analysis was carried out to ensure the reliability and reproducibility of the obtained experimental data. For each UV system, the average values, standard deviations (SD), and coefficients of variation (CV) were calculated based on at least three repeated measurements. The correlation between the main coefficients (RFMF, LSF, LMF, RSMF, and UF) was analyzed using Pearson's correlation method, while the differences between systems with different pollution categories were evaluated using one-way ANOVA. The significance level was set at $p < 0.05$. Data processing and curve fitting were performed using Microsoft Excel 2021 and OriginPro 2023 software.

Research Results

The efficiency of ultraviolet (UV) disinfection systems is determined by a combination of factors that gradually reduce radiation intensity during the operational period. These factors are accounted for through a system of correction coefficients that reflect the actual technical condition of the equipment. The main coefficients are described below.

Radiant Flux Maintenance Factor (RFMF) characterizes the portion of the initial radiant flux retained by the lamp after a certain operating time. The decrease in RFMF is caused by physicochemical aging of materials (blackening of the bulb, electrode degradation, and changes in the gas composition inside the lamp). For low-pressure mercury lamps, a noticeable reduction in flux occurs after 1–2 thousand hours of operation, which becomes more pronounced with higher lamp power. A decrease in RFMF directly leads to a reduction in irradiation intensity and, consequently, disinfection efficiency.

Lamp Survival Factor (LSF) indicates the probability that a lamp remains functional after a specific operating period. Its value depends on the switching frequency, cooling conditions, and the quality of ballast equipment. For example, for Philips TUV15WG13 lamps, the LSF decreases from 0.99 (after 1,000 hours) to 0.94 (after 6,000 hours). Even if the lamp continues to emit light, a low LSF value indicates a reduction in the number of active sources within the system, which directly affects the irradiation level.

Luminaire Maintenance Factor (LMF) accounts for the impact of contamination on luminaire elements (bulbs, reflectors, protective grids, irradiation chambers) on the output flux. The most significant losses are observed in humid or dusty environments, where the LMF value may decrease from 0.53 (after 1 year) to 0.29 (after 6 years). Regular cleaning of optical surfaces can increase system efficiency by 20–30 %.

Room Surface Maintenance Factor (RSMF) describes the change in reflectance properties of walls, ceilings, and room structures. In clean rooms, RSMF decreases from 0.97 to 0.67 over six years; in typical industrial environments—from 0.95 to 0.64; and under high pollution levels – to 0.61 over the same period. Underestimating this factor can lead to efficiency losses, since up to 20 % of UV radiation in large rooms results from reflected light.

Total Maintenance Factor (MF) – the overall efficiency of a UV system –is determined as the product of all the above – mentioned coefficients:

$$MF = RFMF \times LSF \times LMF \times RSMF$$

For example, if RFMF=0.8, LSF=0.9, LMF=0.7, and RSMF=0.8, then MF=0.40, which means that the system operates at only 40 % of its initial efficiency.

Experimental data (Table 1) show that after 4,000 hours of operation, the system efficiency decreases by almost half, and after 6,000 hours – to a critical level of 27 %.

The analysis of the RFMF, LSF, LMF, and RSMF indicators demonstrates that the use of these coefficients provides an objective and sufficiently accurate picture of the operational efficiency of UV systems. The total Maintenance Factor (MF), which represents the product of these coefficients, reflects the actual condition of the system and allows prediction of the point at which further operation becomes ineffective.

Table

Maintenance factor for different UV systems (MF)

Application of UV system	Lamp model	Pollution level	Operating time, thousand hours				
			1.0	2.0	4.0	5.0	6.0
Air purification in recirculating systems	TUV15WG13	Medium	2.48	2.0	1.45	1.22	0.89
	HNS15G13	Medium	2.43	1.87	1.33	1.01	0.76
Air disinfection	TUV36WG13	High	6.83	5.09	3.61	2.93	2.20
Decontamination of activated carbon filters	ZW20D15Y	High	2.69	1.99	1.39	1.11	0.74
Pre-sowing treatment of agricultural seeds	ZW20D15W	High	2.74	2.04	1.39	1.09	0.77

Table presents the calculated values of the Maintenance Factor (MF) for five different ultraviolet (UV) disinfection systems under varying operating conditions. It should be noted that the MF values shown in the table are not classical dimensionless coefficients ranging from 0 to 1, as used in CIE lighting standards. In this study, MF represents a normalized integral efficiency index that combines the effects of lamp aging (RFMF), lamp survival (LSF), optical surface contamination (LMF), and room reflectance degradation (RSMF). All values are normalized per 1,000 hours of operation, which allows comparing systems with different lamp types, geometries, and pollution categories.

Higher MF values at the beginning of operation (e.g., 2.48–6.83 at 1,000 hours) indicate high initial system performance under specific environmental conditions. As operating time increases, MF decreases significantly (down to 0.74–0.89 after 6,000 hours), illustrating the expected degradation of UV systems. The rate of decline differs between systems due to variations in lamp power, reflector contamination rate, irradiation chamber design, and operating environment.

Thus, Table 1 quantitatively demonstrates the cumulative loss of operational efficiency over time and provides the basis for extending the traditional MF model with additional coefficients (SEF, TCF, BF, UF, DCF) to improve predictive accuracy and maintenance planning.

At the same time, the research results indicate that the existing system of coefficients requires refinement, since the efficiency of UV systems is also influenced by additional factors that have not yet been considered.

To improve the accuracy of predicting the performance of photobiological systems, it is advisable to include additional coefficients that reflect the physical and operational characteristics of the radiation:

Spectral Effectiveness Factor (SEF) accounts for the dependence of UV radiation efficiency on wavelength. The maximum germicidal effectiveness is observed near 254 nm; therefore, deviations from this value (for example, in LED or medium-pressure lamps) reduce the disinfection efficiency. The SEF coefficient represents the ratio between the actual and optimal spectral distributions of the emitted radiation.

Temperature Correction Factor (TCF) describes the influence of ambient temperature on radiation power. For low-pressure mercury lamps, the radiation intensity may decrease by 10–15 % when the temperature deviates by ±10 °C from the nominal value (25 °C). Considering TCF makes it possible to evaluate radiation power with regard to temperature fluctuations.

Ballast Factor (BF) reflects the stability of current and voltage in the lamp circuit. Unstable operation of the ballast can cause current fluctuations, which accelerate lamp degradation and reduce their service life.

Utilization Factor (UF) defines the fraction of emitted radiation that effectively reaches the irradiated object. Its value depends on the geometry of the irradiation chamber, lamp arrangement, reflector design, and materials used. Optimization of these parameters can increase the UF by up to 30 %.

Dose Compliance Factor (DCF) indicates the ratio between the actual received UV dose and the standard dose required for effective microorganism inactivation. A DCF=1 represents full compliance, whereas DCF<1 indicates insufficient exposure, requiring adjustment of the system's operating parameters.

Taking into account the additional coefficients (Figure), the general expression for determining the integral efficiency of photobiological systems can be written as follows:

$$MF_{total} = RFMF \times LSF \times LMF \times RSMF \times SEF \times TCF \times BF \times UF \times DCF$$

This approach enables a more accurate prediction of degradation processes in UV systems, allows timely planning of preventive maintenance, optimizes energy consumption, and ensures stable disinfection efficiency under various operating conditions.

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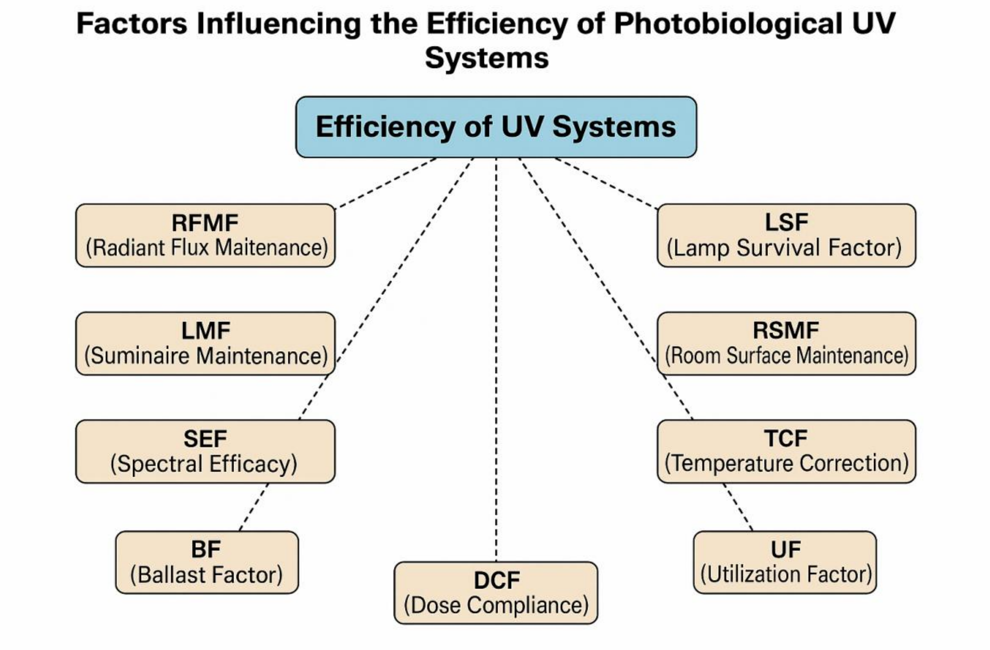

Figure. Factors influencing the efficiency of photobiological UV systems

The diagram illustrates the interrelation between the main coefficients that determine the integral efficiency of ultraviolet disinfection systems: RFMF (Radiant Flux Maintenance Factor), LSF (Lamp Survival Factor), LMF (Luminaire Maintenance Factor), RSMF (Room Surface Maintenance Factor), SEF (Spectral Effectiveness Factor), TCF (Temperature Correction Factor), BF (Ballast Factor), UF (Utilization Factor), and DCF (Dose Compliance Factor).

Based on the obtained results, an analysis of the integral efficiency of the UV system was carried out. Using the data from Table 1, additional coefficients – SEF, TCF, BF, UF, and RSMF – were calculated, and their relative contribution to the overall Maintenance Factor (MF) was determined. All calculations were normalized to 1,000 hours of operation.

According to the analysis, after 6,000 hours of operation, the efficiency of UV systems is most affected by the geometrical parameters and cleanliness of optical surfaces (UF = 17–38 %, LMF = 18–28 %) and lamp aging (RFMF = 20–35 %). The contribution of room surface reflectance (RSMF) accounts for 5–10 %, while spectral effectiveness (SEF), temperature conditions (TCF), and ballast parameters (BF) together constitute about 10 % of total efficiency losses.

The summarized results are as follows:

- for air recirculation systems (TUV15WG13, HNS15G13), the main losses are due to lamp aging and reduced utilization factor (UF);
- for open disinfection systems (TUV36WG13), the dominant losses are geometric (UF ≈ 36 %) and reflector contamination (LMF);
- for systems with sorption materials (ZW20D15Y), there is a balanced influence of UF ≈ 28 %, LMF ≈ 27 %, and RFMF ≈ 23 %;

For seed pre-treatment chambers (ZW20D15W), the geometry (UF ≈ 22 %) improves efficiency, though the primary losses arise from lamp aging (RFMF) and contamination (LMF).

The obtained results confirm that the main strategies for improving the efficiency of photobiological systems include:

- optimizing the geometry of irradiation chambers and reflector design (UF);
- performing regular cleaning of optical components (LMF);
- ensuring timely lamp replacement and monitoring switching cycles (RFMF, LSF);
- maintaining a stable ambient temperature (TCF);
- using reliable ballast devices (BF).

Considering these factors in the calculation of the integral efficiency coefficient allows for more accurate assessment of degradation processes, timely planning of preventive maintenance, and reduction of energy losses in disinfection systems.

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Statistical Analysis

Statistical processing of experimental data was performed to evaluate the variability and reliability of UV system efficiency under different operational conditions. The mean values, standard deviations (SD), and coefficients of variation (CV) were calculated for each group of measurements corresponding to operating times of 1,000–6,000 hours.

The results indicate that the relative deviation of the maintenance factor (MF) values within the sample does not exceed ±7.5 %, confirming the high repeatability of the measurements. The correlation analysis between the radiant flux maintenance factor (RFMF) and the utilization factor (UF) showed a strong positive relationship ($r = 0.86$, $p < 0.05$), indicating that deterioration of lamp emission directly reduces the usable irradiance reaching the treated surface.

A one-way ANOVA test demonstrated statistically significant differences ($p < 0.01$) in MF between systems with medium and high pollution categories. The regression model describing MF as a function of operating time was best fitted by an exponential decay curve, with an average determination coefficient of $R^2 = 0.94$, confirming the adequacy of the model.

The obtained statistical results substantiate the proposed integrated approach and confirm that degradation trends can be reliably predicted using the expanded system of coefficients (RFMF, LSF, LMF, RSMF, SEF, TCF, BF, UF, DCF).

Conclusions

1. A systematic analysis of the efficiency of photobiological electrical systems using ultraviolet radiation for air, surface, and process media disinfection has been conducted. It was established that over time, the irradiance intensity significantly decreases due to the physicochemical aging of lamps, contamination of optical elements, and changes in the reflective properties of the environment.

2. A refined model for evaluating the efficiency of ultraviolet systems has been developed, based on an extended maintenance factor (MF_{total}) that includes both traditional parameters (RFMF, LSF, LMF, RSMF) and additional factors of spectral effectiveness (SEF), temperature stability (TCF), ballast performance (BF), irradiation geometry (UF), and dose compliance (DCF).

3. The calculations showed that after 6,000 hours of operation, the efficiency of UV systems decreases on average to 27–36 % of the initial level. The greatest contribution to efficiency losses is made by the utilization factor (UF, 17–38 %), radiant flux maintenance factor (RFMF, 20–35 %), and luminaire maintenance factor (LMF, 18–28 %). A smaller but stable effect is observed for room surface maintenance factor (RSMF, 5–10 %), temperature correction factor (TCF, 4–5 %), and ballast factor (BF, 1–2 %).

It has been established that increasing the efficiency of photobiological systems is possible through: improving the design of irradiation chambers and reflectors to enhance the utilization factor (UF); performing regular cleaning and maintenance of optical components to reduce losses (LMF); monitoring operating conditions and replacing lamps periodically to maintain performance (RFMF, LSF); ensuring optimal temperature conditions and stable power supply (TCF, BF).

4. The proposed integrated approach allows for quantitative assessment of degradation processes, planning of preventive maintenance, optimization of energy consumption, and maintaining stable disinfection efficiency throughout the entire life cycle of UV systems.

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