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Protection Properties of Woven Fabrics Against High-Intensity UV Radiation Emitted by Artificial Sources

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Abstract
In production processes artificial UV sources are frequently used, which can generate UV radiation within the range from 200 nm to 400 nm. The intensity of UV radiation generated by artificial sources and affecting the body may be hundreds of times larger than natural solar UV radiation. Exposure of the human body to this type of radiation leads to dangerous pathophysiological changes. Typical protective clothing against UV radiation is made of woven fabric where different sizes of clearances make it possible to transmit high intensive UV radiation directly on the human body. In order to analyse UV radiation intensity transmitted by different structures of woven fabric, a stepper motor driven scanner with a UV sensor based on a photodiode was constructed. The scanning resolution was about 0.1 mm × 0.1 mm. As an artificial UV source, a high pressure mercury lamp emitting UV radiation within the range from 210 nm to 400 nm was chosen. Among the woven fabrics tested, which were woven using the same yarn type and weft & warp densities, the most effective UV barriers are plain weave fabrics. A slightly lower value of the coefficient is observed for twill weave fabrics. For satin weave fabrics the attenuation coefficient is the lowest. Distribution images of UV radiation intensity transmitted by the woven fabric samples show irregular areas of different sizes, significantly exceeding the size of individual clearances, which was due to the photosensitive element of the photodiode moving away by 2 - 3 mm from the reverse side of the woven fabric, with the phenomena of UV radiation dispersion passing by the woven fabric clearances.

Key words: *UV artificial source, high-intensity radiation, UV radiation, UV protection, woven fabric.*

Introduction

One of the factors adversely affecting the human organism is ultraviolet radiation (UV radiation). Ultraviolet radiation, sometimes also called ultraviolet light, is invisible electromagnetic radiation of the same nature as visible light, but having shorter wavelengths and higher energies. The wavelength ranges and common names of the UV radiation bands are UV-C: 100 - 280 nm, UV-B: 280 - 315 nm and UV-A: 315 - 400 nm. Two types of UV radiation can be distinguished: natural - which is a component of solar radiation and artificial - generated by electric devices - mainly different kinds of lamps. Of natural radiation, only UVA and about 10% of the UVB rays reach the Earth's surface. UVC rays are totally absorbed by the atmospheric ozone. Artificial sources of UV radiation are used in many different ways in the working environment. The wavelength ranges of artificial sources of UV radiation can be from 100 to 400 nm. In some cases, workers are exposed to some radiation, normally by reflection or scattering from adjacent surfaces. Typical industry processes where high intensity UV radiation is used are curing processes based on photoinitiators, such as curing adhesives, overprints functionalising textiles, sterilization and disinfection, welding, etc.

When the human body, especially skin and eyes are exposed to UV radiation dangerous pathophysiological processes can be observed. They may lead to many dangerous illnesses, which can be divided into five basic groups [1, 2]: genetic and metabolic, photoallergic, cancers, degenerative illnesses intensifyied under the influence of UV radiation, and phototoxic and photoimmunological diseases.

Thus it is necessary to protect the human body against UV radiation in order to prevent these adverse effects. In the case of UV radiation generated by the sun, protection elements have been successfully developed. These are primarily suitable protective creams containing UV filters, goggles with UV filters, and clothing protecting body parts especially exposed to the sun. In the case of flat textiles, UV radiation permeability depends on the structure of fabric and the material of fibres. As far as the structure of fabric is concerned, the following elements are important in the permeability of UV radiation: construction parameters of the product and porosity (e.g. weave, stitch, cover factor, density of threads, linear density of yarns). When it comes to the material of fibre important are: physicochemical structure of the fibre, colour, finishing methods, surface modifications using various chemical compounds and others. The first group of factors influ-

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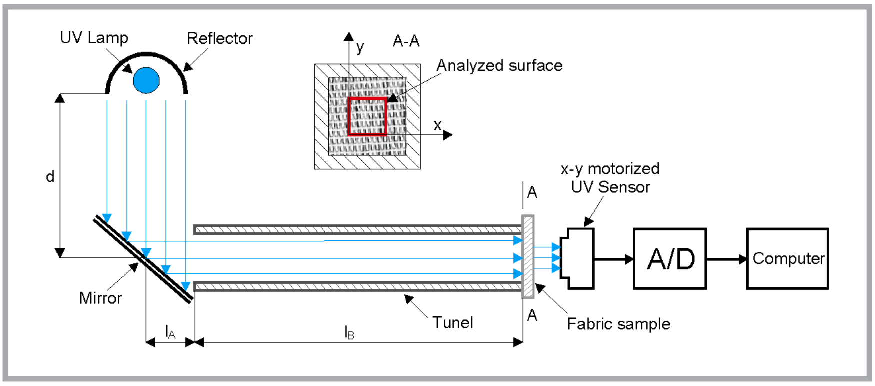


***Figure 1.** Block diagram of the measurement stand.*

ences mainly the transmitted radiation, whereas the second group of factors impacts the absorbed radiation. Modern scientific research concentrated on constructing flat textiles with high UV barrier properties brings new solutions in the area of these elements. However, the research is firmly focused on developing effective textile barriers against natural UV radiation. A broad analysis of various factors affecting the UV barrier properties of textile materials together with an advanced literature study was presented by Saravanan [3].

The influence of the type of weave, porosity, colour and cover of fabrics used for the production of summer clothing on their UV-A and UV-B permeability was analysed by Dubrovsky et al. [4]. It was found out that colour has the greatest impact on the attenuation of UV radiation. The type of weave and fabric cover significantly affect the attenuation of UV radiation in the case of fabrics of bright pastel colors. Studies on the influence of construction parameters of fabric on its permeability to UV radiation were analysed by Dimitrovski et al. [5], in which a mathematical model was worked out for calculating the UPF index (Ultraviolet Protection Factor) of fabric on the basis of its construction parameters. Duleba-Majek analysed UV transmission through fabrics with different weaves by means of 3-D modelling [6, 7]. It was assumed that UV radiation is transmitted only through the fabric clearances and is completely suppressed by the material of the fabric threads. Additionally in the spaces between threads UV radiation is not reflected and absorbed. In the modelling process UV radiation was replaced by visible radiation, which made it possible to carry out basic experiments using the contact print technique. A large dependence was observed between the visible light penetration and the weave of the fabric, as well as in the angle between the beam and fabric surface.

Interesting solutions increasing the UV barrier properties of textiles are connected with modifications of the textile surface. These achievements are largely related to the deposition of ZnO, TiO_2 and ZrO nanoparticles on the surface of textiles [8, 9]. It was found that by surface embedding ZnO nanoparticles, it is possible to obtain UPF values from 30 to 50. Before treatment, UPF values for the fabric were from 8 to 15. The deposition of TiO_2 nanoparticles makes it possible to obtain UPF values of 50+. The deposition technology used in the tests is characterised by very good adhesion of nanoparticles to the textile surface, which allows to obtain good washing resistance The latest ideas concerning obtaining textiles of good UV barrier properties are associated with the use of rare earth elements [10], compounds produced from which allow the absorption of UV radiation energy and transform it into visible light. This transformation made it possible to reduce UV transmittance by more than 80% compared to unmodified fabrics.

In these publications, the barrier properties of textiles were usually considered in relation to natural UV radiation (within the range of 280-400 nm) . Another issue is the influence on the body of UV radiation generated by artificial sources and the development of effective protecting elements. In comparison with natural radiation, the intensity of UV radiation from artificial sources affecting the human body may be up to several hundreds times greater. Additionally, the spectrum of this radiation can have wavelengths from the UV-C range, which are not present in natural solar radiation. Persons operating devices in which artificial UV sources are used require adequate protection against radiation, and therefore a need arises to develop appropriate protective clothing ensuring on the one hand an adequate UV barrier, and on the other adequate comfort level.

Taking these considerations into account, the first objective of this study was to assess the influence of the woven fabric structure on its UV barrier properties during exposure to high-energy UV radiation. It is typical for woven fabrics to have different sizes of clearances which make it possible to transmit dangerous high intensive UV radiation directly on the human body. For this reason, the second objective of this study was to analyse the surface distribution of radiation intensity transmitted by woven fabric in order to detect in the clearances the presence of UV radiation of very high intensity, comparable to that of incident radiation. The results obtained can be taken into account during the designing of protective clothing for workers exposed to high-energy UV radiation.

Methods and materials

Measurement stand

Figure 1 presents a block diagram of a stand for testing the UV barrier properties of fabrics exposed to an artificial high-energy UV radiation source.

A high-pressure lamp of the type HOK 20/100 Philips, emitting ultraviolet radiation, was fixed to a reflector made as an optical concave mirror. The spectral distribution of the lamp used is presented in ***Figure 2***. In the spectral distribution the presence of wavelengths below 280 nm can be seen, which are in the range of UV-C.

The part of light generated by the lamp is reflected by a reflector and falls on the surface of a mirror, which is fixed at an angle of 45° to the reflector. The distance d between the lamp and mirror can be adjusted in the range from 5 cm to 25 cm. Changing this distance makes it possible to adjust the intensity of radiation falling on the sample. The mirror is placed at a distance of l_A = 2 cm from the tunnel. After reflection from the mirror the light propagates through the tunnel of length l_B = 125 cm and then falls on the surface of the test sample. The task of the tunnel, which is made of an aluminum square

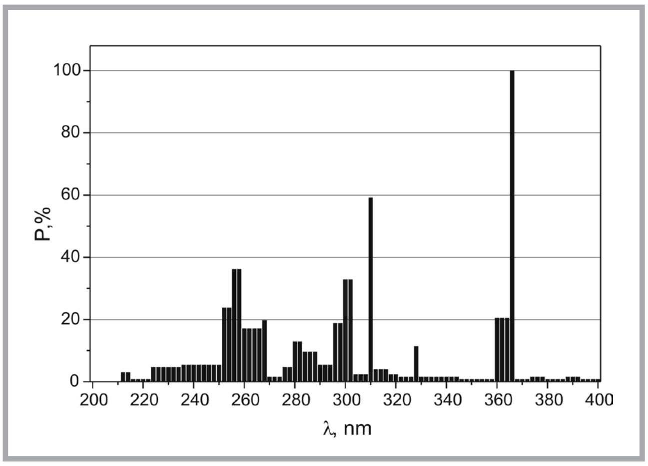


Figure 2. *Spectral distribution of UV radiation generated by high pressure lamp Philips HOK 20/100 [11].*

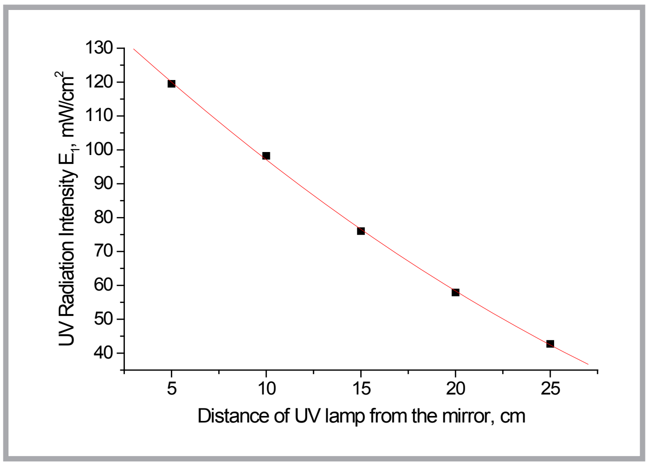


Figure 3. *Influence of the distance between the UV lamp and mirror on the value of the UV radiation intensity.*

section, is to ensure the even distribution of radiation intensity in the sample fixing plane. This is a new solution that has not been used so far in this type of research. The intensity of radiation falling on the sample is denoted as E_1. An UV sensor situated on the other side of the sample measures the intensity of radiation transmitted E_2. A technical description and metrological characteristics of the sensor of UV radiation intensity used in the study are presented in article [12]. The result of measurement of radiation intensity transmitted through the sample is read by a computer system using an analog - digital (A/D) converter. The location of the sensor during the scanning process changes thanks to using two stepper motors (control x-y) controlled by signals u_x and u_y, where u_x is the control signal of the UV sensor location in relation to axis x, and u_y - is the control signal of the UV sensor's position in relation to the y axis. It means the sensor moves step by step by Δx in relation to the x axis, and by Δy in relation to the y axis. During testing, the sample is compressed between two frames and fixed at the end of the tunnel. The sensor scans the sample surface of 10 × 10 mm with a pitch of $\Delta x = 0.09375$ mm horizontally and $\Delta y = 0.125$ mm vertically, and in every discrete position measures the radiation intensity E_2.

Table 1. *Results of measurements of the radiation intensity falling on the sample surface.*

Distance d, cm	Mean value of E_1, mW/cm^2	Std dev of E_1, mW/cm^2	Min value of E_1, mW/cm^2	Max value of E_1, mW/cm^2
5	119.5	3.15	109.6	128.1
10	98.3	3.07	89.7	106.7
15	76.0	2.89	68.3	84.0
20	57.9	2.78	49.8	65.5
25	42.7	2.67	35.6	49.8

While testing barrier properties it is essential that the intensity of E_1 falling on the sample surface of 10 × 10 mm analyzed remains stable. For this purpose, the intensity of incident radiation in the plane of fabric fixing was tested on a surface of 10 × 10 mm. The distance from the UV lamp to the mirror was changed in the range from 5 cm to 25 cm. The measurement results are presented in ***Table 1***.

Analysing the tests results presented in ***Table 1***, it can be stated that the value of radiation intensity E_1 increases when the distance d decreases. The average value of incident intensity E_1 is in the range 42.7 - 119.5 mW/cm^2, depending on the distance d. In comparison with natural intensity, the average radiation intensity of the artificial source obtained was even about twenty times greater. It was concluded that the stand constructed for testing barrier properties ensures the adequate stability of the intensity of radiation falling on the fabric tested. The standard deviation equals approximately 3 mW/cm^2. The minimum and maximum values are remote from the average by about 10 mW/cm^2, and they decrease with increasing distance d. For the purpose of programming radiation intensity falling on the sample on the basis of the research results obtained and approximation with a second degree polynomial, the functional relationship between the intensity E_1 and distance d was determined:

$$E_1(d) = 0.0464\, d^2 - 5.269\, d + 145.1 \quad (1)$$

The results of measurements of the average UV radiation intensity E_1 falling on the surface of the sample tested as a function of distance d between the lamp and mirror and the course of the approximation function are shown in ***Figure 3***.

UV Protection Coefficient

A negative logarithm of permeability coefficient $\boldsymbol{T}$ in the form:

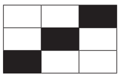
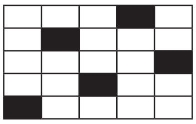
$$\eta = \log\left(\frac{1}{T}\right), \quad (2)$$

was adopted as the coefficient of UV barrier properties of the fabrics. T is the ratio of the intensity of radiation E_2 after passing through the sample to its initial intensity, denoted as E_1. Hence we have:

$$\eta = \log\left(\frac{1}{\frac{E_2}{E_1}}\right) = \log\left(\frac{E_1}{E_2}\right) \quad (3)$$

This coefficient can be compared to the barrier coefficient OD (optical density) defined for optical materials. The greater the value of coefficient η, the better the UV barrier properties of the shield. Attenuation coefficients SPF and UPF, which commonly appear in studies of UV barrier properties of textile materials, were not applied in the research on the barrier properties of fabrics. The reason was that they refer only to wavelengths in the range between 290 and 400 nm, resulting from the spectrum of solar radiation. The aim of this study was, however, the examination of the UV barrier properties of fabrics under the influence of artificial radiation containing all three ranges: UV - A, UV - B, UV - C. In the methodology of testing the UV barrier properties of fabrics adopted, the value calculated by increasing the number 10 to the power η stands for the multiplicity of the reduction in UV radiation intensity transmitted through the fabric tested.

Table 2. *Types of weaves in the fabrics tested.*

Woven fabric parameters	Type of weave		
	Plain	Twill	Sateen
Graphic notation			
Symbolic notation	1/1	1/2	1/4
Weft density, theads/cm	10, 15, 20, 25	15, 20, 25, 30	15, 20, 25, 30

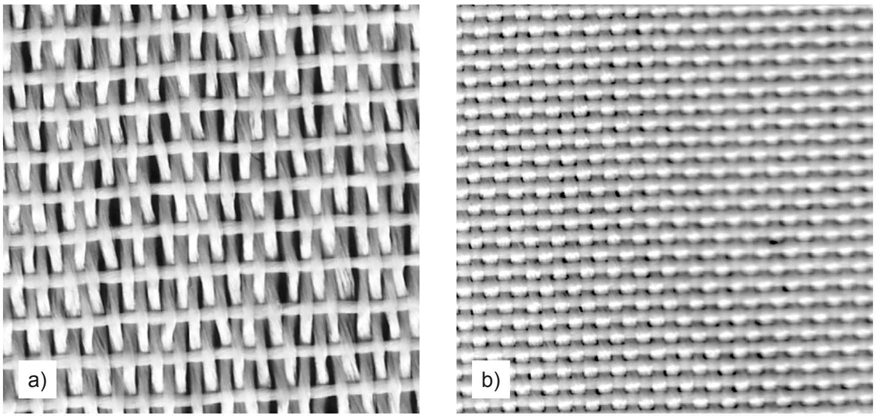


Figure 4. *Plain weave fabrics with different weft densities; a) l_W = 10 threads/cm, b) l_W = 25 threads/cm.*

Woven fabric construction parameters

UV barrier properties during exposure to a high-energy light source were analysed for fabrics made of polyester yarn Torlen TWY 220/48 S300. For this yarn the linear mass is equal to 220 dtex, the number of filaments 48, and the number of twists per meter 300. It was assumed that all the fabric samples tested possess a constant density of warp threads but differ in the density of weft threads and weave type. To that end, all the fabrics were made of a single warp, with a density of 32 threads/cm, installed on a Picanol Luna loom. The weft density was changed from 10, 15, 20, 25 to 30 threads/cm. ***Table 2*** shows the types of weaves that were tested. The focus was primarily on the analysis of fabrics made of basic weaves, as they are commonly used for manufacturing protective clothing.

Figure 4 shows two images of the plain weave fabrics of different weft densities tested.

From the images presented in ***Figure 4***, it can be observed that in fabrics with low weft densities clearances appear, and UV radiation can penetrate through them without any attenuation. Therefore it is highly possible that an object protected by a barrier made of such a fabric would be penetrated by UV radiation of unchanged spectrum and very high intensity. Increasing the weft density decreases the area of clearances.

Results and discussion

Influence of woven fabric weave type on coefficient η

In the first stage, the influence of the weave type of the fabric on its UV barrier properties was analysed while maintaining the same weft and warp density. Studies were carried out for different intensity values of incident UV radiation. During the tests coefficient η was determined for various distances between the lamp and mirror in the range from 5 to 25 cm. We analysed plain, twill and satin weave fabrics of the same weft density, equal to l_W = 25 threads/cm.

Figure 5 shows the dependence of attenuation coefficient η on the intensity of incident radiation for the plain, twill and satin weave fabrics Tested. The test results were approximated with a function in the form of a second degree polynomial. On the basis of the t-Student test, the significance of the parameters of the approximation function was proven.

Analyzing the charts presented in ***Figure 5***, it can be concluded that the highest attenuation coefficient η can be observed in the case of plain weave fabrics. A slightly lower value of this coefficient can be observed for twill weave fabrics. For satin weave fabric the attenuation coefficient is the lowest. These results indicate that in textile products protecting against extreme UV radiation the best solution is to use plain weave fabrics. Analysis of the charts also indicates that the attenuation coefficient is not constant in the function of incident UV radiation intensity and varies more or less by about 0.1 for the range of UV radiation intensity used. With an increase in the intensity of incident radiation, the value of the attenuation coefficient also increases, which is probably related to the absorbing of UV radiation by threads, but it should be verified by additional experiments and considerations.

Influence of woven fabric weft density on coefficient η

The next research stage focused on analysing the influence of the weft density on barrier properties of fabrics made in different weaves, but with the same warp density. The distance from the lamp to the mirror was constant and equaled d = 15 cm, meaning that each time during the test the intensity of incident radiation was constant and the average value of this intensity was equal to E_I = 76.0 mW/cm^2. In ***Figure 6*** the distribution of UV radiation intensity incident on the surface of the woven fabric tested is presented. It is clearly seen that the UV radiation intensity is not constant and varies from 70 to 80 mW/m^2. Additionally in relation to the x-axis, the UV radiation intensity changes periodically and characteristic lines on the surface of the graph are visible, caused by multiple reflections of UV light between the top and bottom wall of the tunnel.

Figure 7 shows the dependence of attenuation coefficient η on weft density for the plain, twill and satin weave fabrics tested. The results of coefficient η for an

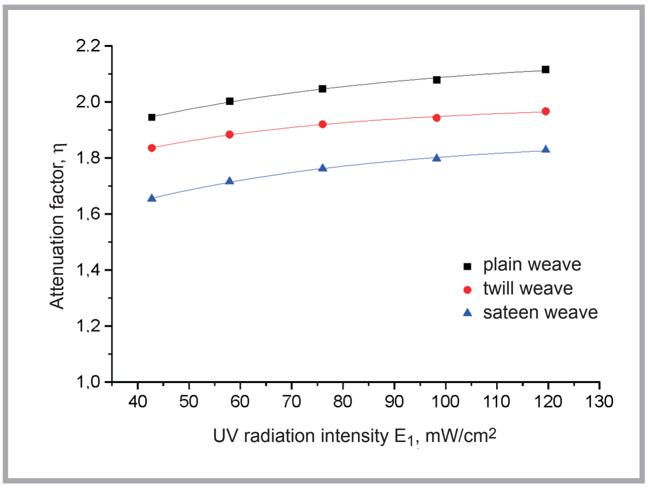


Figure 5. *Dependence of the intensity of incident radiation on the attenuation coefficient η for the weaves tested.*

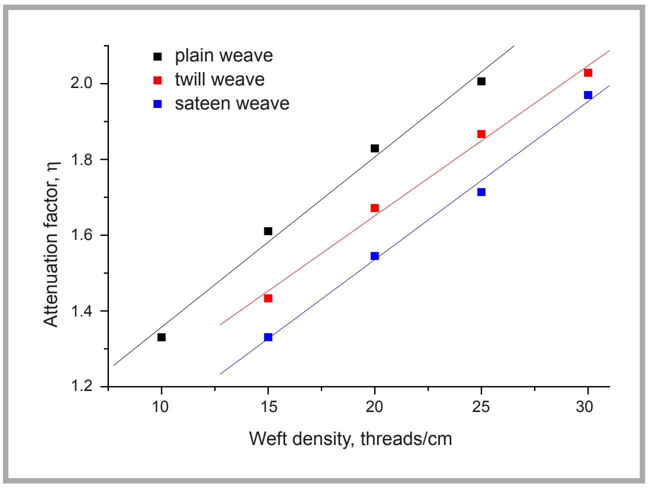


Figure 7. *Dependence of attenuation coefficient η on weft density for the weaves tested.*

assumed value of weft density were calculated as an average value of data obtained during scanning. In the next step the results calculated were approximated with linear functions. For the approximation functions received, tests of the significance of the coefficients of the approximation function were carried out on the basis of the t-Student test. For all the approximation functions the importance of these parameters was demonstrated.

The graph shows that for every fabric the dependence of the attenuation coefficient on weft density is practically linear. For a given weft density, the most effective as UV barriers are plain weave fabrics, and the least effective - satin weave fabrics. It is possible to get the same barrier properties for all weave types by changing the weft density. Therefore, for example, in order to obtain a fabric with an attenuation coefficient of 2, one has to produce a plain weave fabric with a weft density of around 25, a twill weave fabric with a weft density of around 28 or a satin weave fabric with a weft density of around 33.

Figure 8 presents the intensity distribution of radiation E_2 transmitted through the plain weave fabric tested, for weft density l_W = 15 threads/cm and l_W = 25 threads/cm. In the case of fabrics with weft density l_W= 15 threads/cm, the intensity of radiation transmitted is greater than in the case of fabrics with weft density l_W = 25 threads/cm, which is obvious because a lower weft density causes that the area of clearances are larger and the UV radiation is transmitted by the clearances with higher intensity. In the case of fabrics with larger weft densities, the distribution of UV radiation intensity is more uniform, which is due to the minimisation of clearances because of the high density of weft threads.

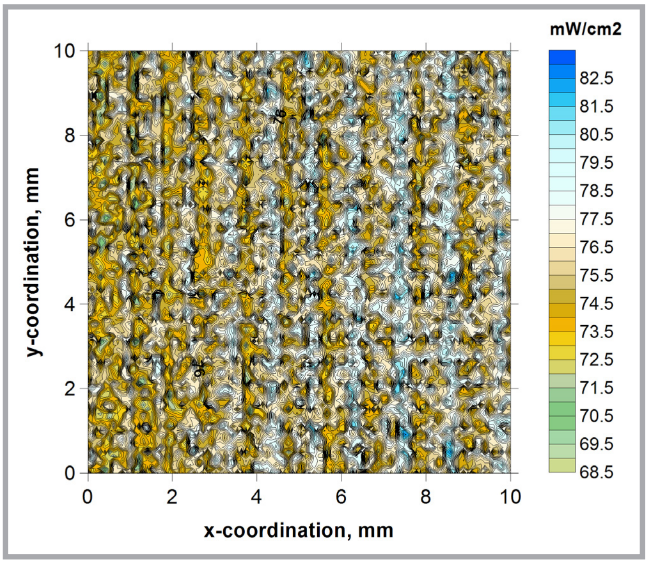


Figure 6. *Distribution of UV radiation intensity incident on the surface of the woven fabric tested.*

Figure 9 shows the intensity distribution of radiation E_2 transmitted through the twill weave fabric with weft density l_W= 15 threads/cm & l_W= 25 threads/cm tested. Just like in the case of plain weave fabrics, the intensity of radiation transmitted is greater for a fabric of smaller weft density. In fabrics of larger weft densities the areas of increased radiation intensity can also be observed, despite the greater density of weft threads in comparison to plain weave fabrics.

Figure 10 presents intensity distribution of radiation E_2 transmitted through the satin weave fabric with weft density l_W= 15 threads/cm and l_W= 25 threads/cm tested. Similar to plain and twill weave fabrics, the intensity of radiation transmitted is greater for a fabric of lower weft density. In fabrics of higher density, areas of increased radiation intensity are also observed.

Taking into account the distributions of UV radiation intensity presented in ***Figures 8 - 10***, it was not precisely confirmed using the scanning system that the incident high intensity UV radiation is transmitted by clearances without attenuation. The possible reason is that the photosensitive element of the scanning photodiode is moved away from the reverse side of the woven fabric by 2 - 3 mm because of quartz glass used in front of the photosensitive element of the photodiode for full attenuation of visible radiation. UV radiation which passes by the clearance is dispersed over a large area, whose value depends on the distance from the clearance. Hence, in practice,

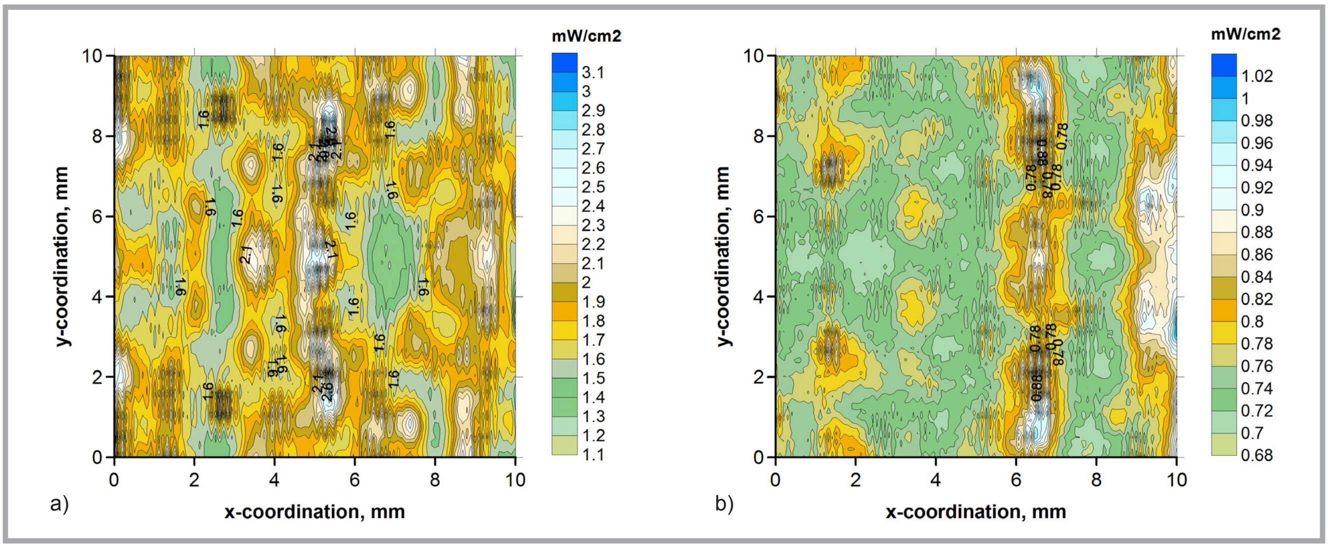


Figure 8. *Distribution of UV radiation intensity* E_2 *transmitted through the plain weave fabrictested, for weft density: a)* l_W *= 15 threads/cm and b)* l_W *= 25 threads/cm.*

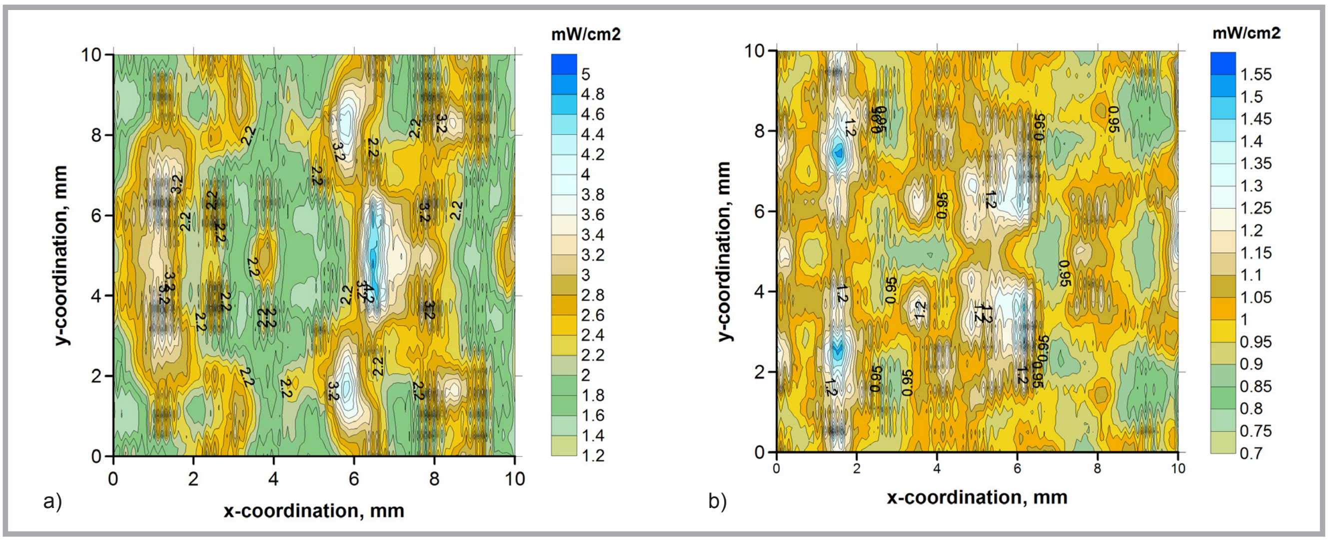


Figure 9. *Distribution of UV radiation intensity* E_2 *transmitted through the twill weave fabrictested, for weft density: a)* l_W *= 15 threads/cm and b)* l_W *= 25 threads/cm.*

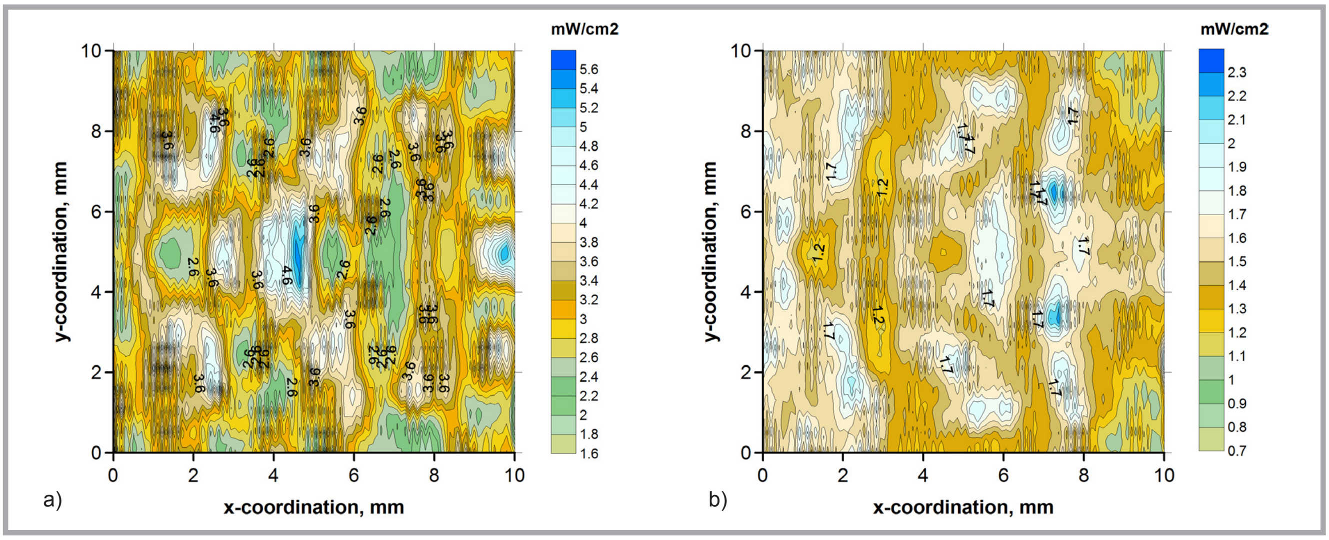


Figure 10. *Distribution of UV radiation intensity* E_2 *transmitted through the satin weave fabric tested, for weft density: a)* l_W *= 15 threads/cm and b)* l_W *= 25 threads/cm.*

UV radiation intensity is not analysed by the photodiode in the reverse side plane of the woven fabric, but in that which is 2 - 3 mm moved away. It is clearly seen in ***Figures 8, 9*** and ***10*** that the areas where UV radiation intensity is increased have a diameter of 0.5 - 3 mm, in dependence on the weave type and weft density. The real dimensions of clearances for the woven fabric tested were more or less 0.15 mm in the weft direction and 0.5 mm in the warp for a weft density equal to 15 threats/cm and 0.3 mm in the warp direction for a weft density equal to 25 threats/cm, which is the reason that the distribution of UV radiation intensity presented in ***Figures 8 - 10*** does not disclose the geometric structure of the woven fabric. It can be seen in ***Figures 8 - 10*** that the areas where UV radiation intensity is increased are irregular. It is an obvious fact that the sample of fabric tested (1cm x 1cm) is not a perfectly regular arrangement of warp and weft threads (see ***Figure 4***).

The distribution of intensity of UV radiation transmitted through the structure of the woven fabric sample does not indicate values comparable with the intensity of the incident radiation, nevertheless the existence of clearances at lower density of the weft threads. This is caused by the position of the sensor measuring the transmitted radiation positioned at a distance of 2 - 3 mm from the surface of the woven fabric tested. The UV radiation passing through a clearance is dispersed and its intensity decreases exponentially with the distance. However, it can be assumed that the radiation intensity behind a clearance at real fabric surface may reach intensity values comparable with those of incident radiation. In order to obtain not disturbed determination of the intensity distribution at the back plane of the woven fabric, the measuring mode of the transmitted radiation should be changed.

Considering the results received, plain weave structures should be used in order to obtain fabrics of high barrier properties protecting from high-energy sources of artificial UV radiation. The weft density of the fabric should be as large as possible. However, the comfort of the user should also be taken into account – clothing should ensure a proper microclimate in the layers which are close to the skin.

Conclusions

The research conducted allows to formulate the following conclusions:

- The construction of the testing stand proposed makes it possible to receive a relatively uniform level of UV radiation falling on the sample. By changing the distance between the lamp and mirror reflecting the radiation, it is possible to adjust the intensity of incident radiation.
- Taking into account the UV barrier properties of fabrics denoted by the attenuation coefficient η proposed, the dependence of the attenuation coefficient on the weft density is linear. Among the fabrics of given weft density tested , the most effective UV barriers are plain weave fabrics. A slightly lower value of the coefficient is observed for twill weave fabrics. For satin weave fabrics the attenuation coefficient is the lowest. These results indicate that plain weave fabrics should be used in textile products designed for protection against extreme UV radiation.
- The attenuation coefficient of the fabrics tested is not constant in the function of incident radiation. Its growth is observed together with the increasing intensity of incident radiation, which is probably related to the absorbing of UV radiation by threads, but it should be verified by additional experiments and considerations.
- The images of UV radiation intensity transmitted by the woven fabric samples show irregular areas of different sizes (1 - 4 mm^2), significantly exceeding the size of individual clearances. A possible reason is that the photosensitive element of the scanning photodiode is moved away from the reverse side of the woven fabric by 2 - 3 mm because of the quartz glass used in front of the photosensitive element of the photodiode for ful attenuation of visible radiation. The UV radiation which passes by the clearance is dispersed over a large area, whose value depends on the distance from the clearance. Hence, in practice, the UV radiation intensity is not analysed by the photodiode in the reverse side plane of the woven fabric but in that which is 2 - 3 mm moved away. It is a challenge to find a photo sensor which will allow to scan transmitted UV radiation intensity precisely in the reverse side plane of a woven fabric.

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