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Transmission of UV Radiation through Woven Fabrics in Dependence on the Inter-Thread Spaces

Abstract

A method of designing woven fabrics is presented from the point of view of protecting humans against UV radiation transmitted by fabric and the shape of inter-thread channels determined by the fabric structure. The method consists of two stages: firstly, the inter-thread channels of basic woven structure modules are analysed, and next the fabric structure is synthesised by appropriate composition of the particular structures. A characteristic feature of this method is taking into account the angle of irradiation of the woven fabric.

Key words: *UV radiation, transmission, woven fabrics, fabric structure, structure modules, modelling, designing.*

Introduction

Ultraviolet (UV) radiation - the invisible part of radiation emitted by the sun - is electromagnetic radiation within the wavelength of 10 nm to 400 nm [1 - 3]. The following sub-ranges are commonly differentiated [4 - 6]:

1. Technical radiation divided into:
   - far UV radiation, with a wavelength of 10 - 200 nm
   - near UV radiation, with a wave length of 200 - 400 nm.
2. General range, from the point of view of the impact on human skin, is divided into:
   - UVP – 'vacuum radiation' of 10 - 200 nm, partially absorbed by N_2O, N_2 and O_2, molecules. In normal conditions it should not reach the Earth's surface, but due to increasing ozone depletion, the Earth is irradiated by waves starting from 80 nm, whose radiation is the most dangerous for the health and life of human beings.
   - UVC – 'short radiation', also known as 'hard radiation', of 200 - 280 nm is characterised by strong bactericidal and sporecidal effects, as well as by the fact that it causes erytema, among others.
   - UVB – 'middle length radiation' of 280 - 320 nm causes a skin pigmentation effect and erytema, as well as the creation of free radicals. On the other hand, waves of this UV subrange are used in therapy due to the creation of vitamin D. All these sub-ranges of UV radiation mentioned above may have a cancerogenous effect.
   - UVA – 'long-wave' radiation of 320 - 400 nm concerns photo-chemical and pigmentation processes with an insignificant erytema effect.

During the UV irradiation of human skin, the majority of energy absorbed is transformed into heat. The erytemal sensitivity, for humans the only parameter which allows to evaluate the efficiency of biological interaction, does not mirror the whole pathogenic influence of UV radiation; it is only a measure of skin burns. From the point of view of the most dangerous potential effects, as a cause of cancer and a decrease in immunology resistance, this parameter is not appropriate. Therefore the barrier properties before UV radiation are a modern feature of products which creates the need for product improvement and the determination of protection standards [7].

Taking into account these considerations, it is clear that textile protection of human skin against UV radiation is a very important problem, and over recent years researchers have shown increasing interest in this area. The requirements concerning the particular features of textile woven and knitted fabrics in dependence on the kind of usage, use conditions and the product structure have been widely discussed.

The energy of UV radiation received by a textile can be divided into the following three components: the energy reflected, absorbed and transmitted by the textile product; the latter irradiates the human organism directly.

These particular components are formed by the physical and chemical parameters of the product matter, which means the features of fibres and the kinds of colour [8 - 10], as well as by structural parameters, such as fabric thickness, fabric structure, and porosity, among others.

Kind of fibres used for manufacturing the fabrics and their barrier properties

Fibres influence the barrier properties of fabrics by the kind of fibre matrix, their porosity as well as the geometrical form and dimension of the fibres. The fibre matrix, especially its chemical structure, the presence of cumulated associated double bonds, among others, have the greatest impact on the barrier properties. In each group of fibres, natural ones as well as those man–made, manufactured from natural and synthetic polymers, can be distinguished by those fibres which have better or worse properties of UV radiation transmission. The barrier properties of synthetic fibres, such as polyester or polyamide, are commonly improved by the addition of ceramic nano-additives in the majority of SiO_2 [11 - 14]. From natural fibres, hemp and flax are known for their good barrier properties against UV radiation. The fibre diameter and fibre localisation in the yarn also have an influence on the barrier properties that change the fabric structure [8]. Commonly, the smaller the fibre diameter, the better the protection properties are, which is due to the decrease in the inter-fibre and inter-yarn distances. This dependence was also confirmed by [15, 16].

Colours of the woven fabric and its barrier properties.

Vital dependencies were noted between the colour of the woven fabric, that of the warp and weft threads, and the kind of dyestuff used with respect to the absorption of UV radiation. Generally, reactive and pigment dyes increase the absorption, as well as dark colours, such as black and blue [10, 17 - 19].

Dependence of radiation transmission on the permeability of fabrics.

It was observed that dependencies exist between the air permeability and radiation transmission, including light transmission. This results from the fact that both quantities depend on the structure of the textile product, especially the inter-thread distances. This feature is caused by the weave phase of the woven fabric, the twist, thickness and hairiness of the thread, as well as by the cover factor of the woven fabric. The air permeability and UV transmission are often considered from the same point of view regarding the use properties of the fabric. Recently, it was noticed that good barrier properties against radiation can be found in fabrics constructed from polyester microfibres, but unfortunately its air permeability is small. On the other hand, a large twist coefficient at a great pitch of the threads leads to an increase in the inter-thread channels in the woven fabric, resulting in the air permeability and UV transmission also rising. The barrier properties of a fabric with respect to its structure can be also considered from the point of view of its porosity. In [20] was indicated that the thread crossings form channels which can be considered as pores. Many works, including those carried out at the Textile Research Institute in Łódź, confirm the importance of porosity for permeability and UV transmission.

Several researchers analysed the problem of protection against UV transmission taking into account more general aspects, considering different structure parameters of the fabric, as well as its colour and the dyes used [10, 19].

Aim of the investigation

The above mentioned research works considered the relations between fabric structure and UV radiation transmission in general, but no one analysed woven fabric porosity as a geometrical structure composed of differentiated modules. The aim of this paper is to present a research work devoted to designing woven fabric of an assumed UV radiation transmission taking into account the shapes and dimensions of inter-thread channels, beginning with an analysis of woven fabric modules and finally considering the synthesizes of complex structures from simpler construction units. Following the assumptions of this work, the following conclusions were made: the fabric matrix is non transparent to UV radiation, UV radiation propagates in direct lines, without diffraction, is not reflected from the surface of the channels and not absorbed by the matrix of the threads comprising the channel walls. Considering these assumptions, the analysis of UV radiation can be substituted by analysing visible light transmission, which can be performed virtually.

Analysis of the structural modules of a woven fabric

The modules of the inter-thread channels of a woven fabric were firstly identified and classified from the point of view of its shapes by Szosland [21 - 25]. In one-layer fabrics of basic weave without a pile, their derivatives and modifications, as well as the composition of each structural module are composed of two pairs of neighboring warp and weft threads.

Szosland indicated that the shape of spaces between the threads of one layer woven fabric primarily depends on the weave. In each weave we can distinguish repeatable structural element characteristics of the weave. Szosland distinguished four different inter-thread spaces called channels or ducts, which are shown in ***Figure1***.

Analysing the transmission of UV radiation through a woven fabric, two kinds of transmission can be distinguished – the transmission through the thread matter and that through the inter-thread channels. In this work only the second kind of transmission was considered while analysing virtual woven fabrics and experimentally checking the transmission using visible light radiation. Irrespective of the assumption that there is a lack of diffraction and reflection from the channel's walls, further assumptions were accepted, such as that the threads have circular cross-sections of equal diameter d, and that the threads are arranged with a pitch equal to two thread diameters (A=2d). Taking into account the above mentioned assumptions, the transmission of each kind of module is the same when the woven fabric surface is irradiated vertically. If the fabric is not irradiated vertically but at a given angle, the transmission of the modules is different.

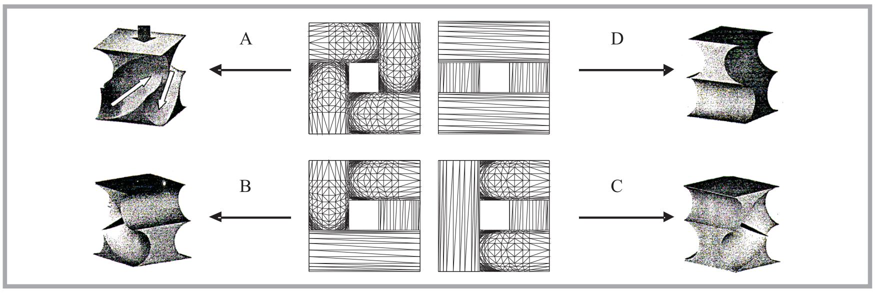

Figure 1. *Four basic cases of structural elements – vertical projections of the threads and perspective views [22 - 25].*

The author proposes to design woven fabrics in two stages: the first consisting in an analysis of the particular modules, determining the inter-thread channels, and the second where the whole structure of the final fabric is synthesised by superpositioning different selected structural elements.

Investigations of radiation transmissions were carried out for virtual woven fabrics by virtual askew irradiation of the fabric. The intensity of the radiation transmitted askew by the fabric was evaluated. In this method the light source and recording camera are not movable. The fabric image was recorded in 17 steps, each step being 12 degrees from 0° to 180°, and for an angle of 90°. This allows to relate the radiation transmission to a particular angle of irradiating the fabric positioned on a human body.

First stage – analysis of the structural modules

Four basic structural modules related to the particular weaves were analysed taking into account the assumptions mentioned before (d = constant, A = 2d). An analysis indicated the need to consider the neighborhood modules. Irrespectively, the angular boundaries of the irradiation range for evaluating the radiation transmission of the particular modules were determined. Further investigation was carried out concerning the variability of the woven fabric parameters (thread diameter, pitch and structural phase). Two planes of accepted movement of the light source were preferred – parallel to the di-

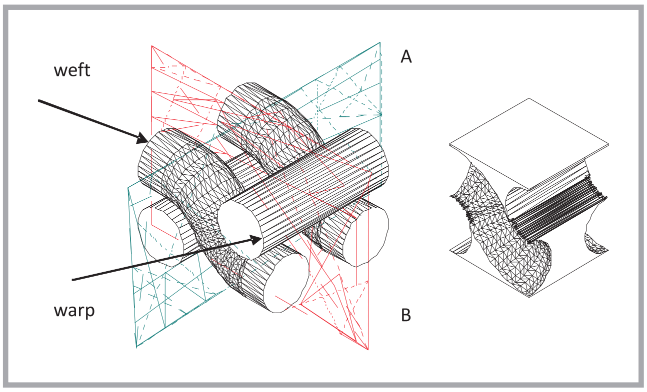

Figure 2. *Planes of testing the radiation transmission at a selected angle for the structural modules, a) Perspective view, b) inter-thread channels [1]; A - Plane of angular displacement of the light source parallel to the warp threads, B - Plane of angular displacement of the light source parallel to the weft threads.*

rections of both thread systems, the warp and weft systems (planes 1 and 2 in ***Figure 2***), due to the possibility of directly influencing the changes in channel shape by altering the pitch and structural phase, as well as the formation or elimination of thread inflexion and the addition of new thread.

The planes were selected on the basis of a summarised round angle measurement range which allows for a continuous characteristic of the module (***Figure 3***).

The results of tests carried out are described by the indications presented below. Module A is characterised by the smallest light transmission in both planes (warp and weft), but it can not assure maximum covering due to its characteristic structure. Module B is characterised by the highest light transmission in both planes. Module C differs from the others in its significantly differentiated light transmission, which means that it is characterised by asymmetry and has greater light transmission for angles other than 90°, as is visible in ***Figure 3*** (which up to the present has not been taken into consideration in the majority of cases). It also allows to obtain maximum covering in one thread system, due to inflected sliding down in the system. The above mentioned features make this module attractive from the point of view of the radiation transmission and structure of the fabric. Module D enables a maximum covering of the fabric at large thread settings, at the same time creating a strong barrier against radiation. Modules A, B and D are characterised by angle symmetry in both planes, and for a single layer fabric_the light transmission is equal for the morphological form of 'right' and 'left' modules. In these modules the threads are not covered by the neighboring threads. Module C, tested by the light source in the plane parallel to the warp threads, is characterised by light transmission which is independent of the neighboring modules, but when tested in the direction parallel to the weft, it depends on the modules by which it is surrounded. The results of investigation of the influence of the thread diameter, pitch and structure phase of the fabric enable to state that it is possible to design barrier woven fabrics that protect against UV radiation using simple technological means.

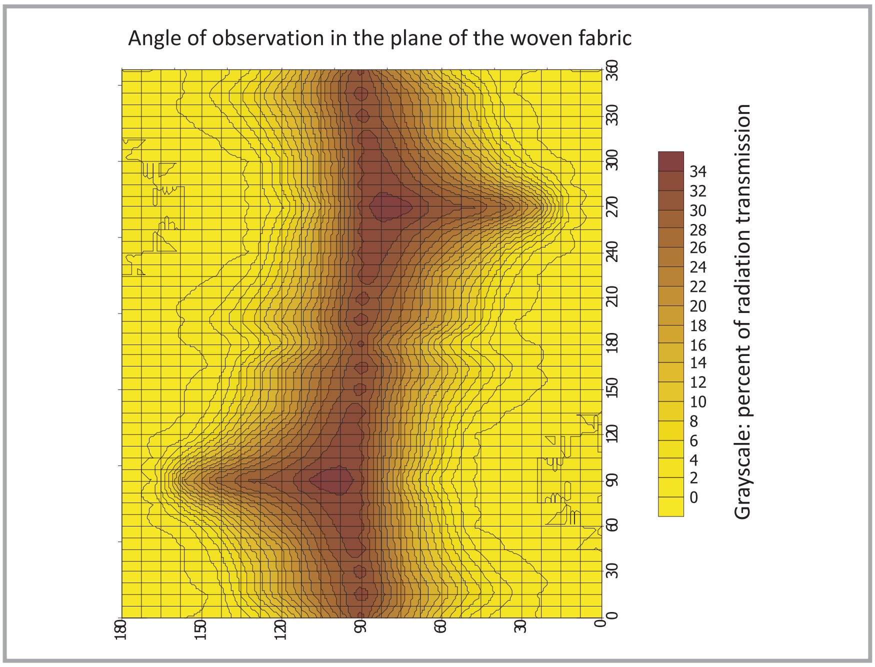

Figure 3. *Graphical characteristic of radiation transmissions of module C by round angle testing [1].*

Second phase – designing the woven fabric weave and evaluating its radiation transmission

On the basis of the analysis of the structural modules, it is possible to design woven fabric of desired properties from the point of view of minimum radiation transmission. Module D was selected as the module which enables the possibility of obtaining the smallest radiation transmission thanks to the choice of minimal pitch in both thread systems. But on the other hand, it should be considered that an increase in the number of modules per unit area worsens the use properties of the woven fabric due to the long interlacement in both thread systems. It is also important to state that only from modules of this kind, can a weave not be constructed, as module D do not enable the formation of interlayced segments in both thread systems, and it should be completed by additional interlacement, called connectors. While designing the interlacements, such modules should be chosen that would best fulfill the criteria of the analysis carried out before. Modules C and A are the next modules which fulfill the requirements established above and the construction possibilities from the point of view of the radiation barrier properties of the fabrics designed. It should be taken into account that with module C it is possible to obtain the same small light transmission as with module D, due to the reduction in the pitches, whereas using module A as a connector is characterised by the smallest light transmission in both planes.

The effect of such a compositions is the woven fabrics of panama weave shown in ***Figure 4*** (see page 46) and those of weft-rep weave presented in ***Figure 5*** (see page 46). Both these weaves are derivatives of basic plane weave.

Table 1 (see page 46) presents the numerical values of virtual light transmis-

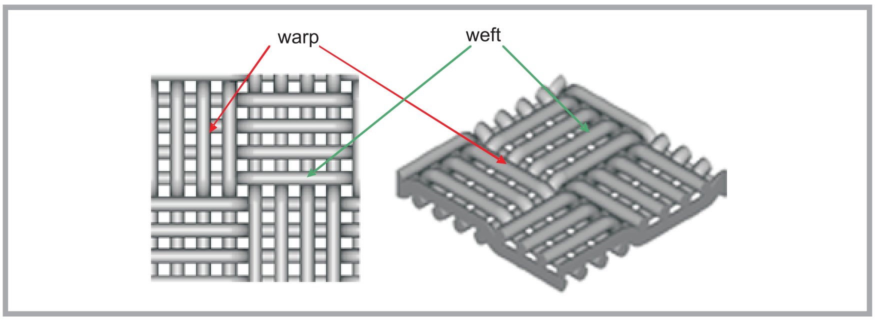

Figure 4. *Perpendicular projection (a) and perspective (b) view of the panama weave.*

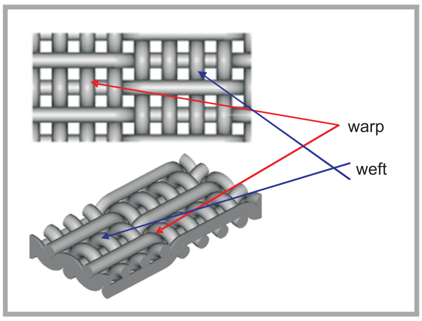

Figure 5. *Perpendicular projection (a) and perspective view (b) of the weft-rep weave.*

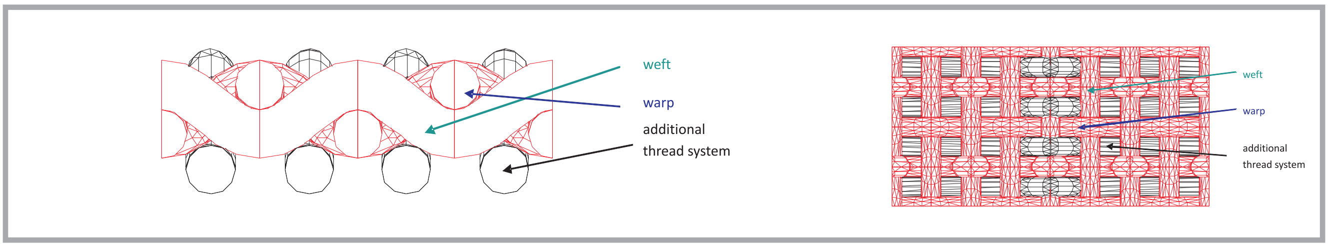

Figure 6. *View of the cross-section (a) and perpendicular projection (b) of a woven fabric of plain weave and a system with an additional layer of threads in the weft direction.*

sion as a function of the irradiation angle for woven fabrics of panama and weft-rep weaves. The values for the weft-rep weave woven fabric were averaged taking into account the values in warp and weft direction which were different.

The considerations above indicate the possibility of designing woven fabrics with an assumed radiation transmission. However, in order to increase the barrier properties, it may often be necessary to enlarge the range of structures beyond the four basic modules with equal thread diameters and pitch of 2d.

Figure 6 presents a design solution for a woven fabric with an over-layered system, i.e. within an additional thread system of one of the basic warp and weft systems with a displacement to the thread system, in order to decrease the radiation transmission by decreasing the inter-thread channels. By transforming the basic modules into a multi-plane structure, it increases the number of modules which can be used in fabric desig. In the case presented, module A was chosen for the module modification, as module A is characterised by the smallest light transmission considering the simetric modules. As only plain weaves can be designed from module A, an additional thread system was incorporated with a displacement equal to half the value of the original pitch, which is the same as the thread diameter, in order to increase the radiation barrier properties. The light transmission values obtained are presented in ***Table 2***. The values of light transmission for a woven fabric of twill weave are also listed in the table for comparison.

From ***Table 2*** it is clearly visible that the woven fabric with an additional layer of threads has a significantly lower light transmission in % for particular irradiation angles than the woven fabric of twill weave.

On the basis of virtual light transmission, the transmission characteristic in dependence on the irradiation angle were determined for a set of different structure modules, which are graphically presented in ***Figure 7***. All woven fabrics of singular weave are characterised by a transmission near zero for a flat irradiation angle (near 0° and 180°), whereas and the highest light transmission occurs in the neighborhood of 90°, which means for irradiation perpendicular to the woven fabric surface. On the other

Table 1. *Radiation transmission in per cent as a function of the irradiation angle for panama and weft-rep fabrics, as schematically presented in **Figures 4** and **5**.*

Light irradiation angle, deg	Light transmission for, %			
	Panama weave (Figure 4)		Weft rep weave (Figure 5)	
	Threads arranged with a pitch equal to 2d	Threads arranged with minimum pitch	Threads arranged with a pitch equal to 2d	Threads arranged with minimum pitch
0	0.000	0.000	0.000	0.000
12	0..000	0.000	0.000	0.000
24	0.000	0.299	0.000	0.000
36	1.268	0.577	0.742	0.000
48	5.684	1.654	4.413	0.261
60	11.267	2.897	8.622	1.518
72	19.258	3.324	15.562	2.368
84	26.354	4.448	24.129	3.312
90	33.333	6.525	33.333	5.168
96	26.548	4.422	24.075	3.223
108	19.574	3.278	14.985	2.317
120	11.006	2.83	8.785	1.535
132	5.016	1.557	3.065	0.237
144	1.365	0.129	1.745	0.000
156	0.000	0.000	0.000	0.000
168	0.000	0.000	0.000	0.000
180	0.000	0.000	0.000	0.000

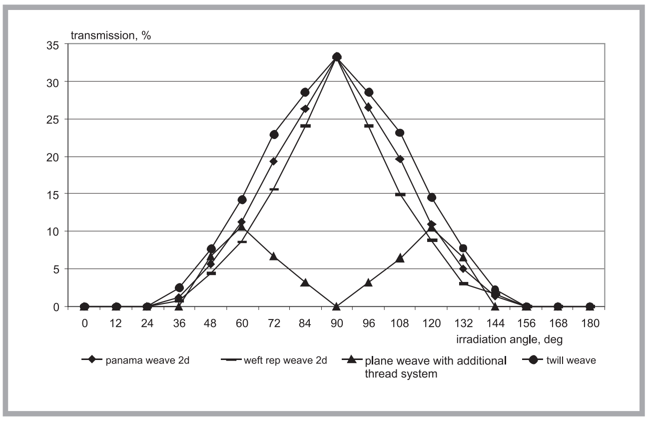

***Figure 7.** Light transmission characteristic in dependence on the irradiation angle within the range of 0° to 180° for selected textile structures (also presented in Tables 1 & 2) virtually obtained.*

hand, a woven fabric with an additional system of threads has a quite different dependence with two smaller maxima and a minimum of transmission at 90°. The disposition of such characteristics by the designer makes it possible to create woven fabrics with an assumed irradiation transmission caused by the inter-thread channels. It should also be emphasised that the asymmetry of the characteristics enables to differentiate the position of a particular part of a fabric on a human body in order to decrease its irradiation from the given direction.

Conclusions

- It is possible to design the barrier properties of a woven fabric by choosing an assumed radiation transmission from the characteristics of the inter-thread channels of the particular structures.
- The UV transmission characteristic of particular structures can be determined by virtual evaluation of the light transmission in dependence on the irradiation angle.
- Analysis of the light transmission of structural modules enables to synthesise the total transmission of the woven fabric at the second stage of fabric design.
- The asymmetry of the transmission characteristic enables an additional differentiation of the position of a woven fabric on the human body.

***Table 2.** Light transmission in per cent as a function of the irradiation angle for a woven fabric of plain weave and with an additional layer of threads in the weft direction, as well as for a woven fabric of twill weave.*

Irradiation angle, deg	Light transmission, %	
	Fabric of plain weave with an additional layer of threads	Woven fabric if twill weave
0	0.000	0.000
12	0.000	0.000
24	0.000	0.000
36	0.000	2.484
48	6.748	7.709
60	10.556	14.276
72	6.703	23.014
84	3.121	28.534
90	0.000	33.333
96	3.213	28.607
108	6.471	23.133
120	10.453	14.530
132	6.548	7.729
144	0.000	2.188
156	0.000	0.000
168	0.000	0.000
180	0.000	0.000

Editorial note

In this article, parts of the Ph.D. Thesis of M. Dulęba-Majek were used, under the title 'Influence of woven fabric structure on UV radiation transmission' directed by prof. J. Słodowy Ph.D., D.Sc.

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Received 18.06.2008 Reviewed 27.03.2009