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Review of fibers and fabrics used for special services' protective clothing in terms of their mechanical and thermal properties

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Abstract. In the paper, special clothing is understood as protective clothing used by services, in particular fire services, but also military and police, working in fire hazard conditions, where the main risk factors for the user are: a high temperature, a contact with hot objects, and a mechanical damage. The presented study deals with the review of special clothing industry and discusses cloths structure for compliance with national and European regulations. The parameters of technical fibers used for production of the above-mentioned clothes used during firefighting in open spaces, made of flame retardant yarns, e.g., aramid yarns or mixtures of flame retardant yarns, were analysed.
Keywords: mechanical engineering, fibers, special fabrics, fire resistance, mechanical strength, national and EU standards
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1. Introduction

Many different definitions are used to describe the term "technical fibers" [1-3], depending on their purpose, functionality, and unusual requirements. These fibers are used for the production of technical fabrics, which are first of all made to obtain specific functional properties (tensile strength, rupture, fire resistance) and not because of their decorative or aesthetic qualities.

These fabrics are used in many industries, e.g., automotive, construction, both as a covering material and as a reinforcement for various types of composites.

The technical textile market growth is estimated in size of 8.0% for the 9-year forecast period (from 2021 to 2029). This significant growth is caused by a wide range of application of technical textiles [4].

Most of technical textiles is made of traditional fibers that are already well known. In fact, more than 90% of all fibers used in the technical sector are of conventional type [5]. Fibers, specifically designed for use in technical textiles, are often expensive to produce and they have limited applications.

Historically, the use of fibers in technical applications has its roots in the days of the early Egyptians and Chinese who used papyrus mats to strengthen and consolidate the foundations of pyramids and Buddhist temples [6]. However, their mass usage in modern engineering projects began after the flood in the Netherlands in 1953, as a result of which the dam protecting the land from the sea was broken and 1,835 people lost their lives. This event contributed to the launch of the famous Delta project, which for the first time entered synthetic fibers to build a large structure — movable dams placed in the river delta to protect against sea waves [7]. Since then, such technical fibers, called geomaterials, have become important and necessary multifunctional materials.

Special fibers have been developed to work under extreme loads and/ or temperature. Technical fabrics are made of special technical fibers for production of special clothing, used by services, in particular fire services, but also military and police, operating in fire hazard conditions, where the main risk factors for the user are: high temperature, contact with hot objects, and mechanical damage. These services must conduct effective rescue operations in conditions of destructive impact of nature (meteorological, hydrological, biological phenomena, etc.) and anthropogenic threats (e.g., fires, accidents by communication and terrorist acts) [8].

The purpose of this paper was to review the technical fibers used in the production of special clothing and to indicate the regulations and standards to which they must be followed. The parameters of technical fibers used for the production of the above-mentioned clothes, used during firefighting in open spaces, made of flame-retardant yarns, e.g., aramid yarns, were analysed.

2. Technical Fibers Overview

Figure 1 shows the basic division of technical fibers along with their selected mechanical parameters. The natural fibers mainly include cotton, wool, linen, jute, hemp, ramie, and silk.

Cotton is a plant-based fiber. It is made of long chains of natural cellulose containing compounds of carbon, hydrogen and oxygen, the so-called polysaccharide. The chain length of these compounds determines the ultimate strength of the fiber.

On average 10,000 monomeric units form individual cellulose chains of approximately 2 mm in length. These particles combine into microfibers to form a cotton fiber. The unique physical properties (high strength, durability and ability to absorb liquids) and aesthetic attributes, combined with the natural method of production and biodegradability, are the reasons for the high popularity of cotton [13].

Wool, on the other hand, is a natural fiber of animal origin (it is obtained from the hair of sheep and lambs). It is made of a mixture of chemically linked amino acids, having a chain structure in the wool fiber with a strong intermolecular and internal hydrogen bond, which is believed to be responsible for many of its unique features, such as high thermal insulation [14].

Silk is another animal-derived (protein) fiber obtained from the cocoon of the mulberry silkworm or the oak silkworm. Silk is structurally similar to wool with a slightly different combination of amino acids making up the protein or fibroin. Silk is the only natural and commercially produced continuous filament with high strength, high gloss, and good dimensional stability [15].

The regenerated fibers include, first of all, viscose — a fiber with high flexural strength and high wettability modulus, comparable in quality to cotton. For the production of viscose, cellulose from trees such as beech, pine, and spruce is used, as well as a number of advanced chemical and technological processes. The natural raw material must be processed, which is why this material is classified as artificial — regenerated fiber. The disadvantage of viscose is its non-ecological production as a solvent, caustic substances such as carbon disulfide (CS_2) and sodium hydroxide (NaOH) are used [16].

Another regenerated fiber is the recently popular lyocell – a form of rayon made of fibers obtained by dissolving cellulose pulp using wet spinning [17]. It was developed in 1972 by a team of employees from the now defunct US fiber plant Enka in North Carolina. Lyocell shares many properties with other cellulose fibers such as cotton, linen, ram, and other types of rayon. Lyocell fibers are soft, absorbent and wrinkle-resistant. In addition, the production of lyocell is environmentally friendly – non-toxic n-methylmorpholine n-oxide (NMMO) is used, which can be reused in the technological process even in 99.5% [18].

All synthetic fibers are the result of the processing of coal or oil [19]. The first synthetic fiber to be introduced to the market was Nylon 66, manufactured by DuPont in 1939. Today, there is an entire line of nylons commonly referred to as polyamides. These are synthetic polymers containing an amide group used, among others, for the production of synthetic fibers with very high tensile strength. They are most often used for the production of knitted fabrics, ropes and lines and, due to their excellent mechanical properties, for bearing shells, gears, etc. [20].

Technical fibres

Conventional fibers	Highly durable and high-modulus organic fibers	Organic fibers with high chemical and fire resistance	High performance inorganic fibers	Ultra-fine fibers and special usage
— Natural, e.g. cotton, wool, silk, jute, etc. — Regenerated, e.g. viscose, acetate, etc. — Synthetic, e.g. polyamide, polyester, polyacrylics, polyurethanes, etc.	— Para-aramids, e.g. Kevlar (DuPont) and Twaron (Acordis) — Poly (butylene terephthalate) (PBT) — Ultra high molecular weight polyethylene, e.g. Byneema (DSM) and Spectra (Allied Signal)	— Metaaramides, e.g. Nomex (DuPont) and Conex (Teijin) — Kermel (Rhodia) — Kynol (Kynol) — Acrylic oxidized fibers, e.g. Panox (SGL) Other: — Aromatic polymers, Polyetherether-ketone, PEEK (Victrex and Zyex), Polyarylether-ketone PEK, Polyphenylene sulfide PPS, e.g. Poly (tetra-fluoroethylene, Teflon (DuPont))	— Coal — Ceramics — Boron — Tungsten — Corundum (e.g. Saffil) — Highly modular silicones — Carbide nitrides and silcones, etc.	— Microfibers (linear density <0.5 dtex) — Solar absorbing fibers (alpha radiation) — Thermo--sensitive fibers (thermo-chromes) — Perfumed fibers — Antibacterial fibers (aseptic chlorofibres) — Fibers with voids — Antistatic fire retardant fibers, etc.
Fatique strength: 0.1-0.5 $Ntex^{-1}$ Modulus: 5-18 $Ntex^{-1}$ % elongation: 2-7	Fatique strength: 1.5-3 $Ntex^{-1}$ Modulus: 25-150 $Ntex^{-1}$ % elongation: 1-8	Fatique strength: 1-2 $Ntex^{-1}$ Modulus: 15-25 $Ntex^{-1}$ % elongation: 1-3	Fatique strength: 0.5-2 $Ntex^{-1}$ Modulus: 70-220 $Ntex^{-1}$ % elongation: 0-1.5	Fatique strength: 0.1-0.4 $Ntex^{-1}$ Modulus: 2-15 $Ntex^{-1}$ % elongation: 2-17

Fig. 1. Technical fibers and their mechanical properties [9-12]

Wool-like properties are demonstrated by other synthetic fibers — polyacrylic, which are produced by the polymerisation of acrylonitrile with the use of polyacrylonitrile doping [21]. Polyolefin fibers include both polyethylene and polypropylene produced by polymerising ethylene and propylene, respectively, and then extruding the blend [22]. Polyethylene has moderate physical properties with a low melting point of 110°C (LDPE — low density polyethylene) and 140°C (HDPE — high density polyethylene), which severely limits its use in high temperature applications. Polypropylene has better mechanical properties and it can withstand temperatures up to 140°C before melting at about 170°C. Both polymers have a lower density than water, which allows them to float on the water, what makes them suitable for lines, fishing nets, etc. [23].

Figure 2 shows typical strength properties of the conventional fibers discussed above.

Another group of fibers, presented in Fig. 1, are organic fibers of high strength and modulus. Examples of such fibers that were first developed in the Netherlands in the 1970s are ultra-high molecular weight polyethylene (UHMWPE) fibers, such as Dyneema or Spectra [25]. They are currently the strongest fibers, with tensile modulus above 70 GNm^{-2}. These fibers are believed to be 15 times stronger than steel and two times stronger than aromatic polyamides such as Kevlar in terms of their weight. Their advantage is also low density, chemical inertness, and resistance to abrasion. The melting point is around 150°C and they thermally decompose at 350°C, which limits their use [26].

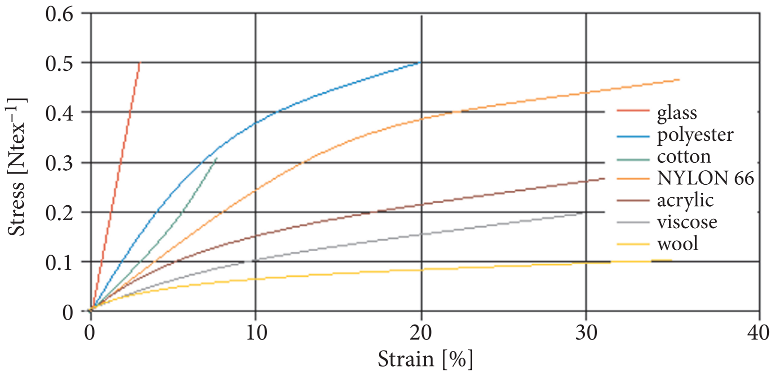

Fig. 2. Typical stress-strain characteristic for selected conventional fibers [24]

On the basis of the above-mentioned fibers, organic fibers with high fire and chemical resistance have been developed. The first of these, the so-called meta-aramids, were Nomex and Conex, produced by DuPont in 1962 and by Teijin in 1972 [27]. Nomex is particularly known for its resistance to combustion, high decomposition temperature before fusion, and high limiting oxygen index (LOI) — the minimum concentration of oxygen, expressed as a percentage, that will support combustion of a polymer [28]. Nomex fabrics are used in the production of non--flammable heat-resistant clothing, for example for Formula 1 drivers, firefighters, the army and other services working in harsh conditions, as protective layers in various devices, as anti-puncture layers in the power industry, etc. Nomex is also used in chemical filters [29].

Aromatic fibers with chains containing paraphenylene rings such as polyether ether ketone (PEEK) [30], polyether ketone (PEK) and poly (p-phenylene sulfide) (PPS) [31] also have high melting points, but because their melting points occur before their decomposition temperature they are not suitable for fire-resistant applications. However, their good chemical resistance makes them suitable for low temperature filtration and in other corrosive environments.

The polyheterocyclic fiber, polybenzimidazole or PBI, made by HoechstCelanese, has even higher LOI than aramids. It has excellent heat and chemical agents' resistance, but remains quite expensive. PBI fabric does not melt, drip and is not brittle. PBI fiber is widely used in the work of fire brigades, police, petrochemical industry, and the military [32].

Oxidized acrylic fiber, best known as Panox (SGL, UK), is another high combustion resistant cross-linked material produced as a result of the combination of oxidation and pyrolysis of acrylic fibers at a temperature of about 300°C [33].

Table 1 shows the range of LOI and fatigue strength of some known, highly resistant to chemicals and combustion organic fibers.

Table 1

LOI and fatigue strength of selected organic fibers [34]

Fiber brand name	Manufacturer	LOI (%)	Fatigue strength (GPa)
Nomex	Du Pont	29	0.67
Conex	Conex	29	0.61
Kermel	Rhone-Poulenc	31	0.53
PBI	Hoechst-Celanese	41	0.39
Panox	RK Textiles	55	0.25

Very fine or micro fibers have been developed partly because of greater precision in engineering techniques and better production control and partly because of the need for lightweight, soft, waterproof fabrics that eliminate the more traditional coating or lamination processes [35]. So far, there are no universal definitions of microfiber. The textile terms and definitions simply describe them as fibers with a linear density of about 1.0 dtex or less. They are usually made of polyesters and nylon polymers. Microfibers are also used to make barrier fabrics in the medical industry. Their combined characteristics of small diameter and compact packing also allow us for effective and more economical dyeing and finishing.

Finally, the continued emphasis on achieving and developing even newer fiber applications has led to the creation of many other and, so far, niche fiber products.

In fact, new ideas tend to combine the basic functional properties of special needs' textile. For example, Solar-Aloha, developed by Descente and Unitik in Japan [36] absorbs light less than 2 mm in length and converts it into heat thanks to the zirconium carbide content. Another interesting material is Toray thermochromic fabric, which has a uniform coating of microcapsules containing heat-sensitive dyes that change at 5°C intervals in the temperature range from –40°C to 80°C, creating "fun" special effects. Cripy 65, on the other hand, is a Mitsubishi Rayon® fragrance fiber that emits fragrant essence from pores along the polyester fibers [37].

Table 2 summarises the application areas of technical fibers.

Table 2

Applications of technical fibers [38]

Civil and agricultural engineering	Automotive and space industry	Medicine	Military and protection	Others
Geotextiles, geomembranes and geocomposites, e.g. utilities for the ground Filtering Drainage Erosion control Waterproof Soil stabilisation for vegetative farming Underground irrigation system (used for irrigation and adding fertilizer and pesticides)	Tire reinforcement Seatbelts Air bags Vehicle interiors Bumpers Wings Engine boost Flexible vehicle tanks Parachutes, balloons	Dressing wounds Bandages Barriers to bacteria Sterile dressings Blood filtration valves (dialysis) Surrogate ligaments Artificial arteries Synthetic filters	Barrier to: chemicals, heat, moisture, flame and sound waves Insulations Workwear Personal armour (vests, helmets, gloves, etc.)	Ship engineering Electronics Filter industry Food processing Sports and recreation (e.g., belts, ropes, kayaks, yachts, cables, cleaning clothes, tennis rackets, tents)

3. Fireproof Properties of Technical Fibers

With the progressive industrialisation of life, human safety has become an important issue. Therefore, the textile industry has become important due to a number of new solutions in the field of fibers, fabrics, protective clothing used, for example, in the automotive and construction industries. The main challenge related to the technology of producing fireproof fabrics for the textile industry is the production of environmentally friendly and non-toxic materials with specific performance properties. In the 90's of the 20th century, there were significant innovations in the field of heat and fire resistance of fibers used in the production of protective clothing for firefighters, steel workers, soldiers, aviation and space personnel and other people who are exposed to high temperature and flame conditions (e.g., described in the previous chapter Nomex, PBI).

To protect against heat and flame, requirements are laid down for garments used in situations where the wearer may be occasionally exposed to moderate levels of radiant heat during a normal working day, and for garments that provide a longer protection period when the wearer is exposed to severe radiation, radiant and convective heat or direct flame, for example firefighter clothing.

The important properties are the ease of ignition, the burning rate and the heat release rate of textiles, which determine the degree of fire hazard. Other factors that influence the level of thermal protection include the melting characteristics and shrinkage of synthetic fibers and the emission of smoke and toxic gases during combustion.

The effect of heat on a textile material can cause both physical and chemical changes [39, 40]. Physical changes occur in thermoplastic fibers in the second order transition (T_g) and the melting point (T_m), while chemical changes occur at the pyrolysis temperatures (T_p) where thermal decomposition occurs. Fabric burning is a complex process involving heating, decomposition to gasification (fuel generation), ignition, and flame.

In protective clothing, a low propensity to ignite from a burning source is desirable or, if the object catches fire, a slow spread of fire with a low heat output. Generally speaking, thermoplastic fiber fabrics such as nylon, polyester fiber and polypropylene fibers meet these requirements because they shrink from the flame and if they burn, they do so with a small slow flame spreading and fall.

There are additional requirements for protective clothing, such as thermal insulation, as well as high dimensional stability of the fabric. The above requirements are met, for example, by aramid fibers (e.g., Nomex, DuPont), cotton or wool with reduced flammability or partially oxidised acrylic fibers [28].

In addition to the characteristics of the fiber, the characteristics of the garment also contribute to the thermal protection of the user. For a given fabric thickness, the lower the density, the greater its thermal resistance. Hence, coarser fabrics made of cotton, wool and other non-melting fibers provide good thermal protection, while thicker thermoplastic-fibrous fabrics cause severe burns.

The thermal properties of the textile fibers are given in Table 3.

Table 3

Thermal properties of selected fibers [41]

Fiber	T_g (°C) Vitrification	T_m (°C) Melting	T_p (°C) Pyrolysis	T_c (°C) Combustion	LOI %
Wool	–	–	245	600	25
Cotton	–	–	350	350	18.4
Viscose	–	–	350	420	18.9
Nylon 6	50	255	403	530	20-21
Nylon 66	80-90	> 320	420-477	480	20-21.5
Polyester	100	165	290	> 250	18.2
Modacrylic	-20	> 240	496	550	18.6
PVC	< 80	> 180	273	690	29-30
PVDC	-17	180-210	> 180	450	37-39
PTFE	126	> 327	> 220	523	60
Oxidised acrylic	–	–	400	560	95
Nomex	275	375	310	500	28.5-30
Kevlar	340	560	590	> 550	29
PBI	> 400	–	> 500	> 500	40-43

In summary, fibers can be divided into two categories:

— flame retardant fibers such as aramid, modacrylic, polybenzimidazole (PBI), Panox;

— chemically modified fibers and fabrics, such as cotton, wool, viscose and synthetic fibers.

4. National Requirements for Fire-Resistant Special Clothing

The progress of civilisation offers a number of improvements and amenities, but also carries a certain risk of a new, different range of dangerous situations. The state, as a legal entity, is obliged to ensure an appropriate level of security for its citizens by preparing appropriate organisational and legal tools, with the help of which system solutions will be implemented to ensure effective combating of potentially dangerous situations. One of the legal tools of this type in Poland, giving the possibility of systemic resolution of emerging dangerous situations, is the organisation of fire protection consisting in the implementation of projects aimed at protecting life, health, property or the environment against fire, natural disaster or other local threats [42].

Currently, in the clothing construction solutions used in Poland, a number of new fibers modifying the properties of fabrics is applied for protective clothing, primarily for fire brigades. Protective clothing has a number of requirements that are summarised in Table 4.

The basic protection of a rescuer is classic special clothing according to the EN-469 standard, but in the world literature a wild land fire suit according to the EN-15614 standard is also known. This suit is normally called an outdoor firefighting garment.

These garments were shown in Fig. 3. The structure is a major difference in the design of these garments. Special clothing EN469 is intended for firefighters to carry out all types of rescue and firefighting activities. Resistance to heat fluxes resulting from rescue operations is of particular importance in a fire environment (hot microclimate).

Fig. 3. Special clothing for fireguards: a) according to EN469 standard;
b) according to EN15614 standard [43, 44]

The design of the special suit has to ensure a significant delay in the transfer of heat fluxes to the zone of direct contact with the rescuer's body. In particular, in relation to the set values determined by fire tests, it is to protect against exceeding the subcritical thresholds, corresponding to the 3rd degree burn.

Table 4

Normative requirements for protective (special) clothing [45]

No.	Requirements type	Fulfillment of requirements method
1	Spread of flame	The flame spread shall be tested according to EN ISO 15025: 202 (procedure A) and shall reach a flame spread index of "3" according to EN 533: 1997 after the pre-treatment specified in clause 6 of this standard and the following requirements shall be met: — no sample should burn to the top edge or side edges; — no sample should form a hole in any layer except for the outer layer or the inner lining; — no flame or molten debris should develop in any sample; — the average burning time should be < 2 s; — the average glow time should be < 2 s. The outer garment assembly should be tested by applying a flame to the outer surface of the garment. If the outer garment is lined, the set of outer garment should also be tested by applying a flame to the lining of that garment. If the garment consists of several separate garments and the inner garment can be exposed to a flame, the garment of that inner garment shall also be tested by exposure to the flame of the outer surface of that garment. If the garment includes a tightening material at the wrist, it should be tested separately by exposing to a flame. If the garment includes accessories, they shall be tested separately by exposing their outer surfaces to a test flame as above. The accessories should still be functional after the test.
2	Heat transfer (flame)	As a result of the heat transfer test, two garment performance levels are determined — 1 and 2. The average heat transfer coefficient for a set of clothing or a multi-layer set of clothing tested in accordance with EN 367 after sample preparation should be HTI_{24}* ≥ 13 for performance level 2 and HTI_{24} ≥ 9 for performance level 1, and for the average value (HTI_{24}-HTI_{12}**)*** ≥ 4 for performance level 2 and (HTI_{24}-HTI_{12}) ≥ 3 for performance level 1.
3	Heat transfer (radiation)	In case of materials or a multi-layer set of clothing tested in accordance with EN ISO 6942, with a heat flux density of 40 kW/m^2, they should reach HTI_{24} ≥ 18 for performance level 2 and HTI_{24} ≥ 10 for performance level 1, and for the average value (HTI_{24}--HTI_{12}) ≥ 4 for performance level 2 and (HTI_{24}-HTI_{12}) ≥ 3 for performance level 1.
4	Tensile strength of material when exposed to thermal radiation	Three samples in the longitudinal direction and three samples in the transverse direction shall be tested according to ISO 13934-1 or EN ISO 1421: 1998 method 1, after having prepared a batch of materials according to EN ISO 6942: 2002 method A, with a heat flux density equal to 10 kW/m^2. Each specimen should attain a tensile strength of ≥ 450 N. The width of the test specimen after thermal action should be 50 mm.
5	Heat resistance	None of the materials used in the garment tested in accordance with the method set out in Annex A shall not melt, drip or burn, it nor shall shrink by more than 5%. The accessories after the test should still be functional. The tests should be carried out in accordance with ISO 17493 at the temperature of 180 ±50°C and for 5 minutes.

cont. table 4

6	Tensile strength	The outer material shall be tested in accordance with EN ISO 13934-1 or EN ISO 1421: 1998 method 1. The breaking force in both the longitudinal and transverse directions shall be ≥ 450 N.
7	Tear strength	Tear strength for external material tested according to EN ISO 4674-1: 2003 method B for coated fabrics and acc. EN ISO 13937-2: 2000 for uncoated fabrics. Both, in the longitudinal and transverse directions, the materials should withstand a force of ≥ 25 N.
8	Surface wetting	The spray rating for the outer surface tested in accordance with EN 24920 at 200°C shall be ≥ 4.
9	Dimensions change	The change in dimensions of the outer material of the garment under test conditions in accordance with ISO 5077 using the procedure specified in point 5.4 shall be < 3% for both the longitudinal and transverse directions.
10	Leakage of liquid chemicals	The test shall be carried out in accordance with ISO 6530 using the application time of the substance of 10 s. The non-wettability index for a component of a set of materials or a multilayer set of clothing tested in accordance with EN 368, using: — 40% NaOH in 20 ±2°C, — 36% HCI in 20 ±2°C, — 30% H_2SO_4 in 20 ±2°C, — 100% o-xylene in 20 ±2°C should be > 80%, with no permeability to the inner surface.
11	Water tightness and water vapor permeability	The test is carried out in accordance with EN 20811 under hydrostatic pressure. After the examination, the classification will be as follows: — level 1 < 20 kPa — for products without a protective barrier against moisture seepage, — level 2 ≥ 20 kPa — for products with a protective barrier against seepage of moisture. It is assumed that samples are taken from critical surfaces, e.g. shoulder seams, and according to EN 31092 in the case of resistance to water vapour transmission.
12	Water vapour resistance	The tests should be performed for clothing with the exception of the barrier protecting against percolation in accordance with EN 31092. The test results should fall within the following ranges: — level 1 > 30 m^2 Pa/W, — level 2 ≤ 30 m^2 Pa/W.

* Heat transfer index HTI_{24} — determines the time after which the temperature increases by 24° under the action of the flame (flame transferred from the outside) (risk of burns 2nd degree)

** Heat transfer index HTI_{12} — determines the time after which the temperature increases by 12° under the action of the flame (flame applied from the outside) (skin pain is felt)

*** Heat transfer index HTI_{24}-HTI_{12} — determines the time left for the firefighter from the first pain to escape without burns.

The design of the special suit has to ensure a significant delay in the transfer of heat fluxes to the zone of direct contact with the rescuer's body. In particular, in relation to the set values determined by fire tests, it is to protect against exceeding the subcritical thresholds, corresponding to the 3rd degree burn.

A burn is a term used to describe damage to the surface layer of the epidermis and dermis, caused by external factors such as thermal energy, electricity, atmospheric discharges, radioactive radiation, and chemicals. Burns are classified into four degrees. The division is conditioned by the depth of the damage and the accompanying symptoms. There are [46]:

— 1st degree burns — caused by strong sunlight or direct contact with boiling substances (most often water or other boiling liquid). The skin of the injured person is red and stinging. Inflammation may develop on its surface. In such situations, the skin should be cooled with water or a cold compress (cooling or with dry ice) and covered with a hydrogel or traditional dressing.

— 2nd degree burns — damage the nerve endings, which is manifested by severe pain at the burn site. A characteristic feature is the appearance of bubbles filled with serous fluid, which under no circumstances should be pierced. Puncture may cause infection.

— 3rd degree burns — caused by prolonged contact with a strongly influencing factor, e.g., fire. In their course, tissue and bone necrosis occurs, therefore the patient must be hospitalised. With such extensive damage, a skin graft may be needed. Third degree burns leave scars.

— 4th degree burns — their prognosis is the worst. The skin is practically charred and vital functions must be supported. Few patients survive such burns. If such a person can be saved, they will require many operations before they are able to function normally.

These parameters result from the reference to the Stoll-Chianta diagram presented in Fig. 4.

Until recently, in a slightly different system, subcritical values were referenced. This system is based on an organoleptic examination resulting from operational rescue and firefighting activities. The threshold value recognised as a direct health hazard (a consequence — burn) is the contact of human skin with an object (solid, gas, liquid) at a temperature of 60°C. This value is sometimes called the so-called pain threshold [48].

An important property to take into account is the so-called breathability. It is based on a parameter defined as vapour permeability. The essence of the breathable material system is shown in Fig. 5.

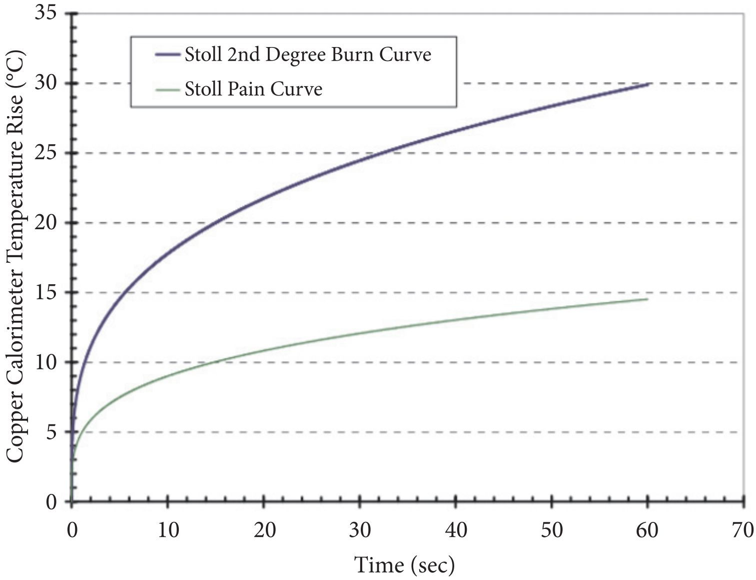

Fig. 4. Stoll-Chianta diagram [47]

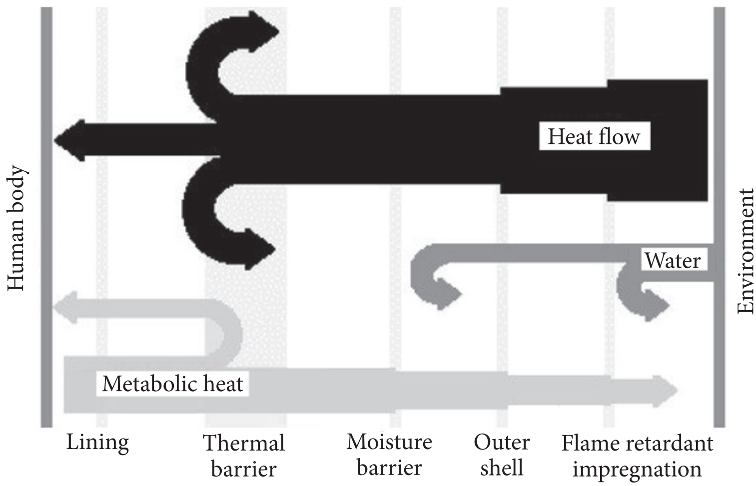

Fig. 5. Heat flow during thermal impact on the rescuer in special firefighting clothing [49]

In the solution shown in Fig. 5, the outer shell is responsible for the transfer of moisture from metabolic processes, in particular sweating of the rescuer, to the outside (i.e., the operating environment), and from the opposite side, blocking the inflow of moisture and water from the environment.

The EN 15614 garment has only one fabric layer (Fig. 6). Its basic property is protection against thermal streams from the environment of rescue and firefighting operations. The significant difference consists in much lower values of thermal parameters of the environment, resulting from the specificity of activities in open spaces, the consequence of which is contact with thermal streams, mainly from the combustion of plant materials, and large energy dispersions. Other properties of clothes according to EN-15614 derive from the requirement to ensure protection against external factors.

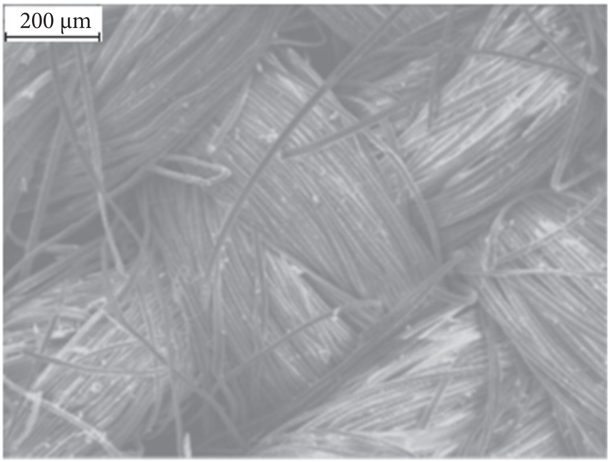

Fig. 6. Image of structure of aramid fabric, covered with a complex ceramic layer made of titanium nitride and silicon nitride — scanning electron microscope [50]

It should be noted, however, that in order to ensure full protection from the outside, as well as the comfort of work of a firefighter rescuer (protection from the inside), the use of multi-layer clothes has been adopted [51].

In general, the external protection is understood as a layer of clothing which is a barrier against heat, water and chemical substances, while the internal protection (work comfort) is understood as breathability. During rescue operations, firefighters are exposed to stress, haste and increased physical exertion. In order not to overheat, the body produces heat and sweat. Too tight layer of material can cause dangerous consequences. One of them are burns. Clothing providing such protection consists of an outer layer, a membrane (moisture barrier), a thermal insulation barrier and a lining, which — depending on the modification — can be a separate layer (four-layer clothing) or be combined with a heat-insulating barrier (three-layer clothing) — Fig. 7. Each layer is made of a different material and has characteristic features that, combined, constitute an effective, innovative solution with a wide range of protection.

Fig. 7. Three-layer material layout in firefighter special clothing

Outer shells of special clothes can be made of the following fabrics [52]:

- Nomex and Kermel aramid fabrics,
- PBI polyamide fabrics (these fabrics cannot be dyed — only available in shades of brown),
- impregnated cotton fabrics.

The membrane (Moisture barrier) is the middle layer of the special garment. Its task is to prevent the penetration of liquids and maintain a proper thermal balance [52].

The basic characteristics of the membrane are:

- waterproof, it is designed to prevent the thermal insulation layer from getting wet,
- permeable to allow the escape of water vapour generated by the wearer's perspiration. Plastics are used for the production of membranes, e.g., polyurethane, and polyester polytetrafluoroethylene (PTFE).

The thermal barrier layer insulates against the external environment and it is a barrier against the penetration of thermal radiation inside the clothes. This goal is achieved by a suitable design solution consisting of a model consisting of fibers with air in between. It is important that the layer is not too thick — and therefore, heavier — as this can reduce wearing comfort and limit movement. For the production of thermal insulation layers, wool, aramid, aramid-viscose, and polyester fibers are used [52].

Finally, the lining is the layer of special clothing that is closest to the body. It can be a separate layer or combined with a heat-insulating layer. The following materials are used for the production of linings [52]:

- impregnated cotton fabrics,
- aramid or aramid viscose fibers.

5. Summary

The classification and selected mechanical and thermal properties of technical fibers and fabrics made of them were presented in the paper. Particular attention was paid to the fabrics used in the production of clothing for services working at elevated temperatures, primarily firefighters — rescuers, but also for the army and police involved in rescue operations during a fire.

Fibers, and hence special fabrics, have different strength properties as well as those related to thermal barrier and flammability. Their selection and application must be based on the analysis of the rescuer's working conditions (flame, high temperature or contact with hot objects). On the other hand, the comfort of human work must be maintained, so the fabrics must be relatively light, but also, for example, provide ventilation to the skin or minimise sweating. Hence, the multi-layered nature of special clothes was indicated.

An important factor is also the adaptation of the clothes to the national and EU standards mentioned in the paper. All uniforms approved for use must therefore pass a series of tests, thanks to which the safety and comfort of a lifeguard acting to protect people in life-threatening conditions, e.g., during a fire, will be ensured.

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Przegląd włókien i tkanin stosowanych w odzieży ochronnej służb specjalnych w aspekcie ich właściwości mechanicznych i cieplnych

Abstrakt. W artykule ubrania specjalne rozumiane są jako odzież ochronna stosowana przez służby, w szczególności pożarnicze, ale także wojskowe i policyjne, pracujące w warunkach zagrożenia pożarowego, gdzie głównymi czynnikami ryzyka dla użytkownika są: wysoka temperatura, kontakt z gorącymi przedmiotami i uszkodzenia mechaniczne. W pracy dokonano rozpoznania branży produkcji ubrań specjalnych i omówiono ich budowę w odniesieniu do zgodności z przepisami krajowymi i europejskimi. Analizie poddano parametry włókien technicznych służących do produkcji ww. ubrań stosowanych podczas gaszenia pożarów w przestrzeni otwartej, wykonanych z przędz trudnopalnych, np. aramidowych, lub z mieszanek przędz trudnopalnych.

Słowa kluczowe: inżynieria mechaniczna, włókna, tkaniny specjalne, ognioodporność, wytrzymałość mechaniczna, normatywy krajowe i EU
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