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SHAPING THE PHYSIOLOGICAL COMFORT PERFORMANCE OF MULTILAYER CLOTHING ASSEMBLIES FOR FIREFIGHTERS

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Content

Abbreviations of word

CV	Coefficient of variation
EU	European Regulation
FPC	Firefighter’s protective clothing
GQI	General Quality Index
GQI_{ext}	Extended values of the General Quality Index
GQI_{rel}	Relative value of the General Quality Index
KES-FB4	Kawabata Evaluation System
KF	Knitted fabric for underwear
KF1,..., KF7	Seven variants of knitted fabric investigated
LOI	Limiting oxygen index
MMT	Moisture Management Tester
PBI	Poly-benzim-idazole
PPE	Personal protective equipment
PPC	Personal protective clothing
PTFE	Poly-tetra-fluoro-ethylene
PU	Polyurethanes
PVC	Poly-vinyl-chloride
REL	Relaxed (un-stretched) state of knitted fabric
SE	Standard error
SD	Standard deviation
SS	Sample Set, multilayer textile sets for firefighter’s protective clothing
SS1,…, SS4	Four variants of Sample sets,
SS+KF	Firefighter’s clothing assembly is composed of Sample Sets and knitted fabrics
ST	Stretched state of knitted fabric

Symbols list

A	area of spreading liquid
a	thermal diffusivity, mm/s
b	thermal absorptivity, $Ws^{1/2}/m^2K$
df	degree of freedom
F	variable of F distribution
f_h	the relative area of clothing parts hanging loosely on the user’s body,
f_l	the relative area of clothing parts lying on supporting surfaces of the user’s body
G	General Quality Index
h	fabric thickness, mm
h_{a1}	thickness of the air in space between the 1st and 2nd layer, mm
h_{a2}	thickness of the air in space between the 2nd and 3rd layer, mm
h_{aj}	thickness of the jth air layer, mm
h_i	thickness of the ith textile layer, mm
h_1, h_2	thickness of particular layers in the multilayer set, mm
h_1, h_2, h_3	thickness of particular layers, appropriately: first, second, and third layer, mm
$h_{1+2\ (set)}$	thickness of the multilayer set, mm
K	a coefficient dependent on the advancing contact angle of the liquid on the fibers, the permeability and thickness of the fabric, and the saturation concentration of the liquid in the fabric, -
L	distance traveled by the liquid
MS	mean square of the error
m	mass per square meter of fabric, g/m^2
m	number of air layers between individual textile layers in clothing assembly
m	number of assessed assemblies (materials)
m_{ab}	mass of testing liquid absorbed by the fibrous material of the bottom surface, g
m_{ab1}	mass of testing liquid absorbed by the fibrous material of the bottom surface of the 1st layer, g

m_{ab2}	mass of testing liquid absorbed by the fibrous material of the bottom surface of the 2nd layer, g
m_{at}	mass of testing liquid absorbed by the fibrous material of the top surface, g
m_{at1}	mass of testing liquid absorbed by the fibrous material of the top surface of the 1st layer, g
m_{at2}	mass of testing liquid absorbed by the fibrous material of the top surface of the 2nd layer, g
m_{sb}	mass of testing liquid spread on the bottom surface, g
m_{sb1}	mass of testing liquid spread on the bottom surface of the 1st layer, g
m_{sb2}	mass of testing liquid spread on the bottom surface of the 2nd layer, g
m_{st}	mass of testing liquid spread on the top surface, g
m_{st1}	mass of testing liquid spread on the top surface of the 1st layer, g
m_{st2}	mass of testing liquid spread on the top surface of the 2nd layer, g
$m_{t\text{-}b}$	mass of testing liquid transferred from the top to the bottom surface, g
$m_{t\text{-}b1}$	mass of testing liquid transferred from the top to the bottom surface of the 1st layer, g
$m_{t\text{-}b2}$	mass of testing liquid transferred from the top to the bottom surface of the 2nd layer, g
m_{tot}	the total amount of testing solution delivered during the MMT test, g
MWRB	Maximum wetted radius for bottom (B) surface, mm
MWRT	Maximum wetted radius for top (T) surface, mm
n	number of layers
n	number of parameters taken for calculation,
n	number of parameters under consideration
OMMC	Overall Moisture Management Capacity
P	volume porosity of fabric, %
P	ratio between the maximal and stationary heat flow
P_{ϕ}	packing density of the fabric. It is equivalent to the filling factor

ρ	relative density of the fiber/polymer, g/cm^3
p	value for the between-groups comparison of the Kruskal-Wallis Test
p	significance level
p	relative water-vapor permeability, %
p_a	saturated water-vapor pressure at ambient temperature, Pa
p_m	saturated water-vapor pressure at the temperature in the air duct the instrument, Pa
Q	heat flow, W/ m^2
q_{max}	peak level of heat flow, W/ m^2
q_o	heat flux density, W/ m^2
q_v	density of the heat flux passing through the measured material, W/m^2
R	accumulative one-way transport index, %
R	thermal resistance, mK/Wm^2
R_{a1}	thermal resistance of the air in space between the 1st and 2nd layer, mK/Wm^2
R_{a2}	thermal resistance of the air in space between the 2nd and 3rd layer, mK/Wm^2
R_{CA}	thermal resistance of multilayer clothing assembly composed of several parallel layers, mK/Wm^2
R_{CA3L}	thermal resistance of clothing assembly consisting of three parallel materials, mK/Wm^2
R_{CA3L+A}	thermal resistance of clothing assembly consisted of three layers of parallel materials and the air spaces between layers, mK/Wm^2
R_{CA+A}	thermal conductivity of multilayer clothing assembly with the air spaces between layers, mK/Wm^2
R_{CAP}	total thermal resistance of clothing assembly creating the parallel connection of thermal resistances of clothing parts hanging lying on the body surface, mK/Wm^2
R_{ct}	range of thermal resistance, m^2K/W
R_{et}	water-vapor resistance, mKm^2/W or m^2Pa/W
R_i	thermal resistance of ith layer, mK/Wm^2
R_h	thermal resistance of clothing parts hanging loosely, mK/Wm^2

R_l	thermal resistance of clothing part lying on the supporting surfaces of the human body, mK/Wm^2
r	thermal resistance, mK/ W.m^2
r_b	rank according to the thermal absorptivity value
r_i	the rank the ith parameter is taken into consideration
r_{OMMC}	rank according to the Overall Moisture Management Capacity value
r_R	rank according to the thermal resistance value
r_{Ret}	rank according to the water-vapor resistance value
r_{WTT}	rank according to the WTT value
SS	sum of squares
T_a	ambient temperature, ^{0}C
T_b	temperature of the human body, ^{0}C
T_1	temperature of the inner surface of clothing assembly, ^{0}C
T_2	temperature of the outer surface of clothing assembly, ^{0}C
T_1, T_2, T_3, T_4	temperature of surface of particular layers, ^{0}C
TAR, BAR	absorption rate of top (T) and bottom (B) surface, %/s
TSS, BSS	Spreading speed on top (T) and bottom (B) surface, mm/s
t	the spreading time, s
t_{HAP}	ambient temperature, ^{0}C
t_i	degree of importance of ith property expressed as a decimal
t_T	body temperature, ^{0}C
u, m, n	exponents
V	the volume of the liquid
V_w	volume share of water in the fabric volume
W_{BHUTP}	humidity in the space of the underwear, %
WTT, WTB	Wetting time of top (T) and bottom (B) surface, s
X1, X2	heat and flame
Y	protection against water penetration
γ	the surface tension
Z	water-vapor resistance

Latin letters

λ	thermal conductivity of the material, mW/mK
λ	thermal conductivity of clothing assembly, mW/mK
$\lambda_1, \lambda_2\ \lambda_3$	thermal conductivity of particular layers, appropriately: first, second, and third layer, mW/mK
λ_a	thermal conductivity of the air, mW/mK
λ_{aj}	thermal conductivity of j^{th} air layer, mW/mK
λ_{a1}	thermal conductivity of the air in space between the 1st and 2nd layer, mW/mK
λ_{a2}	thermal conductivity of the air in space between the 2nd and 3rd layer, mW/mK
λ_{ef}	effective thermal conductivity of textile material, mW/mK
λ_f	thermal conductivity of the fibers, mW/mK
λ_i	thermal conductivity of i^{th} textile layer, mW/mK
λ_w	thermal conductivity of water in the fabric, mW/mK
ρ	the relative density of the fiber/polymer
η	the viscosity

1. The aim and scope of work

The aim of the Ph.D. work is to create theoretical bases enabling shaping the comfort-related properties of the multilayer clothing packages intended for the firefighter’s protective clothing (FPC). This goal is intended to be achieved by analysing the thermal insulation properties - thermal resistance and thermal absorptivity, as well as the ability to transport water-vapor and liquid moisture of the following textile materials:

- multi-layer textile packages intended for the FPC,
- knitwear intended for underwear for firefighter,
- multi-layer textile assemblies consisting of multi-layer textile packages for the FPC and knitted fabrics intended for underwear,

and then an analysis of the impact of the number and configuration of layers on the effectiveness of ensuring thermo-physiological comfort of the created multi-layer textile assemblies.

Research in the aforementioned area will be a significant supplement to the existing state of knowledge in the field of the comfort of usage of the FPC. The investigations of the FPC are the subject of numerous publications, primarily in the field of barrier properties of materials and clothing, by applicable standards. On the other hand, the properties affecting thermo-physiological comfort, although also numerous, did not include the issues of sweat transport in liquid form. Typically, research papers published in this area are based on utility trials with volunteers. Such studies were based mainly on the physiological reactions of the body during the use of clothing, including underwear, in specific microclimate conditions, with specific physical activity. In these studies, the subjective factor related to the characteristics of the user's body played an important role.

In the dissertation, a different is presented. We want to demonstrate the possibility of shaping the comfort-related properties of the multilayer textile packages intended for the FPC and multilayer clothing assemblies including underwear based on instrumental tests of the biophysical properties of individual components of the packages and assemblies.

The utility purpose of the research is to improve the thermo-physiological comfort of the firefighter when using protective clothing.

The thesis of the work is as follows:

Through an appropriate selection of materials of the multi-layer clothing assembly consisting of the protective clothing for the firefighter and underwear, it is possible to shape the properties of clothing assembly (firefighter's protective outfit) affecting the thermo-physiological comfort of the firefighter during their firefighting or other rescue actions.

The range of the research work:

- analysis of the state of the art in the field of the FPC on the basis of the literature review,
- theoretical considerations of heat and liquid moisture transport in multi-layer clothing packages,
- experimental work:
    - testing of multi-layer textile packages, underwear knitted fabrics, and textile assemblies composed of the multi-layer textile packages and knitted fabrics, in the scope of:
        - thermal insulation properties (thermal resistance, thermal absorptivity),
        - water-vapor resistance and water-vapor permeability,
        - transportation of liquid moisture,
    - statistical analysis of test results to assess the influence of the number of layers and the type of materials that create the layers on the comfort-related properties of assemblies consisting of multi-layer textile packages and underwear knitwear,
    - application of the General Quality Indicator (GQI) concept to quantify the quality of created textile assemblies consisting of multi-layer textile packages for the FPC and underwear knitwear,
    - development of recommendations for configuring the sets of clothing – the firefighter's protective outfit consisting of multi-layer protective clothing and underwear in order to ensure the thermo-physiological comfort of a firefighter while usage of the protective clothing.

2. The comfort of usage of the firefighter’s protective clothing – Literature review

2.1. Clothing Protective Properties

The human body can control its internal temperature at a certain level when the external or internal conditions are changing. Specific central and peripheral nervous systems continuously sense the temperature instability in the body and try to keep a balance through biological action. However, under extreme weather conditions, the body needs protection for survival. In the clothing design project, the human body is considered a heat-regulating biological system with its own internal heat generator and closely related to the heat exchange with the external environment. In the course of human development, the ability to fully adapt to extreme heat and cold conditions has not been formed, and the biological ability to balance the heat of the body is limited. From the point of view of biology and psychology, when the temperature of the skin of any part of the human body changes by 4.5^0C, a person becomes uncomfortable. When the temperature of the deep body changes by 1.5^0C, a deadly situation occurs [1].

Clothing plays an important role in people's daily life and creates physiological and psychological comfort [2]. The clothing acts as a second skin, enabling the user to adjust and adapt to the climate in which the user lives. The clothing can also change the way of perceiving the temperature of the surrounding environment [3]. One of the most important functions of clothing is to protect a wearer against extremes of environmental temperature either heat or cold. Clothing acts as a barrier between the human body and the external environment, creating a thermal micro-environment of the body under the influence of the environment. Protection expected from clothing is multi-dimensional. For traditional clothing, the expectation is basically social and determines its effectiveness from modesty and cultural value to fashion-discerning consumers. Protective clothing values are determined by specific protection performance, limiting cultural or fashion perspectives, and even compromising comfort. It is important that the clothes are suitable for the profession and provide conditions for users to work freely as well as be able to fully protect against the adverse conditions of the external environment. It is not only a guarantee of human health but also one of the factors that directly affect labor productivity.

2.1.1. Thermal Comfort Properties

International Standard ISO 7730:2005 [4] defines “thermal comfort” as a mental condition of an individual that expresses satisfaction in a thermal condition. The research institute of Toyobo, a Japanese manufacturer of high-tech materials for clothing, concluded that the environment called the pleasant condition of the human body is formed when the surface temperature of the body is 32 ^{0}C, the relative humidity is 50 % and the air movement is 25 cm/s [5]. The key to thermal comfort is the condition of the skin-clothing microclimate, which depends on two vital factors - humidity and temperature. The level of thermal comfort of the human body is determined by the heat and moisture balance between the body and the environment [6-8]. In brief, this type of comfort can be termed as “thermo-physiological comfort” which refers to the heat and moisture transport properties of clothing and the way the clothing helps to maintain the heat balance of the body. It does not simply depend on one or two key ingredients such as thermal conductivity or insulating properties of the clothing, but many other minor details, such as environment and wearer’s physiomental condition, need to be considered as well.

Scientists have determined that air temperature, wind speed, relative humidity, and amount of solar radiation are the most influential factors in the human body's thermal balance. Of these, the air temperature has a direct effect on the heat loss of the human body and others play the role of increasing or decreasing it [9-11].

Airspeed affects comfort in such a way that the thermal insulation reduces with increased wind velocity as compared with insulation in still air. The moisture content of textiles increases the thermal transport ability. Thus, heat, air, and moisture transport properties should be taken into consideration to predict the thermal comfort of clothing users.

The heat flow can be any form such as conductive, convective, or radiative.

Heat radiation and convection take place in the intermediate spaces of the garment filled with air while heat conduction takes place in the garment material [12]. The processes of heat transfer through clothing are physical processes related to the spread of thermal energy and occur in the same way as the processes of heat exchange between any physical body. Textiles are generally low heat conductive. Hence, convective and radiative heat resistance are primary concerns for designing firefighting protective clothing.

According to Ashoff and others [13, 14] the total heat loss of the human body at a temperature of about 20 ˚C and a relative air humidity of 50% is divided as follows:

- evaporation - 20%,
- conduction - 25%,
- radiation - 45%,
- breathing - 10%.

Different ways of heat transfer from the human body through the human skin usually occur simultaneously. Due to this fact, the total heat transfer from the skin to the outer surface of the garment covering the skin and next to the environment is a complex process. The heat exchange between the body of the clothing user and the environment occurs by:

- convection and radiation inside the air-filled spaces between the layers of clothing, as well as inside the spaces between the fibers in yarns and between the yarns in fabrics that make up the individual layers of clothing,
- heat conduction through the garment (usually fibrous) material.

The crucial measure of the thermal insulation of textile materials is their thermal resistance. It is defined as the temperature difference between the two faces divided by the heat flux and has the unit of $Km^2\ W^{-1}$ [15].

2.1.2. Moisture Management

How well a specific fabric type can manage moisture plays a significant role in wearer comfort. Wearer’s perception of moisture comfort sensations and clothing comfort is directly related to the absorption of moisture or body sweat by the garment in the garment-skin microclimate, and moisture transportation through and across the fabric where it is evaporated.

The sweat produced by the human body during a firefighting activity should be absorbed from the skin by the surface of the next-to-skin layer of clothing and then gradually transferred to the layers further out in the clothing assembly. The use of multiple layers in the FPC makes the liquid transfer difficult by reducing the moisture management capability of the garment, resulting in the accumulation of sweat on the next-to-skin layer. As a consequence, the wearer suffers increased wet clinginess and thermal discomfort which may restrict the work time of the firefighter.

The clothing layers are barriers limiting the passage of water vapor. It results in the condensation of some part of sweat in the form of vapor and the formation of liquid moisture on the human skin, which is a direct reason of the sensation of discomfort. Moisture management properties of clothing are vital in this case [16-19]. Unlike the simple determination of fabric absorbency as well as wetting and wicking properties, a moisture management test measures the behaviour of dynamic liquid transfer in clothing materials. For example, moisture transportation through the FPC is a multidimensional process as a fractional amount of moisture can be absorbed in the first contact surface, some amount can go through the fabrics, and a small amount can be absorbed in the other surfaces [20].

For a firefighter, the transfer of external liquid to the skin is not desirable, whereas it is highly expected that the textile materials used in the FPC should allow the sweat to escape into the environment. These two desirable properties are self-conflicting for any fabric type. How much moisture will be absorbed in the first surface and how much will go to the opposite surface of the fabric depends on many fabric attributes such as fabric construction, raw material composition, surface finish, etc. Therefore, it is important to analyze the moisture management properties of fabrics intended for firefighting protective clothing. For FPC fabrics, moisture permeability is very important. It can be defined in two aspects: the transfer of liquid and the permeability index. The former provides an idea of how much protection the fabric type used may offer against harmful liquids from external sources, whereas the latter expresses the degree of sweat evaporation. The permeability index considers the dry heat resistance of a textile fabric and relates it with the escape of water vapor (sweat evaporation) through the clothing [18].

2.2. Firefighter’s protective clothing and its requirements

The FPC belongs to the category of Personal Protective Equipment. According to the European Regulation (EU) 2016/425 of the European Parliament and the Council [22] the term “personal protective equipment” (PPE) means:

(a) equipment designed and manufactured to be worn or held by a person for protection against one or more risks to that person's health or safety;

(b) interchangeable components for equipment referred to in point (a) which are essential for its protective function;

(c) connexion systems for equipment referred to in point (a) that are not held or worn by a person, that are designed to connect that equipment to an external device or to a reliable anchorage point, that are not designed to be permanently fixed, and that do not require fastening works before use.

According to the Regulation, the PPE must provide adequate protection against the risks against which it is intended to protect. It is a crucial feature and requirement. However, some other aspects are also taken into consideration, especially in the range of ergonomics and comfort.

In the case of ergonomics, the requirement is the following: “PPE must be designed and manufactured so that, in the foreseeable conditions of use for which it is intended, the user can perform the risk-related activity normally whilst enjoying appropriate protection of the highest level possible” [22]. From the thermo-physiological comfort point of view, the PPE must be designed and manufactured in a way that perspiration resulting from use is minimized. If it is not possible, the PPE must be equipped with means of absorbing perspiration.

2.2.1. Effects of the firefighter’s work environment

Due to technical progress in civil and industrial buildings and other sectors of the economy, the probability of fire hazards is increasing. In this regard, fire alarm protection, safety, and preventive measures are taken and the latest technology is used a lot. The difficulty of extinguishing fires requires a constant increase in the professional skills of the firefighter as well as modern technical equipment to ensure safety when extinguishing fires.

Environmental parameters during a fire are always different and are determined by many factors. These include the type of combustible material, stage of fire, size of building space, type of fire extinguishing agent used, etc. [23]. Therefore, the problem of improving the personal protective equipment of the firefighter, namely protective clothing, is of particular importance. According to statistics, exposure to high temperatures is one of the main causes of life-threatening injuries and injuries to the firefighter. Additionally, it should be taken into consideration that the firefighters participate also in different emergency operations such as roadway operations, aircraft fires, emergency medical, or flood. Each kind of emergency operation can pose completely different risks [24]. Due to this fact depending on the operation the firefighter should be equipped with different types of protective clothing. The basic type is so-called structural firefighting protective clothing. It is designed for activities required for rescue, fire suppression, and property conservation in structures, vehicles, vessels, and similar types of properties. Extreme heat exposure combined with high physical exertion can injure a firefighter. Therefore, as the temperature rises sharply in the interior of the FPC, the firefighter's body temperature increases, heart rate, and blood pressure increase which can lead to deterioration of well-being, loss of thermoregulation, and eventually heat stroke or burns [25]. Fire injuries can occur due to intense heat exposure and if proper techniques are not used, there is a high chance of being burned, even when wearing protective clothing. The firefighter needs to choose the right technique to stay in the dangerous fire zone according to the situation. The temperature between the thermal liner and the firefighter’s undergarment can reach from 48°C to 62°C before receiving burn injuries [26]. It has been identified that the pain threshold of human skin is around 44°C [27, 28]. When the skin temperature exceeds this threshold, the absorbed energy determines if and how severe burns will be received [29, 30]. The skin receives second-degree burns when skin temperature approaches 55°C [31].

Working in an extremely hot environment causes the following symptoms in the body system:

- in an environment with extremely high temperatures the normal functioning of the organ system is lost, its efficiency and effectiveness decrease, and it leads to mental tension,
- increased heat exposure can cause injuries such as heat stroke or thermal burns,
- a major cause of unconsciousness is heat stroke, which occurs as a result of general body overheating when the firefighter is exposed to high ambient temperatures for extended periods of time,
- during overheating and excessive sweating the body loses a lot of fluid, the blood thickens, the salt balance in the body is disturbed, and the tissues, especially the brain, are starved of oxygen.

When the firefighter performs operational and tactical tasks involving increased heat flow the normal duration of protective action is reduced. The main reason for this is the increased humidity of the multilayer material due to sweat which is a product of human organisms.

Providing the thermo-physiological comfort of the firefighter's body in the real conditions of working on fire is an important issue including determining the influence of people and the environment on the protective properties of protective clothing, and solving the structure and organization of materials. In order to implement this research it is necessary to measure and determine the temperature and humidity parameters of the underwear environment of the protective clothing, and to calculate the most favorable version of the underwear environment of the firefighter's special protective clothing. Therefore, it is important to study the effect of internal environment temperature and moisture on the protective properties of FPC.

2.2.2. Firefighter’s protective clothing

In general, firefighters wear two types of protective clothing:

- station uniforms while working in fire stations (Fig. 2.1.),

- special protective uniform (Fig. 2.2) while fighting fires such as structural building fires, wildfires, and vehicle fires [32, 33].

Fig. 2.1. *Exemplary station uniform for firefighter; https://starkam.pl/ubrania-koszarowe/1788-ubranie-koszarowe-strazaka-ribstop-kamizb-rekawow.html*

Fig. 2.2. *Exemplary special protective uniform for firefighters; https://pe.msasafety.com/Firefighter-Protective-Clothing/Structural-Firefighting-Garments/Ergotech-Action-2/p/ErgotechAction2*

Firefighters are exposed to many hazards associated with their work. Apart from many toxic substances in the ambient air, high radiant heat intensities and hot flames are common risks in fire extinguishing work [26]. Therefore firefighter wears clothing specially made for the work that they do and according to the predicted risks. The requirement of Personal Protective Clothing (PPC) for firefighters depends on the level of risk. According to Polish Standard [34] there are 2 levels of risk:

- Level 1 - describes the minimum requirements for the firefighting clothing involving work associated with outdoor firefighting and their support activities, taking into account the environments and conditions of the expected operational scenarios of such firefighting activities. Level 1 is not applicable for protection against risks encountered in fighting fires or rescue from fire activities in structures unless combined with a level 2 or other specialized PPE,
- Level 2 – describes the minimum requirements for firefighting clothing for risks encountered in fighting fires and rescue from fire in structures.

The distinction between clothing representing Level 1 and Level 2 is restricted to the requirements for heat and flame (X1 or X2 - Heat and Flame). These levels of protection can be reached by a single garment or a combination of separate garments. Additional marking provides two grades of protection for Y (protection against water penetration) and Z (water-vapor resistance). It is essential that these performance grades are indicated on the marking of the clothing and explained in the instructions for use.

The main task of PPE is protection from external dangers. In the case of the firefighter, this is fire, heat, or extinguishing water. At the same time heat and moisture produced by the human body should be transferred through the PPE to the ambient air and the mobility of the wearer should not be influenced by the PPE [35]. Depending on the conditions of the rescue action the firefighter can be also exposed to electric shocks, toxic substances as well as high or low temperatures [36]. Due to this fact, protection against these factors should be built-in into the functionality of the FPC.

The FPC typically consists of an overcoat, trousers, hood, and gloves. Other non-clothing assemblies may include self-contained breathing apparatus (SCBA), hand tools, ropes, etc. (Fig. 2.3) [37]. The FPC is part of the safety outfit of the firefighter on duty that protects them from dangers associated with heat, flame, hot or toxic liquid contact, abrasion, cuts, etc. Firefighter’s protective gear is a system or assembly combining both textiles and non-textiles to serve the sole purpose of keeping firefighters safe and functional in various hazardous situations. Each item either protects their body or helps them perform their duties.

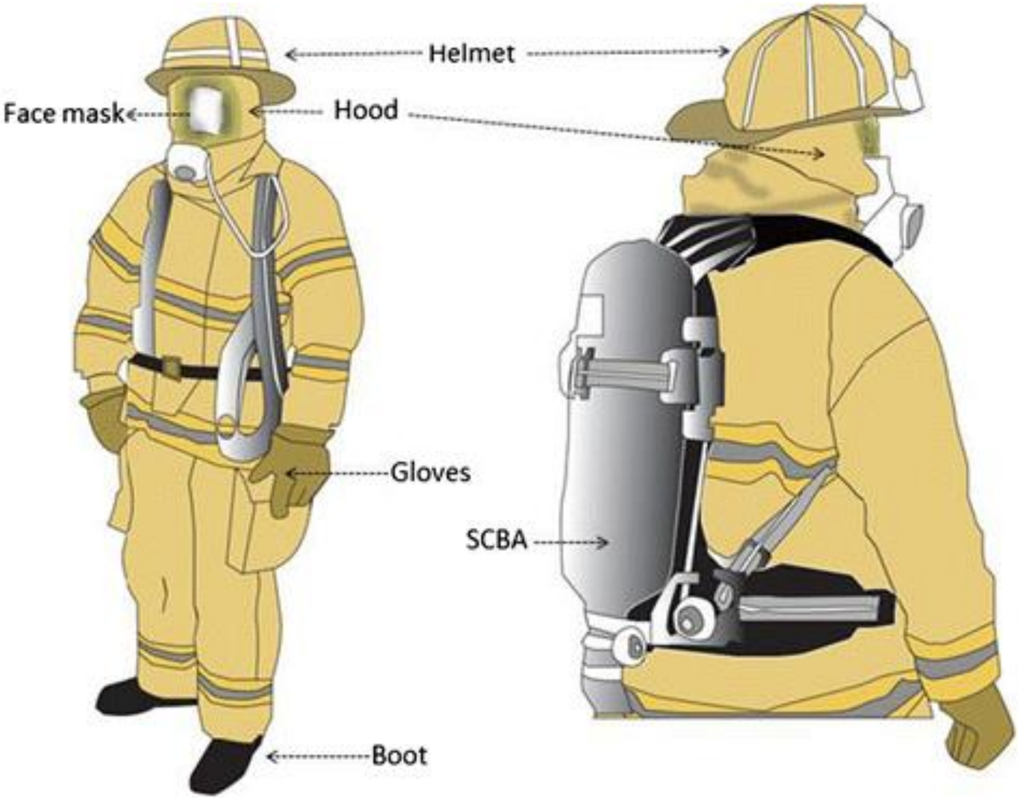


Fig. 2.3. *Firefighter's protective clothing and protective equipment [37]*

The FPC is made of high-quality materials which help to protect the rescuer from the negative impact in emergency situations. Clothing must resist heat, flames, and hot substances. International standards are available for testing such properties [38]. No clothing material can withstand continuous exposure to flame or can provide comfort for an infinite time in hot environments.

The FPC does not necessarily mean the fabric is completely resistant to fire and heat. The FPC is designed to save the firefighter from excessive heat and flash fire conditions by allowing them a time gap for a rescue mission, fighting the fire, or withdrawing from direct flame contact.

The purpose of the clothing is to reduce the rate of heat build-up on the skin caused by the firefighter’s exposure to the intense heat, to give them time to react, and to avoid or minimize any skin burn injury in critically dangerous situations [39-43].

For firefighting garments, the main concern is protection against heat, which can be experienced from any uncomfortably hot object or direct/indirect contact with flame. In burning buildings air may quickly become hot and humid, posing high levels of heat stress on the firefighter. The basic mechanisms of heat transfer in dry air are convection and radiation through clothing. Heat is transferred from the body if skin temperature is higher than ambient temperature. In hot air and in highly radiant conditions heat may flow from the ambiance to the skin surface. But clothing cannot only hide from fire. It also will not allow either strong wind or low temperature indicators to somehow affect the well-being of the rescue service worker. So products are heat-resistant and frost-resistant. The FPC reduces or even completely prevents the body's normal heat exchange with the environment. If it is a hot, dry environment, body cooling may take place by sweat evaporation. This process, however, is also restricted by the thick multilayer clothing.

The FPC is designed to extinguish fires in difficult climatic conditions, this is clothing that protects the human body in extreme conditions from dangerous fire factors and adverse environmental influences: precipitation, wind, and low temperatures (up to minus 50 degrees). In hot, humid air moisture may actually condense in clothing or, in the worst case, on the skin surface. The actual transfer of water-vapor depends on the direction and magnitude of the pressure gradient and the-vapor resistance of the intermediate layers of clothing. Above certain ambient temperature and humidity levels, there is no dissipation of heat by convection, radiation, and evaporation from the body.

The FPC is made from modern heat-resistant and frost-resistant materials with special coatings and impregnations. It is designed to protect the firefighter from the heat flux of high temperatures during firefighting and during related rescue operations as well as from the effects of adverse climatic factors [25, 39-44].

Designing the FPC is a challenging task. It requires making a compromise between two crucial but conflicting factors - maximizing thermal protection and minimizing heat stress. Thermal protection is undoubtedly the primary concern for the FPC. However, its effect on metabolic heat stress is also an important consideration. Hence, the FPC needs to be built with a balance of these two factors.

The process of heat transfer in a chain: Human body-Protective clothing-Environment can work in two modes of firefighter's work (Fig. 2.4):

- in the first mode the environment without the influence of high temperature or normal mode; at this time, the firefighter is performing work that is not related to firefighting (Fig. 2.4 a),
- in the second mode, the firefighter is in the high ambient temperature zone or when performing fire extinguishing operations (Fig. 2.4 b).

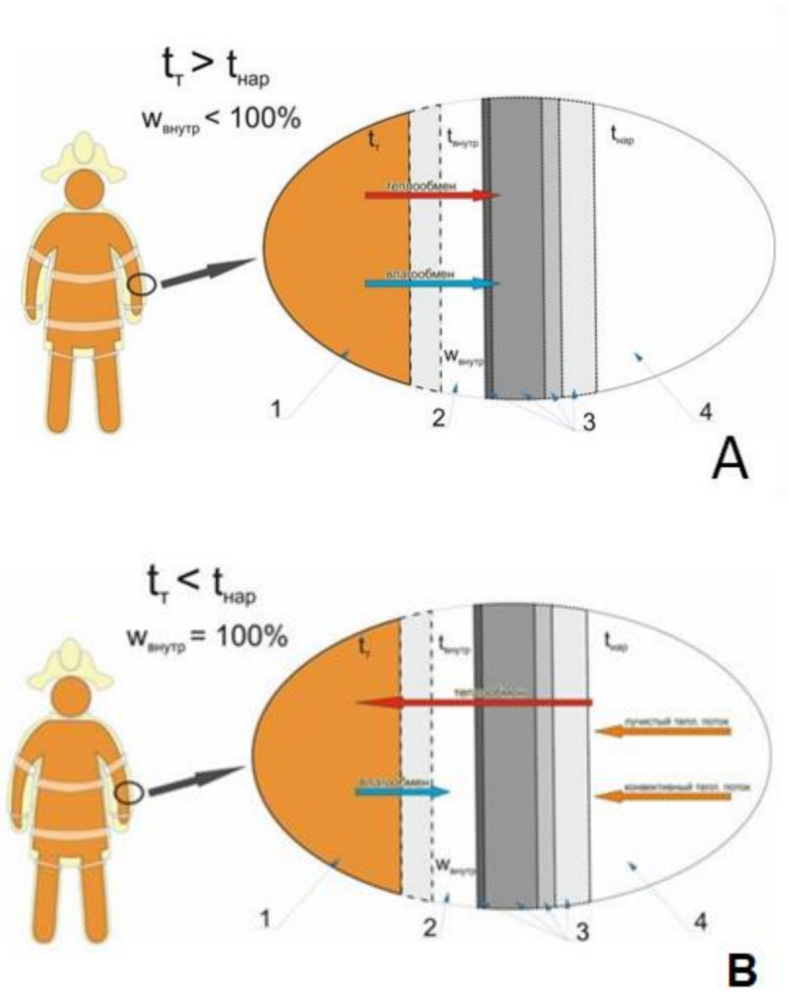


Fig. 2.4. *The process of heat transfer between Human - Protective clothing - Environment: A – environment without the influence of high temperature, B – high ambient temperature*; *1 – firefighter's body, 2 - air layer, 3 - set of protective clothing materials, 4 - external environment [45]*

In normal mode (Fig. 2.4 a), the ambient temperature (t_{HAP}) is lower than the firefighter's body temperature (t_T), and the humidity (W_{BHUTP}) in the space of the underwear is less than 100% (protective clothing is relatively dry). During intensive work the firefighter's body temperature increases, and the natural processes of thermoregulation in the human body are activated, cooling the body through breathing and sweating, and then evaporation of moisture from the body surface. Heat transfer is from a hotter body to a less heated body, and in such conditions heat transfer from the firefighter's body to the protective clothing and environment occurs by means of convection, radiation, etc. Moisture exchange occurs through contact and evaporation of moisture from the body's surface. In the process of moisture exchange the thermal insulation layer of the protective clothing becomes wet due to the perspiration of the firefighter. In order to create comfortable working conditions in normal mode it is necessary to remove heat and moisture from the firefighter's body which happens in practice.

During the high ambient temperature mode (Fig. 2.4 b) the heat transfer occurs differently if the ambient temperature (t_{HAP}) is significantly higher than the firefighter's body temperature (t_T) and the humidity in the space of the underwear (W_{BHUTP}) is 100%. The heat exchange is directed towards the firefighter's body, which causes the temperature inside the clothing to rise, which in turn increases the firefighter's body temperature. In air saturated with water vapor, water cannot evaporate, moisture condenses on the surface of the body, so sweat amount increases, but sweat does not evaporate. Therefore, the thermoregulation of the firefighter's body almost stops and is carried out only by breathing. But the exchange of moisture takes place by touch. Protective clothing becomes wet, and because of this the thermal protection properties are significantly reduced, and a condition is created where thermal shock and burns are possible. In high ambient temperatures, the human body performs thermoregulation with the help of sweating and accelerates the temperature increase in the interior of protective clothing [45].

Harsh thermal conditions directly affect human health, performance, and comfort. The interaction between the human body and functional clothing, e.g. the PPE can be described by measurements of comfort-related parameters of protective clothing and materials used in it. For the PPE these parameters and performance requirements are given in standards such as EN 469:2005 [46] for the firefighter or EN ISO 11611:2007 [47] for welding and allied processes. First, the PPE should protect the wearer from external influences such as fire, heat, weather, and water. Also, it should protect from internal dangers such as overheating which can cause - in the worst case - cardiovascular failure or heat stroke. These important but minimalistic thermo-physiological requirements are given in the standards and describe insensitive sweating. Further, it is desirable that the PPE is comfortable, too. So, the sensible sweating state of the human body should be characterized more in detail for the PPE [35].

The investigations of human body responses to hot environmental conditions have been an object of many research works [48-59]. The investigations concerned psychological, ergonomic, and physiological aspects. In the case of psychological and ergonomic investigations, utility trials with volunteers are most often performed. Numerous investigations confirmed that firefighters are exposed to enormous stress in their work. They should receive psychological help and support from different organizations to reduce operational and post-operational stress. On a psychological level, it could be relevant to help firefighter to have effective strategies in the face of their sustained stress, eliminating rumination and facilitating emotional expression. During firefighting operations, the physiological responses and stress level goes up significantly [56]. This may cause a reduction in the capacity of information processing and decision-making while rescue operations. As stated that the environmental, physical, and emotional stress to which the firefighters are subjected during their firefighting activities could lead to occupational hazards, injuries, and even fatal events. Cardiovascular, thermal, and psychological responses deriving from the firefighter could be caused by fatigue and this could compromise the health and safety of the firefighter. An increase in body temperature leads to a decrease in physical and mental performance [59].

In the case of the physiological aspects, the utility trials with the volunteers are applied on a par with instrumental research [60 – 67]. In the utility trials the core-body temperature, skin temperature, heart rate, and blood pressure are determined while wearing the special FPC in different configurations with station uniform and underwear in climatic chambers of different ambient climatic conditions. At the same time, the temperature and humidity of air in the underclothing space are monitored. The FPC in different sets is also tested instrumentally, usually using thermal manikins [60 - 62]. Most often the textronic solutions are applied to monitor the health and physiological parameters of firefighters in firefighting or other rescue operations (Fig. 2.5) [63, 64].

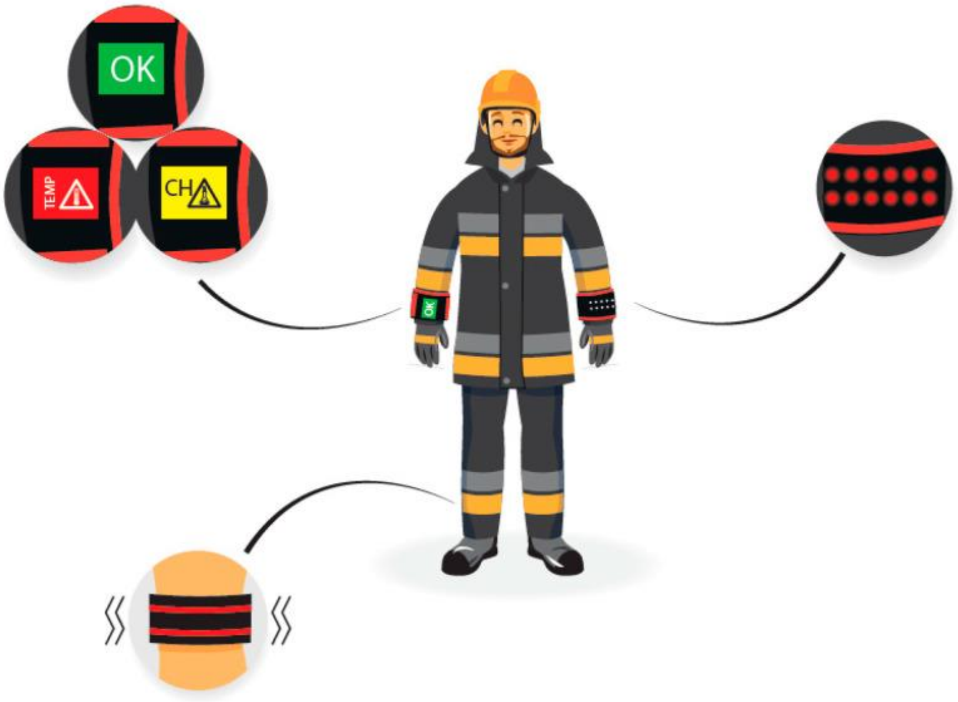


Fig. 2.5. *Scheme of Personal Warning System for integration in the FPC [64]*

In Poland, the leading institute dealing with the testing of the FPC is the Central Institute for Labour Protection – National Research Institute [55, 60, 61, 64, 67].

There are also numerous research works aimed at the investigation and optimization of materials used in the FPC and multilayer assemblies for the FPC [68-71]. In general, the protective properties of the materials and assemblies are tested according to appropriate standards. They are the crucial features of the FPC and their measurement is obligatory for the certification of the materials and clothing [41].

There are also innovative, highly advanced testing methods and computational tools applied in the investigation and optimization of the materials for the firefighter's clothing, such as high-resolution X-ray micro-tomography, thermography or finite element analysis, computational fluid dynamics analysis, neural network, etc. [36, 72-76].

It should be mentioned here that the FPC will decrease the protective properties with wear. During the analysis of the works of researchers [77-81], the following main reasons for the decrease in the thermal protection properties of protective clothing were identified:

- increased humidity of protective clothing materials due to increased perspiration of the firefighter during heavy work at high temperatures, due to the external effects of fire extinguishing agents and internal moisture,
- as a result of mechanical action the thickness of the thermal insulation layer of the FPC is reduced, which is due to repeated mechanical and thermal effects such as bending the knees and elbows in the sitting position, compressing the shoulder area with the weight of the breathing apparatus, and compressing the bundles of materials together; this leads to the absence of air space between the materials, which leads to a decrease in thermal insulation properties,
- increase heat transfer of reflective tapes and logos,
- thermal degradation of the protective clothing material continues without visible changes in the outer layer, leading to a significant reduction in the thermal stability of the material.

2.2.3. Structure and properties of the firefighter’s protective clothing materials

It is impossible to develop a set of modern protective clothing materials without understanding the mechanisms of the effect of fire on people, i.e. the system "Environment - Protective clothing - Human" [21]. The FPC should protect the wearer against different external factors existing in the working (rescue) environment (Fig. 2.6) and simultaneously protect against overheating ensuring the sweat evaporation.

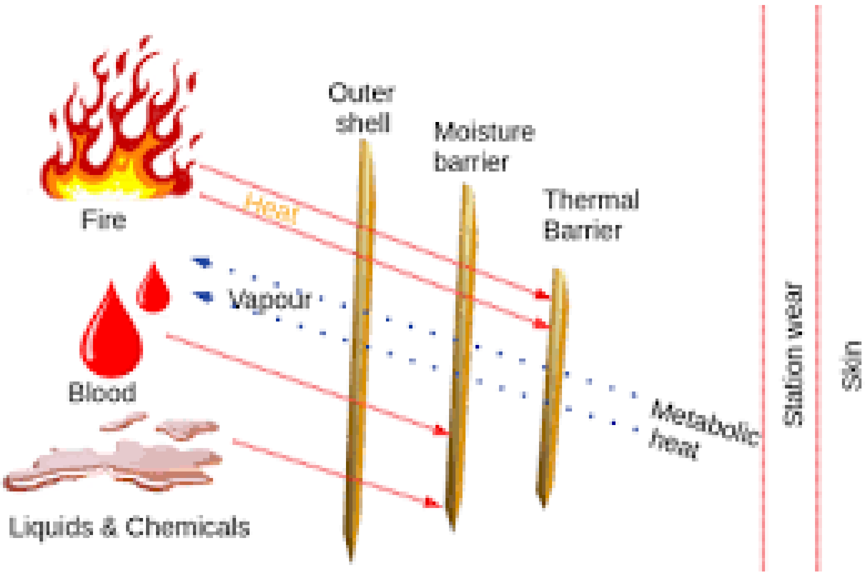


Fig. 2.6. *Environment – firefighter's clothing - body interaction [82]*

The firefighter's protective clothing fabrics are required not only to ensure that the clothing does not become a means of secondary ignition and spreading of fire and causing injury but also to provide a certain degree of comfort from hot and humid situations both externally and internally, while still maintaining acceptable working efficiency through easy and quick movement. Hence, the fiber characteristic, heat source, intensity, time of exposure, and many other variables affect the protection performance.

In general, the FPC is a multilayer assembly composed of various types of woven and nonwoven fabrics, in some cases also knitted fabrics. In many scientific works the FPC is presented as a three-layered assembly (Fig. 2.6, 2.7). The standard turnout coat worn by the firefighter has traditionally been a multilayer structure containing the outer shell, moisture barrier, and thermal barrier (Fig. 2.7, 2.8). The outer shell layer material is made of non-flammable fabric intended for protection against an open fire and mechanical impact. It should also protect against toxic substances. The moisture barrier layer is made of polymer material to protect against the negative effects of moisture and wind, whereas the thermal barrier layer is made of materials with low thermal conductivity to protect against thermal effects.

[60].

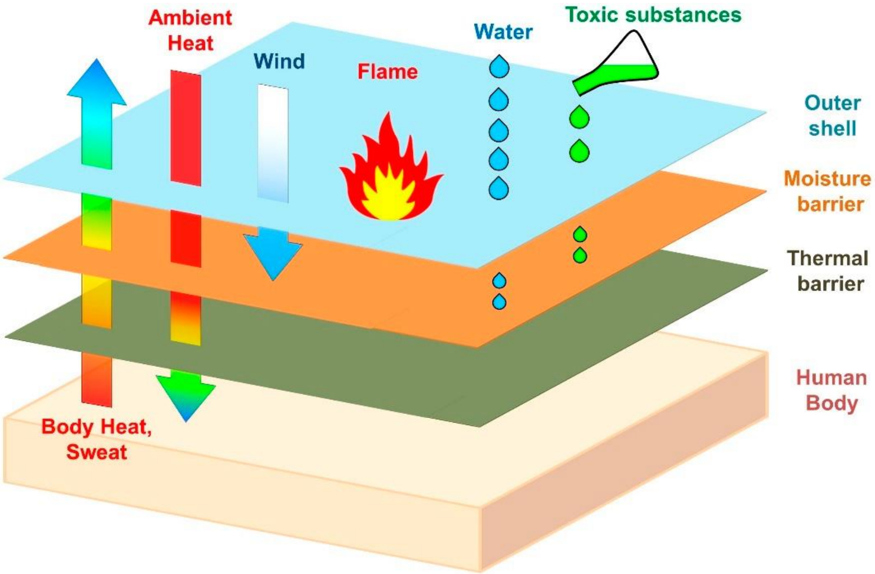


Fig. 2.7. *Exemplary scheme of the multilayer textile assembly applied in the FPC [36]*

Fig. 2.8. *Exemplary picture of layers applied in the FPC [33]*

Considering the FPC as a three-layer assembly is not entirely correct. The mentioned layers: outer shell, moisture barrier, and thermal barrier are the basic components. The outer shell is usually covered by special impregnation, whereas the thermal insulation nonwoven is protected by the lining (Fig. 2.9) [60].

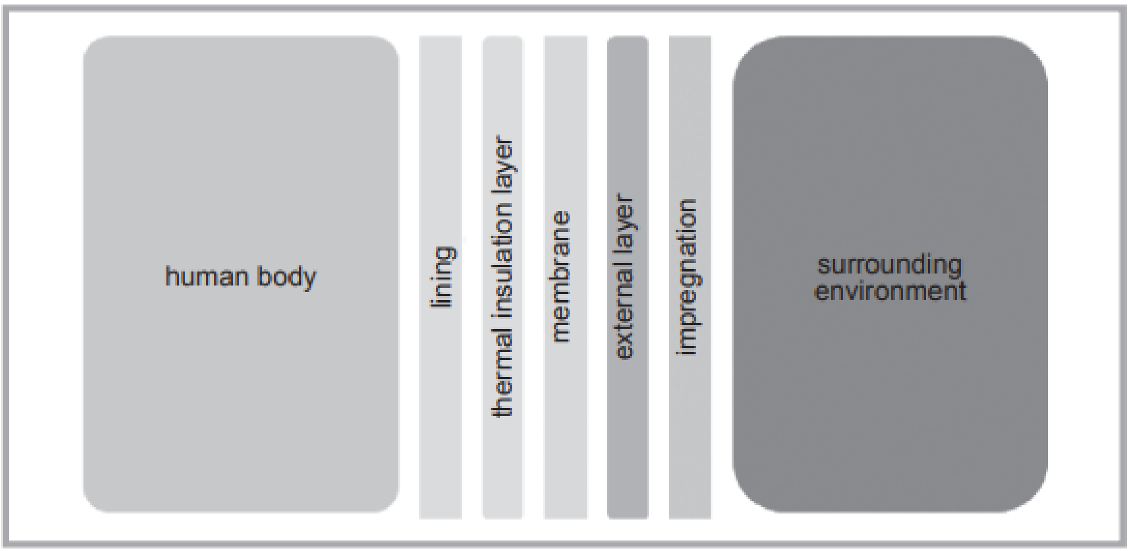


Fig. 2.9. *Structure of a package of the FPC materials [60]*

What's more? In the case of the thermal barrier, it is not single material. It is usually two-layer. Due to the fact that the FPC is thick, stiff, and heavy, it is impossible to wear it without underwear. Thus, while considering the chain: Environment – Firefighter's clothing – Firefighter's body the underwear should be also taken into consideration (Fig. 2.10) [83].

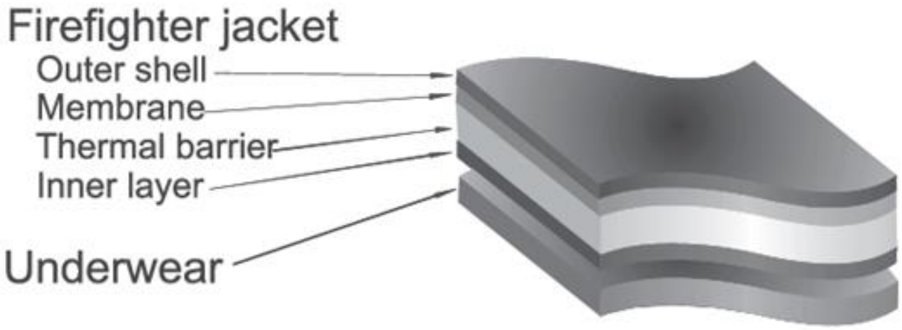


Fig. 2.10. *Scheme of the FPC materials with underwear [83]*

According to current rules, special protective clothing should be worn together with the station uniform (Fig. 2.11) [83].

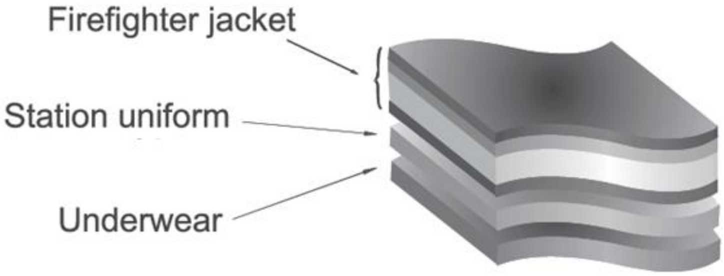


Fig. 2.11. *Scheme of the FPC materials with underwear and station uniform [83]*

Taking the above into consideration the complete firefighter's outfit in action consists of six layers (Fig. 2.12) which are barriers for the dangerous external factors. Unfortunately, they are also barriers to the transfer of metabolic heat and sweat produced by the human body.

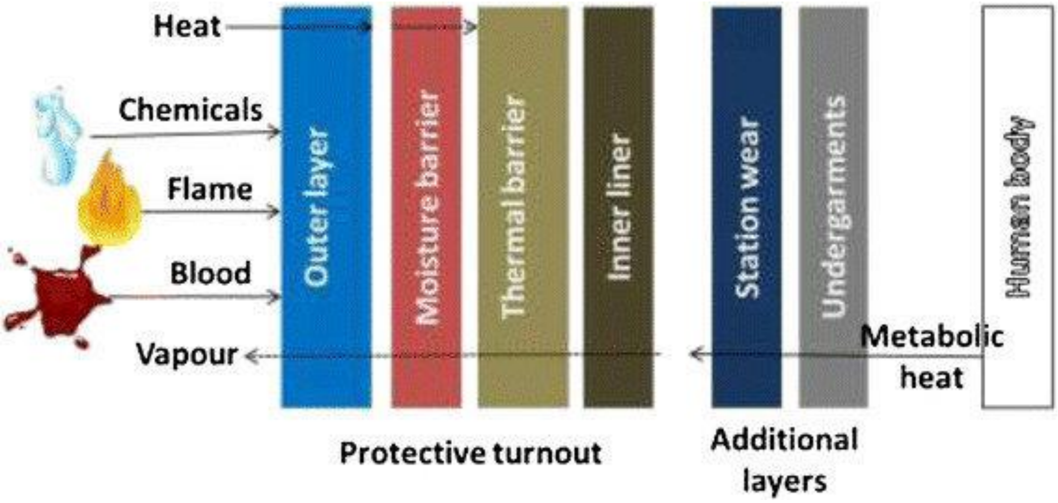


Fig. 2.12. *Schematic diagram of the FPC and function of various layers [49]*

In some publications, the schemes show that the multilayer for the FPC is permeable for both metabolic heat and sweat (Fig. 2.6, 2.7, 2.13).

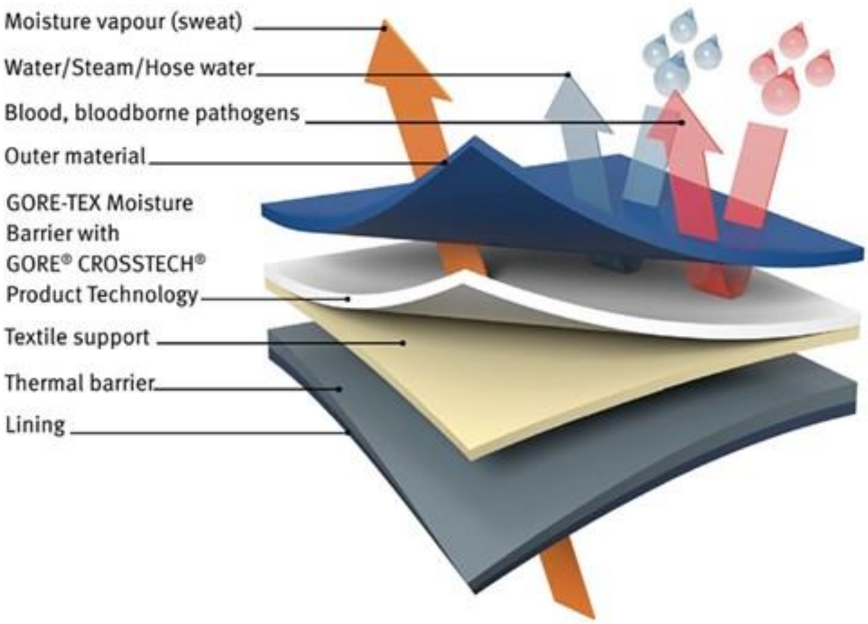


Fig. 2.13. *Scheme of moisture transport through the multilayer package for the FPC; https://www.fire-magazine.com/why-moisture-in-ppe-threatens-firefighter-safety*

But it is not true. The multilayer assembly creating the firefighter outfit is characterized by high water-vapor resistance. Due to this fact, sweat in the form of vapor usually is not fully transferred outside. Some amount of sweat condenses on the skin. The moisture barrier of the FPC is a barrier not only for the external moisture but also for the internal moisture originating from sweat (Fig. 2.14).

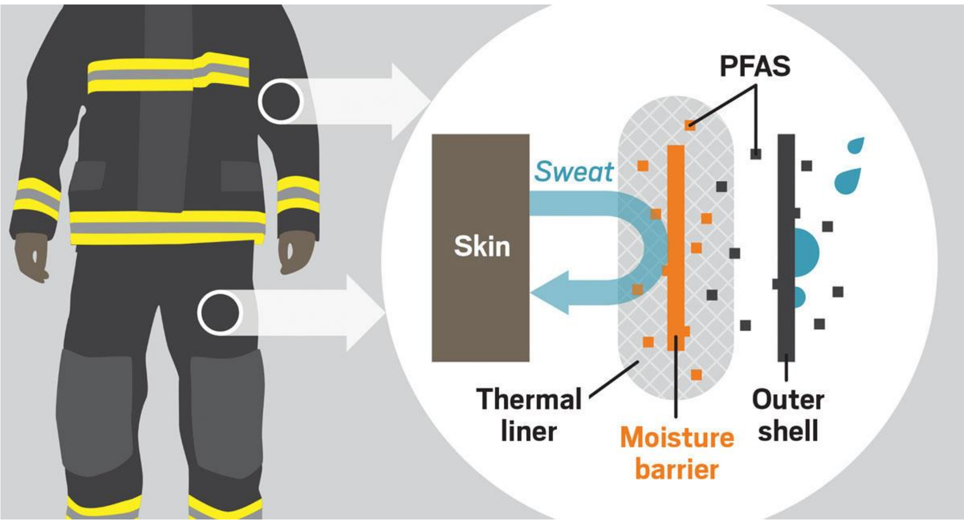


Fig. 2.14*. Scheme of sweat movement inside the FPC; https://cen.acs.org/environment/persistent-pollutants/Protective-gear-expose-firefighters-PFAS/98/i26*

According to the analysis of the publications it should be mentioned that the problem of transport of sweat produced by the human body through the clothing assembly worn by the firefighter in action is not recognized deeply. In some research works it is completely overlooked. Similarly, the issue of underwear which is suitable for the firefighter is not the subject of extensive research.

Nawaz et al., [84] investigated commercially available knitted fabrics suitable for the skin layer of the FPC but only in the range of sensorial comfort. They performed measurement of friction by means of the KES-FB4 (Kawabata Evaluation System) instrument [85, 86]. Measurements have been performed for dry and wet fabric samples. It was stated that fiber content and fabric structure are the most critical parameters to influence the fabric surface properties relevant to sensorial comfort. The single jersey structures turned out to be the best to be used next to the skin and 100% wool and wool blended with bamboo provide better sensorial comfort as compared to 100% cotton, or 100% polyester. The last conclusion is questionable. The wool fibers are rough due to the presence of scales on the surface of the fibers (Fig. 2.15) and thus can irritate the skin. People with sensitive skin cannot always wear wool products next to the skin. Moreover, wool fibers absorb moisture [87]. But they take a long time to dry. It is not beneficial for physiological comfort.

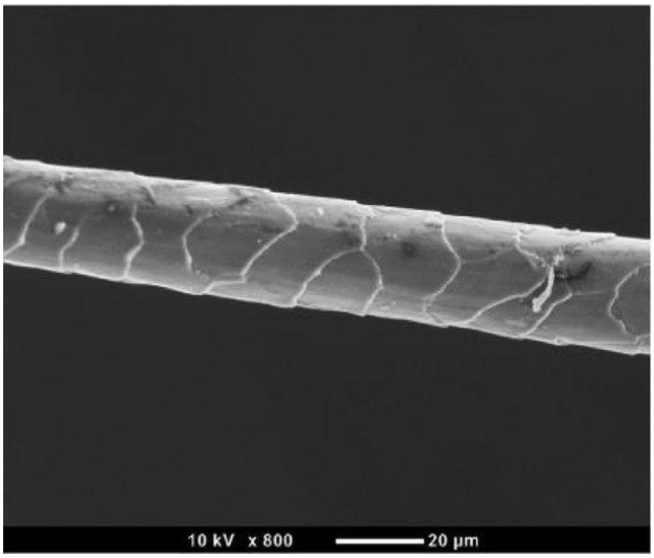


Fig. 2.15. *Microscopic picture of wool fibre [88]*

Petrusic et al., [89] investigated the firefighter underwear fabrics of three fiber compositions (aramid/viscose, cotton, and cotton/Protex®) in the range of moisture transport. The underwear fabrics were also tested in combination with three types of woven linings. They stated that underwear composed of a combination of natural and synthetic fibers transfer liquid moisture away from the next-to-skin surface faster and more efficiently than those based on cotton, regardless of the knit type. The underwear fabric connected with the aramid/viscose lining showed the most satisfying absorption and wicking abilities required for the efficient transfer of liquid moisture and moisture vapor [88]. Matusiak and Sukhbat analyzed the liquid sweat transport in knitted fabrics for underwear [90]. They investigated the fabrics in unstretched and stretched forms. The results showed that stretching significantly influences – improves the ability of the knitted fabrics to transfer liquid moisture through them.

Outer Shell Fabric

The outer shell is the first line of defense for the firefighter. The protection required has various aspects and no single fabric can meet all of those. The outer shell fabric should protect the firefighter from fire in flash-fire conditions or when entering a burning building. It needs to have sufficient tensile strength with acceptable abrasion and cut resistance to support crawling or climbing in rescue missions. FPC also needs to be relatively light, flexible, and breathable to avoid heat stress and hindrance in movement. Hence, the fiber choice for the outer layer is important and needs to consider price, performance, and comfort.

The fiber for the outer layer is traditionally selected from any of the high-performance inherently flame-retardant fibers. As approximately 21% oxygen is present in the air, fiber with a limiting oxygen index (LOI) value over 21% will not support combustion in the air. Thus, the higher the LOI value is, the lower the flammability risk will be [90]. In general, a fabric to be defined as flame retardant should have a minimum LOI value of 26–28% [91]. Currently, aromatic polyamides (aramids), and Polybenzimidazole (PBI) and their blends are commonly found in the outer layer fabric of the FPC due to their price and favorable properties [41]. They are offered on the market with different trade names, such as Nomex (meta-aramid) Kevlar (para-aramid), Twaron (para-aramid), etc. However, due to the emergence of new technologies and novelty fibers, manufacturers of FPC are continuously developing favorable blends with various fiber alternatives to bring optimum balance in price, comfort, and protection.

It is a reality that no single fiber can meet all the requirements of an outer layer fiber. As an example, the widely used p-aramid is famous for its strength and abrasion resistance, but it suffers from degradation and strength loss when exposed to sunlight. M-aramid and PBI are comparatively more stable to ultraviolet degradation and have better heat resistance, but they lack strength. One fiber may have a high LOI value but lower melting temperature, such as Polyvinyl chloride (PVC) fibers, whereas some non-melting fiber, such as Novoloid (phenolic fiber - a thermoset organic fiber produced from a phenolic novolac resin, Kynol®) [91-93], the wool may have a comparatively lower LOI value. The selection of a suitable fiber type and fabric structure is another important consideration.

The flame retardant finishing is also applied for outer shell fabrics made of different fiber blends, for instance, cotton or cotton/ polyester [94-97].

Moisture Barrier

Although a waterproof layer is incorporated into the design of protective clothing to protect against environmental moisture, moisture can enter the material package not only from the environment but also from human perspiration during intense physical exertion and high temperature. The amount of moisture transferred to a package of protective clothing materials can be significant, and it is necessary to account for human perspiration parameters during the intensive work of the firefighter wearing the special protective clothing. In this case, the amount of moisture released can increase the thermal conductivity of the insulating layer of protective clothing. Therefore, if the firefighter performs work at an increased heat flow, the normal duration of the protective action of the protective clothing is reduced. The effect of human body temperature and humidity on the thermal protection properties of the FPC is significant [21].

The purpose of the moisture barrier is to impart breathability in the FPC [36, 41, 98]. This barrier layer makes the FPC impermeable to water while it allows the moisture vapor to pass through. In this way, the firefighter remains protected against hot water and toxic liquids while the sweat can be vaporized and dissipated to the environment.

Moisture barriers may not be mandatory. In some countries, firefighters like to have their fire suits without a moisture barrier, whereas in other countries it is obligatory [38]. Micro-porous hydrophobic, perm-selective membranes, hydrophilic nonporous membranes, or their combination can be used. In most cases, the expanded polytetrafluoroethylene (PTFE) micro-porous membrane (Fig. 2.16) is used as a moisture barrier in a bi-component structure with PU foam that creates an air cushion [49, 99, 100].

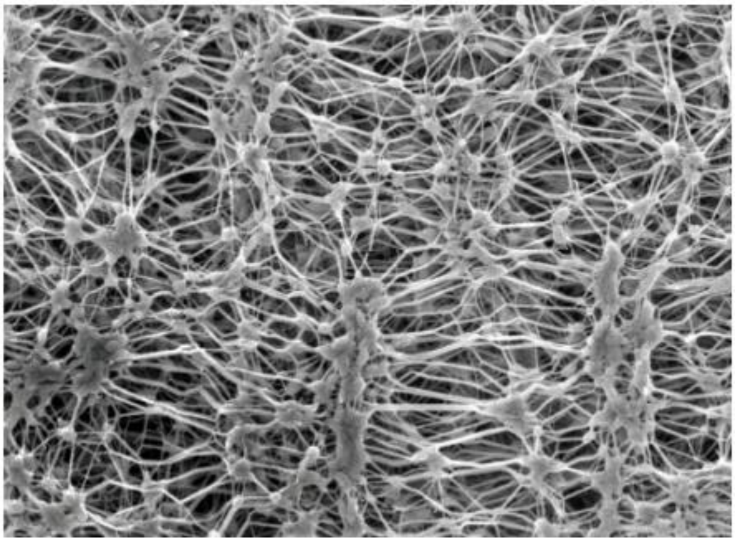


Fig. 2.16. *Microscopic picture of the Gore-tex membrane*
https://www.gore-tex.com/blog/the-gore-tex-membrane-what-it-is-how-it-works-and-why-you-need-it

In the micro-porous hydrophobic membranes, a “breathing” procedure is done by permitting sweat in the form of water-vapor molecules to transmit by interconnecting micro-pores instigated by heat and high humidity. Transportation of liquid water is inhibited by micro-pores because they are 100 times smaller than droplets of water (Fig. 2.17) and by surface tension effect due to the hydrophobic nature of membranes [101, 102]

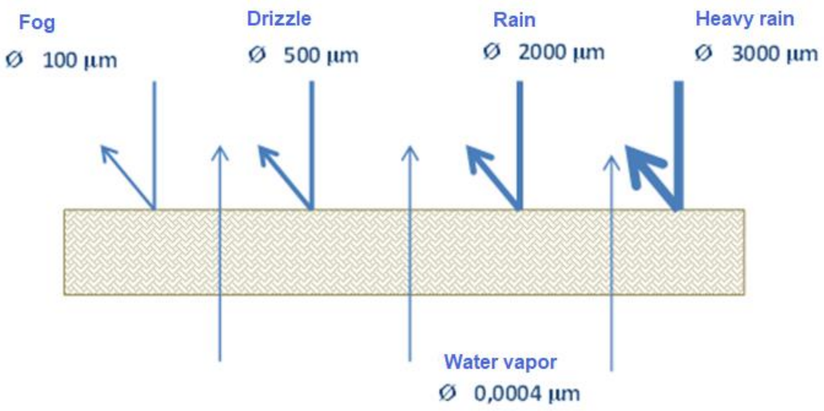


Fig. 2.17. *Principle of work of the semipermeable membrane [102]*

There are also hydrophilic nonporous polymeric membranes (Fig. 2.18) based on polyurethanes (PU), polyester, or polyamides [49, 103].

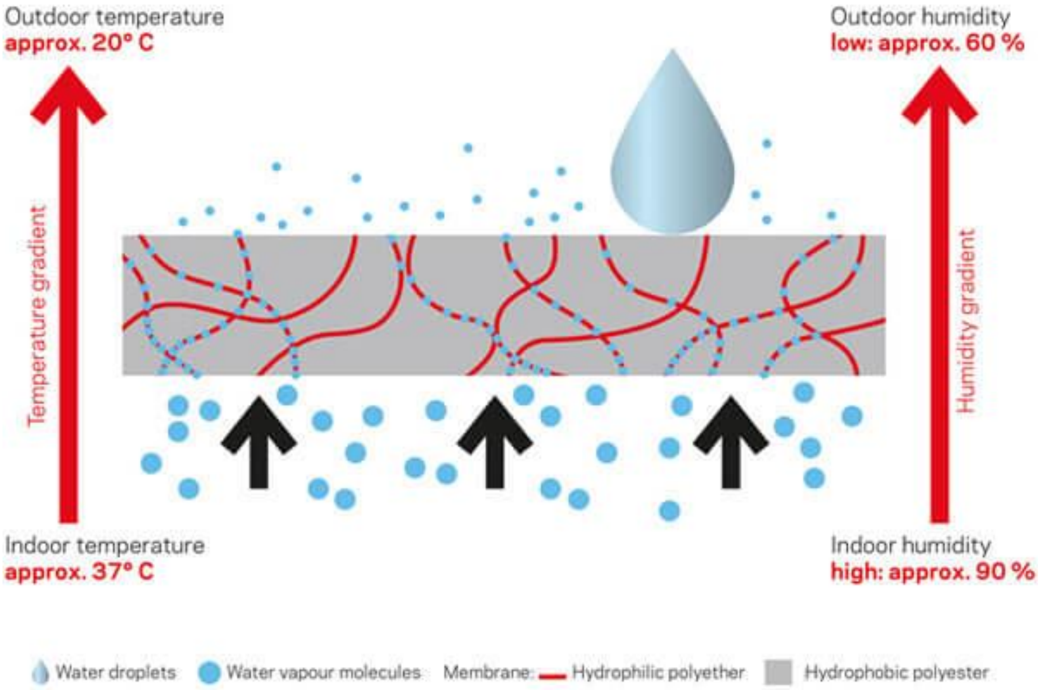


Fig. 2.18. *The idea of the hydrophilic membrane;*
https://www.alpinetrek.co.uk/blog/sympatex/

Breathable moisture barriers in the FPC are generally constructed by lamination or coating of the water-vapor permeable membrane with a woven/non-woven substrate [82]. Sometimes an additional hydrophilic coating is also applied on top of the PTFE membrane [104].

Thermal Insulation Fabric

The thermal insulation layer of the FPC usually contains a nonwoven batting attached to a face cloth. The thermal liner is the most critical component in turnout gear as it has the biggest impact on thermal protection and heat stress reduction. The face cloth of the thermal liner is conventionally a thin woven fabric. Air is trapped in or between the nonwoven materials of the thermal liner, and thus together with the moisture barrier, the thermal liner provides 75% of the total thermal protection of a turnout garment [41].

Nonwoven is a fabric structure built without twisting of the fiber (as in yarn) or interlacing of yarn (as in fabric), resulting in a lofty textile construction unless pressed. Hence, nonwoven textiles can accommodate the high volume of air pockets in much lower-weight textiles, which can be used as a barrier to heat transmission. In knitted or woven fabrics, fibers are held together by frictional force. However, in nonwovens, fibers are held together either by frictional force (fiber entanglement) or an adhesive system (thermal or chemical bonding) [105, 106].

Fig. 2.19 shows a complete fabric assembly in the exemplary FPC where a nonwoven batting material is quilted with the fabric. The face cloth of the thermal insulation layer is conventionally a thin woven fabric.

Fig. 2.19. *Fabric assembly in FPC: from left, Nomex outer layer, STEDAIR moisture barrier and thermal liner showing nonwoven batting and woven Nomex face cloth*

The layers of the protective clothing material package may be integrated with each other. For example, a layer covered with a polymer film (moisture barrier) can be combined with an outer shell material and an inner cotton surface with a thermal protection layer.

The WL Gore company developed non-textile thermal insulation material for the FPC – GORE-TEX® AIRLOCK™ spacer material (Fig. 2.20) made of foamed silicone [41]. The GORE®AIRLOCK® system consists of a two-layer laminate composed of a PTFE layer on a meta-aramid / para-aramid non-woven fabric with chemical-resistant spacers silicone material.

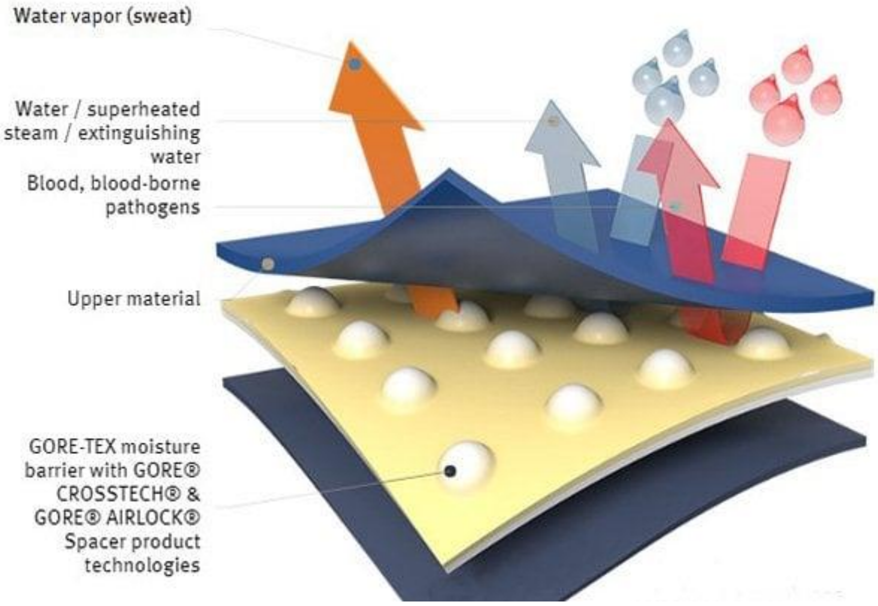


Fig. 2.20. *Airlock™ spacer material;*
https://ballyclarelimited.com/ballyclares-partnership-with-w-l-gore-i27

According to the manufacturer, the combination of thermally protective insulation with a moisture barrier in the inner lining means that less moisture is stored in the individual layers of clothing so that they dry faster. The lighter clothing reduces the risk of heat stress and allows working safely for longer [107].

Knitted fabric for underwear

As has been proven in many studies, clothing worn close to the body (underwear) has a significant impact on the user's thermal sensations. Discomfort associated with the use of protective clothing can be significantly reduced by using appropriate underwear or undergarments. During hard exercise like in the case of a firefighter's mission the sweat produced by the firefighter’s body should be transferred through the clothing material assembly to the ambient air. If this is not the case heat and moisture accumulate in the clothing. Therefore, the concentration and performance of the firefighter decrease [35, 84].

There are currently no requirements for undergarments used under protective clothing. Due to the fact that it is worn close to the body and that protective clothing could increase worker safety when exposed to hot factors, undergarments are very important elements of protective clothing [23].

Underwear as the body's “second skin”, has a function of body protection and ventilation. Due to this fact a choice of material for firefighter’s underwear is also particularly important. People undergo a variety of body movements in daily life while parts of the body’s skin occur in different deformation. If the material can be deformed and can adapt to these resiliencies, it will make people feel comfortable [108]. On the contrary, it will hinder the body’s activity, bring some pressure, people feel discomfort. It has poor elongation performance and high friction of underwear, the body will have a high-pressure feeling, on the contrary, will be more comfortable. But the material resilience and flexibility of the thickness will be a greater impact on the underwear’s comfortable performance.

So far, in the underwear market, cotton, and viscose fibers are the basic raw materials for underwear. Both have similar chemical compositions based on cellulose. Viscose fibers are man-made fibers made of natural cellulose. Viscose is not as durable as cotton, but it's also lighter and smoother in feel [109. 110].

In the knitted fabrics used for the t-shirts, the cotton/polyester blends are used too. They tend to be stronger than pure cotton fabrics, while also offering a wider variety of textures. While 100% cotton may not be as durable as some polyester blended fabrics, its ability to offer comfort across seasons makes garments versatile and offer convenience. It is easy to take care of. Cotton blended with polyester fabric is versatile and durable. They maintain shape longer and have a softer, lighter feel.

The cotton and viscose fibers have very good hygienic properties resulting from moisture absorption. But they are weak while dehydrating (hard to dry). It causes liquid moisture to be retained inside the underwear structure

[111]. Due to this fact currently, synthetic fibers are applied in underwear, especially so-called moisture management fibers [112-115]. They do not absorb the water. Due to the special structure, they transfer the liquid moisture from human skin outside the clothing without absorbing it. The general idea of fibers with the function of "moisture management" is the appropriate shape of the fibers (Fig. 2.21), enabling maximum absorption of sweat and its rapid spreading over the surface of the product, which ensures its rapid evaporation.

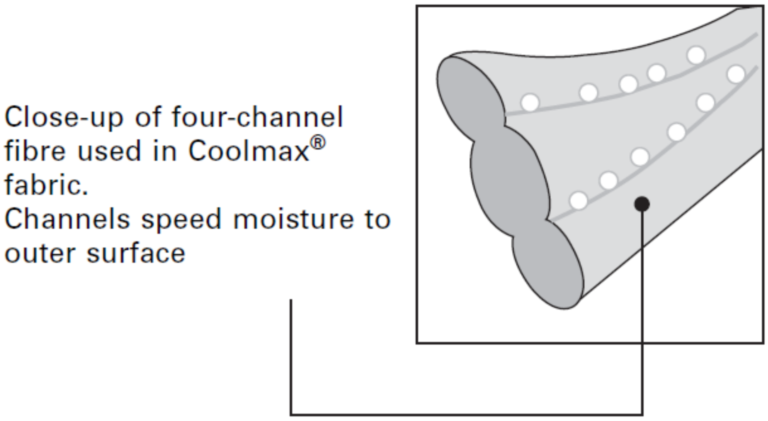

Close-up of four-channel fibre used in Coolmax® fabric.
Channels speed moisture to outer surface

Fig. 2.21. *The Idea of the Coolmax fibres [113]*

The term "moisture management fibers" is more and more commonly used, which describes this group of fibers very well. On the surface of these fibers there are channels that facilitate and direct gas exchange between the human body and the environment.

The underwear usually has been made from a knitted fabric and does in the form of a T-shirt and shorts [23, 84, 116-120]. Knitted fabric is a finely textured garment material created by looping a single yarn and tying the loops together. Knitted fabrics must meet the requirements of hygiene and durability (using). Knitted garments are less wrinkled than woven garments, have good elasticity and contraction without restricting the free movement of the human body, have good heat and air permeability, are easy to wash and clean, and can withstand multiple washes, and wear has several advantages such as. Knitted fabrics are used in a variety of garments and are widely used in underwear that comes in direct contact with the human body [116].

Underwear is a regular item of clothing regardless of the season. Underwear is the closest to the human body, so the material must be breathable, comfortable, non-allergenic, non-irritating, and well-absorbed. Therefore, underwear knitwear needs to be moisture and air permeable, low shrinkage, light, soft, and easy to clean. The main parameter that determines the properties of knitted fabrics for underwear is the composition of the fibers or fabrics involved. The most important thing is the texture of the material used for underwear. Therefore, cotton, polyester, viscose, linen, silk, and their various variants are usually used. The fabric properties, such as moisture and air permeability and heat retention depend on it's the composition of the fibers in a fabric.

The underwear material that a person wears every day, must be able to allow air to pass through and absorb perspiration without interfering with the body's thermal conductivity in hot weather, and in combination with other layers of clothing to maintain the body's thermal balance in cold weather. Knitted fabrics are generally light in weight, comfortable to wear even during travel, but yet require little care to keep their neat appearance. The tendency of knits to resist wrinkling is another factor to boost up their popularity. Knitted fabrics are used for designing active clothing such as sportswear [120].

Another parameter of the underwear material is the density of the material. The density of the fabric is expressed in weight per square meter and varies from 90 to 250 grams, depending on the type and quality of the material. The higher the density of the material, it's the higher the wear resistance. However, the density of the fabric does not reflect all the properties of the material. Thinner fabrics are more comfortable, stronger, and more durable. The density of the material is directly related to the type of loop and yarn, and the thickness of the fabric. What distinguishes a knitted fabric from other materials is its ability to stretch and shrink, which depends on the type of loop of the knitted material and the properties of the yarn [121].

Stretching of the knitted fabric is characterized by an increase in its size under the action of external forces. Stretching is the advantage of knitted fabric and is determined by the amount of deformation during stretching and the amount of stretching during tearing. Clothing made of elastic knitwear provides good freedom of movement, is comfortable to wear, and returns to its original shape after stretching. Knitted materials are classified according to their stretching as low stretching (0-40%), medium stretching (40-100%), and high stretching (more than 100%). The amount of stretching is inversely related to the diameter of the yarn and is directly related to the length of the loop. The longer of loop and the narrower of yarn, it is the greater stretching of the knit.

Shrinkage is the inverse property of stretching and is the property of decreasing the length and width of a material over a period of time after stretching or during processing. Shrinkage of knitted fabrics also lasts longer during use, especially after washing.

In addition to geometric and mechanical properties, physical properties are important in knitted fabrics. Underwear is in direct contact with the human body, which has a positive effect on maintaining the body's thermal balance during changes in physical activity, as well as be able to maintain a balance of perspiration, moisture, and the microclimate that develops around the skin, which can be caused by body heat. The thermal stability of the human body is measured by the temperature of the skin, which is lost through the microenvironment of the garment to the underwear and then to the external environment. Therefore, the thermal properties of underwear materials are one of the important application properties. The thermal properties of the fabric depend on the density of the fabric, the thickness of the material, the size of the loop, and the composition of the yarn [122].

Since the structure and properties of lingerie knitwear are interrelated, it is important to choose the appropriate option depending on the application environment.

2.3. Conclusion from the literature review

Summing up the literature review it must be stated that the source literature is very broad. It is obvious because the topic is of great significance. It is impossible to describe all research works performed in the field of the FPC. The clothing is multifunctional and influences the safety and health of firefighters in action.

Some conclusions are the most important:

- protection against dangerous external factors existing in firefighting and other rescue actions such as fire, flame, high temperature, chemicals, and radiation is the main/ crucial role of the FPC,
- the protective functions of the FPC are obtained and provided by an application of innovative fires, materials, and technologies,
- the protective properties of the FPC are tested and certified according to appropriate international standards
- the comfort-related properties of the FPC are also very important for ensuring the efficiency of the firefighter in action,
- in some cases the protective properties of the FPC are in contradiction with its comfort-related properties; it concerns mostly the transport of sweat produced by the firefighter's body,
- the FPC is a multilayer assembly; each layer plays its specific function or functions,
- the material composition of the firefighter's clothing assembly should be selected taking into account the conditions and dangerous factors existing in firefighting or rescue actions,
- the FPC is worn together with the underwear which should be taken into consideration while assessing and/or modelling the protective and comfort-related performance of the firefighter's outfit,
- there are not any specific requirement concerning the underwear for the firefighter; it is important gap taking into account that the underwear is next-to-skin layer of the firefighter's outfit in action.

3. Theoretical considerations of the heat and liquid moisture transfer of textile assembly for protective clothing

As it was mentioned earlier (Chapter 2) the FPC is composed of several layers. Mostly there are four layers:

- outer shell made of woven fabric,
- moisture barrier; it can be a semipermeable membrane,
- thermal insulation layer; usually the nonwoven
- lining made of woven fabric.

Additionally, it is obvious that the FCP is worn together with underwear, and due to this fact, the transfer of heat and mass in clothing worn by the firefighter should be considered as a complex phenomenon consisting of several components. Apart from the physical phenomena, it is necessary to take into consideration the transfer of heat and mass in particular layers as well as the transfer of heat and mass in the air layers between particular components of clothing assembly.

3.1. Heat transfer in the multilayer textile assembly

Clothing creates the thermal barrier for heat flow from the human body to the environment. Usually, clothing is a multilayer assembly constituted of different textile materials: woven, knitted, and/or nonwoven. Particular fabrics creating the individual layer of the garment are characterized by their thermal resistance. It is a measure of the temperature difference by which an object or material resists a heat flow. The thermal resistance of textile material is expressed by the following equation [123]:

$$R = \frac{h}{\lambda} \qquad (3.1)$$

Where: R – thermal resistance,
h – fabric thickness,
λ – thermal conductivity of the material.

The temperature difference is the driving force of the heat flow. Usually, the ambient air temperature is lower than the temperature of the human body (Fig.3.1). Due to this fact, heat flows from the human body to the environment.

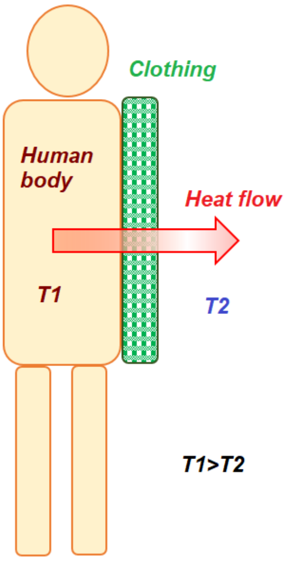


Fig. 3.1. *Heat flow from the human body to the environment through the clothing*

In such a situation, the heat flows through the clothing barrier as follows:

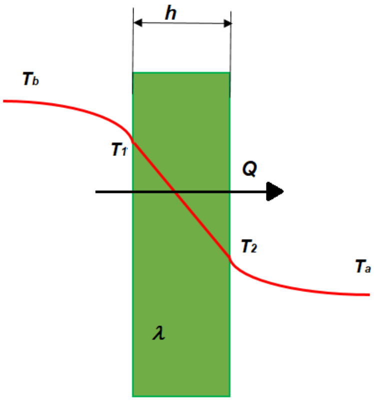


Fig. 3.2. *The scheme of heat flow through the barrier*

Where: Q – heat flow through the clothing assembly,

h – thickness of the clothing assembly,

λ – thermal conductivity of clothing assembly,

T_1 – temperature of the inner surface of clothing assembly,

T_2 – temperature of the outer surface of clothing assembly,

T_b – temperature of the human body,

T_a – ambient temperature ($T_a < T_b$).

The presented scheme is very simplistic and assumes that a clothing assembly is a homogeneous object. In reality, the clothing assembly consists of different materials of particular layers. Each material creating the clothing assembly has its thermal conductivity which is a feature of the material. The thickness of each layer can be also different. Taking into, account the scheme of the heat flow through the clothing assembly can be presented as follows:

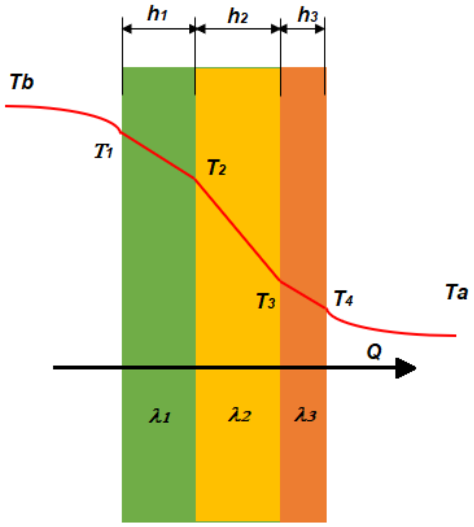


Fig. 3.3. *The scheme of heat flow through 3-layer textile assembly*

In the Fig. 3.3 the following symbols are applied:

Q – heat flow,

Tb – temperature of the human body,

Ta – ambient temperature,

λ_1, λ_2 λ_3 – thermal conductivity of particular layers, appropriately: first, second and third layer,

h_1, h_2, h_3 – thickness of particular layers, appropriately: first, second, and third layer,

T_1, T_2, T_3, T_4 – temperature of the surface of particular layers.

In the presented situation, the individual layers of clothing assembly create the serial connection. In analogy to the electrical resistance, the thermal resistance of a multilayer textile assembly is a sum of the thermal resistances of individual layers creating the assembly. The set presented in Fig.3.3 above (three-layer set), it is:

$$R_{CA3L} = R_1 + R_2 + R_3 \qquad (3.2)$$

Taking into account equation (3.1) it is:

$$R_{CA3L} = \frac{h_1}{\lambda_1} + \frac{h_2}{\lambda_2} + \frac{h_3}{\lambda_3} \qquad (3.3)$$

Where:

R_{CA3L} – thermal resistance of clothing assembly consisting of parallel materials,

h_1, h_2, h_3 – thickness of individual layers, appropriately: first, second, and third layer,

λ_1, λ_2 λ_3 – thermal conductivity of individual layers, appropriately: first, second, and third layer.

The general formula for the multilayer clothing assembly composed of several parallel layers is as follows:

$$R_{CA} = \sum_{i=1}^{n} R_i \qquad (3.4)$$

Where:

R_i – thermal resistance of the i^{th} layer,

i = 1 – n, where: n - number of layers,

and in consequence:

$$R_{CA} = \sum_{i=1}^{n} \frac{h_i}{\lambda_i} \qquad (3.5)$$

Where:

h_i – thickness of the i^{th} layer,

λ_i – thermal conductivity of the i^{th} layer.

Thermal conductivity is a characteristic feature of the material. In the case of textile materials, it is assumed that they are homogenous objects. In reality, there are not homogenous. In the structure of the textile materials, there are fibers and air spaces. The fibers can be in the form of yarns (knitted, woven fabrics) or in the form of loose fibers (nonwovens). The air spaces are between the fibers and between the yarns in the fabric (Fig. 3.4).

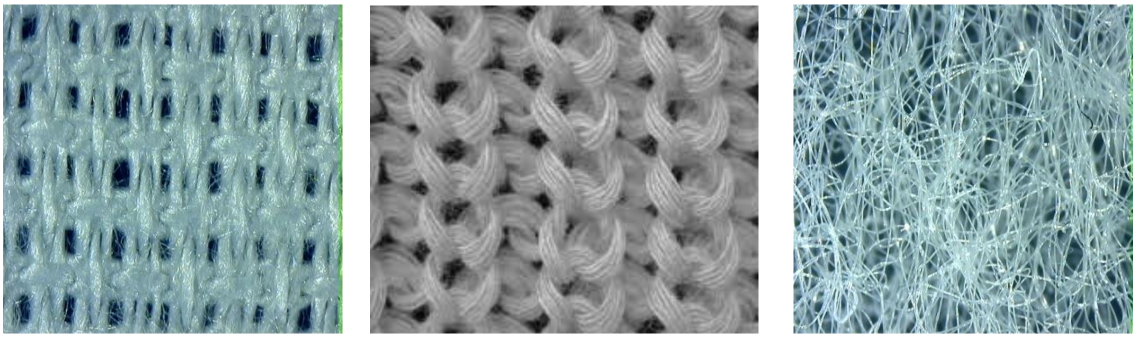


Fig. 3.4. *Microscopic pictures of the textile materials: woven, knitted, and nonwoven*

Due to this fact, in the case of textile material of a porous structure, the term effective or equivalent thermal conductivity is more accurate. The effective thermal conductivity of the textile materials depends on the content of fibrous material and air in the fabric volume. The effective thermal conductivity of the textile materials depends on the mass per square meter which expresses the quantity of the fibrous component being a good thermal conductor, the thermal conductivity of fibers, and volume porosity which expresses a volume of air closed into the fabric's structure. The volume porosity of textile materials is expressed by the following equation [124]:

$$P = 100\left(\frac{1-m}{1000}\right)h\rho \qquad (3.6)$$

Where:

P – volume porosity of fabric, in %

m – mass per square meter of fabric, in g/m^2,

h – thickness of fabric, in mm,

ρ - the relative density of the fiber/polymer, in g/cm^3.

Taking it into account, the effective thermal conductivity of textile material is the function of mass per square meter and thickness of the fabric, the relative density of the fibers, the thermal conductivity of the fibers, the thermal conductivity of the air:

$$\lambda_{ef} = f(m, h, \rho, \lambda_f, \lambda_a) \qquad (3.7)$$

Where:

λ_{ef} – effective thermal conductivity of textile material,

λ_f – thermal conductivity of the fibers,

λ_a – thermal conductivity of the air.

It should be mentioned that the thermal conductivity of the air depends on the humidity of the air.

Dias and Delkumburewatte [125] elaborated on the following model:

$$\lambda_{ef} = \frac{\lambda_f \cdot \lambda_a \cdot \lambda_w}{(1-P) \cdot \lambda_a \cdot \lambda_w + (P - P \cdot V_w) \cdot \lambda_f \cdot \lambda_w + P \cdot V_w \cdot \lambda_f \cdot \lambda_a} \tag{3.8}$$

Where:

λ_w – thermal conductivity of water in the fabric,

V_w – volume share of water in the fabric volume.

It is very difficult to determine the volume share of water in the fabric structure. Due to this fact, the Farnworth model is more convenient to express the effective thermal conductivity of textile materials [126]:

$$\lambda_{ef} = (1 - P_\phi) \cdot \lambda_a + P_\phi \cdot \lambda_f \tag{3.9}$$

Where:

P_ϕ - packing density of the fabric. It is equivalent to the filling factor.

Taking the above into consideration the effective thermal conductivity of fabric should be introduced into the equation (3.5) [127]. The effective thermal conductivity is usually determined by measurement using different testing methods, for instance, the Alambeta [127].

While analyzing the thermal resistance of the multilayer textile assembly applied while clothing wearing, it is necessary to take into consideration that the individual layers of clothing assembly may be adjacent to each other or they may be at some distance (Fig. 3.5). In the second case, there are the air spaces between the individual layers. The air closed in a small limited area is a thermal insulator because the thermal resistance of the air in spaces between individual layers of textile assembly is greater than the thermal resistance of textile materials. In such a case, the thermal resistance of multilayer clothing assembly with the air spaces between the individual layers creating serial connection is as follows (Fig. 3.5):

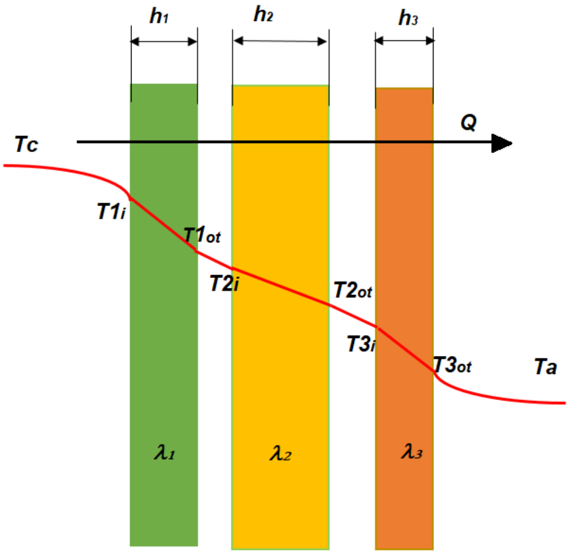


Fig. 3.5. *Scheme of heat flow through three-layer textile assembly with air zones*

For the case of the three-layer assembly presented above (three-layer assembly with air zones between layers), the thermal resistance of the assembly is the sum of the thermal resistance of individual textile layers and the thermal resistances of the air zones:

$$R_{CA3L+A} = R_1 + R_2 + R_3 + R_{a1} + R_{a2} \qquad (3.10)$$

Where:

R_{CA3L+A} – thermal resistance of clothing assembly consisted of three layers of parallel materials and the air spaces between layers,

R_{a1} – thermal resistance of the air in space between the 1st and 2nd layer,

R_{a2} – thermal resistance of the air in space between the 2nd and 3rd layer.

Finally:

$$R_{CA3L+A} = \frac{h_1}{\lambda_1} + \frac{h_2}{\lambda_2} + \frac{h_3}{\lambda_3} + \frac{h_{a1}}{\lambda_{a1}} + \frac{h_{a2}}{\lambda_{a2}} \qquad (3.11)$$

Where:

h_{a1} – thickness of the air in space between the 1st and 2nd layer,

h_{a2} – thickness of the air in space between the 2nd and 3rd layer,

λ_{a1} – thermal conductivity of the air in space between the 1st and 2nd layer,

λ_{a2} – thermal conductivity of the air in space between the 2nd and 3rd layer.

According to the PN-EN ISO 6946 standard, the thermal conductivity of air in unventilated air depends on the thickness of the air layer. For the horizontal heat flow, it is:

- in the zone of 0 mm width is 0 $m^2 \cdot K/W$,
- in the zone of 5 mm width is 0.11 $m^2 \cdot K/W$,
- in the zone of 7 mm width is 0.13 $m^2 \cdot K/W$,
- in the zone of 10 mm width is 0.13 $m^2 \cdot K/W$.

Intermediate values can be obtained by linear interpolation.

For poorly ventilated air layers their thermal resistance is assumed to be 50% of the value read for unventilated air layers.

The general form of the equation (3.11) for multilayer clothing assembly with the air spaces between layers is the following:

$$R_{CA+A} = \sum_{i=1}^{n} \frac{h_i}{\lambda_i} + \sum_{j=1}^{m} \frac{h_{aj}}{\lambda_{aj}} \qquad (3.12)$$

Where:

R_{CA+A} – thermal conductivity of multilayer clothing assembly with the air spaces between layers,

h_i – thickness of the i^{th} textile layer, i = 1 – n,

λ_i – thermal conductivity of the i^{th} textile layer, i = 1 – n,

n – number of textile layers in the clothing assembly,

h_{aj} – thickness of the j^{th} air layer,

λ_{aj} – thermal conductivity of the j^{th} air layer,

m – number of air layers between individual textile layers in clothing assembly, j = 1 – m and m = n - 1.

While wearing clothing, the direction of the clothing assembly varies dependably on the shape of the body surface covered by clothing. Some parts of the clothing area lie on the body being covered some others are hanging. In clothing engineering, we distinguish the supporting surfaces of the body. For garments hanging over the shoulders, the retaining surfaces are limited by the spatial curves of the circumference of the neck and upper parts back, shoulders, and breasts and lines that run through the most protruding points of the breasts and shoulder blades (Fig.3.6).

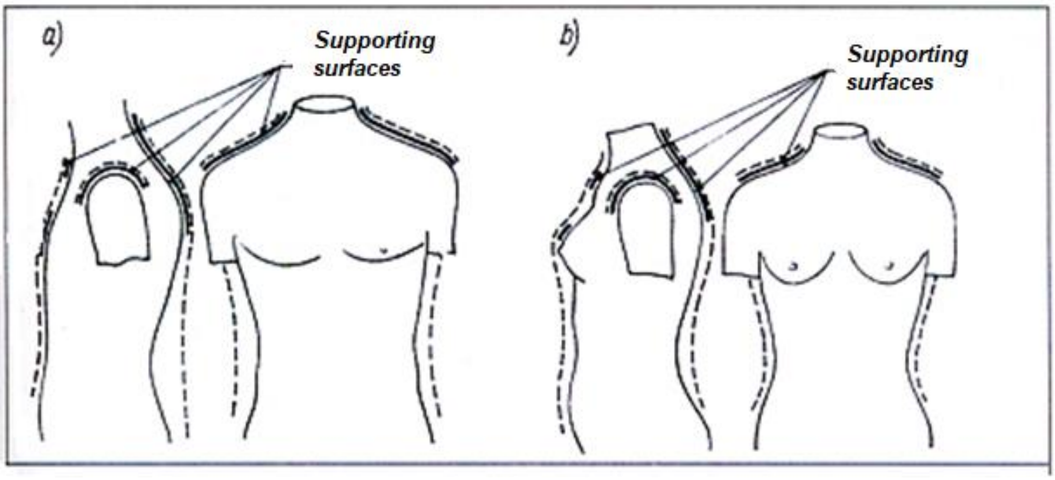
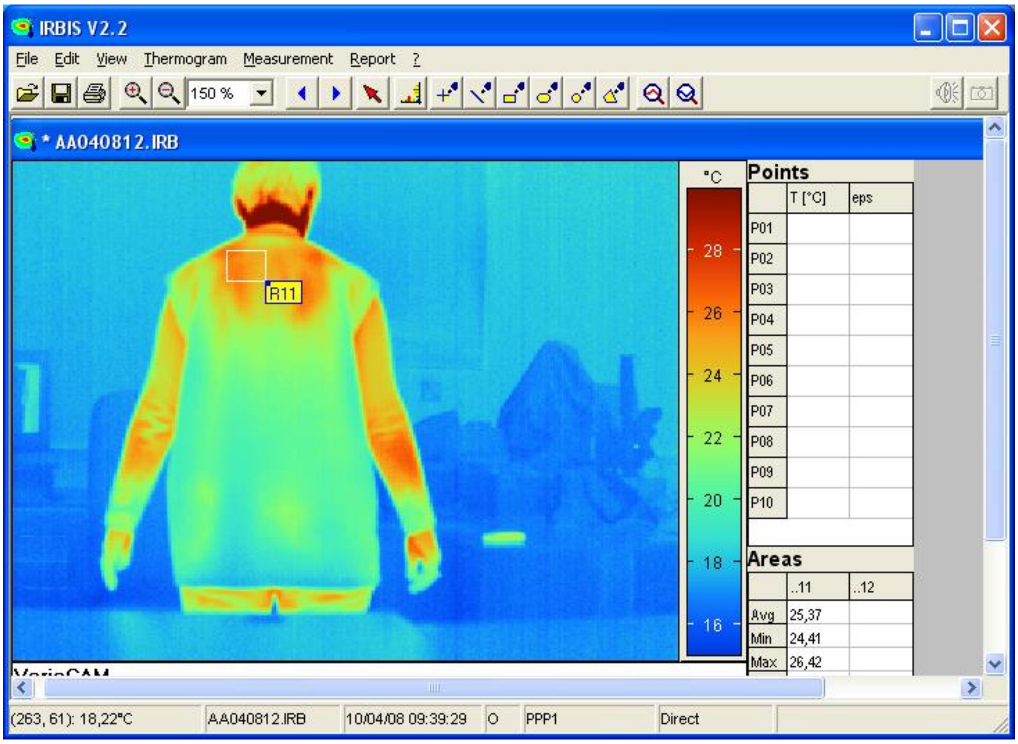


Fig. 3.6. *Supporting surfaces of clothing: a) men's clothing, b) women's clothing [128]*

The clothing adheres to the user's body on these surfaces, and the layers of clothing assembly stick to each other due to gravity. On the rest of the body surface the clothing is hanging more or less freely depending on the garment's construction and fit. In these parts of clothing assembly, the air spaces exist and influence the thermal insulation of clothing. Due to this fact, the heat transfer through the clothing assembly can be different in different areas of the assembly (Fig. 3.7) although the material structure of the assembly is the same as the whole surface. In the picture below it is clearly seen that on the shoulders and neck, the temperature is significantly higher than on the other surface of the vest being measured. It means that in these areas (shoulders and neck) the thermal insulation of clothing assembly is lower than in the areas where clothing is hanging loosely.



Points

	T [°C]	eps
P01		
P02		
P03		
P04		
P05		
P06		
P07		
P08		
P09		
P10		

Areas

	..11	..12
Avg	25,37	
Min	24,41	
Max	26,42	

Fig. 3.7. *Thermogram from the IR camera presenting the temperature distribution on the vest surface*

The FPC is rather loose fitting-clothing. Due to this fact, the thermal insulation of air layers between the individual materials creating the FPC should not be omitted. It is difficult to assess the share of loose hanging parts of the FPC and parts lying on the human body in the total area of the FPC. However, it is necessary to distinguish both kinds of garment area. Parts lying on the user's body and parts hanging freely create a parallel connection. In analogy, the electric resistance, the total thermal resistance of clothing assembly creating the parallel layout of individual thermal resistances can be expressed by the following equation:

$$\frac{1}{R_{CAP}} = \frac{f_h}{R_h} + \frac{f_l}{R_l} \qquad (3.13)$$

Where:

R_{CAP} – total thermal resistance of clothing assembly creating the parallel connection of thermal resistances of clothing parts hanging lying on the body surface,

R_h – thermal resistance of clothing parts hanging loosely,

R_l – thermal resistance of clothing part lying on the supporting surfaces of the human body.

f_h – the relative area of clothing parts hanging loosely on the user’s body,
f_l – the relative area of clothing parts lying on supporting surfaces of the user’s body.

The relative area means the share of a given area in the total area of clothing. For the three-layer textile assembly applied in the garment it should be:

$$\frac{1}{R_{CAP}} = \frac{f_h}{R_1+R_2+R_3+R_{a1}+R_{a2}} + \frac{f_l}{R_1+R_2+R_3} \quad (3.14)$$

According to the equation (3.1), the formula is the following:

$$\frac{1}{R_{CAP}} = \frac{f_h}{\frac{h_1}{\lambda_1}+\frac{h_2}{\lambda_2}+\frac{h_3}{\lambda_3}+\frac{h_{a1}}{\lambda_{a1}}+\frac{h_{a2}}{\lambda_{a2}}} + \frac{f_l}{\frac{h_1}{\lambda_1}+\frac{h_2}{\lambda_2}+\frac{h_3}{\lambda_3}} \quad (3.15)$$

From equation (3.15), the thermal resistance of the three-layer clothing assembly that consisted of the parts adjacent to the user’s body and the hanging loosely on the user’s body can be calculated as follows:

$$R_{CAP} = \frac{1}{\frac{f_h}{\frac{h_1}{\lambda_1}+\frac{h_2}{\lambda_2}+\frac{h_3}{k_3}+\frac{h_{a1}}{\lambda_{a1}}+\frac{h_{a2}}{\lambda_{a2}}} + \frac{f_l}{\frac{h_1}{\lambda_1}+\frac{h_2}{\lambda_2}+\frac{h_3}{\lambda_3}}} \quad (3.16)$$

In the aforementioned analysis, the convective heat transfer was omitted and at the same times the convective resistance from the air and convective resistance to air. The general formula of the total thermal resistance of the multilayer clothing assembly is the following:

$$\frac{1}{R_{CA}} = \frac{f_h}{\sum_{i=1}^{n}\frac{h_i}{\lambda_i}+\sum_{j=1}^{n-1}\frac{h_{aj}}{\lambda_{aj}}} + \frac{f_l}{\sum_{i=1}^{n}\frac{h_i}{\lambda_i}} \quad (3.17)$$

3.2. Liquid moisture transfer in multilayer textile assembly

Liquid moisture flows through textile materials is controlled by two processes: wetting and wicking. The term „wetting” is usually used to describe the displacement of a solid-air interface with a solid-liquid interface [129]. It is an initial process, involved in fluid spreading on the fabric surface. This process is controlled by the surface energies of the involved solid and liquid [130]. Wettability is a potential of a surface to interact with liquids with specified characteristics [131]. According to Harnett and Mehta [132], wettability is the initial behavior of a fabric, yarn, or fiber when brought into contact with a liquid. It also describes the interaction between the liquid and the substrate prior to the wicking process.

Wicking is the spontaneous flow of a liquid in a porous substrate driven by capillary forces. As capillary forces are caused by wetting, wicking is a result of spontaneous wetting in a capillary system [130, 133]. Wicking can only occur when a liquid wets fibers assembled with capillary spaces between them. The resulting capillary forces drive the liquid into the capillary spaces [131, 133]. As the gaps between the individual fibers become thin the force increases. Thus, finer fibers will have smaller gaps and better moisture transport.

In the research work performed in the Ph.D. thesis, the Moisture Management Tester (MMT) has been applied to assess the liquid moisture transport in individual materials and the set of materials issued in the FPC. In the applied testing method the samples being measured are placed vertically. Due to this fact during the test, the vertical wicking process takes place.

In textile materials made of hygroscopic fibers such as cotton, the liquid is absorbed by fibers. Cotton fibers are built of pure cellulose, a naturally occurring polymer. In cellulose molecules, there are negatively charged OH groups on the outer edge. These groups attract the water molecules and make cellulose and cotton absorb water well. These hydroxyl groups of cellulose bond water inside the cotton fibers [134]. This bonding limits the movement of liquid caused by capillary forces because this movement takes place in capillaries between fibers whereas absorbed liquid is inside the fibers’ structure. It also concerns other hygroscopic fibers and materials made of them.

While measuring the liquid moisture transport using the MMT the liquid movement is observed in three aspects [135 - 139]:

- liquid absorption by inner and outer surfaces of the sample due to the hygroscopicity of fibrous component,
- spreading the liquid on the inner and outer surfaces of the sample due to the capillary forces.

- one-way transport of liquid from the inner surface to the outer surface of the measured sample (fabric).

It is difficult to assess the share of the particular aforementioned mechanism in the total movement of liquid during the MMT test. It depends on the structure of the fabric being investigated, especially the compactness of the structure, the geometric surface of the inner surface of the investigated fabric as well as the hygroscopic properties of the fibrous component. In the case of multilayer clothing assembly, it is difficult to assess the movement of liquid in particular layers. However, some assumptions can be done based on the procedure of measurement using the MMT.

Wicking on the fabric takes place when the fabric is completely or partially immersed in a liquid or in contact with a limited amount of liquid, such as a drop on the fabric. In the case of woven fabrics or other fibrous materials, the wicking refers to two kinetically different processes [140]:

- a spontaneous flow of a liquid within the capillary spaces into the fabric,
- a diffusion of a liquid into the interior of the fibers from which the fabric is made.

When the penetration of liquid is limited only to the capillary flow and the fibers do not imbibe the liquid the wicking process is called capillary sorption. When the fabric is made of fibers absorbing liquid, such as cotton the swelling of the fibers occurs. The swelling reduces capillary spaces between fibers. At the same time the kinetics of the wicking phenomena changes.

Assumption 1: While measuring the sample is placed horizontally.

Due to this fact, the vertical wicking does not occur. During the test only the horizontal wicking takes place. For horizontal wicking, Kissa [141] developed the equation describing the area of spreading. According to Kissa, area A covered by the spreading liquid was found to be:

$$A = K(\gamma \mathrm{LV}/\eta)^{u} V^{m} t^{n} \qquad (3.18)$$

Where:

K - a coefficient dependent on the advancing contact angle of the liquid on the fibers, the permeability and thickness of the fabric, and the saturation concentration of the liquid in the fabric.

t - the spreading time,
γ - the surface tension,
L - distance traveled by the liquid,
V - the volume of the liquid,
η - the viscosity.

The exponents: u, m, and n were found to be 0.3, 0.7, and 0.3 respectively, for n - alkanes spreading on polyethylene terephthalate/cotton, polyethylene terephthalate, and cotton fabrics. The equation holds when the fibers are impermeable to the spreading liquid. When the liquid diffuses into the fibers, e.g., water into cotton fibers, the exponent n depends on the drop volume [141]. Unfortunately, the values of exponents are not known for the commonly applied woven fabrics.

Assumption 2: a precisely defined amount of liquid is delivered to the fabric surface.

In liquid transport in fibrous materials two cases can occur:

- the fluid is continuously supplied to the surface of the fabric in an indefinite amount,
- a precisely defined amount of liquid is delivered to the fabric surface in the form of drops.

In the case of test performance using the MMT, the second case occurs, i.e. a constant amount of liquid in the form of drops is delivered to the surface of the fabric in the first 20 seconds of measurement [142, 143]. This strictly defined amount of liquid is transported in different directions on the surface and inside the fabric as a result of parallel phenomena: wetting, wicking, and sorption.

Assumption 3: The pores in woven fabrics are discontinued as well as irregular in size and direction.

Due to this fact, it is difficult to determine theoretically the capillarity phenomenon in the fabric made by yarns manufactured from staple fibers. The twist of yarns is also an important factor influencing the capillary flow. Due to this fact, Kissa stated that indirectly determined effective capillary radius has to be used instead of the radius [141]. However, there is very difficult to determine the effective radius of capillaries in the fabrics. Moreover, it is a kind of average value. It means that half of the capillaries have a radius smaller than the effective and the second half has a radius greater than the effective radius. It means that the effective radius applied in the equation describing horizontal wicking is completely theoretical and does not allow us to assess the phenomena of liquid transport in textile materials.

In the MMT test, the testing liquid is spread on both surfaces upper and bottom, absorbed by the fibrous material, and transferred from the upper to the bottom surface. Thus the transport from the upper to the bottom surface is a result of three phenomena:

- spreading on the top surface,
- transport through the vertically and close to vertically oriented pores between the fibers and yarns,
- spreading on the bottom surface.

In the case of fabrics made of hygroscopic fibers additional two phenomena occur:

- absorption of the fibrous hygroscopic component of the top surface,
- absorption of the fibrous component of the bottom surface.

As it was mentioned earlier, the precisely determined amount (0.21 ± 0.01. g) of testing liquid is divided into parts controlled by the above-mentioned mechanisms. The transport of liquid moisture through the fabric while the MMT can be presented in a schematic way as follows:

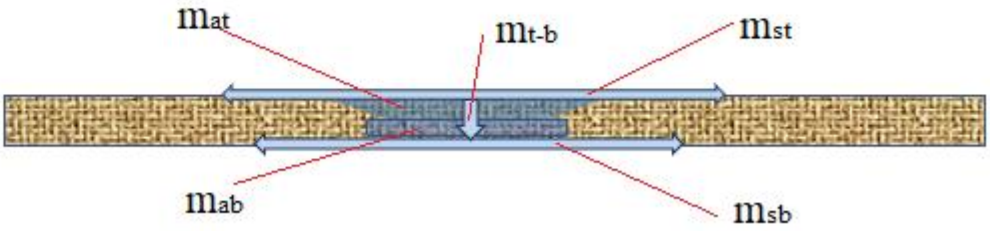


Fig. 3.8. *The scheme of the liquid moisture transport through the sample during the MMT test:* m_{st} *– the mass of testing liquid spread on the top surface,* m_{sb} *– the mass of testing liquid spread on the bottom surface,* m_{t-b} *– the mass of testing liquid transferred from the top to the*

bottom surface, m_{at} *– the mass of testing liquid absorbed by the fibrous material of the top surface,* m_{ab} *– the mass of testing liquid absorbed by the fibrous material of the bottom surface*

Depending on the properties of the measured specimen the amount of liquid spread on the top and bottom surface and transferred from the top to the bottom surface can vary significantly. It is difficult to determine of share of particular parts of liquid in the total amount of liquid deliver during a single test. In the presented case the sum of the liquid amount controlled by the above three processes is equal to the total amount of testing solution delivered during the first 20s of the MMT test.

$$m_{st} + m_{at} + m_{ab} + m_{sb} = m_{tot} = 0.21g \quad (3.19)$$

Where:

m_{st} – it is a mass of testing liquid spread on the top surface,

m_{sb} – it is a mass of testing liquid spread on the bottom surface,

m_{at} – the mass of testing liquid absorbed by the fibrous material of the top surface,

m_{ab} – the mass of testing liquid absorbed by the fibrous material of the bottom surface,

m_{tot} – the total amount of testing solution delivered during the MMT test; it is 0.21 ±0.01 g [137]

It should be pointed out here that in the majority of cases the mass of liquid transferred from the top to the bottom surface is divided into the mass of liquid moisture absorbed by the hygroscopic component of the bottom surface and spread on the bottom surface:

$$m_{t-b} = m_{ab} + m_{sb} \qquad (3.20)$$

In such situation, the liquid trace is observed on both fabric surfaces (Fig. 3.9).

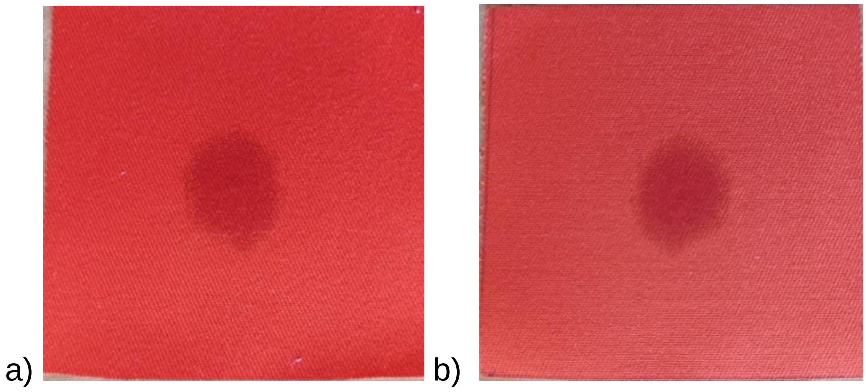


Fig. 3.9. *The liquid trace after the MMT test on both fabric surfaces: a) top surface, b) bottom surface*

Depending on the structure of both surfaces of the measured fabrics and the hygroscopic properties of the fibrous components of both surfaces, the share of particular components of the equation (3.19) is different.

In the case of clothing for firefighters, the transport of liquid moisture through the multilayer textile package should be analyzed, because the FPC usually consists of several layers including underwear. The scheme of liquid moisture transport through the two-layer textile set is presented in Fig. 3.10.

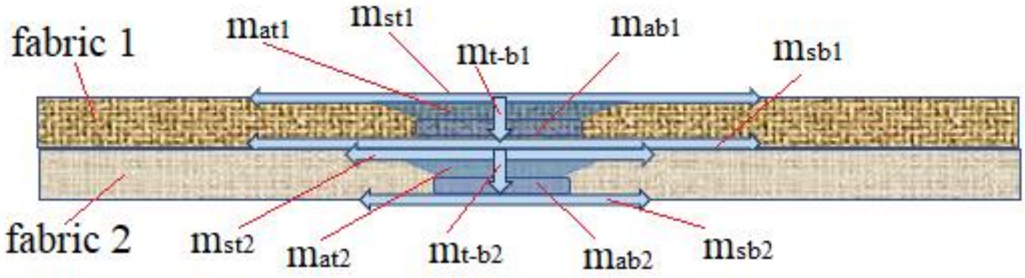


Fig. 3.10. *The scheme of the liquid moisture transport through the two-layer textile set during the MMT test: m_{st1} – the mass of testing liquid spread on the top surface of 1st layer, m_{at1} – the mass of testing liquid absorbed by the fibrous material of the top surface of 1st layer, m_{t-b1} – the mass of testing liquid transferred from the top to the bottom surface of 1st layer, m_{ab1} – the mass of testing liquid absorbed by the fibrous material of the bottom surface of 1st layer, m_{sb1} – the mass of testing liquid spread on the bottom surface of 1st layer, m_{st2} – the mass of testing liquid spread on the top surface of 2nd layer, m_{at2} – the mass of testing liquid absorbed by the fibrous material of the top surface of 2nd layer, m_{t-b2} – the mass of testing liquid transferred from the top to the bottom surface of 2nd layer, m_{ab2} – the mass of testing liquid absorbed by the fibrous material of the bottom surface of 2nd layer, m_{sb2} – the mass of testing liquid spread on the bottom surface of 2nd layer.*

In the case of a two-layer textile set, the balance of liquid moisture mass delivered in the MMT test and transferred through the measured set can be expressed by the following equation:

$$m_{st1} + m_{abt1} + m_{abb1} + m_{sb1} + m_{st2} + m_{abt2} + m_{abb2} = m_{tot} = 0.21g \qquad (3.21)$$

Where:

m_{st1} – the mass of testing liquid spread on the top surface of 1st layer,

m_{at1} – the mass of testing liquid absorbed by the fibrous material of the top surface of 1st layer,

$m_{t\text{-}b1}$ – the mass of testing liquid transferred from the top to the bottom surface of 1st layer,

m_{ab1} – the mass of testing liquid absorbed by the fibrous material of the bottom surface of 1st layer,

m_{sb1} – the mass of testing liquid spread on the bottom surface of 1st layer,

m_{st2} – the mass of testing liquid spread on the top surface of 2nd layer,

m_{at2} – the mass of testing liquid absorbed by the fibrous material of top surface of the 2nd layer,

$m_{t\text{-}b2}$ – the mass of testing liquid transferred from the top to the bottom surface of 2nd layer,

m_{ab2} – the mass of testing liquid absorbed by the fibrous material of the bottom surface of 2nd layer,

m_{sb2} – mass of testing liquid spread on the bottom surface of the 2nd layer, and where:

$$m_{t-b1} = m_{ab1} + m_{sb1} \qquad (3.22)$$

$$m_{t-b2} = m_{ab2} + m_{sb2} \qquad (3.23)$$

Depending on the structure of the surfaces of fabrics creating the particular layers of the investigated set and the hygroscopic properties of the fibrous components of surfaces of both layers, the share of particular components of the equation (3.21) is different.

In the case of the set containing the layer or surface impermeable to liquid moisture, the transfer of liquid stops on this surface/layer.

4. Materials and methods

The experimental part include the measurement of the materials applied in the FPC and underwear in the range of comfort-related properties and assessment of the ability of the textile clothing assemblies for the firefighter in the aspects of their ability to ensure thermo-physiological comfort.

4.1. Materials investigated

The FPC is primarily designed to protect against high temperatures and burns. For the production of the FPC, there are usually used materials made of aramid fibers such as Nomex, Kevlar, and Kermel as well as fireproofed impregnated cotton fabrics with a sufficiently large areal mass [144].

Protective clothing made of aramid fiber materials is characterized by high temperature and ignition resistance, excellent chemical resistance, as well as excellent resistance to abrasion. Water tightness is achieved by using vapor-permeable membranes that allow perspiration to evaporate during usage.

In the case of the clothing for the firefighter, physiological comfort can significantly influence the effectiveness of the firefighters during the rescue operation. Due to this fact, it is necessary to select very carefully the materials and set of materials for FPC.

First of all the protective features of the materials should be taken into consideration because they determine the safety of the firefighter. However, ensuring thermo-physiological comfort is also a very important aspect of designing and manufacturing such kind of protective clothing [14, 98]. Due to this fact, in the presented work the materials of certified protective properties for the FPC have been the objects of the investigations. Additionally, the knitted fabrics appropriate for underwear have been also investigated because it is impossible to wear the FPC without underwear in the conditions of firefighting and rescue actions.

4.1.1. Multilayer textile packages for the firefighter’s protective clothing

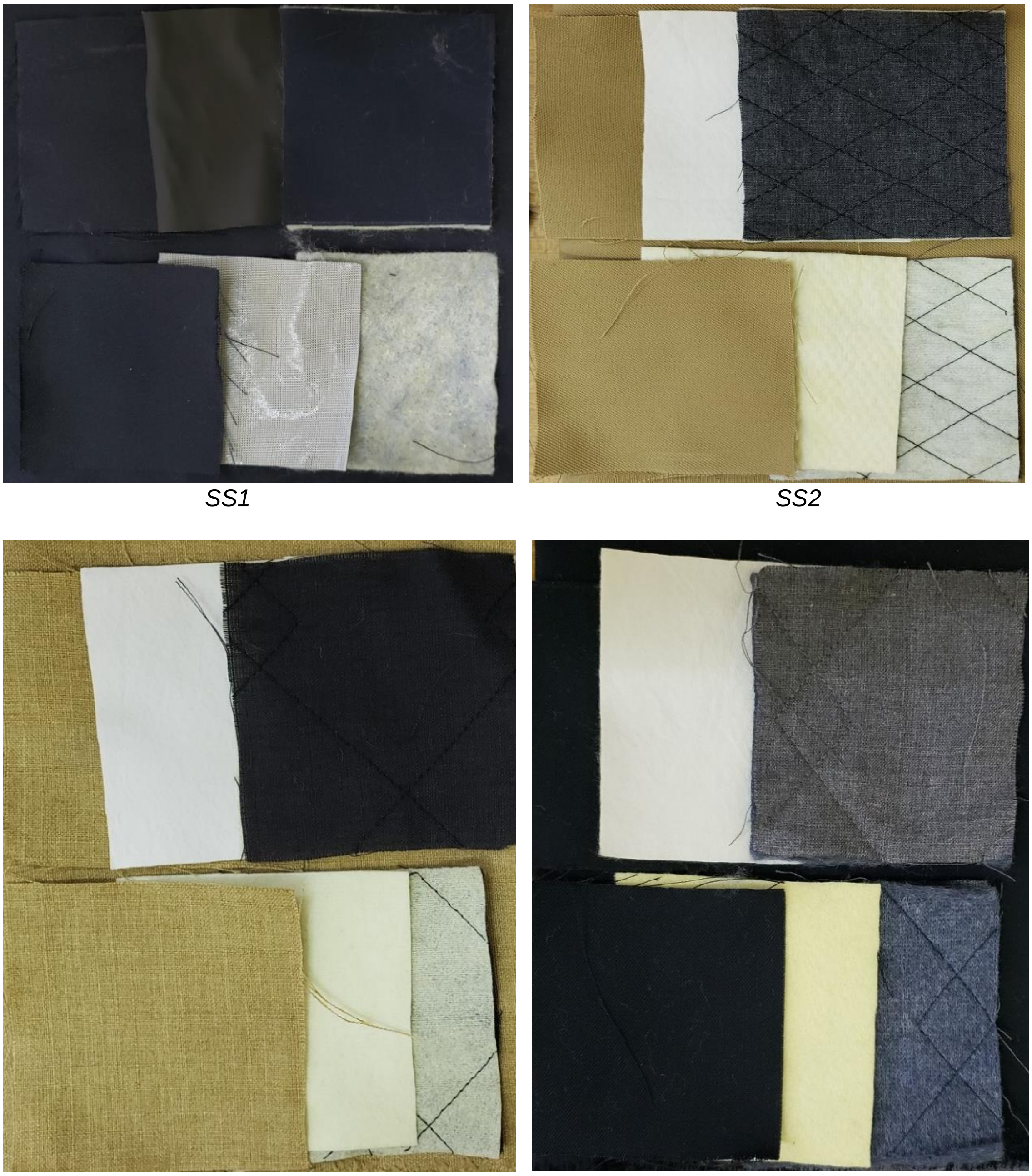
Four variants of multilayer textile packages for the FPC were the objects of the investigations. Each of them was composed of three or four different layers: material next to the skin, internal thermal-insulation material, and external material creating the outer shell. In further steps of the investigation, the materials are marked as SS – it means the Sample Set. The multilayer sets have been taken from the Polish industry. They are commercially available multilayer textile packages especially developed for the FPC. Their protective properties have been checked according to appropriate standards and certified. In the frame of the dissertation, the protective properties against fire, flame, chemicals, and other dangerous factors have not been analyzed. The comfort-related properties of the sample sets were the objects of measurement and analysis.

The properties of each layer of the set of materials investigated in the research are presented in Table 4.1. The data have been provided by the manufacturer. However, it was not allowed to present all detailed data of particular components due to the competitiveness of the market.

Particular layers of the measured sample sets are presented in the pictures (Fig. 4.1). At the top of each picture the right side of the materials forming the layers is presented, at the bottom - the left side.

Table 4.1. *Characteristic parameters of sets of clothing materials for the firefighter*

Sample Set			**Kind of material**	**Material composition**	**Weight of per square, g/m^2**
SS1	Outer shell		woven fabric	99% Aramid 1% Antistatic fibre	210
	Moisture barrier		knitted fabric laminated	100% Polyester, PU laminate	80
	Thermal barrier	lining	woven fabric	100% Cotton, flame retardant finish	275
		thermal barrier	nonwoven	Aramid fibres	
SS2	Outer shell		woven fabric	98% Meta-aramid 2% Antistatic fibre	210
	Moisture barrier	right side	laminate	PTFE	165
		lift side	nonwoven	100% Aramid	
	Thermal barrier	lining	woven fabric	50% Aramid 50% Viscose FR	125
		thermal barrier	felt	100% Aramid	50
SS3	Outer shell		woven fabric	58% Para-aramid 40% PBI 2% Antistatic fibre	205
	Moisture barrier	Right side	laminate	PTFE	100
		Lift side	underlay	100% Aramid	
	Thermal barrier	Lining and felt	quilted	100% Aramid	170
SS4	Outer shell		woven fabric	99% Aramid 1% Antistatic fibre	210
	Moisture barrier		laminate	65% Kevlar 35% PU	120
	Thermal barrier	lining	woven fabric	50% Aramid 50% Viscose	270
		thermal barrier	knitted fabric	Aramid + FR fibres	



SS1 *SS2*

SS3 *SS4*

Fig. 4.1. *Sample sets of multilayer clothing materials for the firefighter*

4.1.2. Knitted fabrics

Seven kinds of knitted fabrics have been selected for the study. The fabrics' samples have been taken from the t-shirts available on the market. They were made of cotton and cotton blends. The characteristics of the knitted fabrics being investigated in the frame of the dissertation are presented in Table 4.2.

Table 4.2. *Characteristic of the investigated knitted fabrics*

Knitted fabric	**Stitch**	**Fibre composition**	**Thickness, mm**	**Mass per square meter, gr/m^2**
KF1	Single jersey	100% cotton	0.47	161.09
KF2	Rib stitch	100% cotton	0.61	138.59
KF3	Pique	97% cotton, 3% elastane	1.27	198.44
KF4	Single jersey	95% cotton, 5% viscose	0.96	149.53
KF5	Single jersey	54% cotton, 46% polyester	1.32	205.47
KF6	Single jersey	cotton, TransDry	0.62	178,44
KF7	Single jersey	51% modacrylic, 26% cotton, 19% polyamide, 2% antistatic fibre 1% elastane	0.59	182.50

The pictures of the t-shirts and knitted fabrics from the t-shirts are presented in Fig. 4.2 - 4.8. The fabrics are shown at magnification obtained with the weaving loupe.

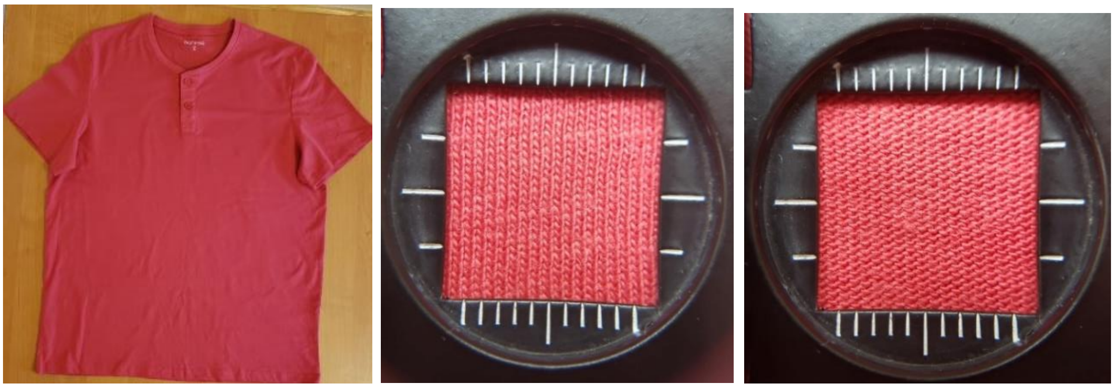


Fig. 4.2. *The KF1 (red); from the left: t-shirt, right side, left side*

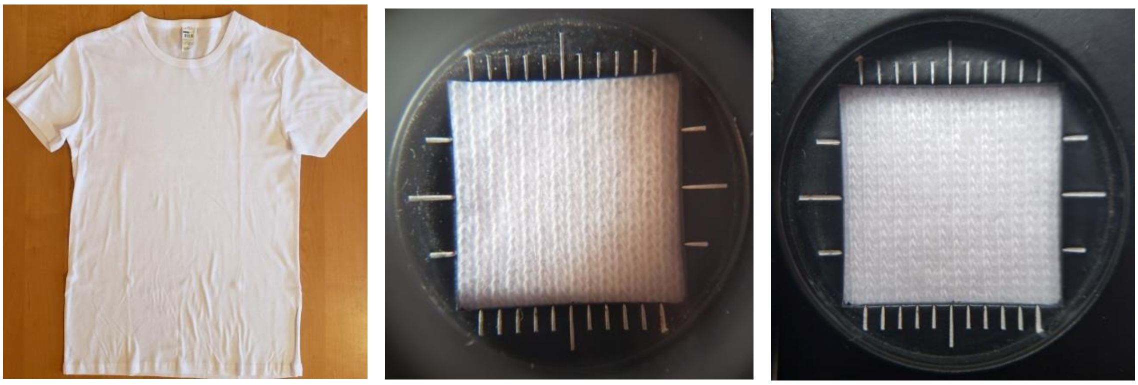


Fig. 4.3. *The KF2 (white); from the left: t-shirt, right side, left side*

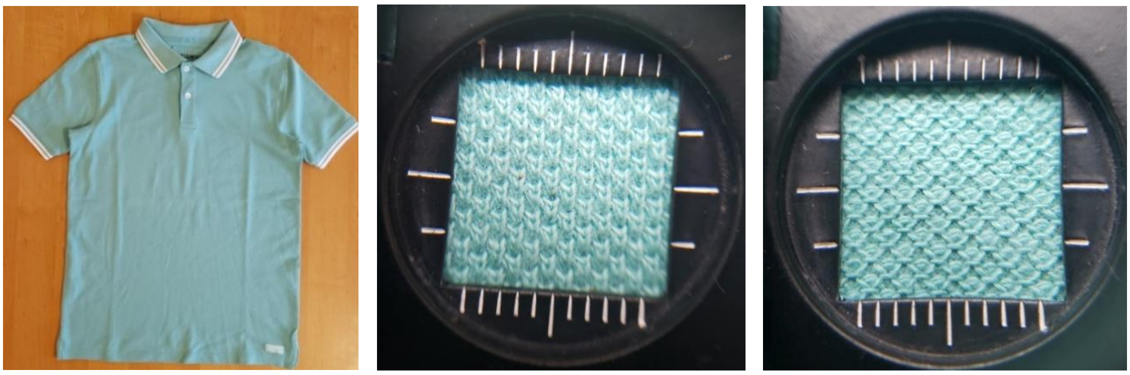


Fig. 4.4. *The KF3 (green); from the left: t-shirt, right side, left side*

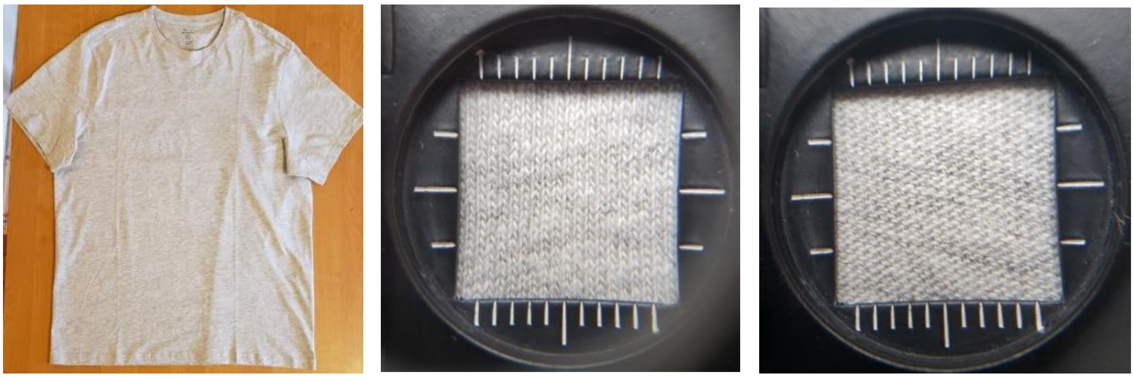


Fig. 4.5. *The KF4 (grey); from the left: t-shirt, right side, left side*

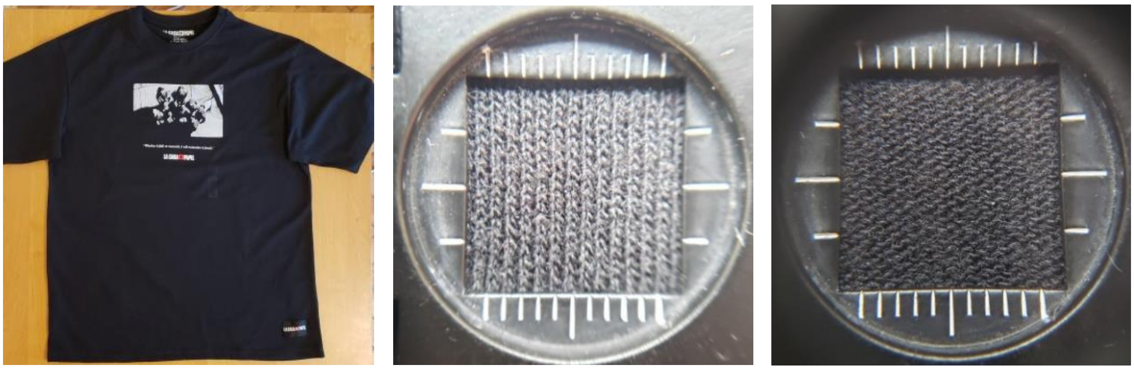


Fig. 4.6. *The KF5 (black); from the left: t-shirt, right side, left side*

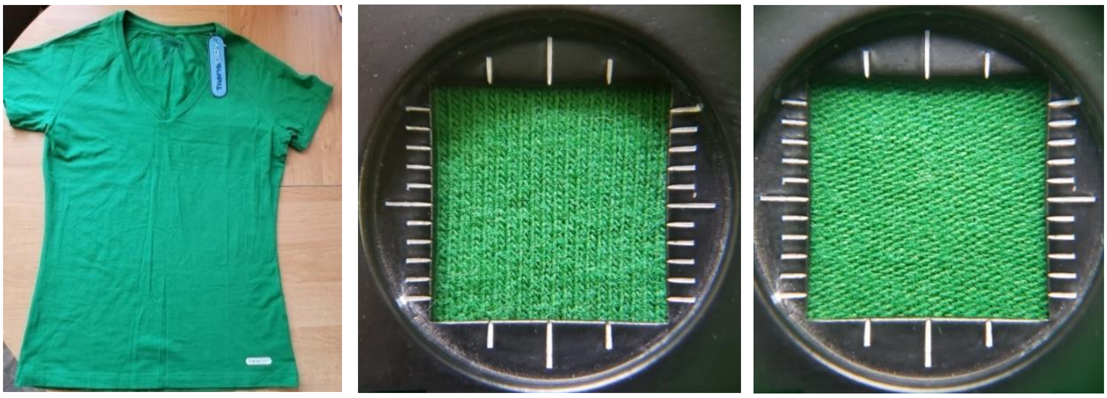


Fig. 4.7. *The KF6 (green); from the left: t-shirt, right side, left side*

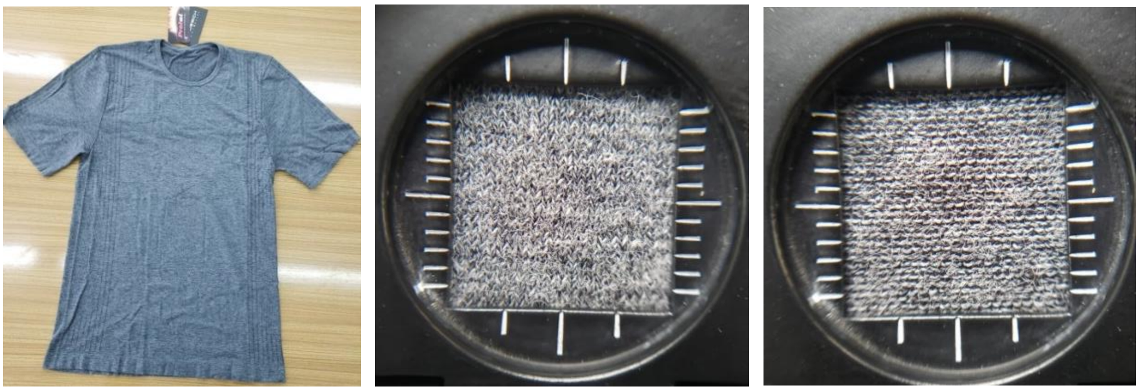


Fig. 4.8. *The KF7 (dark grey); from the left: t-shirt, right side, left side*

The KF6 knitted fabric is made using the special technology developed by Cotton Incorporated – TransDry® [145]**.** The TransDRY® technology combines the comfort of cotton with moisture-wicking performance that rivals any fiber. It is a patented, high-performance moisture management application that allows fabrics to wick and spread perspiration as well as, or better than, most high-tech synthetic fabrics. TransDRY® fabrics can be constructed to move moisture from the inside of the garment to the outside, in both horizontal and vertical directions depending on fabric construction [57].

Cotton yarns are treated with a special process to make them water-water-repellent. The repellent yarns are blended with the right amount of absorbent cotton yarns to create channels for the movement of moisture (Fig. 4.9). As a result, TransDRY® fabrics do not become over-saturated during exercise and have a lower overall absorbent capacity that mimics that of polyester and nylon. The technology provides effective moisture management performance in a variety of product categories.

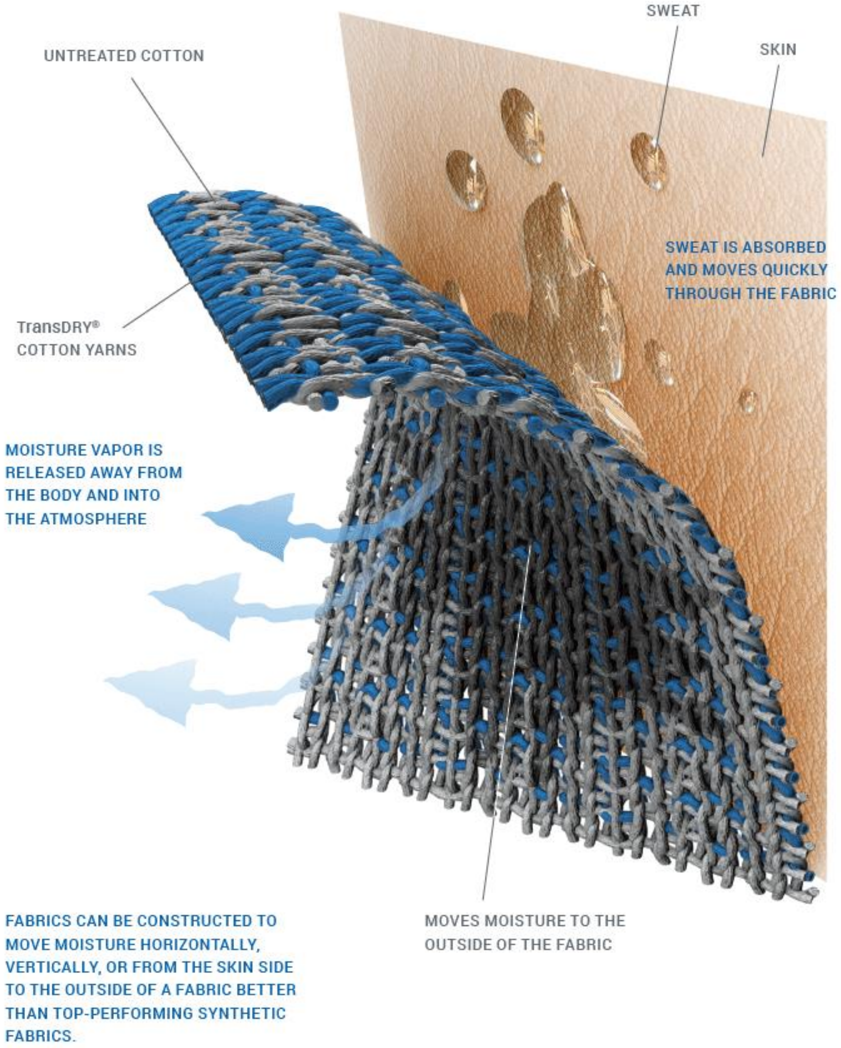


Fig. 4.9. *The idea of TransDry® technology for cotton [145]*

The KF7 fabric is taken from the t-shirt for the firefighter. It is made of flame retardant / antistatic material. It is a certified flame retardant and antistatic thermo-active underwear from the PROTECT line [146]. Flame retardant properties of the knitted fabric KF7 have been confirmed by the EN ISO 11612 standard (levels A1, B1, and C1) for protective clothing and electrostatic properties by the PN EN 1149 standard [145].

4.1.3. Multilayer clothing assemblies for the firefighter’s protective outfit

The multilayer clothing assemblies have been created from the Sample Sets (SS) and knitted fabrics (KF). Each Sample Set was joined with each knitted fabric. In this way, 28 multilayer clothing assemblies for the firefighter’s protective outfit have been created. They have been marked by both symbols of Sample sets and knitted fabric. For instance the symbol: SS1+KF1 means the assembly created by joining the Sample Set 1 and knitted fabric 1.

4.2. Methods used

Measurements of the investigated materials in the range of comfort-related properties have been performed using the following instruments:

- Moisture Management Tester,
- Alambeta,
- Permetest.

4.2.1. Moisture Management Tester - MMT M290

Fabric liquid moisture transport properties in multi-dimensions called moisture management properties influence the human perception of moisture sensations significantly.

Some standards and test methods can be employed to evaluate the fabric’s simple absorbency and wicking properties, and the liquid strike-through time of nonwovens also can be tested according to ISO 9073-8. However, the existing standards are unable to measure the behavior of dynamic liquid transfer of the clothing materials.

In the presented work an assessment of the liquid moisture transport capacity of the materials and their sets was done by means of the Moisture Management Tester MMT M290 (Fig. 4.10) by SDL Atlas [143, 147].

Fig. 4.10. *Moisture Management Tester MMT M290*

The Moisture Management Tester (MMT) is an instrument designed to measure the dynamic liquid transport properties of textile materials in three dimensions [143]:

- Absorption Rate - Moisture absorbing time of the fabric’s inner and outer surfaces
- One-way Transport Capability – Liquid moisture one-way transfer from the fabric’s inner surface to the outer surface
- Spreading/Drying Rate – Speed of liquid moisture spreading on the fabric’s inner and outer surfaces.

This instrument consists of upper and lowers concentric moisture sensors (Fig. 4.11), between which the fabric being tested is placed (Fig. 4.12).

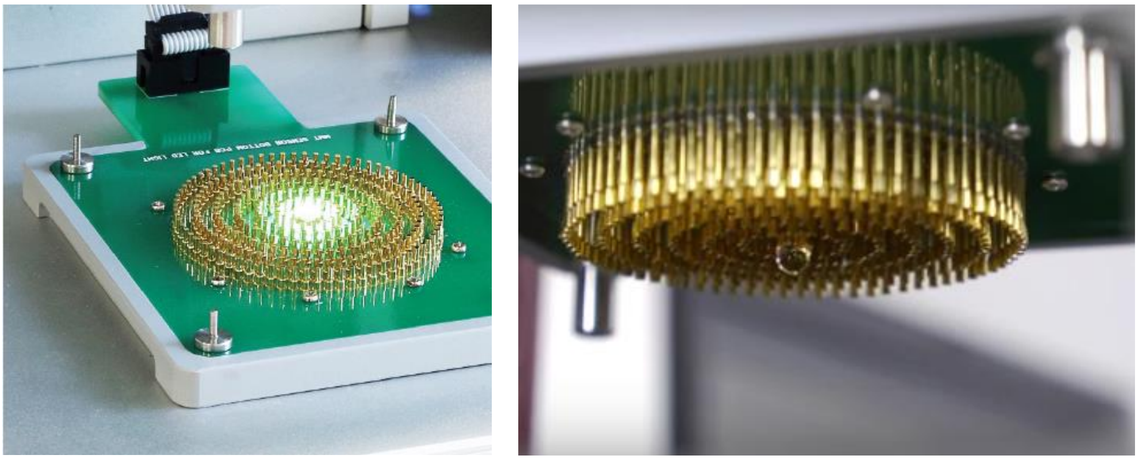


Fig. 4.11. *Sensor of the MMT device; from left: bottom sensor, top sensor*

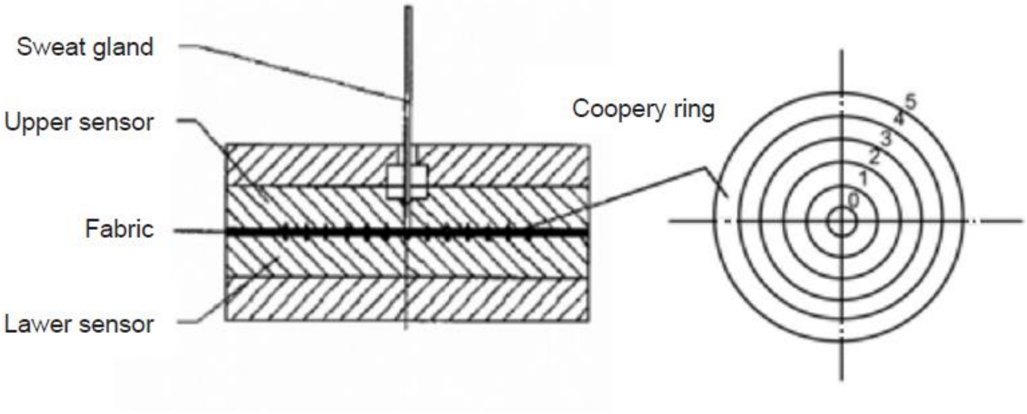


Fig. 4.12. *Placement of measured sample in the MMT device [148]*

A pre-defined amount of test solution (synthetic sweat) is introduced onto the upper (skin side) side of the fabric, and then the test solution will transfer onto the material in three directions:

- spreading outward on the upper surface of the fabric,
- transferring through the fabric from the upper surface to the bottom surface,
- spreading outward on the bottom surface of the fabric.

The MMT is designed to sense, measure and record the liquid moisture transport behaviors in these multiple directions. A series of indices are defined and calculated to characterize the liquid moisture management performance of the test specimen.

The instrument can calculate the following parameters:

- WTT, WTB – wetting time of top (T) and bottom (B) surface [s],
- TAR, BAR – absorption rate of top (T) and bottom (B) surface [%/s],
- MWRT, MWRB – maximum wetted radius for top (T) and bottom (B) surface [mm],
- TSS, BSS – spreading speed on top (T) and bottom (B) surface [mm/s],
- R – accumulative one-way transport index [-],
- OMMC – Overall Moisture Management Capacity [-].

The device cooperates with the PC and the MMT290 software. Measurement was performed according to the procedure described in the AATCC Test Method 195-2011 [149]. Measurement was done in standard climatic conditions for samples cut into 80 mm x 80 mm squares. For each fabric, 5 repetitions of measurement are performed.

The knitted fabrics were measured in relaxed (un-stretched) and stretched forms. It was done due to the fact that while using knitted underwear is worn in the stretched form. Stretching causes temporary changes in the knitted structure which influences the properties and performance of the fabrics, especially in the aspect of the heat and moisture transport as well as air permeability.

For the measurement of the knitted fabrics in the stretched form, the MMT Stretch Fabric Fixture device by SDL Atlas has been applied [150].

MMT Stretch Fabric Fixture

The function of this MMT Stretch Fabric Fixture is to extend the fabric to a certain extent. Combined with MMT, it is helpful to simulate the sweat permeation process of the clothes on the body under the stretching state during exercise. The MMT Stretch Fabric Fixture is comprised of 3 pieces that will prepare a fabric sample in a stretched position for testing: Fabric table, Fabric weight, and Fabric clamp (Fig. 4.13).

The percentage of stretch can be adjusted to the test's requirements using the scale on the fixture's handle. Samples can be stretched up to 50%. The MMT Stretch Fabric Fixture can extend the fabric to several different sizes: 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% [150].

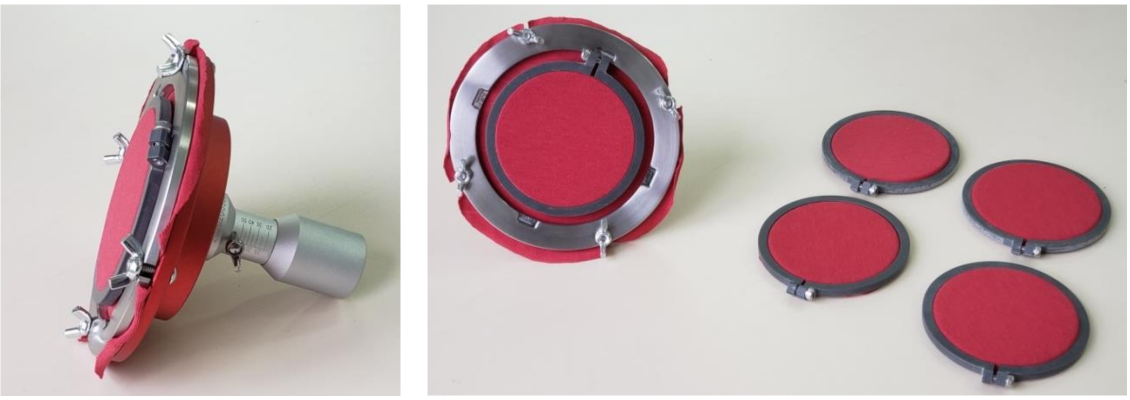


Fig. 4.13. *Stretch Fabric Fixture*

Once the percentage of stretch is set by the fixture, the stretched sample is clamped into place with a Stretch Fabric Clamping Ring, removed from the fixture, and placed directly onto the MMT's test area for moisture management testing [151].

The MMT Stretch Fabric Fixture will offer more accurate testing for how a fabric will behave while in use by the end user. When the fabric is tested in the un-stretched form the results may not reflect performance for some types of fabrics, particularly those with stretch properties like knitted fabrics used for athletic clothing and underwear which are stretchable [90].

4.2.2. Alambeta - fabric thermal properties tester

The Alambeta device (Fig. 4.14) by Sensora (Czech Republic) is an instrument developed to measure the thermal insulation properties of textile materials. It enables the measurement of the following thermal parameters: thermal conductivity, thermal absorptivity, thermal diffusivity, thermal resistance, and sample thickness. Thermal properties of textiles such as thermal resistance, thermal conductivity, and thermal absorptivity are influenced by the yarn composition and structure, fabric structure, density, humidity, type of textile construction, surface treatment, filling and compressibility, air permeability, surrounding temperature, and other factors.

Fig. 4.14. *Alambeta - fabric thermal properties tester*

Thermal conductivity coefficient (λ) presents the amount of heat, which passes from a 1m^2 area of material through the distance of 1m within 1s and creates the temperature difference of 1K. The highest thermal conductivity is exhibited by metals, whereas polymers have low thermal conductivity, ranging from 0,2 to 0,4 W/m/K. The thermal conductivity of textile structures generally reaches levels from 0,033 to 0,01 W/m/K.

Thermal absorptivity (b) of fabrics introduces to characterize thermal feeling (heat flow level) during short contact of human skin with the fabric surface. The higher is thermal absorptivity of the fabric; the cooler is its feeling. In the textile praxis, this parameter ranges from 20 Ws$^{1/2}$/m^2 /K for fine nonwoven webs to 600 Ws$^{1/2}$/m^2 /K for heavy wet fabrics [152].

Thermal resistance r depends on fabric thickness h and thermal conductivity λ, i.e. the equation is given by the relation:

$$R = h/\lambda \qquad (4.1)$$

The Alambeta simulates the dry human skin and its principle depends on mathematical processing of the time course of heat flow passing through the tested fabric due to different temperatures of the bottom measuring plate (22°C) and measuring head (32°C). When the specimen is inserted, the measuring head drops down, touches the fabrics, and the heat flow levels are processed in the computer and the thermo-physical properties of the measured specimen are evaluated [153].

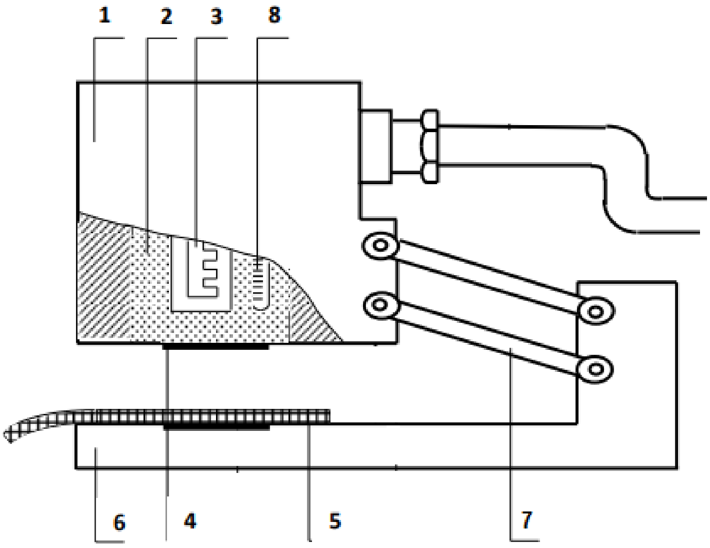


Fig. 4.15. *The scheme of the Alambeta: 1 – measuring head, 2 - copper block, 3 – electrical heater, 4 – heat flow sensor, 5 – sample, 6 - cold plate, 7 – movement mechanism, 8 – thermometer; on the basis of [153]*

The measuring head 1 (Fig. 4.15) contains a copper block 2, which is heated to 32°C, simulating human skin temperature by means of an electrical heater 3. The temperature is controlled by a thermometer 8 connected to the regulator. The lower part of the heated block is equipped with a direct heat flow sensor 4. The sensor measures the thermal drop between the surfaces of a very thin non-metallic plate using multiple differential micro-thermocouple. This sensor is 0.2 mm thick, and in contact with a subject of a different temperature, reaches the maximum heat flow q_{max} in 0.2 seconds. Thus, it simulates the human skin, which is approximately 0.5 mm thick and whose neutron end; located in the middle, also take 0.1 ÷ 0.3 second to reach q_{max} as the heat begins to flow through the contact subject.

Before the measurement, the head is kept above the base plate 6 covered by sample 5. Mechanism 7 ensures the correct movement of the measuring head. The pressure of the head onto the fabric can be adjusted within the range of 100 to 1000 Pa and substantially affects the results. It has been determined that the level of thermal absorptivity depends on the contact pressure alone, which also corresponds to the real situation. The test starts by placing the head on the sample. The heat starts to flow through the sample; then the surface temperature of the sample suddenly changes, and the instrument’s computer registers the heat flow course. This procedure is similar to putting a finger on a fabric to be selected. Simultaneously the sample thickness is measured [154].

The temperature drop is measured just after the heat flow measurement, i.e. before a user is asked to lift the head up.

Physical values are filtered using a moving average of 5 samples for the heat flow and 10 samples both for the temperature drop and the base temperature.

The following parameters are determined by means of the Alambeta:

λ – thermal conductivity, mW/m.K,

a – thermal diffusivity, mm/s,

b – thermal absorptivity, $Ws^{1/2}/m^2K$,

r – thermal resistance, $mK/W.m^2$,

h – thickness, mm,

P – the ratio between the maximal and stationary heat flow, -,

q_{max} – a peak level of heat flow, W/m^2.

In the performed investigations for each fabric sample, three repetitions of measurement were done. The measurements have been performed according to the standard procedure [154] in standard climatic conditions.

4.2.3. Permetest

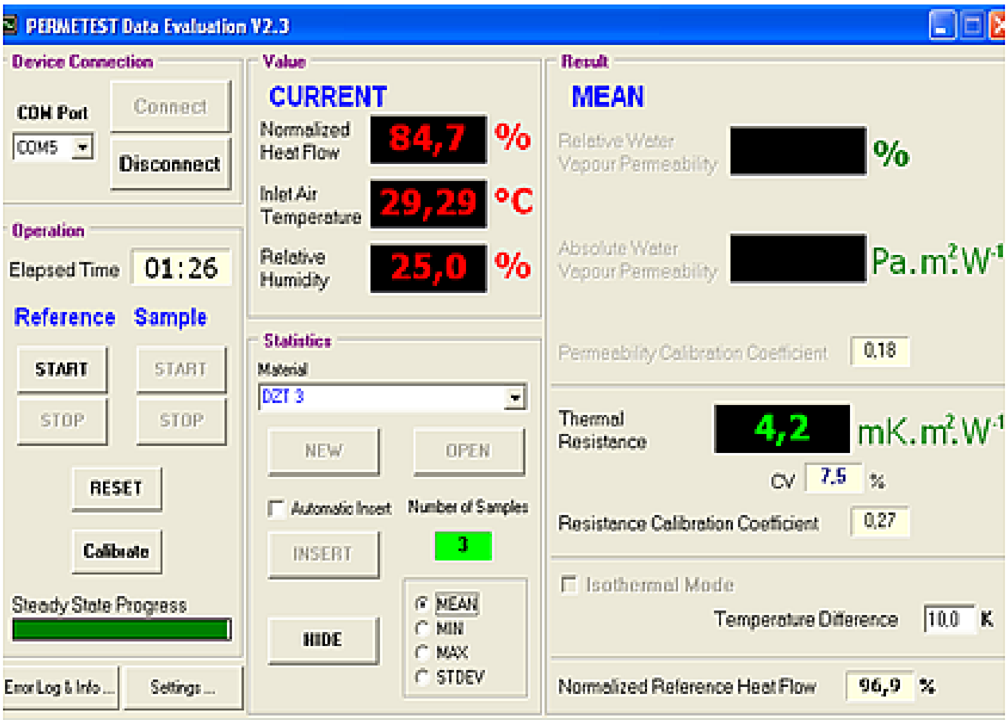
The Permetest by Sensora (Czech Republic) is a new fast response measuring instrument for the non-destructive determination of water-vapor and thermal resistance or permeability of textile fabrics, nonwovens, foils, and paper sheets (Fig. 4.16).

Fig. 4.16. *Permetest*

The PERMETEST measures:

- water-vapor resistance, m^2Pa/W,
- relative water-vapor permeability, %,
- thermal resistance, ^{2}K/W.

The Permetest can be considered as a small-scale portable “skin model”. The instrument provides all kinds of measurements very similar to the ISO Standard 11092 [155], and the results are evaluated by the identical procedure as required in ISO 11092. The differences in relation to this standard depend on the smaller sample, the application of the 20°C – 22°C isothermal laboratory temperature instead of 35°C (at the water-vapor resistance measurements), and an application of the environmental water-vapor concentration (humidity) of the parallel air flow 45% – 60%, instead of the air humidity level of 40%. The Permetest is controlled by the PC. All results are calculated by the appropriate software and presented on the computer screen (Fig. 4.17).



COM Port: COM5

Elapsed Time: 01:26

Normalized Heat Flow: 84,7 %

Inlet Air Temperature: 29,29 °C

Relative Humidity: 25,0 %

Material: DZT 3

☐ Automatic Insert

Number of Samples: 3

● MEAN
○ MIN
○ MAX
○ STDEV

Relative Water Vapour Permeability: %

Absolute Water Vapour Permeability: Pa.m².W⁻¹

Permeability Calibration Coefficient: 0,18

Thermal Resistance: 4,2 mK.m².W⁻¹

CV: 7,5 %

Resistance Calibration Coefficient: 0,27

☐ Isothermal Mode

Temperature Difference: 10,0 K

Normalized Reference Heat Flow: 96,9 %

Fig. 4.17. *Permetest dialog box*

The Permetest simulates dry and moist human skin from the point of view of its thermal sensation. At the beginning of the measurement, the measuring head is covered with a semi-permeable foil in order to keep the measured sample dry. First, the heat flux density q_0 is determined without the sample, then the product to be assessed, without the need to cut the sample, is placed between the measuring head (Fig. 4.18) and the lower opening in the instrument's air channel and the heat flux density with the sample is measured- q_v.

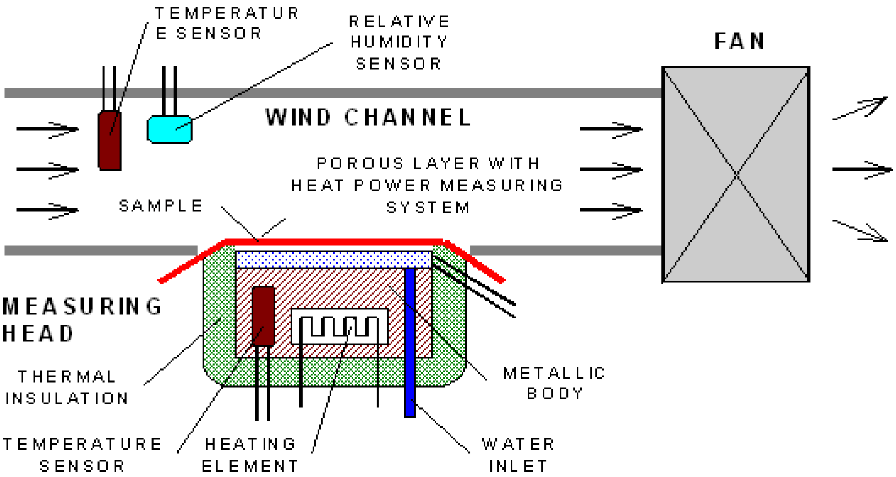


Fig. 4.18*. The scheme of the Permetest [156]*

The main technical parameters of the Permetest are the following [155]:

- range of water-vapor resistance R_{et}, from 1 to 200 m^2Pa/W,
- range of relative water-vapor permeability p, from 1.5 to 100 %,
- range of thermal permeability, from 1 to 50 $W/m^2/K$,
- range of thermal resistance R_{ct}, from 0.02 to 1 m^2K/W,
- range of fabric thickness, from 0.1 to 7 mm (or more at lower precision).

In the presented work the Permetest has been applied to measure the water-vapor resistance and relative water-vapor permeability of the investigated materials. During the measurement of water-vapor resistance using the Permetest, the measuring plate of the device is wetted by the distilled water containing 0,1 % of pure non-aggressive liquid soap. The measuring head is maintained at the same temperature as the ambient temperature.

The water-vapor resistance R_{et} determined by the Permetest is expressed by the following formula:

$$R_{et} = (p_m - p_a) \cdot \left(\frac{1}{q_v} - \frac{1}{q_o} \right) \qquad (4.2)$$

Where:

p_m - saturated water-vapor pressure at the temperature in the air duct of the instrument,

p_a - saturated water-vapor pressure at ambient temperature,

q_v - density of the heat flux passing through the measured material,

q_o - heat flux density passing from the surface of the uncovered head material to the air in the measuring channel.

The Permetest determines also the parameter called the relative water-vapor permeability. It is not a normalized index. However, it is a very practical tool for assessing textiles from the point of view of their ability to provide physiological comfort. The relative water-vapor permeability P is given by the equation:

$$P = 100 \cdot \frac{q_v}{q_o} \qquad (4.3)$$

Where:

q_v - density of the heat flux passing through the measured material,

q_o - heat flux density passing from the surface of the uncovered head material to the air in the measuring channel.

The relative water-vapor permeability P is expressed in percentage. The value of the relative water-vapor permeability P = 100% means the total water vapor permeability. The lower the value of the relative water-vapor permeability the poorer the physiological comfort of using a given product.

The measurements have been performed according to the Permetets manual in standard climatic conditions. For each material, three repetitions have been done.

4.2.4. Statistical analysis

In order to assess an influence of a kind of material on the comfort-related properties of the investigated materials a statistical analysis has been performed.

In the majority of cases, the statistical analysis was done using the nonparametric post-hoc tests: Kruskal-Wallis ANOVA and Median tests. The nonparametric tests have been applied since the normality assumption has not been confirmed. However, the nonparametric tests do not provide an opportunity to assess the impact of many factors and the interactions between these factors. Moreover, using the nonparametric tests maximum of 6 groups of results can be analyzed. In such situations - two main (independent) factors - the multifactor ANOVA has been applied.

An ANOVA test is a type of statistical test used to determine if there is a statistically significant difference between two or more categorical groups by testing for differences of means using variance. It works by analyzing the levels of variance within the groups through samples taken from each of them.

There are different types of ANOVA tests. The two most common are a “One-Way” and a “Two-Way.” The difference between these two types depends on the number of independent variables in the test [157].

A one-way ANOVA (analysis of variance) has one categorical independent variable (also known as a factor) and a normally distributed continuous (i.e., interval or ratio level) dependent variable. The independent variable divides cases into two or more mutually exclusive levels, categories, or groups. The one-way ANOVA test for differences in the means of the dependent variable is broken down by the levels of the independent variable.

A two-way ANOVA (analysis of variance) has two or more categorical independent variables (also known as a factor), and a normally distributed continuous (i.e., interval or ratio level) dependent variable. The independent variables divide cases into two or more mutually exclusive levels, categories, or groups. A two-way ANOVA is also called a factorial ANOVA.

The Kruskal-Wallis test is a non-parametric version of the one-way ANOVA test**.** The nonparametric tests have been applied because the variables under consideration do have not a normal distribution.

5. Thermal insulation properties of textile materials for firefighter's clothing

Measurement of the thermal resistance and other thermal insulation properties: such as thermal conductivity, thermal absorptivity, thermal resistance, and fabric thickness has been performed using the Alambeta device. The following sequence of measurements has been applied:

- measurement of the Sample Sets for the firefighter's protective clothing (SS),
- measurement of the knitted fabrics for underwear (KF),
- measurement of the firefighter's clothing assemblies composed of sample sets and knitted fabrics (SS+KF).

For each object being investigated three repetitions of measurement have been performed. The samples have been placed on the device so that the left (close to the skin) side of the fabric or set of fabric has adhered to the upper (warm) plate of the device, which has a temperature close to the temperature of human skin.

5.1. The thermal insulation properties of Sample Sets

The thermal properties of four types of multilayer textile sets for the FPC are presented in Table 5.1.

Table 5.1. *Thermal properties of multilayer materials for the firefighter's protective clothing according to the Alambeta measurement*

Sample set		Thermal conductivity **λ** mW/mK	Thermal absorptivity **b** $Ws^{1/2}/m^2K$	Thermal resistance **R** mK/Wm^2	Thickness **h** mm
SS1	Average	39.07	102.00	104.63	4.092
	SD	0.60	3.64	14.07	0.606
SS2	Average	36.20	118.23	86.53	3.128
	SD	1.56	8.29	3.89	0.045
SS3	Average	37.50	149.27	51.33	1.923
	SD	1.68	3.44	2.29	0.001
SS4	Average	38.33	108.67	104.53	3.989
	SD	3.22	19.15	13.78	0.443

SD – standard deviation

On the basis of the presented results, it was stated that the investigated multilayer textile sets for FPC (called further the Sample Sets – SS) differ from each other in the range of all parameters measured by the Alambeta. In order to assess the influence of the Sample Set variant on the thermal insulation properties of the sets the statistical analysis has been performed using the nonparametric post-hoc tests: Kruskal-Wallis ANOVA and Median tests. The nonparametric tests have been applied because the variables under consideration do have not a normal distribution. In the analysis, the kind of the Sample Set was applied as an independent variable, and the thermal insulation parameters were analyzed as dependent variables. In the analysis, the default p-value for highlighting is 0.05. The interpretation of the results is the following: if the significance level p is lower than 0.05 the differences between analyzed groups are statistically significant; otherwise if p>0.5 the differences are significant. It means that the independent variable influences the value of the dependent variable in a statistically significant way.

The thermal conductivity of the Sample Sets being investigated is in the range of 36.20mW/mK (SS2) to 39.07mW/mK (SS1). Results of the statistical analysis for the thermal conductivity are presented in Table 5.2. In the table, there are presented the p-values for two-sided comparisons.

Table 5.2. *The between-group comparison of the thermal conductivity of Sample Sets*

Dependent variable λ	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 12) =4.451462; p =0.2167			
	SS1 R:9.0000	SS2 R:3.3333	SS3 R:5.6667	SS4 R:8.0000
SS1		0.3255	1.0000	1.0000
SS2	0.3254		1.0000	0.6775
SS3	1.0000	1.0000		1.0000
SS4	1.0000	0.6775	1.0000	

The results of statistical analysis showed that the influence of a kind of Sample Set on the thermal resistance is statistically insignificant at the significance level of 0.05.

Fig. 5.1 presents the mean values and scatter of results of thermal conductivity of the Sample Sets being analyzed.

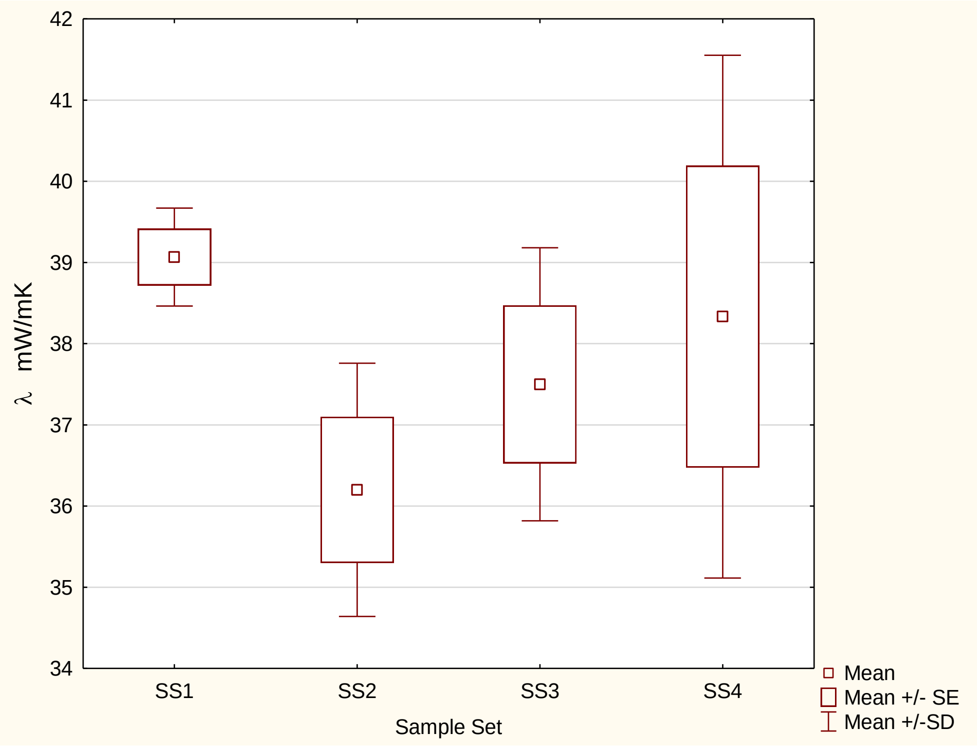


Fig. 5.1. *Thermal conductivity of multilayer textile sets (Sample Sets) for the firefighter's protective clothing*

The greatest value of the thermal absorptivity occurs for the SS3 variant (149.27 $Ws^{1/2}/m^2K$), the lowest (102.00 $Ws^{1/2}/m^2K$) – for the SS1 variant (Fig. 5.2). In the case of the thermal absorptivity the influence of the SS variant on the parameters' values is statistically significant at the significance level 0.05 (Table 5.3). In Table 5.3 the statistically significant difference is marked by red color. The statistically significant difference occurs only between the SS3 and SS1 variants.

Thermal absorptivity represents the amount of heat that passes at the difference of temperatures of 1°K through one unit of area in one unit of time as a result of heat accumulation in a volume unit. It is a parameter characterizing a warm-cool feeling while first contacting the human skin with the material. The greater the thermal absorptivity the cooler feeling. In the case of the Sample Sets being investigated, they are intended for the FPC. This protective clothing is not worn next to the human skin but over underwear or over underwear and barracks clothing. Thus, there is no direct contact with the user's skin. Therefore, the thermal absorptivity of these Sample Sets is not as important as in the case of underwear or other clothing worn next to the human skin. In the case of the Sample Sets being investigated the thermal absorptivity is useful for better characterization of the sets and their comparison.

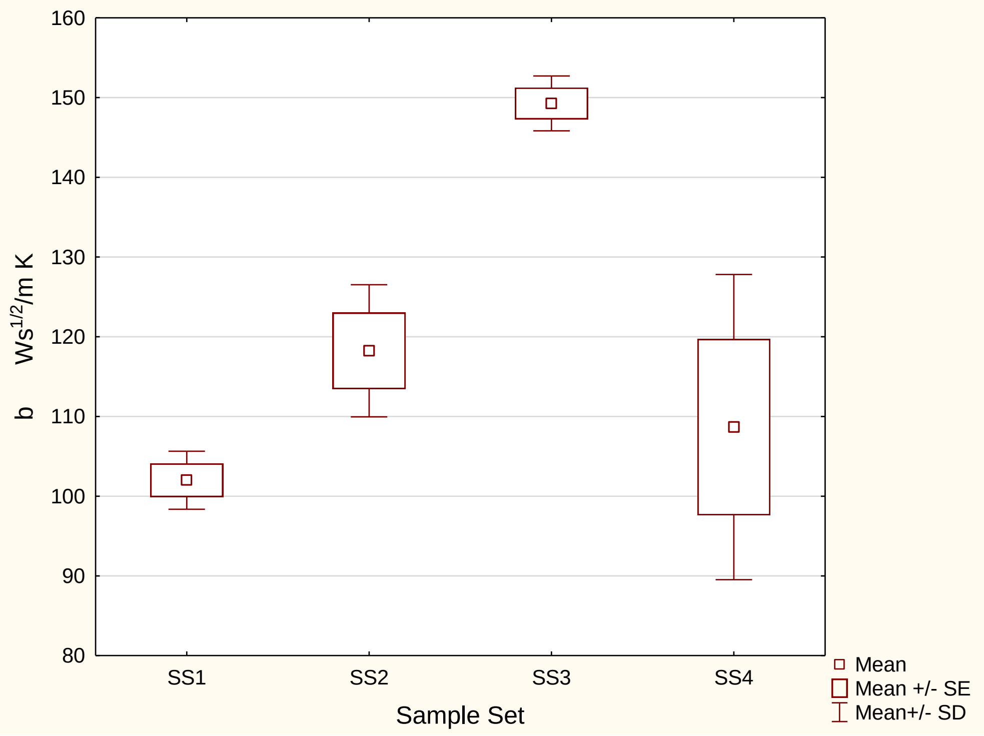


Fig. 5.2. *Thermal absorptivity of multilayer textile sets (Sample Sets) for firefighter's protective clothing*

Table 5.3. *The between-group comparison of the thermal absorptivity of Sample Sets*

Dependent variable **b**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 12) =7.847953; p =0.0493			
	SS1 R:3.0000	SS2 R:6.6667	SS3 R:11.0000	SS4 R:5.3333
SS1		1.0000	0.0395	1.0000
SS2	1.0000		0.8462	1.0000
SS3	0.0395	0.8462		0.3255
SS4	1.0000	1.0000	0.3255	

Thermal resistance expresses the difference of the temperature across a unit area of the material of unit thickness when a unit of heat energy flows through it in a unit of time. The thermal resistance is a measure of the thermal insulation ability of the material. The highest, and practically the same values of the thermal resistance were stated for the SS1 and SS4 variants - appropriately: 104.63 and 104.53 mK/Wm² (Fig. 5.3). The values are almost twice higher than the thermal resistance of the SS3 variant, for which the lowest thermal resistance was measured for (51.33 mK/Wm^2).

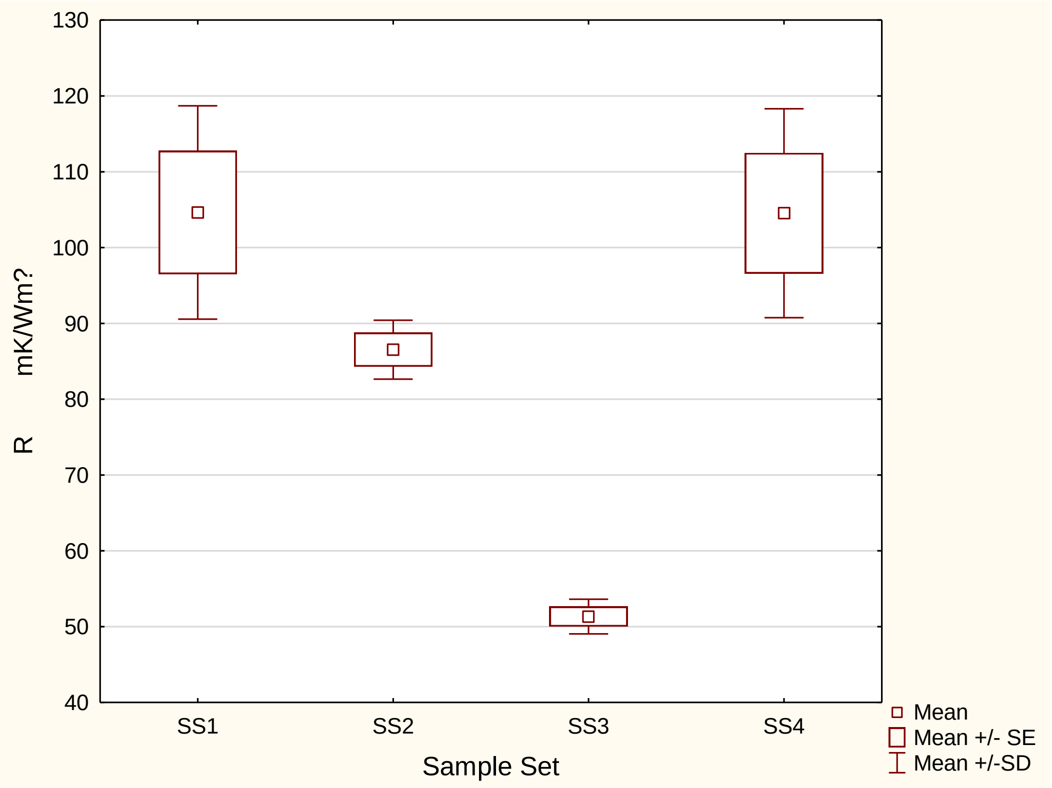


Fig. 5.3. *Thermal resistance of multilayer textile sets for the firefighter's protective clothing*

In the case of the thermal resistance, the influence of a kind of multilayer textile set on the values of thermal resistance for the whole set of the results was also assessed by the Kruskal-Wallis test as significant at the significance level 0.05 (Table 5.4). The between-groups comparison shows that the differences between particular groups are statistically insignificant.

Table 5.4. *The between-group comparison of the thermal resistance of Sample Sets*

Dependent variable **R**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 12) =8.7454; p =0.0329			
	SS1 R:9.6667	SS2 R:5.3333	SS3 R:2.0000	SS4 R:9.0000
SS1		0.8462	0.0552	1.0000
SS2	0.8462		1.000000	1.0000
SS3	0.0552	1.0000		0.1045
SS4	1.0000	1.0000	0.1045	

The FPC is intended for use during firefighting and related activities, such as rescue operations or assistance in combating the consequences of disasters [43, 158]. The FPC should be characterized primarily by resistance to flame spread. The essential purpose of the use of the FPC is to protect against heat transfer from flame and heat radiation. Considering that the clothing described is used in various conditions, it should also provide protection against soaking and cold. The materials and material assemblies for the FPC have to be certificated according to appropriate standards. In the presented investigations we applied the Sample Sets of justified protective properties required for the FPC. The measurements performed in the frame of the Ph.D. thesis were aimed at an assessment of the Sample Sets in the aspect of thermo-physiological comfort of firefighters and comfort-related properties of the materials used in firefighters' clothing. Depending on the conditions of usage of such clothing different properties are required. The thermal resistance should be as high as possible to protect against heat transfer from flame, and heat loss in cold conditions while used in rescue operations or assistance in combating consequences of disasters as well as in journeys to and from the rescue and other operations. From this point of view, the SS1 and SS4 variants are the best among all investigated multilayer textile packages.

The differences in the thermal resistance of the investigated material set result from the difference in the sets' thickness (Fig. 5.4). It is according to expectations. It was confirmed that there is a strong correlation between the thermal resistance and thickness of the textile materials [159, 160].

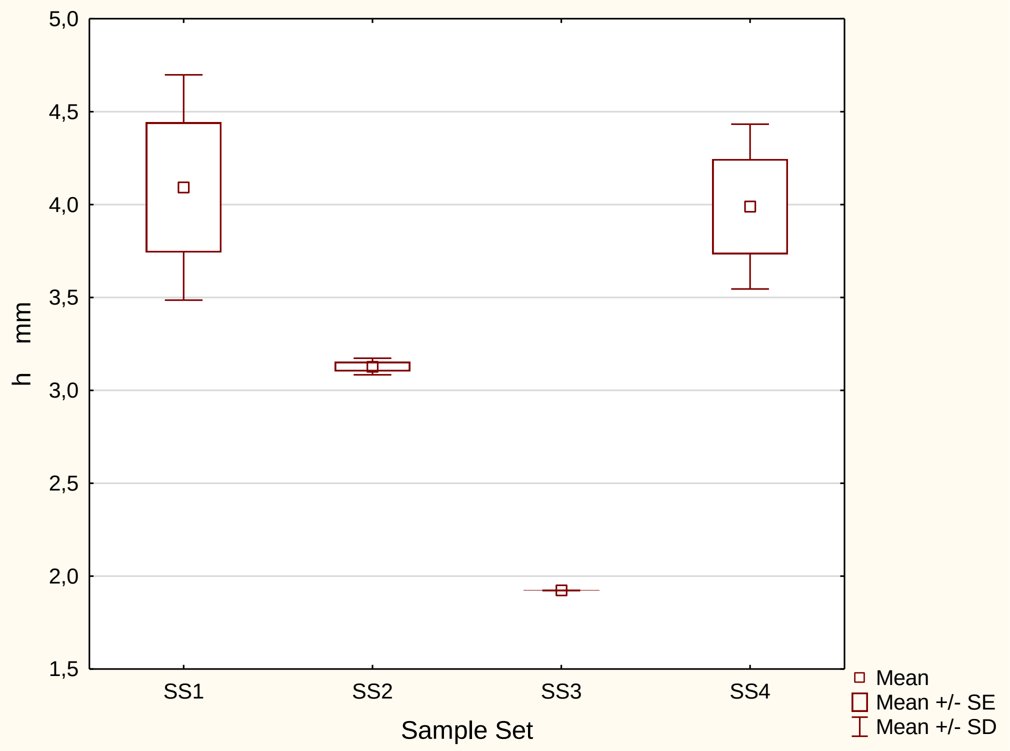


Fig. 5.4. *Thickness of multilayer textile sets for the firefighter's protective clothing*

The Kruskal-Willis test confirmed that the variant of the Sample Set influences the thickness of the multilayer textile sets for the FPC in a significant way at the significance level (p=0.0245). The differences between groups were assessed as insignificant (Table 5.5).

Table 5.5. *The between-group comparison of thickness of the Sample Sets*

Dependent variable **h**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 12) =9.3918; p =0.0245			
	SS1 R:9.6667	SS2 R:5.0000	SS3 R:2.0000	SS4 R:9.3333
SS1		0.6775	0.0552	1.0000
SS2	0.6775		1.0000	0.8462
SS3	0.0552	1.0000		0.0764
SS4	1.0000	0.8462	0.0764	

5.2. Thermal insulation properties of knitted fabric

The thermal properties parameters of seven types of knitted fabric for underwear are shown in Table 5.6.

Table 5.6. *Thermal properties of knitted fabrics for underwear according to the Alambeta measurement*

Knitted fabric		Thermal conductivity λ mW/m K	Thermal absorptivity **b** $Ws^{1/2}/m^2K$	Thermal resistance **R** mK/Wm^2	Thickness **h** mm
KF1	Average	38.30	166.87	11.67	0.447
	SD	0.20	17.43	0.06	0.003
KF2	Average	37.90	145.67	16.43	0.622
	SD	1.55	11.27	0.67	0.010
KF3	Average	44.57	166.50	16.00	0.712
	SD	2.51	11.78	0.72	0.010
KF4	Average	35.67	175.07	11.60	0.415
	SD	0.71	15.69	0.46	0.011
KF5	Average	39.80	140.47	16.50	0.657
	SD	0.70	9.93	0.44	0.018
KF6	Average	42.23	164.90	14.57	0.615
	SD	0.25	2.88	0.32	0.013
KF7	Average	38.20	120.00	17.53	0.669
	SD	0.10	6.02	0.15	0.005

Measurements of the knitted fabrics for underwear also confirmed differences between them in the range of thermal insulation properties. In the case of the knitted fabrics being measured statistically significant differences are observed for all analyzed thermal insulation parameters.

The greatest thermal conductivity (Fig. 5.5) was observed for the KF3 knitted fabric (44.57 mW/mK) followed by the KF6 fabric (42.23 mW/mK). The lowest thermal conductivity occurred for the KF4 fabric (35.67 mW/mK). The KF3 knitted fabric is made of cotton 97% and elastane 3%. The application of elastane causes the thickening of the fabric structure. Due to this fact in the volume unit of the KF3 fabric, a greater amount of fibrous material is in comparison with other investigated knitted fabrics. Heat conduction takes place in fibrous material. Then the greater share of fibrous material in the fabric volume is the higher thermal conductivity. The KF 6 fabric is made of cotton, but a part of the yarn applied is specially treated to make it hydrophobic. Probably, the agent used for finishing the yarn improved the thermal conductivity of the KF6 fabric. The KF4 knitted fabric shows the lowest thermal conductivity (35.67 mW/mK). It is a fabric made of cotton 95%, and viscose 5%. The thermal conductivity of viscose fires is lower than the thermal conductivity of cotton fibers. Although the share of viscose fibers in the KF4 fabric is low together with low mass per square meter of the KF4 fabric it can result in the lowest thermal conductivity of the KF4 among the group of the investigated knitted fabrics.

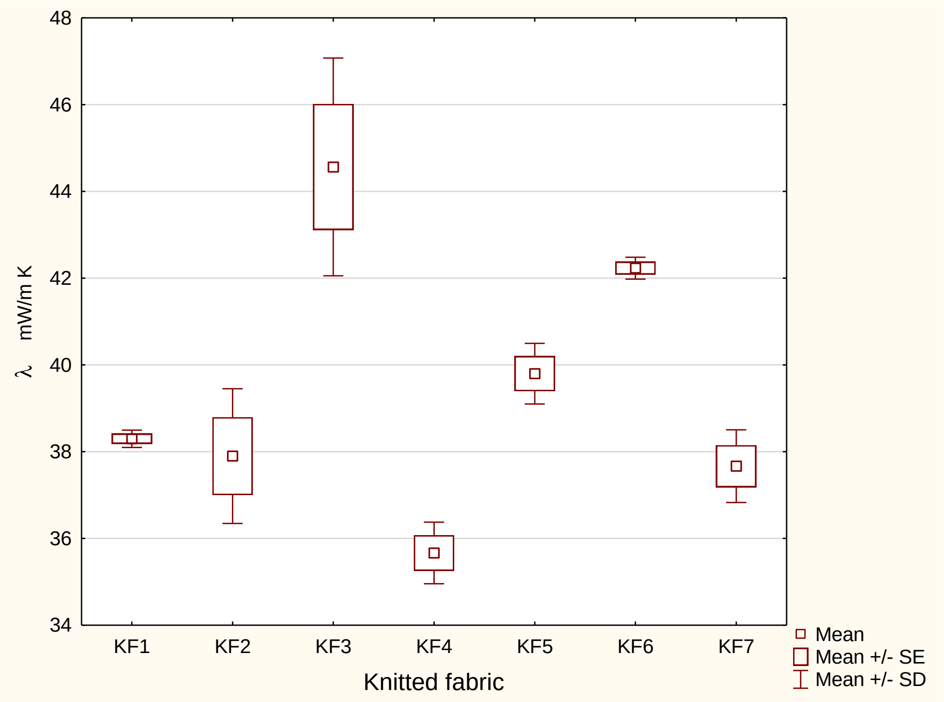


Fig. 5.5. *Thermal conductivity of knitted fabrics for underwear*

The two-sided comparison confirmed that statistically significant differences occur between the KF3 and KF4 as well as between the KF4 and KF6 (Table 5.7).

Table 5.7. *The between-group comparison of thermal conductivity of knitted fabrics*

Dependent variable λ	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 21) =17.86875; p =0.0066						
	KF1 R:9.500	KF2 R:7.667	KF3 R:19.000	KF4 R:2.000	KF5 R:13.667	KF6 R:18.000	KF7 R:7.167
KF1		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
KF2	1.0000		0.5310	1.0000	1.0000	0.8691	1.0000
KF3	1.0000	0.5310		0.0166	1.0000	1.0000	0.4096
KF4	1.0000	1.0000	0.0166		0.4471	0.0333	1.0000
KF5	1.0000	1.0000	1.0000	0.4471		1.0000	1.0000
KF6	1.0000	0.8691	1.0000	0.0333	1.0000		0.6823
KF7	1.0000	1.0000	0.4096	1.0000	1.0000	0.6823	

Thermal absorptivity (Fig. 5.6) of the analyzed knitted fabrics is in the range from 120 $Ws^{1/2}/m^{2}K$ (KF7) to 175.07 $Ws^{1/2}/m^{2}K$ (KF4). In the case of the fabric for underwear, thermal absorptivity is a very important property. It determines warm/cool feelings while contacting the fabric with human skin. In the case of underwear for the firefighter usually, it is advisable to provide a cool feeling. While firefighting and related activities there is intense sweating due to the intensity of physical exertion and the feeling of overheating. In such situations, the cool touch provides a better thermal sensation for the clothing user. The highest values of the thermal resistance for the KF4 (175.07 $Ws^{1/2}/m^{2}K$), next to the KF1 (166.87 $Ws^{1/2}/m^{2}K$), KF3 (166.50 $Ws^{1/2}/m^{2}K$) and KF6 (164.90 $Ws^{1/2}/m^{2}K$) fabric variants mean that the underwear made of them can ensure pleasant cool feeling in warm conditions. The lowest thermal absorptivity was stated for the KF7 (120.00 $Ws^{1/2}/m^{2}K$) fabric variant. The KF7 will give the warmest feeling in touch in comparison to other knitted fabrics being analyzed.

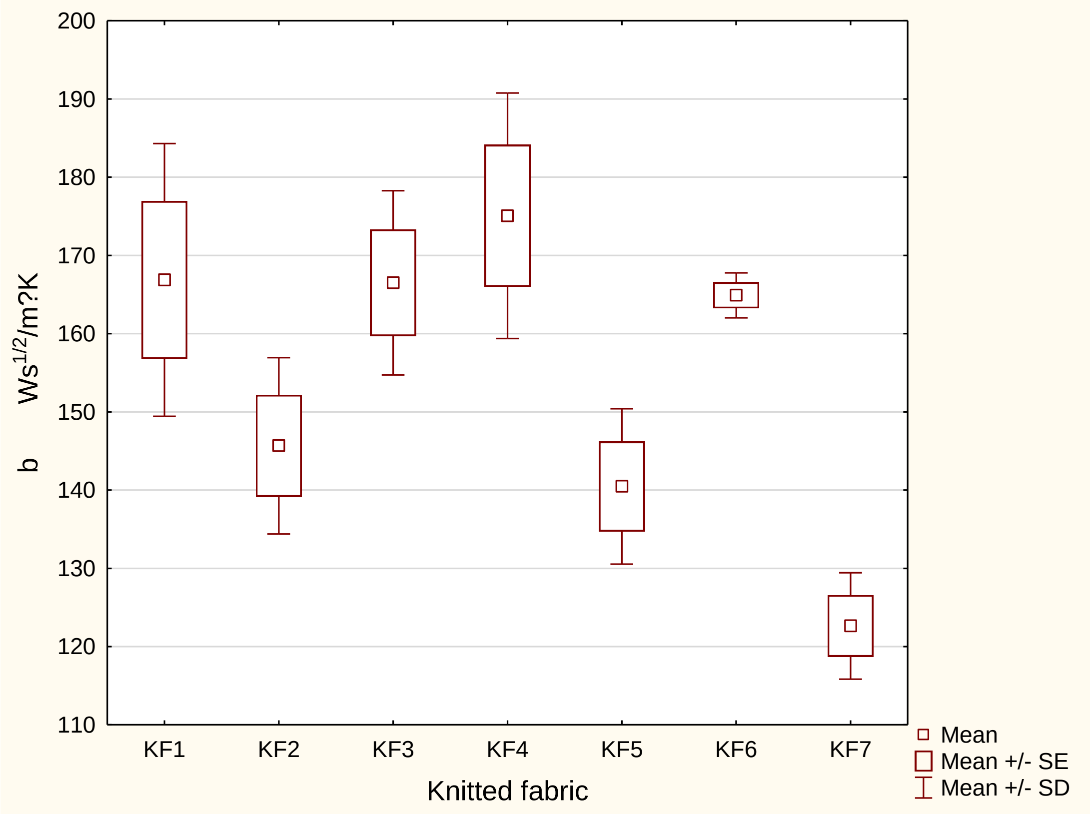


Fig. 5.6. *Thermal absorptivity of knitted fabrics for underwear*

Statistical analysis confirmed that the knitted fabrics' variant influences the thermal absorptivity of the fabrics but the differences between particular groups are statistically insignificant at the significance level of p=0.05 (Table 5.8).

Table 5.8. *The between group comparison of thermal absorptivity of the knitted fabrics*

Dependent variable **R**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 21) =18.2216; p =0.057						
	KF1 R:4.000	KF2 R:14.833	KF3 R:12.500	KF4 R:3.000	KF5 R:14.667	KF6 R:8.000	KF7 R:20.000
KF1		1.0000	1.0000	1.0000	1.0000	1.0000	0.2606
KF2	1.0000		1.0000	1.0000	1.0000	1.0000	1.0000
KF3	1.0000	1.0000		1.0000	1.0000	1.0000	0.2160
KF4	1.0000	1.0000	1.0000		0.6282	1.0000	0.0796
KF5	1.0000	1.0000	1.0000	0.6282		1.0000	1.0000
KF6	1.0000	1.0000	1.0000	1.0000	1.0000		0.1784
KF7	0.2607	1.0000	0.2160	0.0796	1.0000	0.1784	

The thermal resistance of the investigated fabrics (Fig. 5.7) is in the range from 11.60 mK/Wm² to 17.53 mK/Wm². The highest thermal resistance was stated for the KF7 (17.53 mK/Wm²) fabric variant. It is a fabric applied in the special T-shirt for the firefighter. The thermal resistance results from the raw material composition with 51 % of modacrylic fibers. The lowest thermal resistance is for the KF4 (11.60 mK/Wm²) and KF1 (11.67 mK/Wm²) fabric variants. The thermal resistance is strongly connected with the thickness of the analyzed knitted fabrics (Fig. 5.8, 5.9). The thicker the fabric is the greater the thermal resistance.

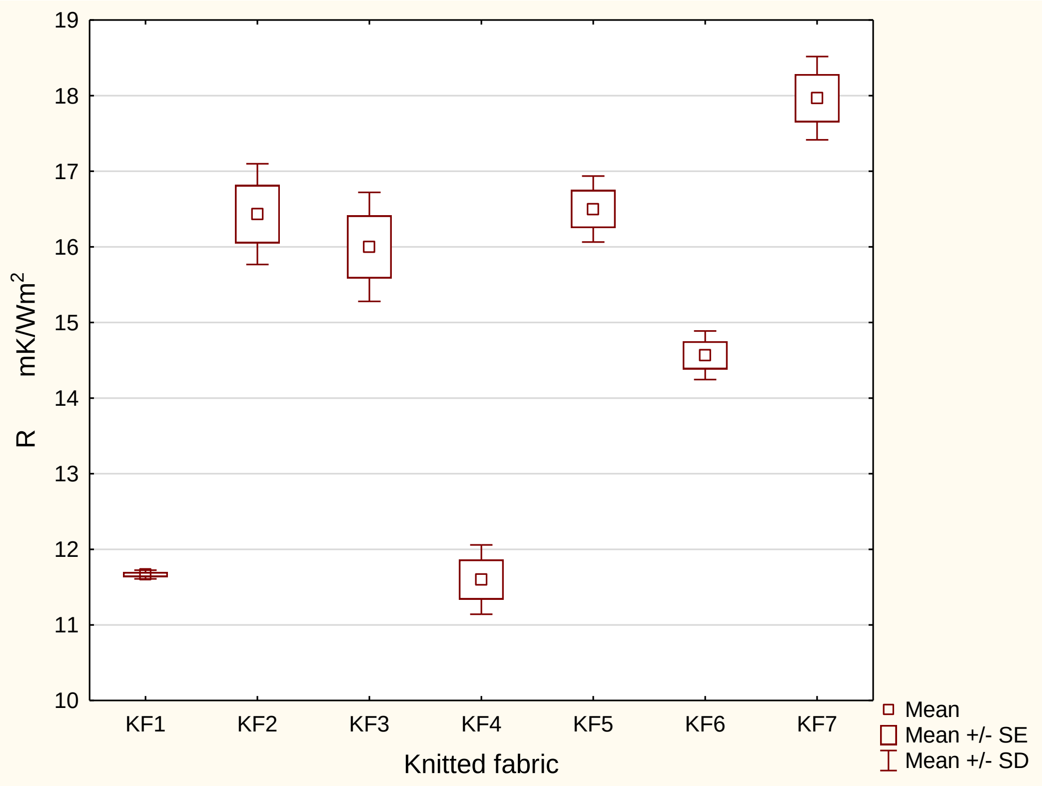


Fig. 5.7. *Thermal resistance of knitted fabrics for underwear*

Table 5.9. *The between-group comparison of thermal resistance of the knitted fabrics*

Dependent variable **b**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 21) =15.6537; p =0.0157						
	KF1 R:14.667	KF2 R:7.667	KF3 R:15.000	KF4 R:16.000	KF5 R:5.667	KF6 R:15.333	KF7 R:2.000
KF1		0.6823	1.0000	1.0000	0.7403	1.0000	0.0333
KF2	0.6823		1.0000	0.4096	1.0000	1.0000	1.0000
KF3	1.0000	1.0000		1.0000	1.0000	1.0000	1.0000
KF4	1.0000	0.4096	1.0000		0.4471	1.0000	0.0166
KF5	0.7403	1.0000	1.0000	0.4471		1.0000	1.0000
KF6	1.0000	1.0000	1.0000	1.0000	1.0000		0.3749
KF7	0.0333	1.0000	1.0000	0.0166	1.0000	0.3749	

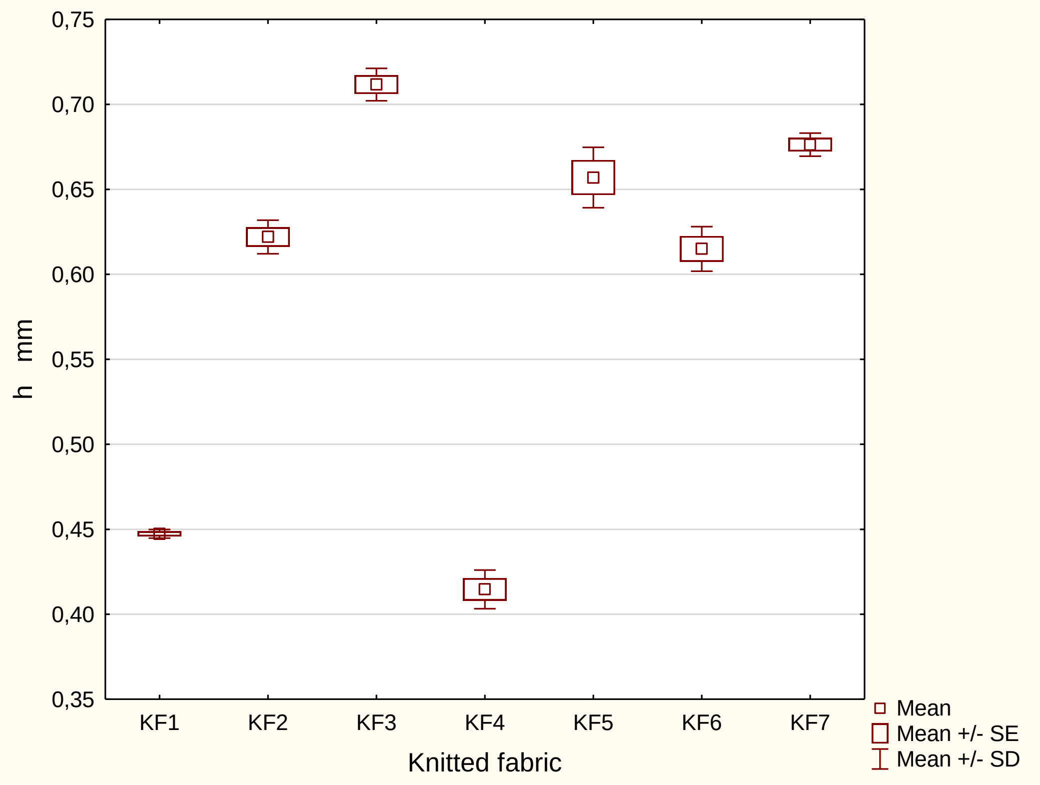


Fig. 5.8*. Thickness of knitted fabrics for underwear*

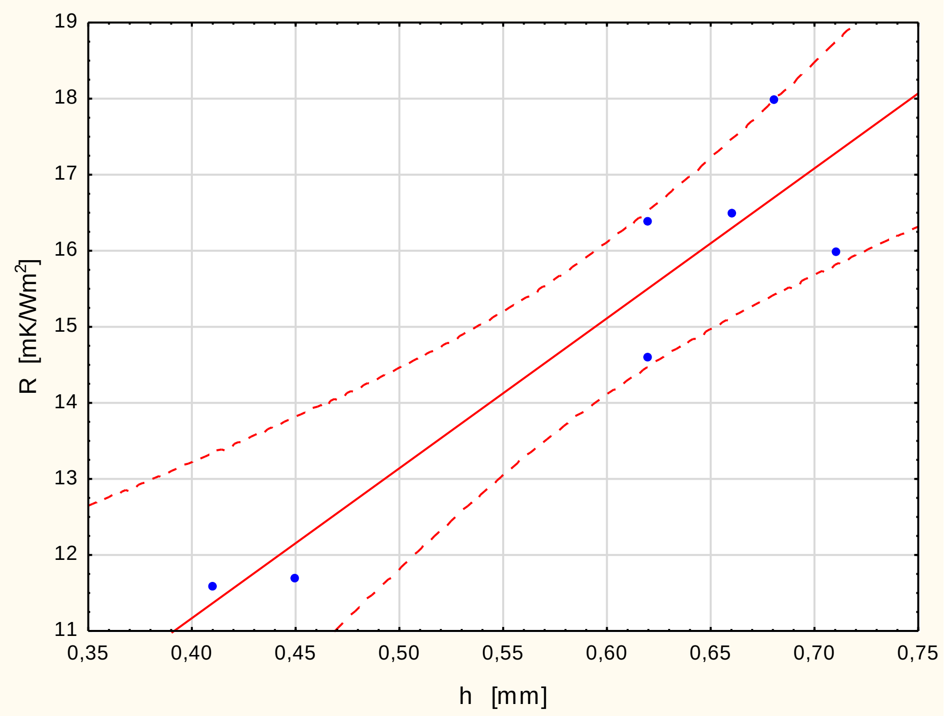


Fig. 5.9.*Thermal resistance vs. thickness of the knitted fabrics*

5.3. The thermal resistance of the firefighter’s protective assemblies made of the Sample Sets and knitted fabrics

The Sample Sets for the FPC have been assembled with the knitted fabrics taken from the T-shirts. It is because the FPC is worn together with the underwear, usually in the form of a T-shirt. It was assumed that **the thermal insulation properties of the firefighter’s clothing assembly can be shaped by an appropriate selection and connection of both the outer layer created by the protective clothing and the inner layer created by underwear**. In the presented investigations each variant of the investigated Sample Sets (4 variants) has been joined with each variant of knitted fabrics (7 variants). Together 28 variants of the firefighter’s clothing assemblies have been measured using the Alambeta to assess their thermal insulation properties.

The results of measurements of the created firefighter’s clothing assemblies are presented in the tables below (Tables 5.10 – 5.13).

Table 5.10. *Thermal insulation properties of the firefighter's clothing assemblies consisted of the Sample Set 1 and knitted fabrics*

Sample set	Knitted fabric		Thermal conductivity **λ** mW/m K	Thermal absorptivity **b** W $s^{1/2}$/m^{2}K	Thermal resistance **R** mK/Wm^2	Thickness **h** mm
SS1	KF1	Average	38.17	111.73	107.73	4.108
		SD	0.42	7.78	5.22	0.162
	KF2	Average	43.77	119.33	97.33	4.256
		SD	0.97	8.08	14.27	0.583
	KF3	Average	45.80	131.60	96.93	4.438
		SD	0.78	7.62	12.33	0.505
	KF4	Average	43.50	124.57	96.63	4.204
		SD	0.40	8.32	7.39	0.357
	KF5	Average	37.63	108.50	103.23	3.896
		SD	1.55	11.80	13.14	0.633
	KF6	Average	45.47	110.07	115.30	5.246
		SD	0.85	13.33	21.78	1.019
	KF7	Average	43.43	95.17	110.87	4.820
		SD	1.23	10.77	6.64	0.404

Table 5.11. *Thermal insulation properties of the firefighter's clothing assemblies consisted of the Sample Set 2 and knitted fabrics*

Sample set	Knitted fabric		Thermal conductivity **λ** mW/m.K	Thermal absorptivity **b** W$s^{1/2}$/m^{2}K	Thermal resistance **R** mK/Wm^2	Thickness **h** mm
SS2	KF1	Average	37.43	112.30	99.40	3.721
		SD	0.42	3.99	1.21	0.085
	KF2	Average	44.00	109.90	91.30	4.013
		SD	0.72	9.10	8.86	0.327
	KF3	Average	45.03	127.30	90.53	4.082
		SD	2.11	7.62	7.22	0.505
	KF4	Average	43.03	120.30	92.20	3.944
		SD	1.70	0.62	17.59	0.596
	KF5	Average	36.33	107.97	100.37	3.649
		SD	0.15	19.01	20.94	0.780
	KF6	Average	44.13	107.47	93.43	4.125
		SD	0.12	10.41	6.91	0.310
	KF7	Average	42.67	94.07	101.73	4.345
		SD	1.47	8.03	10.84	0.553

Table 5.12. *Thermal insulation properties of the firefighter's clothing assemblies consisted of the Sample Set 3 and knitted fabrics*

Sample set	Knitted fabric		Thermal conductivity λ mW/mK	Thermal absorptivity **b** Ws$^{1/2}$/m^{2}K	Thermal resistance **R** mK/W.m^2	Thickness **h** mm
SS3	KF1	Average	33.77	130.30	68.10	2.302
		SD	0.55	5.69	11.62	0.424
	KF2	Average	44.37	125.80	65.87	2.918
		SD	1.03	3.41	6.89	0.241
	KF3	Average	45.87	134.67	71.07	3.261
		SD	0.47	7.55	3.61	0.137
	KF4	Average	44.27	140.53	59.73	2.640
		SD	1.14	11.38	6.48	0.229
	KF5	Average	35.43	103.40	74.40	2.638
		SD	0.80	17.31	11.23	0.415
	KF6	Average	45.07	131.57	65.60	2.954
		SD	0.67	5.06	2.77	0.113
	KF7	Average	42.23	103.20	77.60	3.268
		SD	1.40	4.76	9.83	0.332

Table 5.13. *Thermal insulation properties of the firefighter's clothing assemblies consisted of the Sample Set 4 and knitted fabrics*

Sample set	Knitted fabric		Thermal conductivity λ mW/mK	Thermal absorptivity **b** Ws$^{1/2}$/m^{2}K	Thermal resistance **R** mK/Wm^2	Thickness **h** mm
SS4	KF1	Average	39.13	120.80	118.00	4.617
		SD	0.55	7.22	5.99	0.283
	KF2	Average	45.40	116.17	92.67	4.203
		SD	1.91	5.52	3.52	0.082
	KF3	Average	47.47	127.77	89.03	4.226
		SD	0.81	5.35	0.75	0.100
	KF4	Average	44.67	110.07	112.60	5.028
		SD	0.40	5.82	4.49	0.242
	KF5	Average	38.90	96.10	105.20	4.098
		SD	0.56	3.82	8.22	0.357
	KF6	Average	45.10	106.47	114.00	5.150
		SD	0.85	4.13	5.72	0.353
	KF7	Average	44.50	88.17	121.73	5.415
		SD	1.31	8.46	15.16	0.667

The post-hoc nonparametric tests allow us to assess the influence of one main parameter on the value of the variable under consideration. In the case of the multilayer clothing assemblies for the firefighter’s protective outfit, two main factors can influence their thermal properties: a kind of Sample Set and a kind of knitted fabric. It is also possible interaction between main factors. Moreover, the post-hoc nonparametric tests allow assessing no more than 10 groups. In the investigations, 28 variants of assemblies have been created. It means that a comparison of 28 groups should be performed. Due to the aforementioned reasons, to assess the influence of the Sample Set variant and variant of knitted fabrics on the thermal insulation properties of created firefighter’s clothing assemblies the statistical analysis of the results has been performed using the two-factor (two-way) ANOVA. For the analysis, the variant of the Sample Sets and variant of the knitted fabrics have been taken as main factors independent variables, whereas the parameters from the Alambeta: thermal conductivity, thermal absorptivity, thermal resistance, and thickness have been applied as dependent variables. Each thermal insulation property has been analyzed separately. The results of the ANOVA are presented in Table 5.14. The statistically significant relationships are marked in red color in this table.

The statistical analysis confirmed the assumption that by an appropriate selection of the Sample Set and underwear and by appropriately joining them into one clothing package it is possible to shape the thermal insulation properties of firefighter’s clothing assembly. Both factors the variant of Sample Sets and a variant of knitted fabrics in a statistically significant way influence all analyzed thermal insulation properties of the assemblies. There is also a statistically significant interaction between the main factors.

Table 5.14. *The results of two-way ANOVA for thermal insulation properties of firefighter's clothing assemblies consisted of Sample Sets (SS) and knitted fabrics (KF)*

<table>
<tr><td colspan="6">Thermal conductivity</td></tr>
<tr><td>Effect</td><td>SS</td><td>df</td><td>MS</td><td>F</td><td><i>p</i></td></tr>
<tr><td>Intercept</td><td>150850,8</td><td>1</td><td>150850,8</td><td>139815,3</td><td>0,000000</td></tr>
<tr><td>SS variant</td><td>52,2</td><td>3</td><td>17,4</td><td>16,1</td><td>0,000000</td></tr>
<tr><td>KF variant</td><td>991,7</td><td>6</td><td>165,3</td><td>153,2</td><td>0,000000</td></tr>
<tr><td>SS * KF</td><td>48,7</td><td>18</td><td>2,7</td><td>2,5</td><td>0,004540</td></tr>
<tr><td>Error</td><td>60,4</td><td>56</td><td>1,1</td><td></td><td></td></tr>
<tr><td colspan="6">Thermal absorptivity</td></tr>
<tr><td>Intercept</td><td>1107636</td><td>1</td><td>1107636</td><td>14069,16</td><td>0,000000</td></tr>
<tr><td>SS variant</td><td>2736</td><td>3</td><td>912</td><td>11,59</td><td>0,000005</td></tr>
<tr><td>KF variant</td><td>10225</td><td>6</td><td>1704</td><td>21,65</td><td>0,000000</td></tr>
<tr><td>SS * KF</td><td>1807</td><td>18</td><td>100</td><td>1,28</td><td>0,239512</td></tr>
<tr><td>Error</td><td>4409</td><td>56</td><td>79</td><td></td><td></td></tr>
<tr><td colspan="6">Thermal resistance</td></tr>
<tr><td>Intercept</td><td>742562,4</td><td>1</td><td>742562,4</td><td>6837,539</td><td>0,000000</td></tr>
<tr><td>SS variant</td><td>19260,6</td><td>3</td><td>6420,2</td><td>59,117</td><td>0,000000</td></tr>
<tr><td>KF variant</td><td>2739,0</td><td>6</td><td>456,5</td><td>4,203</td><td>0,001470</td></tr>
<tr><td>SS * KF</td><td>2168,9</td><td>18</td><td>120,5</td><td>1,110</td><td>0,367917</td></tr>
<tr><td>Error</td><td>6081,6</td><td>56</td><td>108,6</td><td></td><td></td></tr>
<tr><td colspan="6">Thickness</td></tr>
<tr><td>Intercept</td><td>1333,501</td><td>1</td><td>1333,501</td><td>6737,373</td><td>0,000000</td></tr>
<tr><td>SS variant</td><td>40,941</td><td>3</td><td>13,647</td><td>68,950</td><td>0,000000</td></tr>
<tr><td>KF variant</td><td>7,870</td><td>6</td><td>1,312</td><td>6,627</td><td>0,000025</td></tr>
<tr><td>SS * KF</td><td>4,245</td><td>18</td><td>0,236</td><td>1,191</td><td>0,299418</td></tr>
<tr><td>Error</td><td>11,084</td><td>56</td><td>0,198</td><td></td><td></td></tr>
</table>

Legend: SS – sum of squares, df – degree of freedom, MS – mean square of error, F – variable of F distribution, p – significance level.

Fig. 5.10 presents the influence of the Sample Set variant on the thermal conductivity of created assemblies. The highest thermal conductivity was stated for the group of assemblies created on the basis of the Sample Set SS4, and the lowest – for the assemblies created on the basis of the SS3 set. The variant of knitted fabrics also influences the value of the thermal conductivity of the assemblies (Fig. 5.11). The highest thermal conductivity was stated for the group of assemblies created with the KF3 variant, and the lowest - for the groups of assemblies created with the KF1 and KF5 knitted fabric variants.

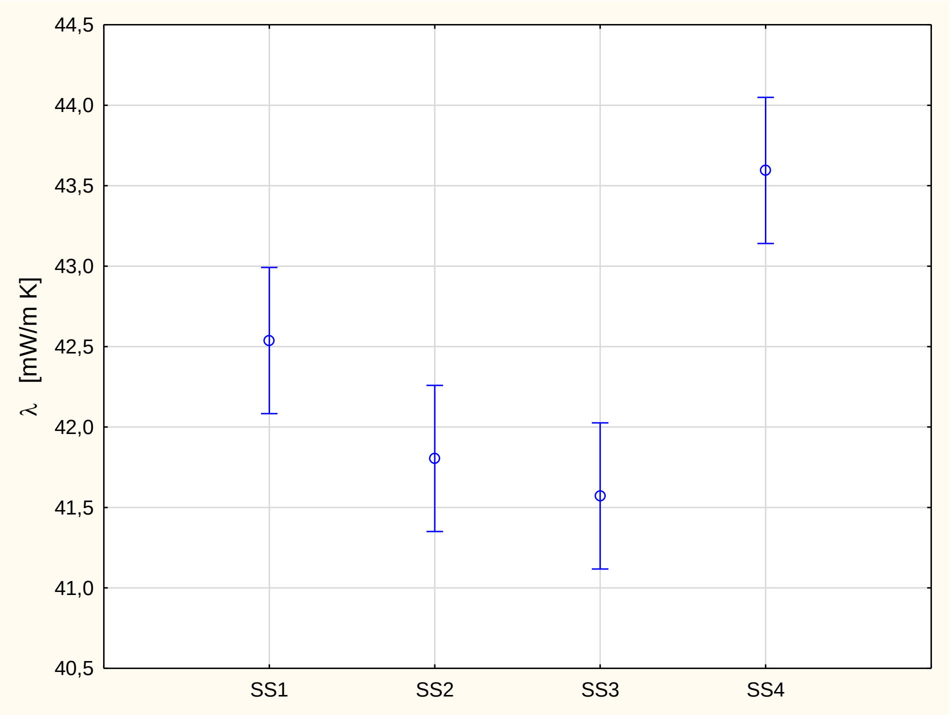


Fig. 5.10. *The influence of Sample set (SS) variant on the thermal conductivity of multilayer clothing assembly with knitted fabric*

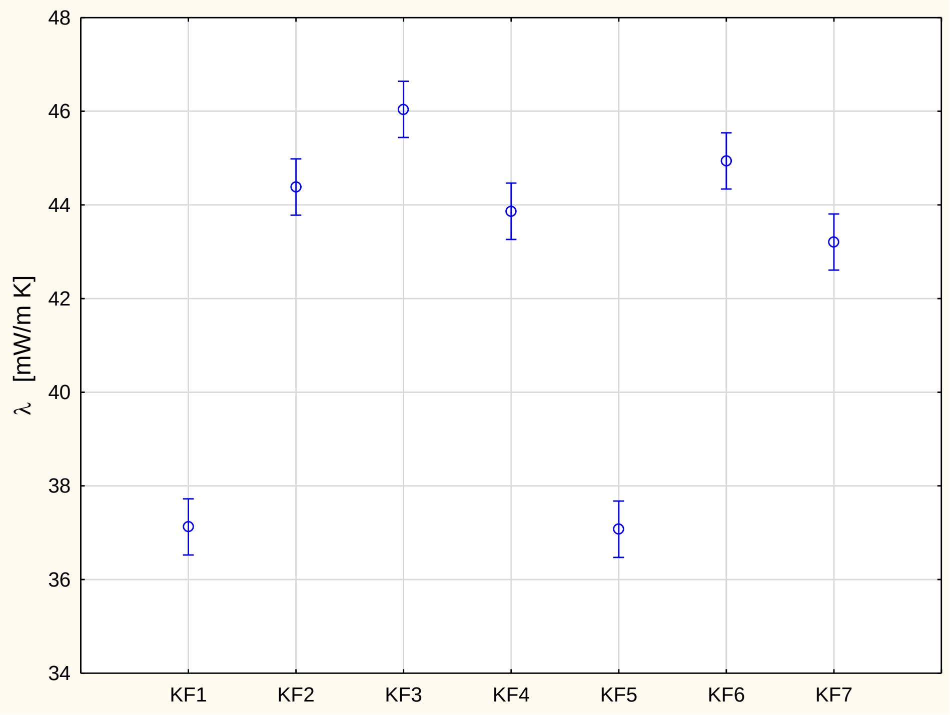


Fig. 5.11*. The influence of knitted fabric (KF) variant on the thermal conductivity of multilayer clothing assembly*

The statistical analysis showed that there is a statistically significant interaction between both main factors: variant of SS and variant of KF. The influence of the variant of Sample Sets changes the influence of the knitted fabric variant on the assembly thermal conductivity (Fig. 5.12). Generally, the thermal conductivity of the multilayer clothing assemblies created based on the SS4 Sample set has the highest value in comparison to the assemblies created based on the rest of the Sample Sets. But when joining the Sample sets with the KF6 knitted fabric the highest thermal conductivity occurred for the assembly created based on the SS1 Sample set. In the case of the multilayer clothing assemblies containing the KF1, KF5, and KF7 knitted fabric the lowest thermal conductivity was stated for the assemblies created based on the SS3 Sample set variant. For assemblies containing created based on the SS3 and the rest of the knitted fabrics (KF2, KF3, KF4and KF6) their thermal conductivity has a middle value (between maximum and minimum values) stated for particular groups of multilayer clothing assemblies.

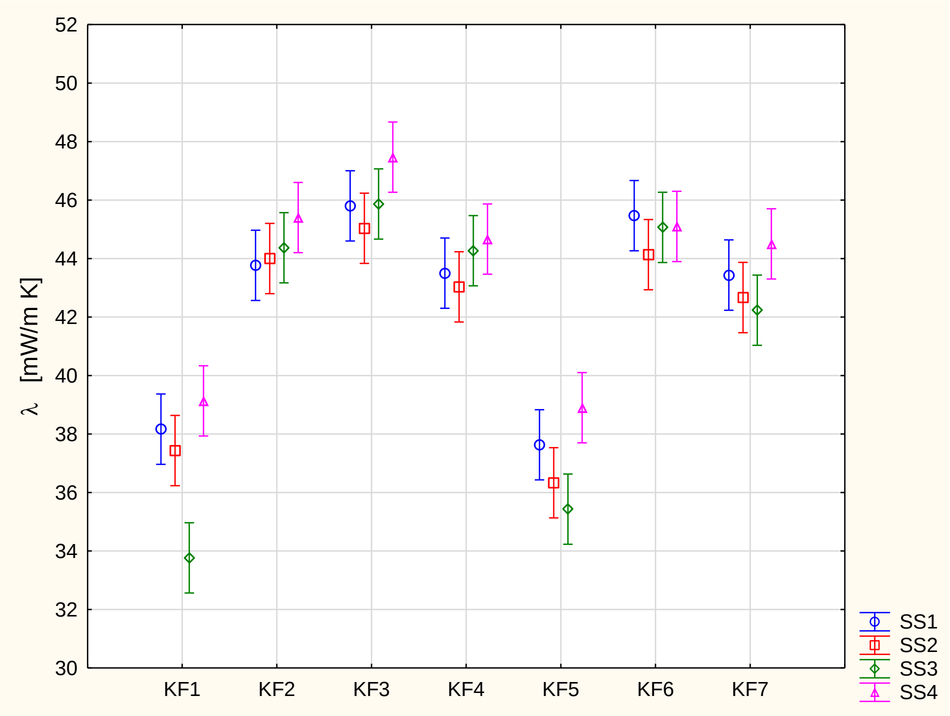


Fig. 5.12. *The influence of Sample set (SS) and knitted fabric (KF) variant on the thermal conductivity of the multilayer clothing assembly*

Thermal absorptivity of created multilayer clothing assemblies varies significantly depending on the Sample Set variant applied in the assembly (Fig.

5.13). The highest value of the thermal absorptivity and in the same way the coolest feeling was stated for a group of assemblies created on the basis of the SS3 Sample Set. The lowest average value of the thermal absorptivity and in the same time the wormer touch was stated for the group of assemblies created on the basis of the SS4 Sample Set. The influence of the Sample Set variant on the thermal absorptivity of the created multilayer clothing assemblies is statistically significant at the significance level of 0.05.

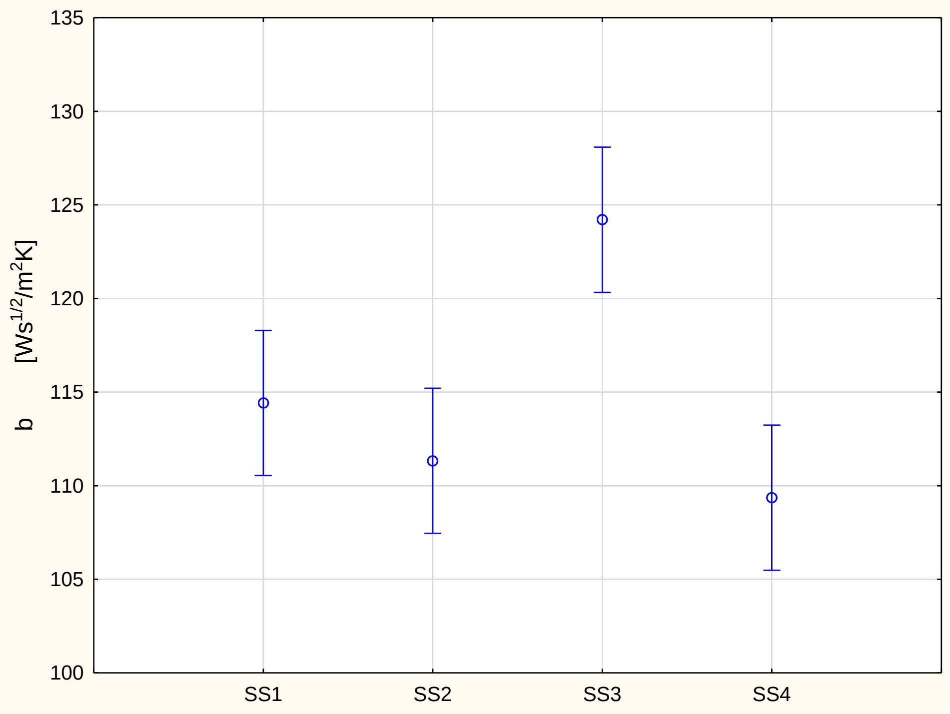


Fig. 5.13. *The influence of Sample set (SS) variant on the thermal absorptivity of multilayer clothing assembly*

The influence of the knitted fabric variant on the thermal absorptivity of assemblies is also statistically significant (Table 5.14, Fig. 5.14). The highest thermal absorptivity was stated for the group of assemblies containing the KF3, and the next KF4 knitted fabric variants, and the lowest – was for the group of assemblies containing the KF7 knitted fabric variant. There is an interaction between the knitted fabric variant and the Sample set variant (Fig. 5.15) but it is statistically insignificant (Table 5.14). On the basis of the results presented in Fig. 5.15, it can be stated that the coolest feeling while touching (the highest thermal absorptivity) is given by the following assemblies:

- SS3+KF4 (b = 140.54 $Ws^{1/2}/m^2K$),
- SS3+KF3 (b = 134.67 $Ws^{1/2}/m^2K$),
- SS1+KF3 (b = 131.60 $Ws^{1/2}/m^2K$),
- SS3+KF6 (b = 131.57 $Ws^{1/2}/m^2K$),
- SS3+KF1 (b = 130.30 $Ws^{1/2}/m^2K$).

The warmest feeling (the lowest value of the thermal absorptivity) is given by:

- SS4+KF7 (b = 88.17 $Ws^{1/2}/m^2K$),
- SS2+KF7 (b = 94.07 $Ws^{1/2}/m^2K$),
- SS1+KF7 (b = 95.17 $Ws^{1/2}/m^2K$),
- SS4+KF5 (b = 96.10 $Ws^{1/2}/m^2K$).

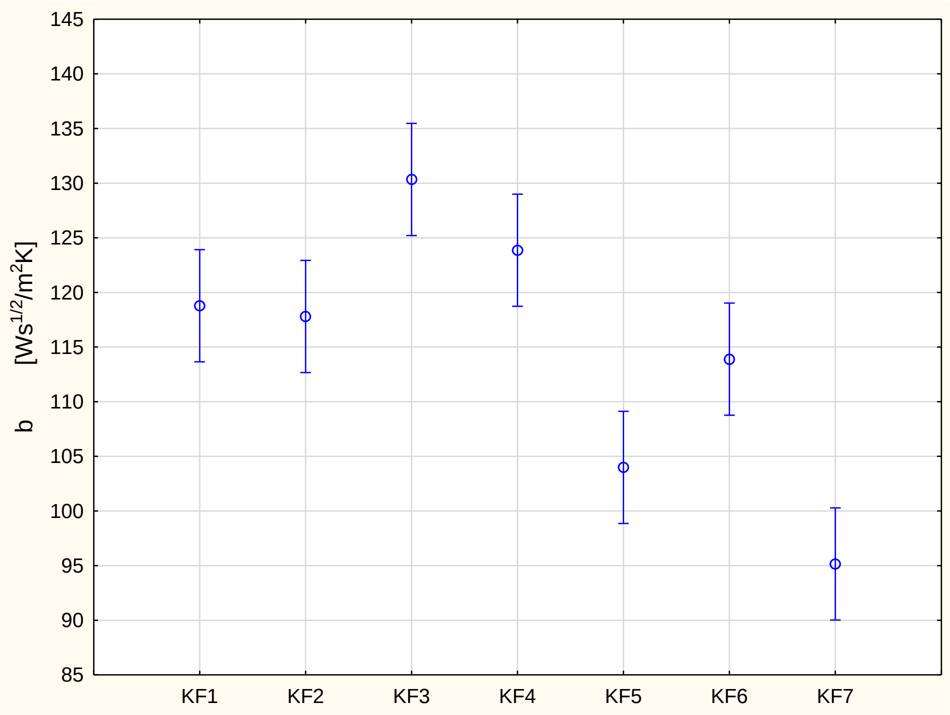


***Fig. 5.14**. The influence of knitted fabric (KF) variant on the thermal absorptivity of multilayer clothing assembly*

The thermal absorptivity of the multilayer clothing assemblies is an important property of the created assemblies. They contain knitted fabrics that are applied to T-shirts used as underwear. While usage of the assemblies they will adhere to human skin. The warm or cool feeling while touching influences the thermo-physiological comfort of the clothing user.

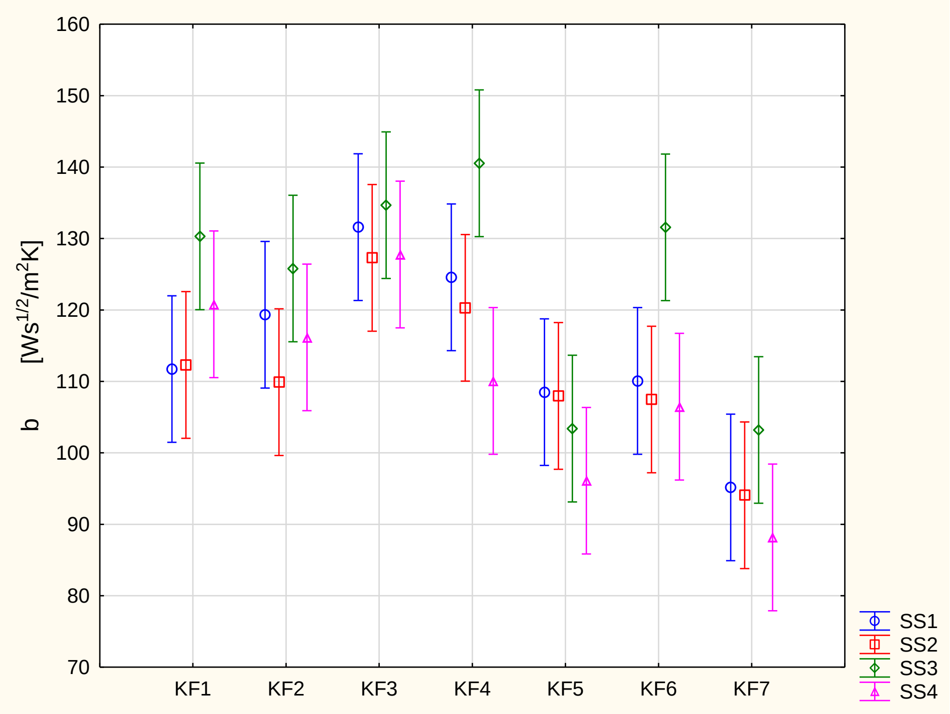


Fig. 5.15*. The influence of Sample set (SS) and knitted fabric (KF) variant on the thermal absorptivity of multilayer clothing assembly*

The thermal resistance of the multilayer textile assemblies is also influenced by both the variant of Sample Sets and the variant of knitted fabrics (Fig. 5.16, 5.17). Similarly to the thermal absorptivity, the influence of both main factors is statistically significant, whereas the interaction between the main factors is statistically insignificant at the significance level of 0.05 (Table 5.14, Fig. 5.18). The greatest average thermal resistance occurred for the multilayer clothing assemblies created on the basis of the SS4 Sample Set, and next – on the basis of the SS1 Sample Set variant. The lowest average thermal resistance was stated for the group of the multilayer clothing assemblies made on the basis of the SS3 Sample Set variant (Fig. 5.18). In the aspect of knitted fabrics applied in the multilayer clothing assemblies, the highest average thermal resistance is observed for the group of assemblies containing the KF7 knitted fabric, and next - the KF1 knitted fabric. The lowest average thermal resistance was stated for the group of assemblies with the KF2 and KF3 knitted fabrics. It should be mentioned here that the KF7 knitted fabric is a fabric taken from the special T-shirt for firefighters. Apart from the resistance to flames, it ensures high thermal resistance. The results confirmed that the design and raw material composition of the special T-shirt for firefighters ensure that the T-shirt fulfills its function.

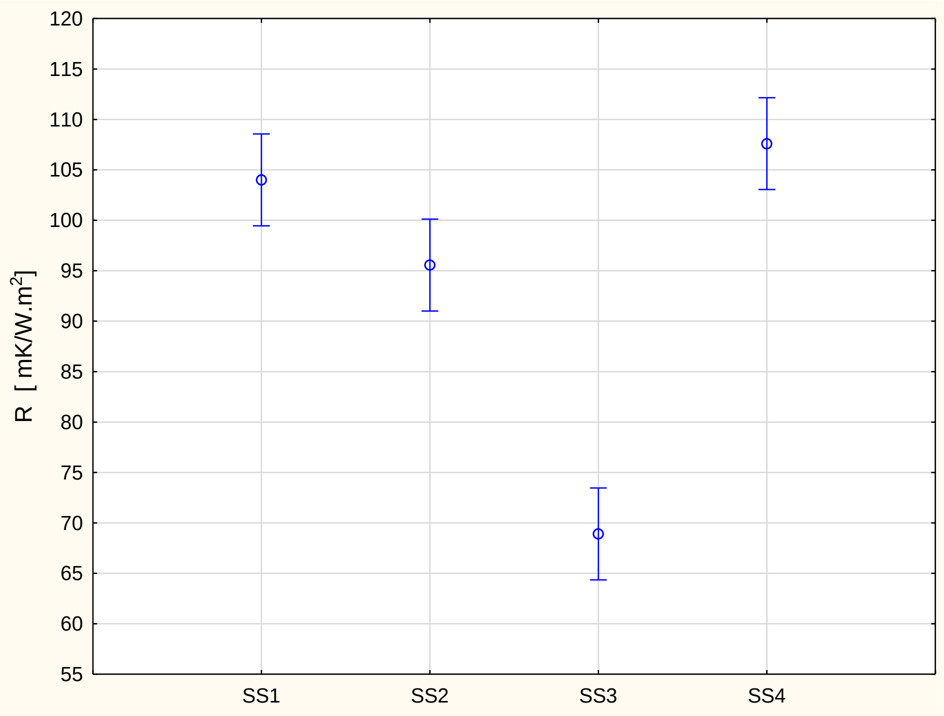


Fig. 5.16. *The influence of Sample set (SS) variant on the thermal resistance of multilayer clothing assembly*

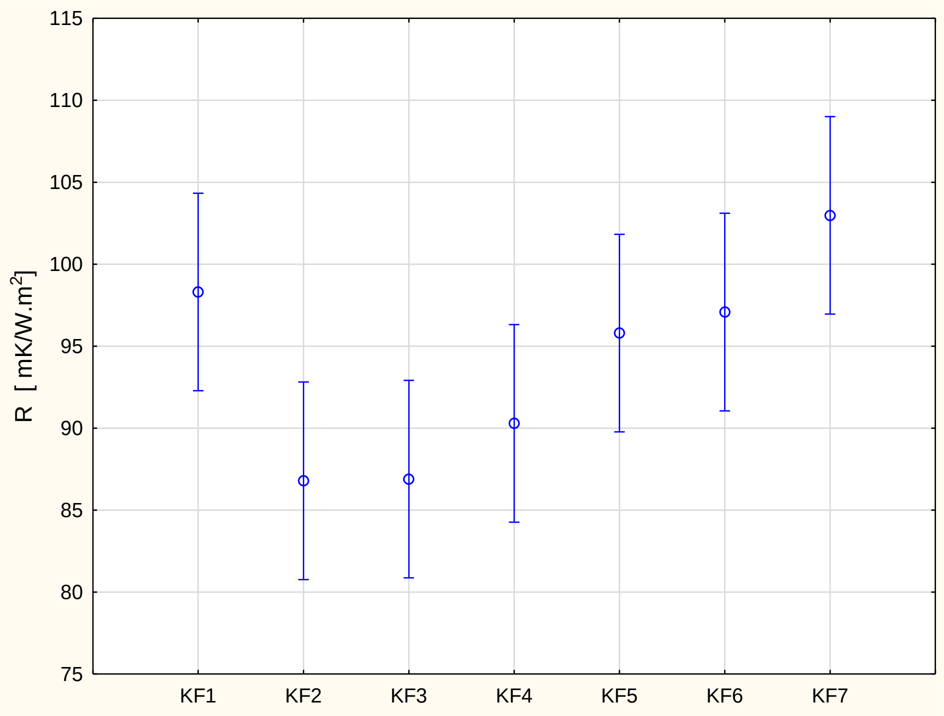


Fig. 5.17. *The influence of knitted fabric (KF) variant on the thermal resistance of multilayer clothing assembly with knitted fabric*

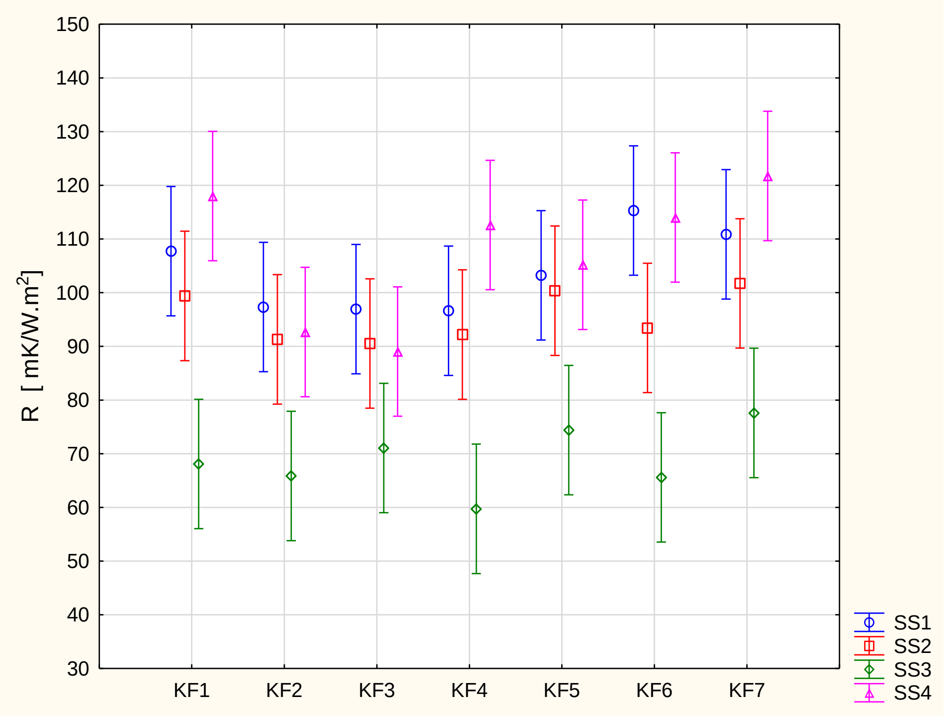


Fig. 5.18. *The influence of Sample set (SS) and knitted fabric (KF) variant on the thermal resistance of the multilayer clothing assembly with knitted fabric*

According to theory the thermal resistance of the multilayer thermal barrier is a sum of the thermal resistance of particular layers. In the theory of solid objects, it is additional thermal resistance in the multilayer barriers resulting from the air spaces occurring between the surfaces of joined objects. It is co-called thermal contact resistance (Fig. 5.19) Due to the surface roughness of the solid objects only a small fraction of the nominal surface area is actually in contact. If a heat flux is imposed across the junction, the uniform flow of heat is generally restricted to conduction through the contact areas /points.

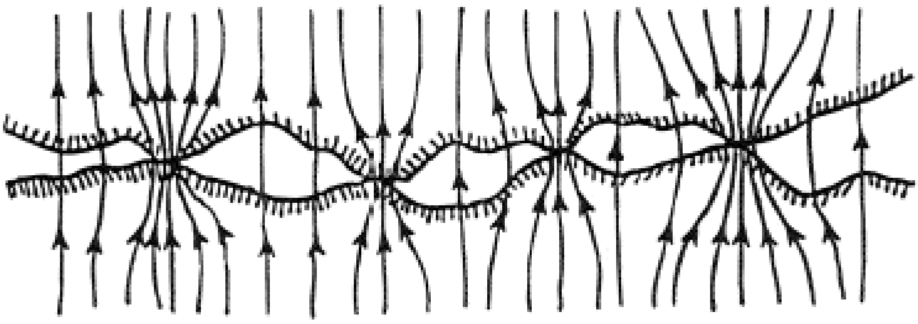


Fig. 5.19. *Illustration of thermal contact resistance*
[https://www.thermopedia.com/content/1188/#THERMAL_CONTACT_RESISTANCE_FIG1]

The limited number and size of the contact area result in an actual contact area that is significantly smaller than the apparent contact area. This limited contact area causes contact resistance or thermal contact resistance.

On the basis of the obtained results from the Alambeta, the thermal resistance of created multilayer clothing assemblies was calculated according to the equation (3.4) as a sum of the thermal resistance of particular layers, i.e. the thermal resistance of the Sample set and thermal resistance of knitted fabric joined together in one assembly. Next, the measured and calculated values of the thermal resistance of multilayer clothing assemblies were compared. The comparison is presented in Fig. 5.20.

It is clearly seen that in the majority of cases, the calculated values are greater than the measured ones. Fig. 5.21 presents the difference between the calculated and measured values of the thermal resistance of the assemblies. The lowest differences occurred for the assemblies created on the basis of the SS3 Sample Set. Obtained results are in agreement with the results published by the researchers dealing with the thermal insulation of textile materials [127, 161].

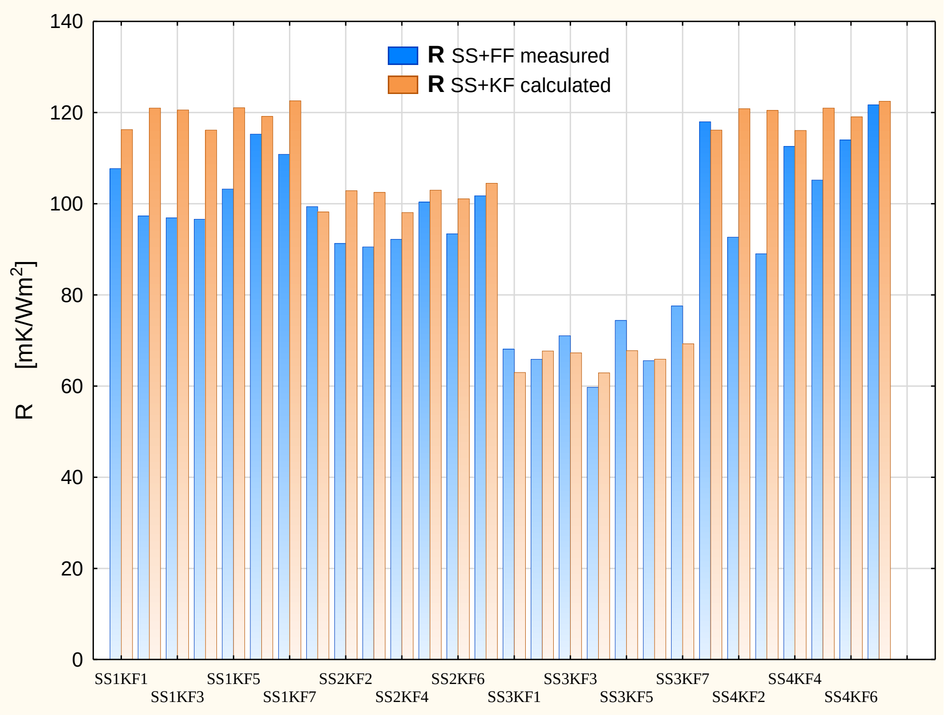


Fig. 5.20. *Comparison of the measured and calculated values of thermal resistance of multilayer clothing assemblies*

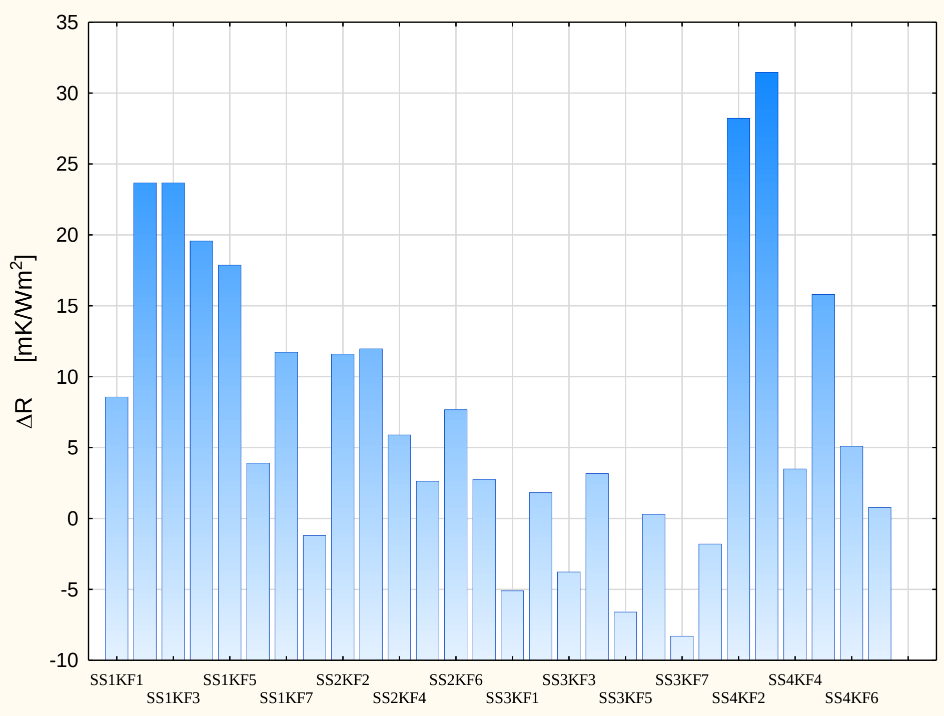


Fig. 5.21. *Difference between the calculated and measured values of the thermal resistance of multilayer clothing assemblies*

In the case of textile materials, they are soft, flexible, and easy to deform. Due to the flexibility and geometric structure of the surface of textile materials, especially their texture, different directions of fibers in particular materials creating layers, two factors can occur [161, 162]:

- increased number of contact points,
- fulfilling the pores in one layer by the elements of the adjacent layer (Fig. 5.22).

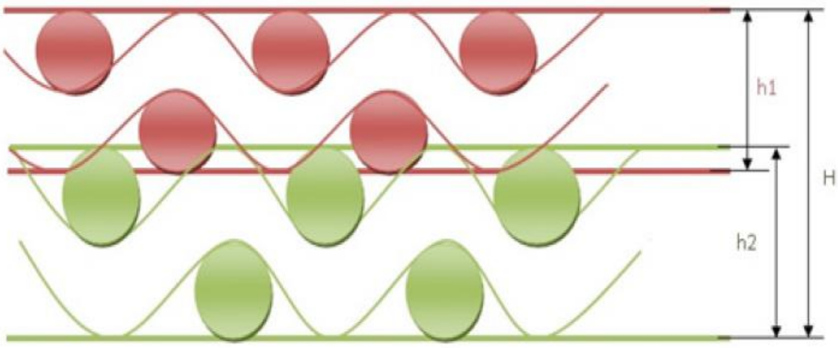


Fig. 5.22. *Schematic cross-section of multilayer textile assembly [161]*

It causes the thermal flow can occur on a greater surface than the nominal contact surface of adhering fabrics. And what is more important, due to the fulfilment of the pores (concave elements) in one layer by the convex elements of the adjacent layer and presser of the upper plate of the Alambeta the thickness of the assemblies while measuring is smaller than that calculated as the sum of thickness measured for particular layers. Results presented in Fig. 5.23 confirm it.

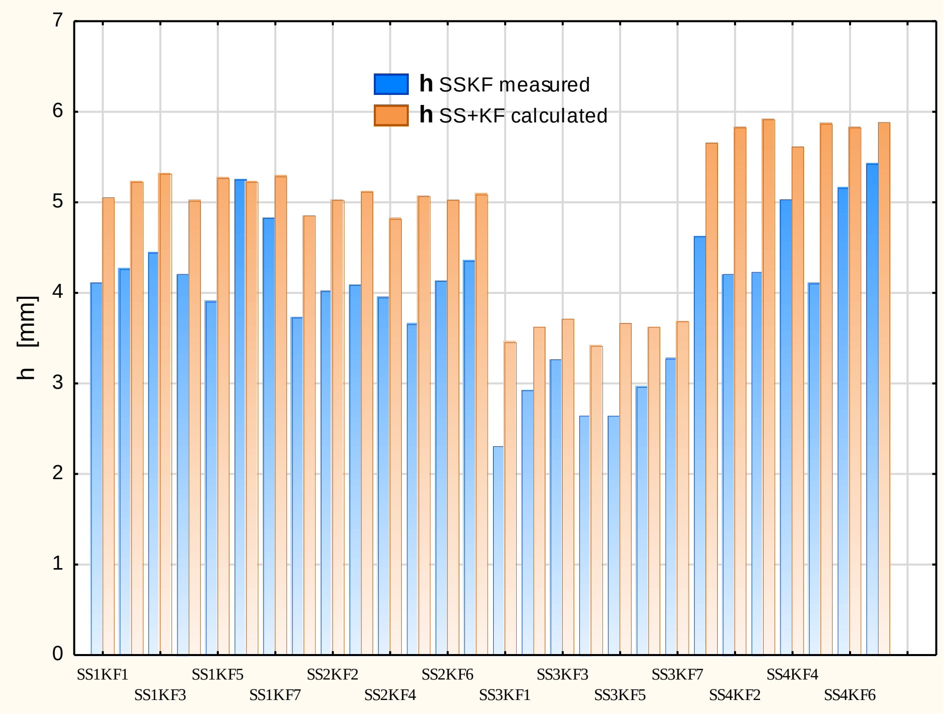


Fig. 5.23. *Comparison of calculated and measured thickness of multilayer textile assemblies*

The phenomenon can be partially explained by the schemes presented below (Fig. 5.24).

While measuring the multilayer textile sets by means of the Alambeta the pressure of the upper (hot) plate of the device can cause a deformation of the materials. The pressure is very low and normally it is neglected. However, when measuring the sets of textile materials the pressure of the hot plate makes it easy that the convex spots on the surface of one material can fill concave spots on the surface of another material. It leads to a smaller thickness of the multilayer set detected by the Alambeta, than the sum of the thickness of particular layers measured individually. And in consequence:

$$h_{1+2\ (set)} < h_1 + h_2 \qquad (5.1)$$

Moreover, the volume of air spaces between the plates of the Alambeta being the main source of the thermal resistance is lower while measuring the fabrics' sets (Fig. 5.24 c) than that a sum of air spaces occurring while measuring the particular fabrics individually (Fig. 5.24 a and Fig. 5.24 b).

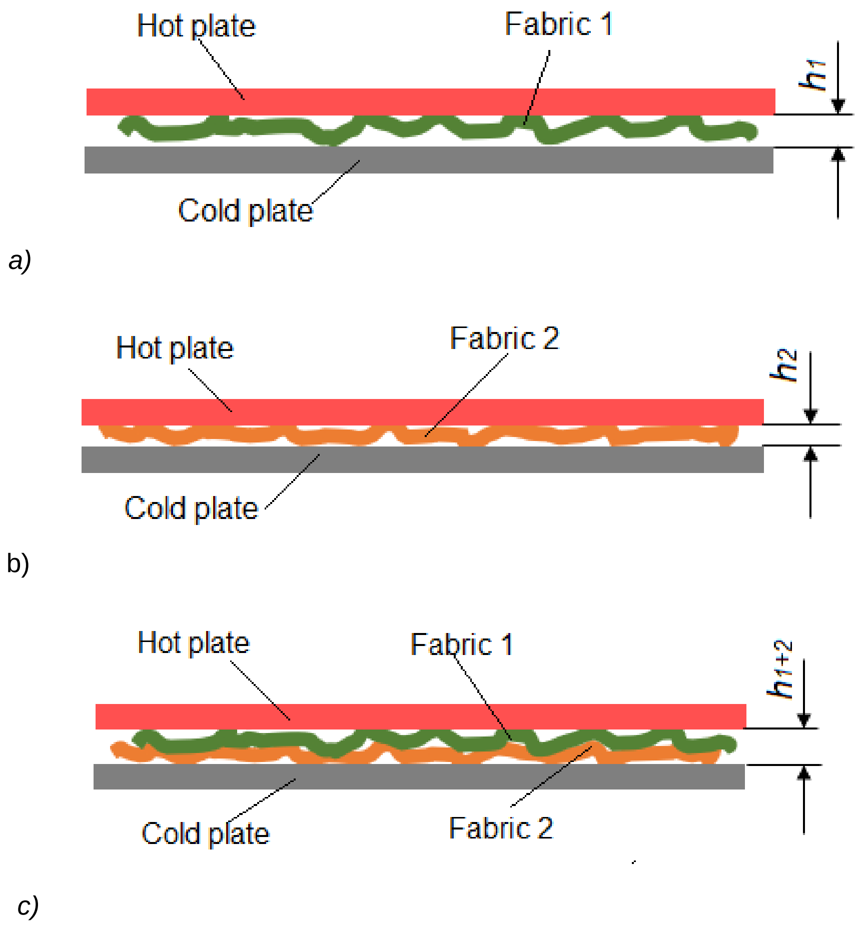


***Fig. 5.24**. Schematic presentation of measurement of textile materials by the Alambeta: a) measurement of fabric 1, b) measurement of fabric 2, c) measurement of sets of both fabrics*

5.4. Conclusion

On the basis of the performed investigations, it was stated that the variants of investigated multilayer textile sets for the FPC (called Sample Sets) differ from each other in the range of the thermal-insulation properties.

The highest thermal resistance was stated for the SS1 and SS4 Sample Sets as well as for the KF7, KF5, and KF 2 knitted fabrics. The highest thermal resistance of the created multilayer clothing assemblies occurred for the following assemblies:

- SS4+KF7,
- SS4+KF1,
- SS1+KF6.

The lowest value of thermal resistance was stated for the SS3+KF4 and SS3+KF 6 variants of the multilayer clothing assemblies. The difference between the variants of the highest and the lowest thermal resistance in the group of created assemblies was 62 mK/Wm². is a value greater than the thermal resistance of the SS3+KF4 variant, for which the thermal resistance is 59.73 mK/Wm².

Obtained results show very clearly **that by appropriate selection of the components of the firefighter's clothing outfit, it is possible to improve significantly the thermal resistance of the outfit** and in the same way to improve the safety and comfort of firefighter wearing the protective clothing. The thermal resistance can be even doubled.

In the case of thermal absorptivity and thermal resistance, the influence of the kind of the Sample Set influences the values of the parameters in a statistically significant way at the significance level of 0.05. The thermal resistance of the Sample Set is in agreement with their thickness.

The thermal insulation properties of the knitted fabrics for underwear also differ between each other dependably on the knitted fabric variant. The influence of the KF variant on the values of thermal-insulation properties is statistically significant at the statistical significance of 0.05. There is a statistically significant correlation between the thermal resistance and thickness of the knitted fabrics being analyzed.

The multilayer textile assemblies created on the basis of the Sample Sets and knitted fabrics are characterized by different thermal insulation properties dependably on the variant of assembly. Statistical analysis confirmed that the influence of both a kind of the Sample Set and a kind of knitted fabric significantly influence the thermal properties of the created assemblies at the significance level of 0.05. In the case of thermal resistance, the interaction between both independent variables is also statistically significant.

The coolest feeling (the highest value of the thermal resistance) while first touching the assembly with human skin is given by the assemblies created on the basis of the SS3 Sample Set and KF4, KF3 knitted fabrics.

Obtained results partially confirm the theoretical consideration of the thermal resistance of multilayer barrier – equation (3.4). However, there is some deviation from the theoretical assumptions. In the majority of cases, the measured thermal resistance of multilayer textile assemblies is lower than that calculated as a sum of the thermal resistance of the Sample Set and knitted fabric. It is in agreement with previously published research works [127, 161, 162]. It results from the rough surface of textile materials and their flexibility. It causes the area of the contact surface between the layer through which the heat flow occurs can be higher than the nominal area of the surface of adhering layers.

6. Analysis of the water-vapor permeability properties of textile materials for firefighter’s clothing

The evaporation of sweat is very important from the point of view of the physiological comfort of clothing usage. The water-vapor permeability of clothing materials is a critical property of clothing systems that must maintain thermal equilibrium for the wearer. Clothing materials with high water-vapor permeability allow the human body to take advantage of its ability to provide cooling due to sweat production and evaporation [163]. It is important to measure the rate at which a material can transmit moisture vapor for assessing the potential of that material in enhancing or reducing comfort. Measurement of the water-vapor resistance Ret [mK.m^2/W], and relative water-vapor permeability P [%] has been performed using the PERMETEST device.

The following sequence of measurements has been used:

- measurement of water-vapor resistance of the Sample Sets (SS),
- measurement of the knitted fabrics for underwear (KF),

For each object being investigated three repetitions of measurement have been performed.

Unfortunately, due to the instrument failure, it was impossible to measure the created assemblies consisting of the Sample Sets and knitted fabrics.

6.1. Water-vapor resistance of Sample Sets

Table 6.1 shows the water-vapor permeability of four types of multilayer textiles for the FPC.

Based on the presented results it was found that the multilayer materials of the FPC differ from each other in the parameters measured by the Permetest. The highest average water-vapor resistance was stated for the SS1 Sample Set. For it the Ret = 117.8 mK m^2/W (Fig. 6.1).

Table 6.1. *The water-vapor permeability properties parameters of multilayer materials for the firefighter's protective clothing*

Sample Set	Parameter	R_{et} [mKm^2/W], p [%]				
		Average	Min	Max	CV [%]	SD
SS1	Ret	117.8	112.3	124.3	5.2	6.1
	p	7.6	7.1	8.1		0.5
SS2	Ret	49.4	19.6	55.0	46.2	19.3
	p	14.1	12.9	15.3		11.6
SS3	Ret	28.5	26.5	32.0	10.6	3.0
	p	21.5	12.5	26.0		7.8
SS4	Ret	77.3	63.3	92.6	17.6	14.7
	p	10.4	8.3	11.9		1.8

Temperature: 24.5^{0}C, Humidity: 40, Calibration coefficient: 0.35

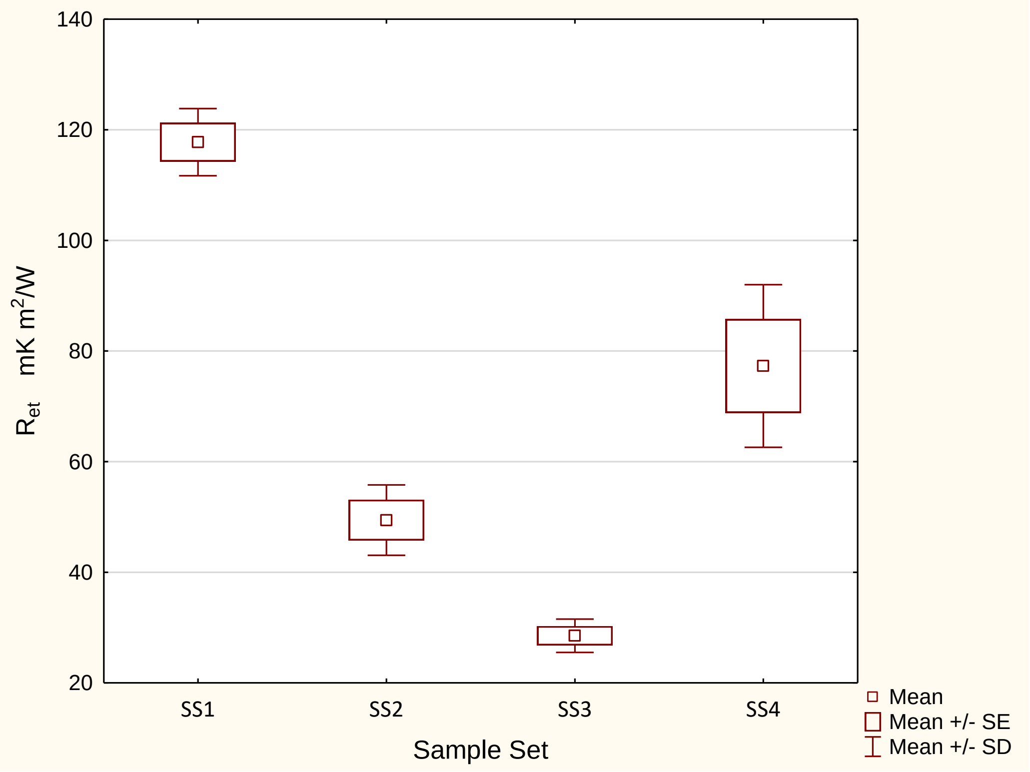


Fig. 6.1. *The water-vapor resistance of multilayer textile sets for the firefighter's protective clothing*

It is very high value. For the protective clothing protecting against cold [164] the classification according to the water-vapor resistance is the following:

- Class 1: Ret > 40 mK m^2/W,
- Class 2: 25 < Ret ≤ 40 mK m^2/W,

- Class 3: $15 < Ret \le 25$ mK m^2/W,
- Class 4: $Ret \le 15$ mK m^2/W.

Only the SS3 variant (R_{et} = 28.5 mKm^2/W) can be classified into Class 3. The rest of the Sample Sets are in Class 1 – the worst one in the aspect of water-vapor permeability.

Fig. 6.2 presents the relative water-vapor permeability p of the investigated multilayer textile sets for the FPC. The value of the parameter p can be in the range from 0 to 1. The highest value is the better ability of the material to transfer the water vapor. In the case of the investigated Sample Sets the value of the relative water vapor permeability is low (Fig.6.2). The highest value was stated for the SS3 variant (p= 21.5%) the lowest – for the SS1 variant (p = 7.6%).

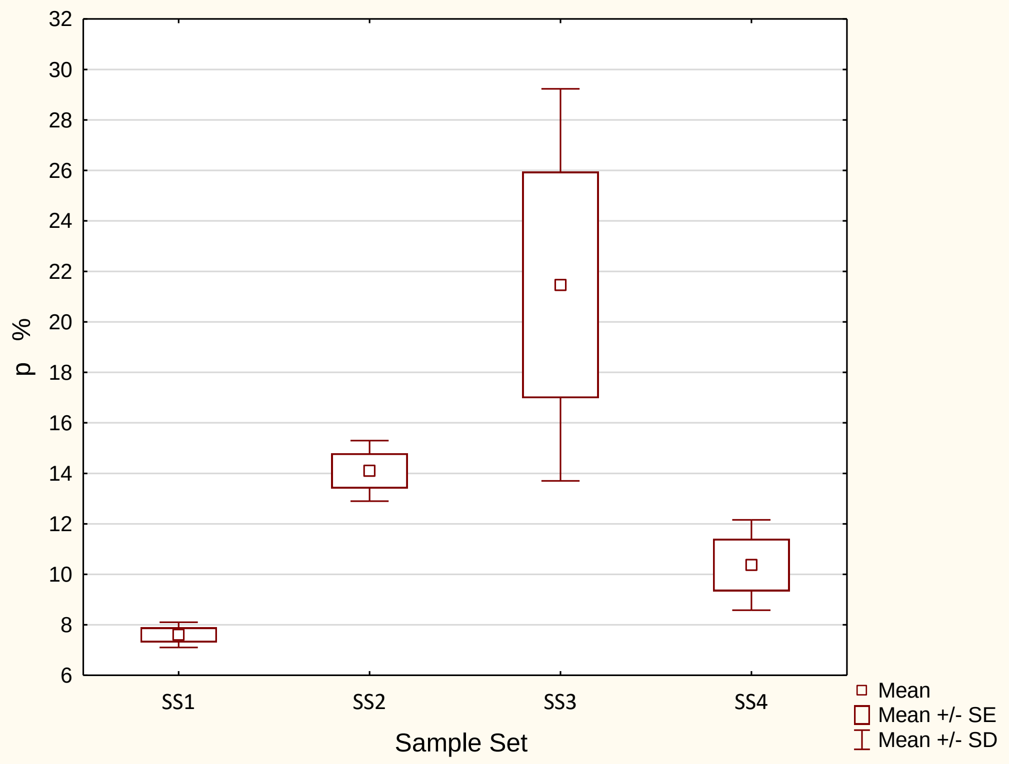


Fig. 6.2. *The water-vapor resistance of multilayer textile sets for the firefighter's protective clothing*

To evaluate the influence of the Sample set variant on water-vapor permeability properties the statistical analysis was performed using nonparametric post-hoc Kruskal-Wallis ANOVA and Median tests. In the tables showing the results of statistical analysis (Table 6.2 and 6.3), statistically significant influence at a significance level of 0.05 was indicated by red numbers. In both cases: water-vapor resistance and relative water-vapor permeability the influence of the SS variant on the parameters is statistically significant at the significance level 0.05. The two-sided comparison showed that the statistically significant differences occurred between the SS1 and SS3 variants.

Table 6.2. *The between-group comparison of water-vapor resistance of the Sample sets*

Dependent variable **R_{et}**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 12) = 10.3846; p =0.0156			
	SS1 R:11.000	SS2 R:5.000	SS3 R:2.000	SS4 R:8.000
SS1		0.2492	0.0134	1.0000
SS2	0.2492		1.0000	1.0000
SS3	0.0134	1.0000		0.2492
SS4	1.0000	1.0000	0.2492	

Table 6.3. *The between-group comparison of relative water-vapor permeability of the Sample sets*

Dependent variable **P**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 12) = 9.4615; p =0.0237			
	SS1 R:2.000	SS2 R:9.000	SS3 R:10.000	SS4 R:5.000
SS1		0.1045	0.0395	1.0000
SS2	0.1045		1.0000	1.0000
SS3	0.0395	1.0000		0.5366
SS4	1.0000	1.0000	0.5366	

The multilayer materials investigated for the FPC consist of three/four layers among which is a moisture barrier layer. This moisture barrier acts as a significant barrier to water-vapor permeability. Therefore, it was studied how the permeation of water vapor from the human body penetrates the inner layer in the multilayer material for the FPC and reaches the moisture barrier. The water-vapor permeability properties parameters of four types of the inner layer in multilayers textile sets - Sample Sets for the FPC are presented in Table 6.4.

Table 6.4. *The water-vapor permeability properties parameters of the inner layer in multilayer materials for the firefighter's protective clothing*

Sample	Parameter	**Ret [mKm^2/W]**				
		Average	Min	Max	CV [%]	SD
SS1 Inner layer	Ret	17.3	16.2	18.0	5.5	0.9
	p	29.1	27.9	29.7		1.0
SS2 Inner layer	Ret	6.2	6.1	6.5	4.2	0.3
	p	54.2	52.9	54.9		1.1
SS3 Inner layer	Ret	4.5	4.3	5.0	9.0	0.4
	p	61.7	59.0	63.2		2.4
SS4 Inner layer	Ret	10.3	9.3	11.8	12.6	1.3
	p	42.6	39.4	44.5		2.8

Temperature: 24.9^{0}C, Humidity: 40, Calibration coefficient: 0.35

Measurements of the inner layer in the multilayer textile package for the FPC also confirmed differences between them in terms of the water-vapor permeability properties (Fig. 6.3 and 6.4).

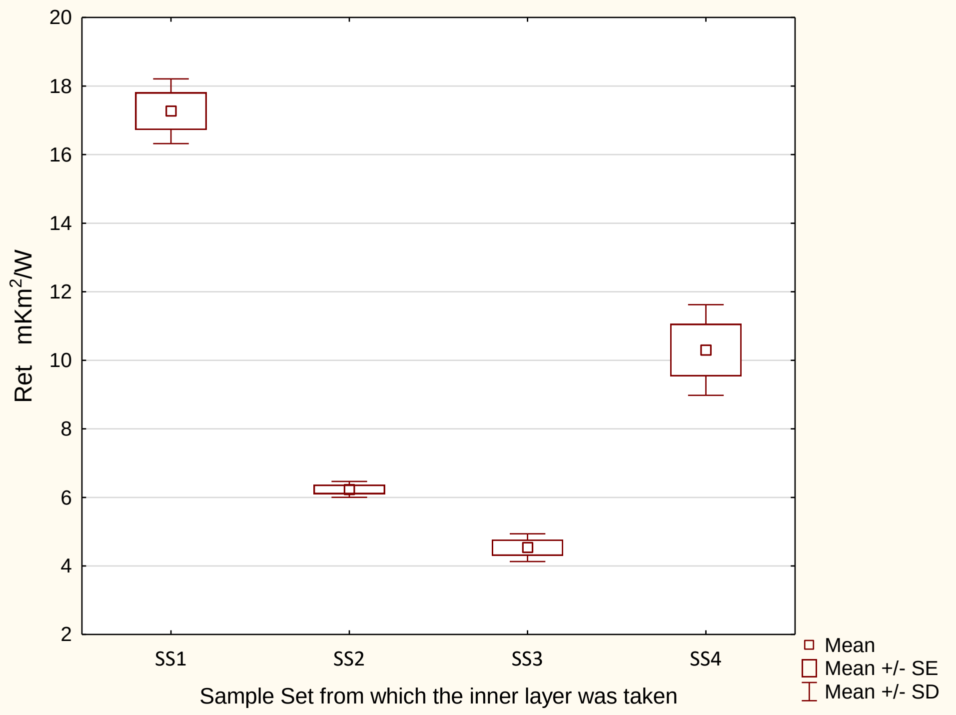


Fig. 6.3. *The water-vapor resistance of the inner layer in multilayer textile sets for the firefighter's protective clothing*

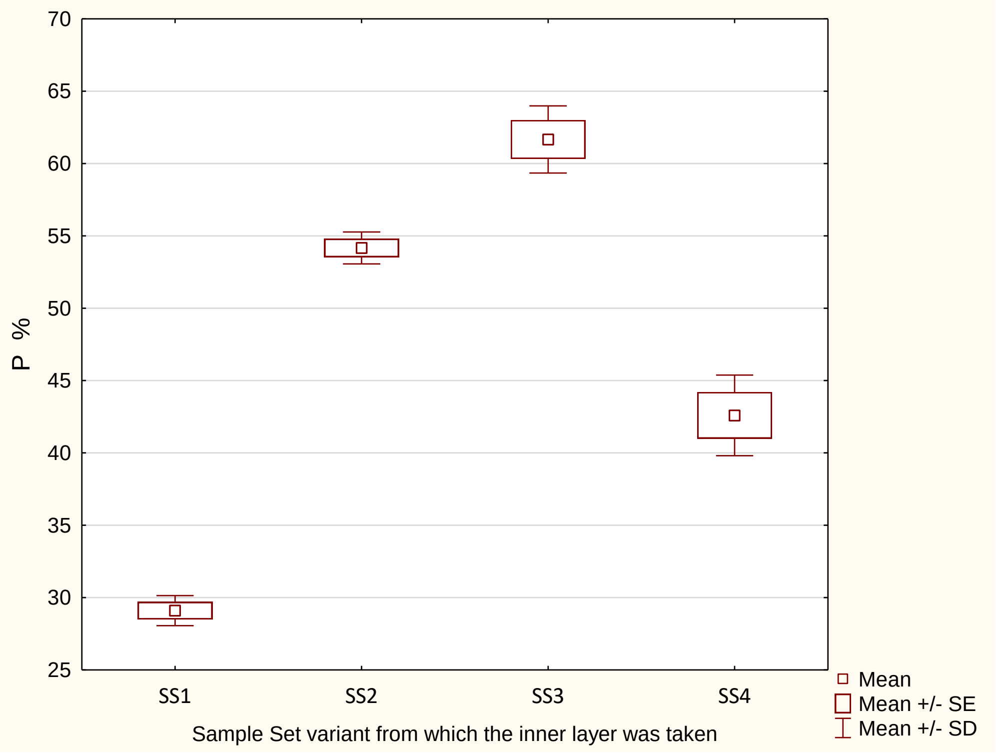


Fig. 6.4. *The relative water-vapor permeability of the inner layer of multilayer textile sets for the firefighter’s protective clothing*

In the case of the inner layers being measured the statistically significant differences were observed similarly as for whole Sample sets:

- for the water-vapor resistance *p*= 0.0151
- for relative water-vapor permeability *p* = 0.0153.

A comparison of the water-vapor resistance of the whole Sample Sets and the inner layers taken from them is presented in Fig.6.5 It is clearly seen that the water-vapor resistance of the inner layer is several times lower than the thermal resistance of the whole Sample set.

The relative water-vapor permeability of the inner layer of the Sample Sets is more than twice greater than the relative water-vapor permeability of whole Sample Sets (Fig. 6.6).

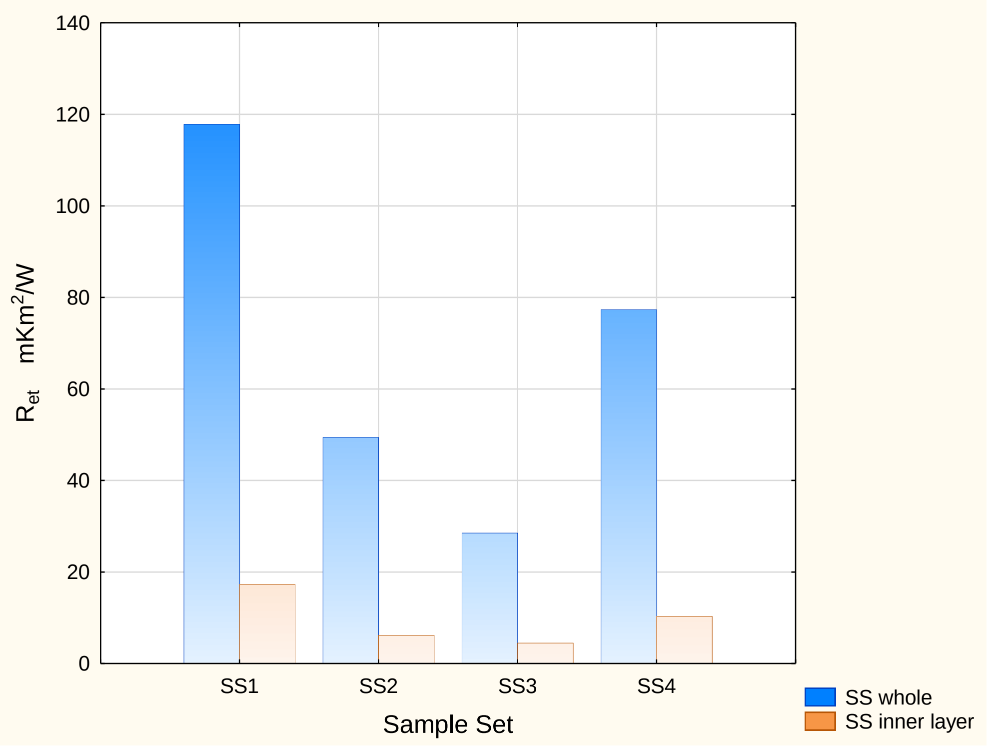


Fig. 6.5. *Comparison of water-vapor resistance of the inner layer and multilayer material sets for the firefighter's protective clothing*

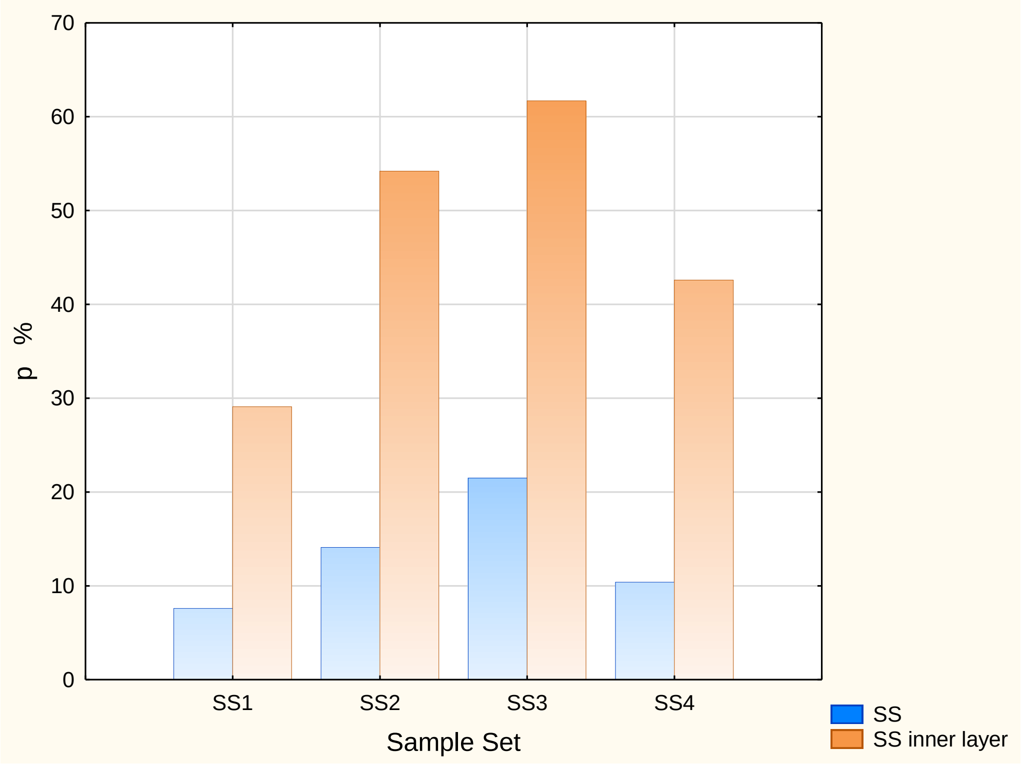


Fig. 6.6. *Comparison of relative water-vapor permeability of the inner layer and multilayer material sets for firefighter's protective clothing*

Based on the presented results it can be stated that the water-vapor permeability of multilayer textile sets for the FPC is very low. It means that the sweat produced by the human body is not transferred effectively outside. It is an important factor because the firefighter works in very difficult conditions accompanied by intensive effort and high stress. High water-vapor resistance of the FPC leads to physiological discomfort of the firefighter during firefighting and rescue actions. In the same way, it leads to a decrease in the effectiveness of firefighters in action. Additionally, the high water-vapor resistance of the whole Sample sets in comparison to the very low water-vapor resistance of the inner layer of Sample Sets means that the water vapor is partially transferred by the inner layer and remains between the inner layer and middle layer – moisture barrier.

Due to the very low effectiveness of water-vapor transport through the multilayer textile sets for the FPC (Sample Sets), some amount of sweat produced by the firefighter's body condenses on the firefighter's skin. It cause also discomfort because the liquid sweat can be absorbed by underwear and finally the underwear sticks to the human skin. Taking it into account, in order to select the materials and clothing for the firefighter's protective outfit, it is necessary to analyze the materials in the aspect of their ability to transfer the liquid sweat. It will be done in the next chapter of the dissertation.

6.2. Water-vapor resistance of knitted fabric

The knitted fabrics used for the production of underwear or any kind of next-to-skin wear are in contact with human skin, and therefore it is especially important for them to achieve a good comfort sensation. Owning to their looped structure, knitted fabrics have good stretchability, which is an important element in the achievement of optimal sensorial comfort. At a given activity level and defined environmental conditions, the ranges in which the knitted ensemble will be defined as comfortable depends on the rate at which the fabric allows water vapor to pass through it [165]. The water-vapor permeability parameters of seven types of underwear knitted fabrics are presented in Table 6.5.

The measurement results of knitted fabric for underwear showed that the knitted fabrics differ in water-vapor permeability.

The underwear is the first layer through which the water-vapor that evaporates from human skin. In this sense, the results of the measurement confirmed that all analyzed knitted fabrics meet the requirement of high water-vapor permeability for the knitted material for underwear.

Table 6.5. *The water-vapor permeability properties parameters of knitted fabric for underwear*

Sample	Parameter	R_{et} [mKm^2/W]				
		Average	Min	Max	CV [%]	SD
KF1	Ret	2.9	2.8	3.0	3.8	0.1
	p	66.2	65.2	67.2		1.0
KF2	Ret	3.7	3.6	3.9	4.2	0.2
	p	60.7	59.4	61.4		1.0
KF3	Ret	4.0	3.7	4.4	9.2	0.4
	p	61.4	58.9	63.5		2.3
KF4	Ret	2.6	2.3	2.8	8.4	0.2
	p	69.5	67.6	71.3		1.9
KF5	Ret	3.8	3.7	3.9	3.2	0.1
	p	60.1	59.3	61.1		1.0
KF6	Ret	3.6	3.2	3.9	9.5	0.3
	p	61.4	59.6	63.8		2.1
KF7	Ret	3.4	3.3	3.6	3.4	0.2
	p	71.5	71.0	71.8		0.4

Temperature: 24.3^{0}C, Humidity: 41, Calibration coefficient: 0.35

The KF3 fabric variant (R_{et} = 4.0 mKm^2/W) followed by the KF5 variant (R_{et} = 3.8 mKm^2/W) showed the highest value of water-vapor resistance, while the KF4 knitted fabric variant (R_{et} = 2.6 mKm^2/W) showed the lowest value (Fig. 6.7). The KF3 knitted fabric is a fabric with elastane (3%), which increases the water-vapor resistance of the fabric because the elastane compacts the structure of the fabric Also, the thickness of the KF3 knitted fabric is relatively great compared to other knitted fabrics, which increases the resistance to water-vapor. The KF5 knitted fabric is a cotton/polyester (54%/46%) blend fabric, and the thickness is the highest than other knitted fabrics, which contributes to the increase of water-vapor resistance. The KF2 knitted fabric is made of pure cotton, the thickness of the fabric is lower than others, but the structure of the knitted fabric is different (rib stitch) which affects the increase in water-vapor resistance. But the KF6 knitted fabric is made of specially treated cotton fabric, which increases the mass per square meter of the fabric, causing an increase in water-vapor resistance. The KF4 knitted fabric is a cotton/viscose (95%/5%) blend fabric, and although its thickness is average compared to others, it has one of the lowest masses per square meter, indicating that it has a fluffy texture. This causes it to exhibit the lowest value of water-vapor resistance among the groups of knitted fabrics studied.

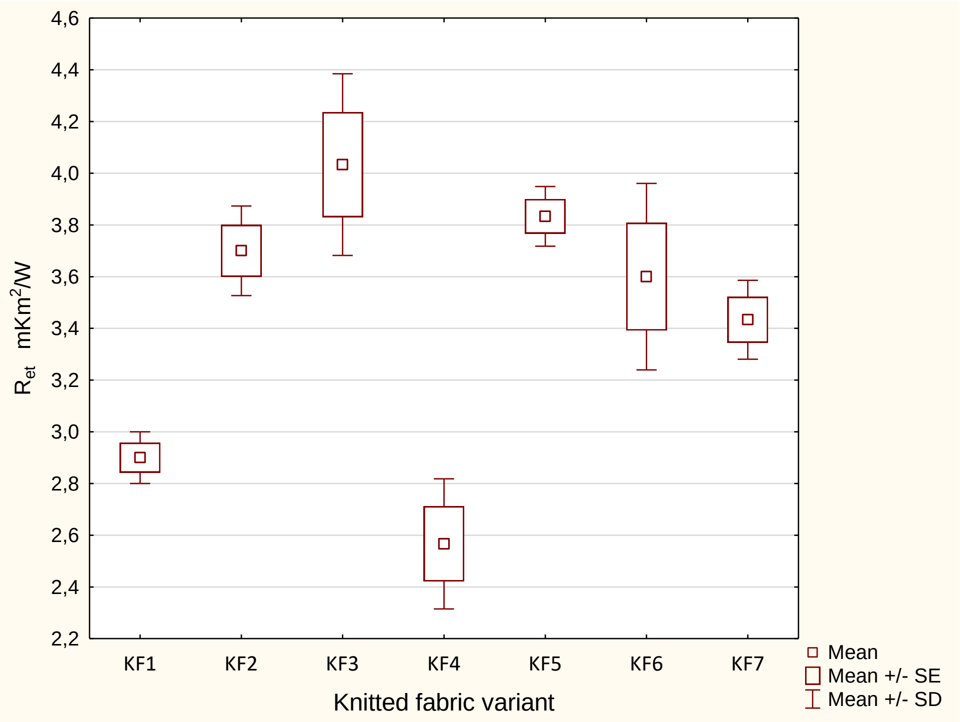


Fig. 6.7. *The water-vapor resistance of knitted fabric for underwear*

The water vapor released from the human skin increases the temperature and humidity of the interior of the clothing, causing discomfort. Therefore, one of the functions of underwear is to quickly transport this water vapor away from the human skin. This requires a high water-vapor permeability of materials that come into direct contact with human skin.

On the basis of the relative water-vapor permeability (p), it is easy to assess the ability of the fabric to transfer the water vapor from the underclothing outside zone. The value of the parameter p is from 0 to 1. The higher value of the parameter p the greater the water-vapor permeability.

The highest value of the relative water-vapor permeability is observed for the KF7 knitted fabric (71.5 %), followed by the KF4 (69.5%) and the KF1

(66.2%). The KF7 knitted fabric is taken from the special T-shirt for the firefighter and the material design and composition of raw materials made it show a high value of water-vapor permeability. The lowest values of the relative water-vapor permeability were observed in the KF5 (60.1%) and KF2 (60.7%) knitted fabrics (Fig. 6.8).

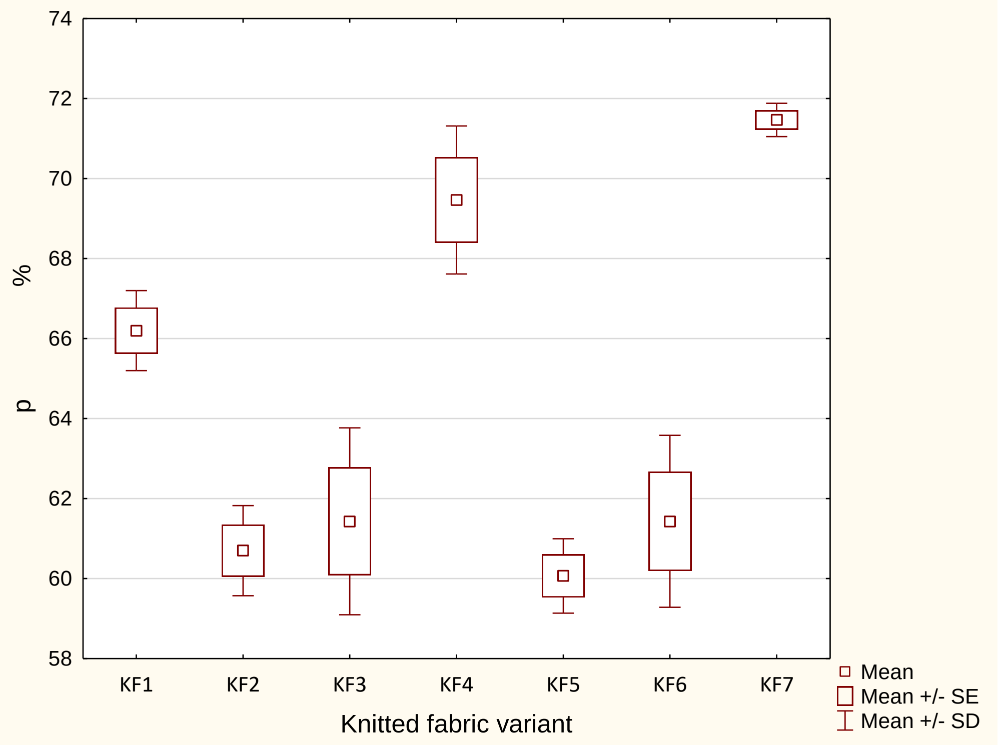


Fig. 6.8. *The relative water-vapor permeability of knitted fabric for underwear*

Statistical analysis of the results by means of the Kruskal-Willis Anova and Media tests confirmed that the kind of knitted fabric influence both parameters characterizing the water-vapor permeability of fabrics (Tables 6.6, 6.7). The influence is statistically significant at the significance level of 0.05.

Table 6.6. *The between-group comparison of water-vapor resistance of knitted fabrics*

Dependent variable **R_{et}**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 21) =16.4979; p =0.0113						
	KF1 R:4.833	KF2 R:13.167	KF3 R:18.333	KF4 R:2.167	KF5 R:16.333	KF6 R:12.833	KF7 R:9.333
KF1		1.0000	0.1618	1.0000	0.4874	1.0000	1.0000
KF2	1.0000		1.0000	0.6282	1.0000	1.0000	1.0000
KF3	0.1618	1.0000		0.0298	1.0000	1.0000	1.0000
KF4	1.0000	0.6282	0.0298		0.1086	0.7403	1.0000
KF5	0.4874	1.0000	1.0000	0.1086		1.0000	1.0000
KF6	1.0000	1.0000	1.0000	0.7403	1.0000		1.0000
KF7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	

Table 6.7. *The between-group comparison of relative water-vapor permeability of knitted fabrics*

Dependent variable **p**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 21) =16.3636; p =0.0119						
	KF1 R:14.000	KF2 R:6.667	KF3 R:7.333	KF4 R:17.333	KF5 R:4.667	KF6 R:7.333	KF7 R:19.667
KF1		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
KF2	1.0000		1.0000	0.7403	1.0000	1.0000	0.2160
KF3	1.0000	1.0000		1.0000	1.0000	1.0000	0.3132
KF4	1.0000	0.7403	1.0000		0.2606	1.0000	1.0000
KF5	1.0000	1.0000	1.0000	0.2606		1.0000	0.0644
KF6	1.0000	1.0000	1.0000	1.0000	1.0000		0.3132
KF7	1.0000	0.2160	0.3132	1.0000	0.0644	0.3132	

6.3. Conclusion

On the basis of the performed investigations of the water-vapor permeability of the analyzed materials, it was stated that the multilayer textile sets for the FPC (Sample Sets) are characterized by very high water-vapor resistance and very low relative water-vapor permeability. It means that they are not able to effectively evacuate sweat from the underclothing space to the outside. Especially, sweat transport will be not effective while activity in firefighting or other rescue actions accompanied by intensive effort and stress.

The main barrier for transporting sweat in the form of vapor is the middle layer of the sets – the moisture barrier. The inner layers of the investigated multilayer sets - thermal barriers are characterized by significantly higher relative water-vapor permeability. Due to this fact, the sweat will remain partially inside the clothing structure and partially it will condense on the firefighter's skin.

Taking it into consideration, it is also necessary to analyze the ability of the fabrics and clothing for the firefighter's protective outfit in the range of their ability to transfer the sweat in the form of liquid.

The FPC is worn together with underwear. The underwear is the next to skin layer of the firefighter's protective outfit. Due to this fact underwear is the first barrier to the sweat produced by the human body. While selecting the materials for the FPC it is necessary to take into account the interaction between the properties of underwear and clothing.

Unfortunately, due to the Permetest malfunction, it was impossible to perform the measurements of the water-vapor permeability of the textile assemblies consisting of the Sample Sets and knitted fabrics for underwear.

In further investigations, the water-vapor resistance of the multilayer clothing packages containing the Sample Sets and knitted fabrics will be approximated on the basis of the results for the Sample Sets and knitted fabrics.

7. Liquid moisture transport of textile materials for firefighter's clothing

In the frame of the presented work, studies on the transport of liquid moisture in multilayer sets of materials designed for the FPC have been performed. Measurement has been done in standard climatic conditions. For each material and multilayer set 5 repetitions of measurement were done and next the average values of each parameter being determined were calculated. Measurement was carried out for the multilayer packages as well as for single materials creating particular layers of the packages. The conducted research allowed the evaluation of individual layers in terms of their ability to provide physiological comfort in the aspect of liquid moisture transport.

7.1. Liquid moisture transport of Sample Sets

The liquid moisture transport properties of four types of multilayer textile sets (Sample Sets - SS) for the FPC are presented in Tables 7.1 and 7.2.

Table 7.1. *The liquid moisture transport parameters of multilayer materials for the firefighter's protective clothing*

Sample Set		**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
S1	Mean	34.07	119.61	271.42	0.00	4.00	0.00
	SD	47.15	0.88	264.13	0.00	2.24	0.00
	CV	1.38	0.01	0.97	0.00	0.56	0.00
S2	Mean	2.43	120.00	80.36	0.00	30.00	0.00
	SD	0.64	0.00	4.77	0.00	0.00	0.00
	CV	0.26	0.00	0.06	0.00	0.00	0.00
S3	Mean	7.49	120.00	107.68	0.00	19.00	0.00
	SD	8.10	0.00	113.02	0.00	8.94	0.00
	CV	1.08	0.00	1.05	0.00	0.47	0.00
S4	Mean	3.24	120.00	61.99	0.00	29.00	0.00
	SD	0.16	0.00	1.89	0.00	2.24	0.00
	CV	0.05	0.00	0.03	0.00	0.08	0.00

Table 7.2. *The liquid moisture transport parameters of multilayer materials for the firefighter's protective clothing; continuation*

Sample Set		**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
S1	Mean	0.35	0.00	-804.94	0.01
	SD	0.26	0.00	481.07	0.02
	CV	0.75	0.00	0.60	2.24
S2	Mean	7.24	0.00	-951.73	0.00
	SD	1.92	0.00	35.20	0.00
	CV	0.27	0.00	0.04	0.00
S3	Mean	8.30	0.00	-1353.1	0.00
	SD	9.97	0.00	216.92	0.00
	CV	1.20	0.00	0.16	0.00
S4	Mean	4.63	0.00	-962.94	0.00
	SD	0.22	0.00	34.57	0.00
	CV	0.05	0.00	0.04	0.00

For an assessment of the fabrics in the range of their ability to transport liquid moisture, the most important parameters are the following: R – accumulative one-way transport index, and OMMC – Overall Moisture Management Capacity.

The accumulative one-way transport index R is calculated as the difference of the accumulative moisture content between two surfaces of the fabric: bottom and top in relation to the testing time [147]. As can be seen from Table 7.2, the parameters at the bottom surface of the multilayer set such as absorption rate, maximum wetting radius, and spreading speed are all equal to zero. A fabric with good accumulative one-way transport from the top (inner) fabric side to the outer side (high value of the parameter) offers good sweat management to the wearer. It is due to the fact that with a high accumulative one-way transport index the fabric keeps the skin of the wearer dry due to transporting the perspiration towards the outer side of the fabric which is away from the skin. Positive and high values of the accumulative one-way transport index (R) show that liquid sweat can be transferred from the skin to the outer surface easily and quickly [23, 147]. But in all four cases, it was shown a negative value.

The Overall Moisture Management Capacity (OMMC) is an index to indicate the overall capability of the fabric to manage the transport of liquid moisture. The value of OMMC is calculated using the formula presented in AATCC Test Method 195-2011 [149]. Generally, the OMMC is based on the absorption rate for the bottom surface, the spreading speed for the bottom surface, and the one-way transport capability. The Overall Moisture Management Capacity of the textile packages tested is not satisfactory (Table 7.2). In all cases of multilayer sets the liquid moisture was not observed on the outer layer of the textile packages [166]. It means that the liquid moisture does not reach the outer layer of the package and thus it is not drained outside the clothing (Figure 7.1). Due to this fact, all Sample Sets for the FPC being investigated were classified by the MMT as "water-proof materials".

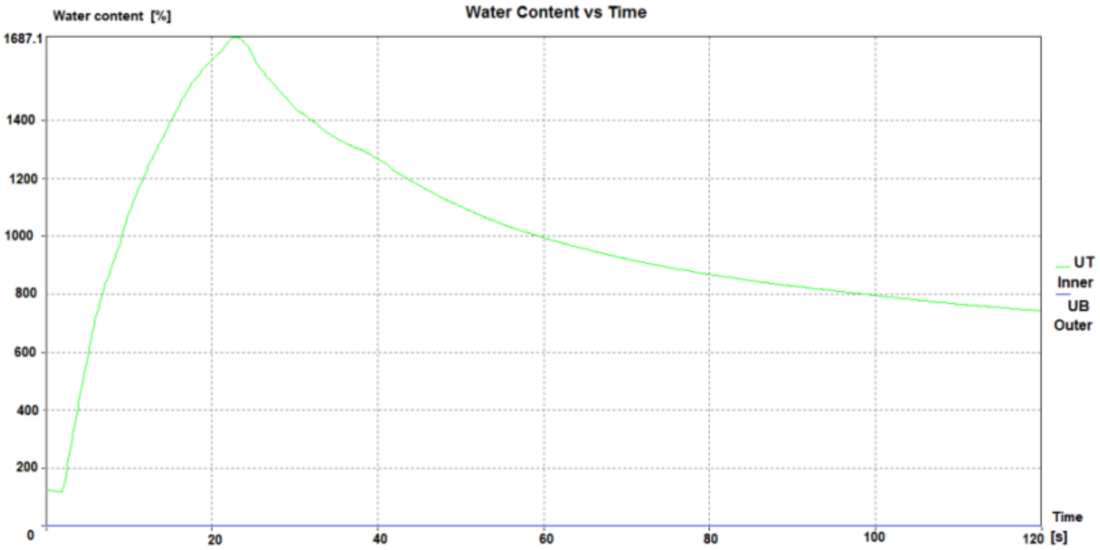


Fig. 7.1. *Exemplary results from the Moisture Management Tester – Water Content vs. Time for the multilayer textile package No.1 (SS2): green line – top surface, blue line – bottom surface*

Investigations have shown that for all four multilayer textile packages being investigated moisture transport covers only the first and second layers.

7.1.1. Liquid moisture transport of inner layer in Sample Sets

As a result of the measurement of liquid moisture transport properties of the textile package of the FPC, in all cases, the one-way transfer of liquid moisture occurred only for the materials creating the first (inner) layer of the multilayer packages. Therefore, there was a need to assess the liquid moisture transport properties of the inner layer in the textile package for the FPC. The investigated four variants' inner layers were connected to their thermal insulation barrier by stitching and glue. The liquid moisture transport properties of the inner layers of four types of multilayer textile sets for the FPC are presented in Tables 7.3 and 7.4.

Table 7.3. *The liquid moisture transport parameters of the inner layer of multilayer materials for the firefighter's protective clothing*

Sample		**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
S1 inner layer	Mean	12.04	39.31	394.39	22.48	7.00	9.00
	SD	3.71	47.34	216.43	18.93	2.74	5.48
	CV	0.31	1.20	0.55	0.84	0.39	0.61
S2 inner layer	Mean	2.30	60.88	75.89	4.26	30.00	3.00
	SD	0.47	54.38	3.87	4.32	0.00	4.47
	CV	0.20	0.89	0.05	1.01	0.00	1.49
S3 inner layer	Mean	2.64	37.98	71.74	24.50	29.00	11.00
	SD	1.44	45.71	20.14	20.57	2.24	9.62
	CV	0.55	1.20	0.28	0.84	0.08	0.87
S4 inner layer	Mean	2.73	6.40	62.34	40.45	30.00	16.00
	SD	0.91	1.15	6.61	6.37	0.00	2.24
	CV	0.33	0.18	0.11	0.16	0.00	0.14

As a result of measurements taken from the MMT of the inner layer of the textile package of the FPC, the parameters such as absorption rate, maximum wetted radius, spreading speed, and OMMC show positive values. Based on the presented results, it was shown that the inner layers in the multilayer textile package sets of the FPC differ from each other in all measured by MMT parameters. Statistical analysis was performed using non-parametric Kruskal-Wallis ANOVA and Median tests to assess the influence of the Sample Set variant on the liquid moisture transport properties of the inner layer of SS. Non-parametric tests were used because the variables considered were not normally distributed. In the analysis, the Sample Set variant was used as the independent variable, and liquid moisture transport properties parameters were analyzed as the dependent variable.

Table 7.4. *The liquid moisture transport parameters of the inner layer of multilayer materials for firefighter's protective clothing; continuation*

Sample		**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
S1 inner layer	Mean	0.48	0.57	-168.88	0.18
	SD	0.16	0.37	594.09	0.20
	CV	0.34	0.65	3.52	1.10
S2 Inner layer	Mean	7.76	0.37	-1026.4	0.01
	SD	1.88	0.63	37.44	0.02
	CV	0.24	1.70	0.04	2.24
S3 inner layer	Mean	13.41	0.97	-849.57	0.08
	SD	46.11	1.10	736.61	0.07
	CV	3.44	1.14	0.87	0.87
S4 Inner layer	Mean	5.07	2.51	-598.44	0.21
	SD	0.98	0.48	58.13	0.03
	CV	0.19	0.19	0.10	0.14

In four cases the Accumulative One-way transport index (R) of the inner layer in Sample Sets being investigated are in the range minus values. Results of the statistical analysis for the R-index are presented by the p-values for two-sided comparisons (Table 7.5).

Table 7.5. *The between-group comparison of the Accumulative One-way transport index of the inner layer in the Sample Sets*

Dependent Variable **R**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 20) =6,782857 p =,0792			
	SS1	SS2	SS3	SS4
SS1		0.0836	0.5231	1.0000
SS2	0.0836		1.0000	0.6529
SS3	0.5231	1.0000		1.0000
SS4	1.0000	0.6529	1.0000	

The R-index characterizes the liquid transport from the inner to the outer side of the fabric. A fabric with good accumulative one-way transport from the inner fabric side to the outer side (high value of the parameter) offers good sweat management to the wearer. The influence of the Sample Set variant on the Accumulative One-way transport index is not statistically significant at the 0.05 significance level.

Overall Moisture Management Capacity (OMMC) is an index to indicate the overall capability of the fabric to manage the transport of liquid moisture. Fig. 7.2 presents the mean values and scatter of results of OMMC of the inner layer in the Sample Sets being analyzed. The greatest value of the OMMC index occurred for the SS4 variant (0.21), and the lowest (0.01) for the SS2 variant.

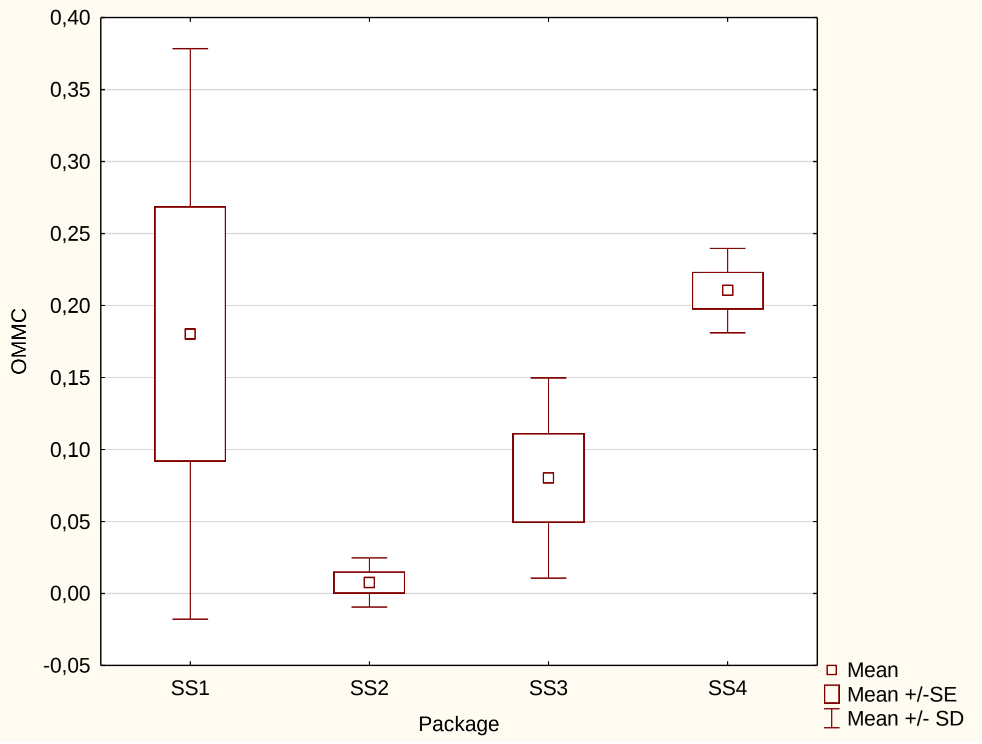


***Fig. 7.2.** The OMMC of the inner layer in the multilayer textile sets (SS) for firefighter's protective clothing*

In the case of the OMMC, the influence of the SS variant on the parameters' values is statistically significant at the significance level of 0.05 (Table 7.6). A statistically significant difference occurs between the SS4 and SS2 variants.

Table 7.6. *The betwee- group comparison of OMMC of the inner layer in the Sample Sets*

Dependent Variable **OMMC**	p – value for the between-groups comparison Kruskal-Wallis Test H (3, N= 20) =11,94579 p =,0076			
	SS1	SS2	SS3	SS4
SS1		0.270125	1.000000	1.000000
SS2	0.270125		1.000000	0.005518
SS3	1.000000	1.000000		0.208446
SS4	1.000000	0.005518	0.208446	

In the case of the inner layer applied as a lining each of them was classified as a "fast absorbing and slow drying" by the MMT (Fig. 7.3).

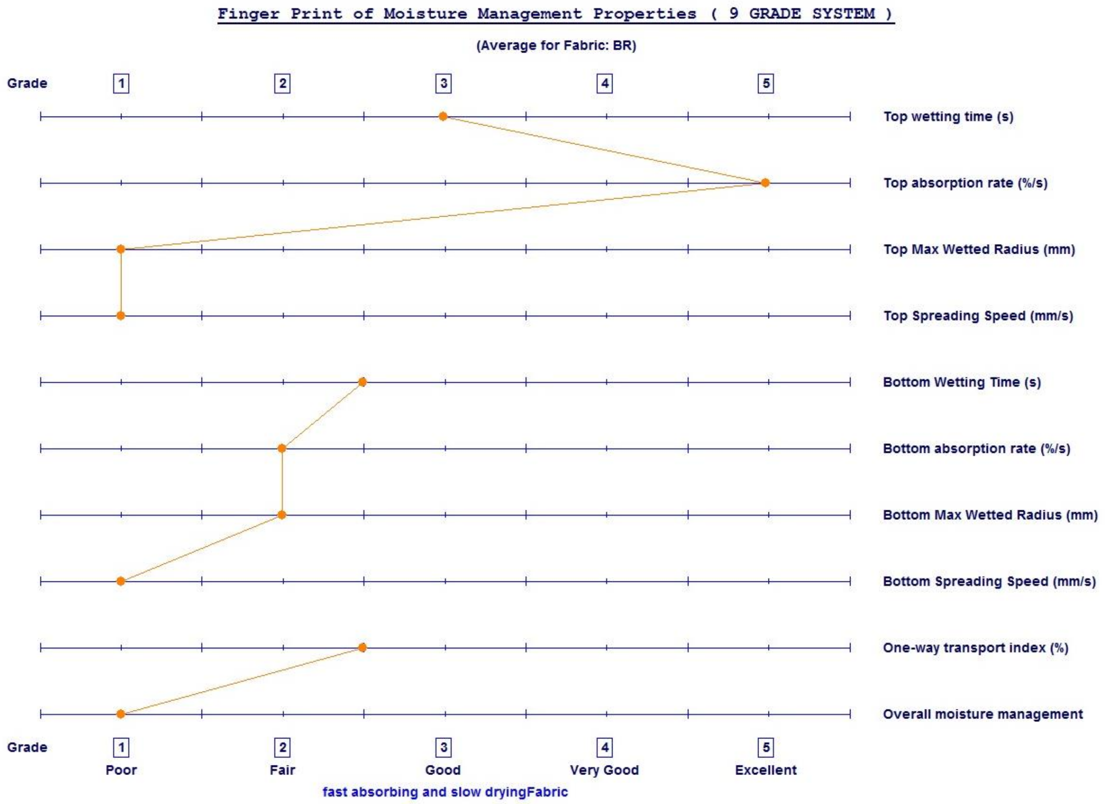


Fig. 7.3. *Exemplary results from the Moisture Management Tester – Finger Print for the inner layer in the multilayer textile package No.1 (SS1)*

The results of the analysis confirmed that the liquid moisture transport in the textile package of the FPC can be transported through the inner layer, and the existence of moisture transport through the middle layer should be further investigated.

7.1.2. Liquid moisture transport of middle layer in Sample Sets

The liquid moisture transport properties of the middle layer in the textile sets for the FPC are shown in the following tables (Tables 7.7 and 7.8).

Table 7.7. *The liquid moisture transport parameters of the middle layer of multilayer materials for the firefighter's protective clothing*

Sample		**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT mm)**	**MWRB (mm)**
S1 middle layer	Mean	8.28	61.07	248.55	3.85	5.00	5.00
	SD	0.99	4.30	175.93	0.08	0.00	0.00
	CV	0.12	0.07	0.71	0.02	0.00	0.00
S2 middle layer	Mean	13.34	120.00	294.73	0.00	5.00	0.00
	SD	3.11	0.00	269.83	0.00	0.00	0.00
	CV	0.23	0.00	0.92	0.00	0.00	0.00
S3 middle layer	Mean	7.16	120.00	75.80	0.00	5.00	0.00
	SD	0.73	0.00	11.99	0.00	0.00	0.00
	CV	0.10	0.00	0.16	0.00	0.00	0.00
S4 middle layer	Mean	7.16	120.00	258.60	0.00	5.00	0.00
	SD	0.07	0.00	198.00	0.00	0.00	0.00
	CV	0.01	0.00	0.77	0.00	0.00	0.00

Table 7.8. *The liquid moisture transport parameters of the middle layer of multilayer materials for the firefighter's protective clothing; continuation*

Sample		**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
S1 middle layer	Mean	0.59	0.08	-1162.2	0.00
	SD	0.07	0.01	25.37	0.00
	CV	0.12	0.07	0.02	0.00
S2 middle layer	Mean	0.38	0.00	-1039.6	0.00
	SD	0.09	0.00	58.38	0.00
	CV	0.23	0.00	0.06	0.00
S3 middle layer	Mean	0.68	0.00	-1023.2	0.00
	SD	0.07	0.00	31.33	0.00
	CV	0.10	0.00	0.03	0.00
S4 middle layer	Mean	0.68	0.00	-926.50	0.00
	SD	0.01	0.00	29.05	0.00
	CV	0.01	0.00	0.03	0.00

As can be seen from the table, in all four cases, the parameters characterizing the liquid moisture transport showed values equal to zero on the bottom surface of the middle layer in the textile sets. The results obtained from the MMT indicate that liquid moisture transport does not occur through the middle layer in the textile sets of the FPC. Therefore, it means that the transport of sweat and moisture from the human body stops against this middle layer. The middle layer in the textile set is the layer responsible for the water barrier of the FPC and is classified as a "water-repellent fabric" according to the MMT (fig.7.4). For the middle layers the liquid moisture was spread on the upper surface.

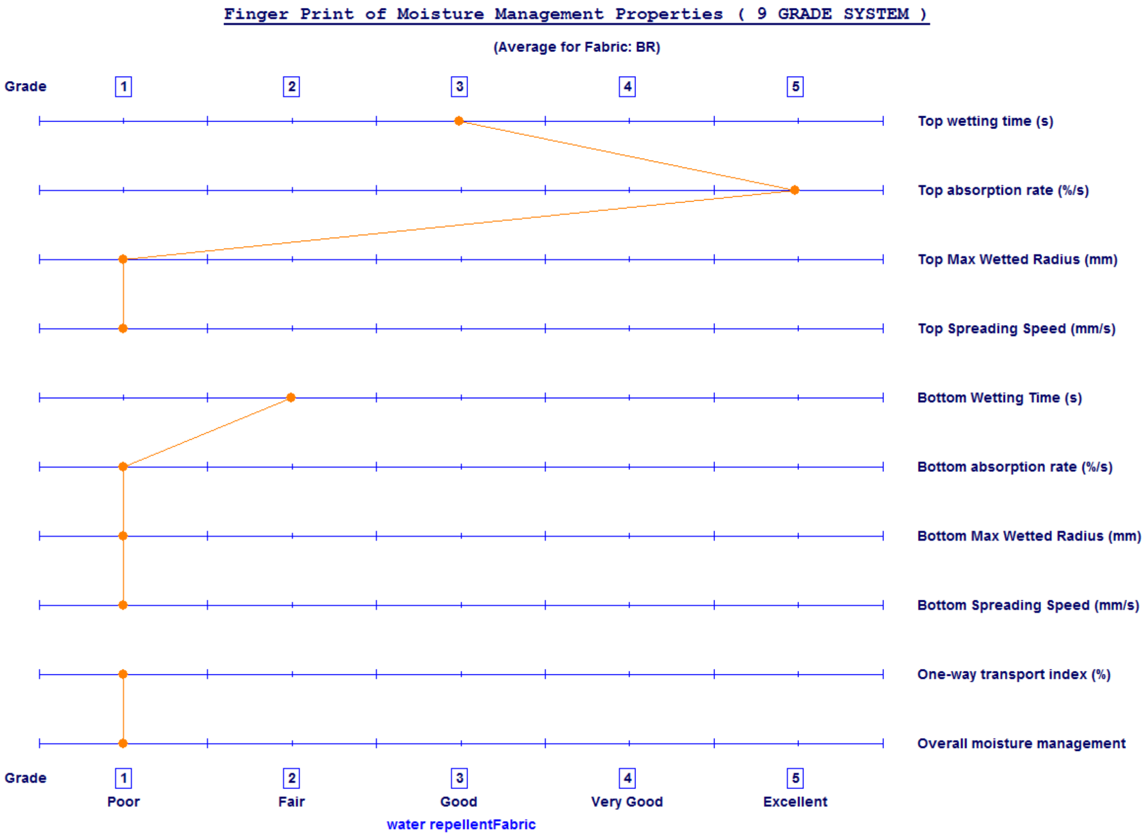


Fig. 7.4. *Exemplary results from the Moisture Management Tester – Finger Print for the middle layer in the multilayer textile package No.1 (SS1)*

7.2. Liquid moisture transport of knitted fabric for underwear

During the process of human activity, the liquid sweat and vapor moisture released from the skin, are transported to the clothing layer closest to the skin. Moisture transport in the liquid form is especially important for underwear and its material because the underwear adheres directly to the human skin and is in contact with the liquid sweat on the skin’s surface. Underwear and its materials play an important role in transporting and absorbing moisture from the human body and maintaining comfort for a long time. In the case of firefighters, underwear is often used inside protective clothing and it is considered as an independent layer of the protective clothing collection. There are currently no requirements for undergarments used under protective clothing. Due to the fact that it is worn close to the body and that protective clothing could increase worker safety when exposed to hot factors, undergarments are very important elements of protective clothing [23]. Knitted fabrics currently available on the market show satisfactory biophysical properties in terms of their use in underwear worn in a hot microclimate.

The study of liquid moisture transport properties through this underwear material is an important part of protective clothing comfort research. The study analyzed the seven most commonly used underwear options and developed the results. The parameters of the liquid moisture transport ability of seven variants of underwear materials with the characteristics mentioned in the section on the thesis of "materials and methods" are shown in tables 7.9 and 7.10

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Table 7.9. *The liquid moisture transport parameters of knitted fabrics for underwear*

Sample		**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
KF1	Mean	55.53	6.48	245.49	50.85	3.00	5.00
	SD	58.89	1.95	232.31	8.65	2.74	0.00
	CV	1.06	0.30	0.95	0.17	0.91	0.00
KF2	Mean	53.69	74.47	228.55	29.65	3.00	2.00
	SD	60.55	62.35	256.16	40.74	2.74	2.74
	CV	1.13	0.84	1.12	1.37	0.91	1.37
KF3	Mean	32.67	76.90	351.06	65.04	4.00	2.00
	SD	48.89	59.33	209.24	114.66	2.24	2.74
	CV	1.50	0.77	0.60	1.76	0.56	1.37
KF4	Mean	63.86	8.82	74.66	77.92	3.00	7.00
	SD	51.85	2.15	155.17	6.97	2.74	2.74
	CV	0.81	0.24	2.08	0.09	0.91	0.39
KF5	Mean	90.66	8.76	22.68	73.88	2.00	10.00
	SD	46.16	2.56	44.47	30.45	2.74	0.00
	CV	0.51	0.29	1.96	0.41	1.37	0.00
KF6	Mean	5.02	5.07	36.33	50.03	26.00	25.00
	SD	0.75	0.81	8.20	9.18	2.24	0.00
	CV	0.15	0.16	0.23	0.18	0.09	0.00
KF7	Mean	33.64	97.16	393.73	10.85	4.00	1.00
	SD	48.28	51.07	233.47	24.26	2.24	2.24
	CV	1.44	0.53	0.59	2.24	0.56	2.24

In the case of the investigated fabrics, three of them (KF1, KF4, and KF5) are characterized by high values of the R parameter (Fig. 7.5). According to the classification presented in the MMT manual [143, 147], the fabric can be classified as excellent (R > 400). The fabrics KF1, KF4, and KF5 were assessed as water-penetration fabrics. This indicates a small spreading area and excellent one-way transport.

Table 7.10. *The liquid moisture transport parameters of knitted fabrics for underwear; continuation*

Sample		**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
KF1	Mean	0.24	0.80	424.31	0.41
	SD	0.23	0.24	523.47	0.24
	CV	0.94	0.30	1.23	0.59
KF2	Mean	0.32	0.32	-59.64	0.27
	SD	0.30	0.44	1093.38	0.37
	CV	0.95	1.39	18.33	1.37
KF3	Mean	0.39	0.31	-370.51	0.18
	SD	0.25	0.58	860.32	0.29
	CV	0.65	1.84	2.32	1.59
KF4	Mean	0.12	0.95	913.70	0.71
	SD	0.12	0.68	248.48	0.05
	CV	1.00	0.72	0.27	0.07
KF5	Mean	0.08	2.06	1021.32	0.76
	SD	0.15	0.50	193.55	0.10
	CV	1.83	0.24	0.19	0.14
KF6	Mean	3.02	3.06	-12.62	0.33
	SD	0.55	0.47	40.67	0.06
	CV	0.18	0.15	3.22	0.18
KF7	Mean	0.33	0.17	-551.04	0.12
	SD	0.18	0.37	786.12	0.28
	CV	0.56	2.24	1.43	2.24

In the case of the fabrics KF2, KF3, KF6, and KF7 the R parameter value is negative. This means that they are classified as very poor. These fabrics were classified as waterproof fabrics. This indicates very slow absorption, slow spreading, and no one-way transport, with no penetration [143].

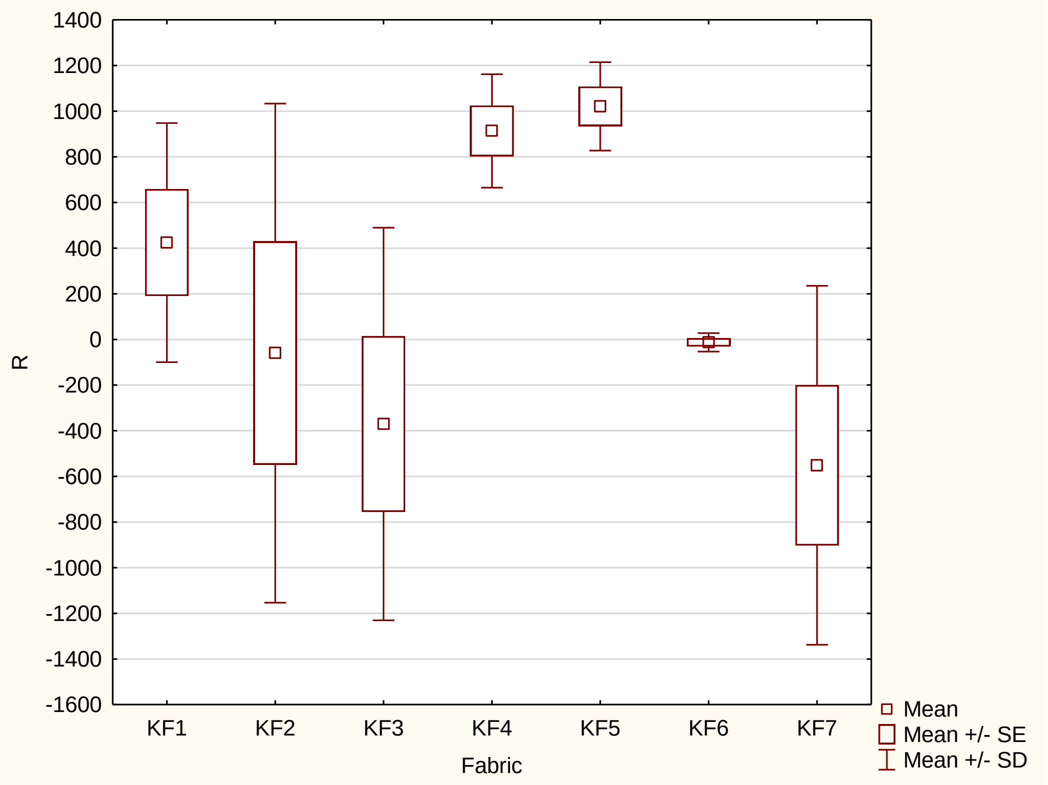

Fig. 7.5. *The Accumulative One-way transport index-R of knitted fabrics for underwear*

The influence of variant of knitted fabric on the values of index-R for knitted fabric for underwear was also assessed by the Kruskal-Wallis test as significant at the significance level 0.05. (Table 7.11). The between-groups comparison shows that the differences between particular groups are statistically insignificant.

Table 7.11. *The between-group comparison of the Accumulative One-way transport index-R of knitted fabrics for underwear*

Dependent Variable **R**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 35) =16,19048 p =,0128						
	KF1	KF2	KF3	KF4	KF5	KF6	KF7
KF1		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
KF2	1.0000		1.0000	1.0000	1.0000	1.0000	1.0000
KF3	1.0000	1.0000		0.2391	0.1046	1.0000	1.0000
KF4	1.0000	1.0000	0.2391		1.0000	1.0000	0.1264
KF5	1.0000	1.0000	0.1046	1.0000		0.8751	0.0523
KF6	1.0000	1.0000	1.0000	1.0000	0.8751		1.0000
KF7	1.0000	1.0000	1.0000	0.1264	0.0523	1.0000	

The KF2, KF3, and KF7 fabrics are characterized by very high values of the WTB parameter (Fig. 7.6). This is a wetting time of the bottom surface. High values of this parameter mean that the bottom surface of the fabric is wetting very slowly and at the same time, evaporation of sweat from the outer surface of the fabric is limited.

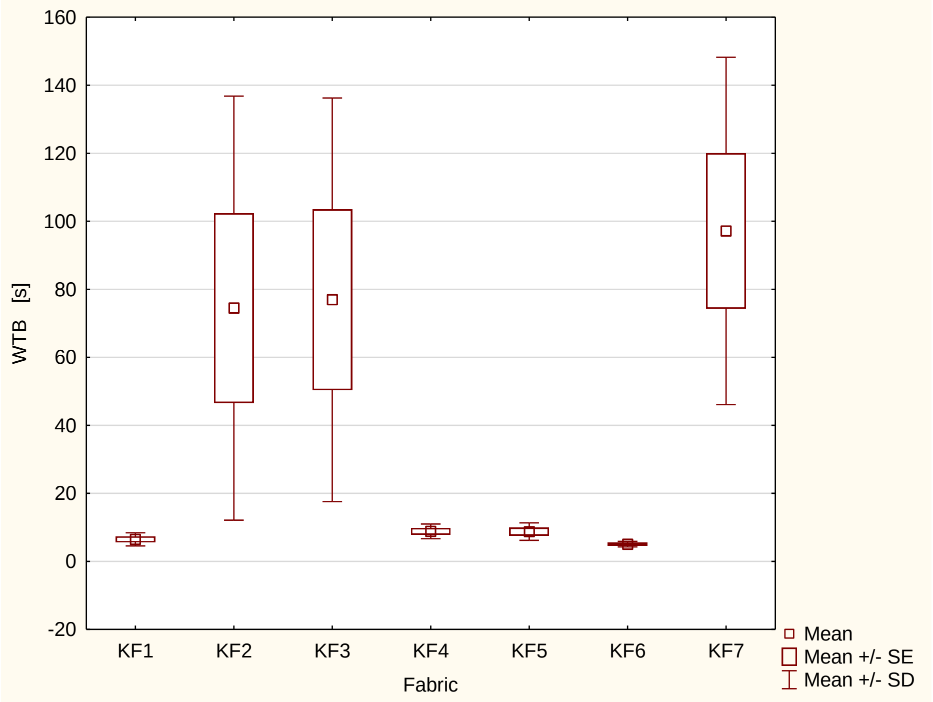

Fig. 7.6. *The wetting time of the bottom surface of knitted fabrics for underwear*

The two-sided comparison confirmed that statistically significant differences occur between the KF6 and KF7 variants (Table 7.12).

Table 7.12. *The between-group comparison of the wetting time of the bottom surface of knitted fabrics for underwear*

Dependent Variable **WTB**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 35) =14,61878 p =,0234						
	KF1	KF2	KF3	KF4	KF5	KF6	KF7
KF1		1.0000	1.0000	1.0000	1.0000	1.0000	0.3991
KF2	1.0000		1.0000	1.0000	1.0000	0.2726	1.0000
KF3	1.0000	1.0000		1.0000	1.0000	0.1914	1.0000
KF4	1.0000	1.0000	1.0000		1.0000	1.0000	1.0000
KF5	1.0000	1.0000	1.0000	1.0000		1.0000	1.0000
KF6	1.0000	0.2726	0.1914	1.0000	1.0000		0.0472
KF7	0.3991	1.0000	1.0000	1.0000	1.0000	0.0472	

The value of the OMMC parameter is calculated using the formula presented in the AATCC Test Method 195-2011 [136]. The OMMC calculation is based on the absorption rate for the bottom surface (BAR), the spreading speed for the bottom surface (SSB), and the one-way transport capability (R) at appropriate weights of mentioned parameters. The value of the OMMC can be in the range from 0 to 1. Higher values of the OMMC parameter mean better liquid moister management capacity. The highest values of the OMMC parameter were stated for the fabrics KF5, KF4, and KF1. The lowest values – are stated for the fabrics KF7, KF3, and KF2 (Fig. 7.7). On the basis of the OMMC values, the KF2 fabric can be classified as poor, whereas the fabric KF3 and KF7 as very poor from the point of view of the liquid moisture measurement. The OMMC results are in agreement with the R values.

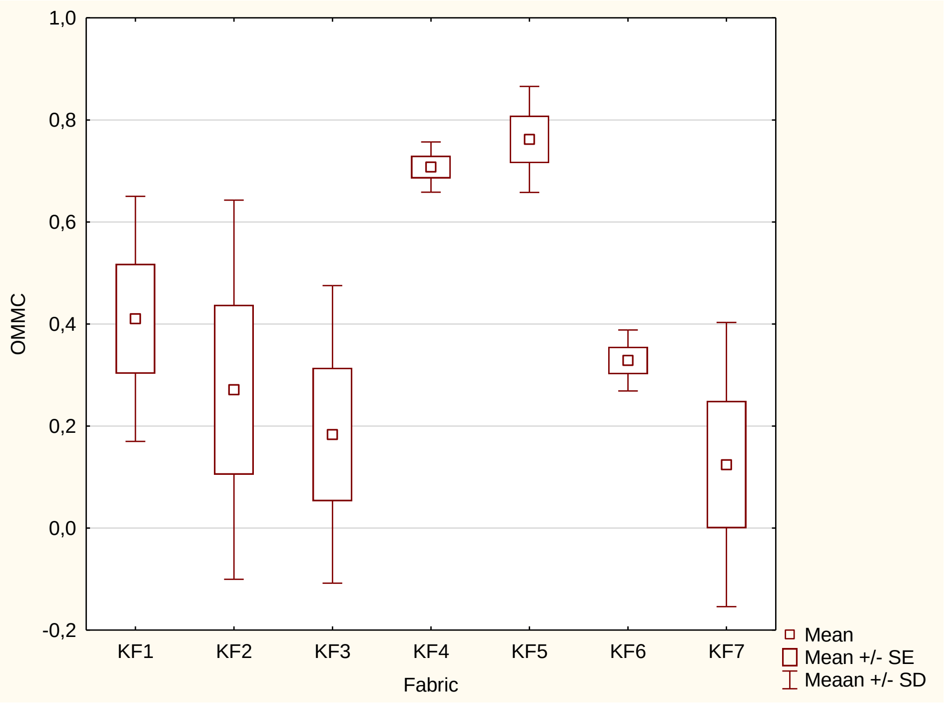

Fig. 7.7. *The Overall Moisture Management Capacity of knitted fabrics for underwear*

Results of the statistical analysis of the p-values for two-sided comparisons of the OMMC were presented in Table 7.13. The results of statistical analysis showed that the influence of the variant of knitted fabric on the OMMC is statistically significant at the significance level of 0.05. Statistically significant differences occur between the KF7 variant and both KF4 and KF5 variants.

Table 7.13. *The between-group comparison of the Overall Moisture Management Capacity of knitted fabrics for underwear*

Dependent Variable **OMMC**	p – value for the between-groups comparison Kruskal-Wallis Test H (6, N= 35) =20,67103 p =,0021						
	KF1	KF2	KF3	KF4	KF5	KF6	KF7
KF1		1.0000	1.0000	1.0000	0.8751	1.0000	1.0000
KF2	1.0000		1.0000	0.5305	0.2094	1.0000	1.0000
KF3	1.0000	1.0000		0.1595	0.0551	1.0000	1.0000
KF4	1.0000	0.5305	0.1595		1.0000	1.0000	0.0472
KF5	0.8751	0.2094	0.0551	1.0000		0.5097	0.0144
KF6	1.0000	1.0000	1.0000	1.0000	0.5097		1.0000
KF7	1.0000	1.0000	1.0000	0.0472	0.0144	1.0000	

The underwear that is usually used inside the FPC is mostly made of knitted fabric and the properties of comfort for the human body vary depending on the individual characteristics of the fabric (such as the fiber composition, the stitch, the thickness, and the mass per square meter) has been confirmed by research.

7.2.1. Liquid moisture transport of knitted fabric in the stretched state

A problem arises from the fact that while using the underwear material it is constantly stretched during human movement. The underwear and also clothing made of knitted fabrics are usually stretched while wearing. The same situation occurs while wearing underwear and clothing containing elastomers. The stretching causes changes in the fabrics' structure and in the same way, changes in the mechanism of liquid moisture transport in the fabrics [167]. Due to this fact, it is necessary to assess the stretchable knitted fabrics in the stretched form. In order to analyze the influence of stretch on the liquid transport properties of knitted fabrics five variants of cotton and cotton blended fabrics were measured by means of the Moisture Management Tester. Measurements have been performed for samples in the unstretched state and samples stretched by 15%. To precisely stretch the fabrics, the MMT Stretch Fabric Fixture has been applied.

Generally, it can be clearly seen that stretching changed the values of the parameters characterizing the liquid moisture transport in the investigated knitted fabrics. It is also seen that the changes are different for different fabric variants. Summarizing the results for the stretched fabrics, it can be stated that the capability of the investigated fabrics to manage liquid moisture was improved in all cases (comparing tables 7.9 and 7.10).

Table 7.14. *The liquid moisture transport parameters of stretched knitted fabrics for underwear*

Sample		**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
KF1	Mean	97.42	29.19	28.92	57.05	1.00	4.00
	SD	50.48	50.77	64.67	32.07	2.24	2.24
	CV	0.52	1.74	2.24	0.56	2.24	0.56
KF2	Mean	120.00	6.12	0.00	67.06	0.00	7.00
	SD	0.00	0.93	0.00	3.11	0.00	2.74
	CV	0.00	0.15	0.00	0.05	0.00	0.39
KF3	Mean	79.21	8.24	196.79	83.07	2.00	5.00
	SD	55.88	5.55	269.49	34.26	2.74	0.00
	CV	0.71	0.67	1.37	0.41	1.37	0.00
KF4	Mean	120.00	8.09	0.00	145.16	0.00	9.00
	SD	0.00	2.23	0.00	144.95	0.00	2.24
	CV	0.00	0.28	0.00	1.00	0.00	0.25
KF5	Mean	76.68	13.82	15.04	172.57	2.00	10.0
	SD	59.40	19.40	26.15	220.82	2.74	0.00
	CV	0.77	1.40	1.74	1.28	1.37	0.00

Table 7.15. *The liquid moisture transport parameters of stretched knitted fabrics for underwear; continuation*

Sample		**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
KF1	Mean	0.14	0.60	690.39	**0.54**
	SD	0.31	0.34	935.82	0.30
	CV	2.24	0.56	1.36	0.56
KF2	Mean	0.00	1.61	1091.9	**0.72**
	SD	0.00	1.13	23.51	0.08
	CV	0.00	0.71	0.02	0.11
KF3	Mean	0.11	0.73	644.93	**0.50**
	SD	0.15	0.26	653.74	0.25
	CV	1.38	0.35	1.01	0.50
KF4	Mean	0.00	2.09	1177.2	**0.80**
	SD	0.00	0.84	69.21	0.07
	CV	0.00	0.40	0.06	0.09
KF5	Mean	0.20	2.29	963.93	**0.77**
	SD	0.30	0.96	388.60	0.11
	CV	1.52	0.42	0.40	0.14

The most significant improvement was stated for the KF2 and KF3 fabrics. In the case of the KF2 fabric, stretching to 15% caused a significant reduction in the wetting time of the bottom surface, from 74.47 s to 6.12 s, and complete elimination of liquid absorption by the top surface. This means that the liquid dropped on the top surface travels directly through the pores in the fabric to the bottom surface and is spread on the bottom surface. For the KF2 fabric, after stretching, the maximum wetted radius on the bottom surface increased from 2 mm to 7 mm, whereas any spreading was observed on the top surface. The liquid transport performance of the KF3 fabric was also significantly improved. The KF2 and KF3 fabrics, previously assessed as waterproof, after stretching were classified as water penetration fabrics.

The KF5 fabric, which, in the relaxed (unstretched) state, was assessed as the best one among all investigated fabric variants, in the stretched form, showed the same level of the OMMC parameter. This denotes a similar capability of liquid moisture transport in the unstretched and stretched state. After stretching, KF1, KF4, and KF5 were classified as the same type, of water-penetration fabrics, as before stretching. It should be mentioned here that great variation in the results was observed for fabrics in the unstretched and stretched form.

The results from the MMT were statistically analyzed using multifactor ANOVA in order to assess the influence of stretch on the parameters characterizing the moisture transport through the knitted fabrics (Table 7.16). In the statistical analysis, the variants of the knitted fabrics: KF1, KF2, KF3, KF4, KF5, and the state: unstretched, stretched were applied as independent variables, and the parameters from the MMT: WTT, WTB, TAR, BAR MWRT, MWRB, SST, SSB, R, and OMMC were applied as dependent variables. Each parameter from the MMT was analyzed separately. The statistical significance was assessed at the probability level of 0.95 and the statistically significant relationships are marked in red color.

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Table 7.16. *The results of the two-way ANOVA for the liquid moisture transport properties of stretched knitted fabric for underwear*

Wetting Time Top (WTT)					
Effect	**SS**	**df**	**MS**	**F**	***p***
Intercept	311823.6	1	311823.6	132.4544	0.0000
SS variant	7887.8	4	1971.9	0.8376	0.5095
KF variant	19386.0	1	19386.0	8.2347	0.0065
SS * KF	9778.8	4	2444.7	1.0384	0.3994
Error	94167.9	40	2354.2		
Wetting Time Bottom (WTB)					
Intercept	29011.06	1	29011.06	27.86171	0.0000
SS variant	10517.75	4	2629.44	2.52526	0.0557
KF variant	6048.35	1	6048.35	5.80873	0.0206
SS * KF	18773.40	4	4693.35	4.50741	0.0042
Error	41650.07	40	1041.25		
Top Absorption Rate (TAR)					
Intercept	676505	1	676505.3	25.34578	0.0000
SS variant	410179	4	102544.8	3.84192	0.0098
KF variant	232351	1	232351.3	8.70522	0.0053
SS * KF	89069	4	22267.2	0.83426	0.5115
Error	1067642	40	26691.0		

<table>
<tr><td colspan="6">Bottom Absorption Rate (BAR)</td></tr>
<tr><td>Intercept</td><td>338046.6</td><td>1</td><td>338046.6</td><td>38.48263</td><td>0.0000</td></tr>
<tr><td>SS variant</td><td>45533.9</td><td>4</td><td>11383.5</td><td>1.29588</td><td>0.2880</td></tr>
<tr><td>KF variant</td><td>25893.6</td><td>1</td><td>25893.6</td><td>2.94768</td><td>0.0937</td></tr>
<tr><td>SS * KF</td><td>14165.0</td><td>4</td><td>3541.2</td><td>0.40313</td><td>0.8052</td></tr>
<tr><td>Error</td><td>351375.8</td><td>40</td><td>8784.4</td><td></td><td></td></tr>
<tr><td colspan="6">Top Max Wetted Radius (MWRT)</td></tr>
<tr><td>Intercept</td><td>200.0000</td><td>1</td><td>200.0000</td><td>36.36364</td><td>0.0000</td></tr>
<tr><td>SS variant</td><td>15.0000</td><td>4</td><td>3.7500</td><td>0.68182</td><td>0.6087</td></tr>
<tr><td>KF variant</td><td>50.0000</td><td>1</td><td>50.0000</td><td>9.09091</td><td>0.0044</td></tr>
<tr><td>SS * KF</td><td>15.0000</td><td>4</td><td>3.7500</td><td>0.68182</td><td>0.6087</td></tr>
<tr><td>Error</td><td>220.0000</td><td>40</td><td>5.5000</td><td></td><td></td></tr>
<tr><td colspan="6">Bottom Max Wetted Radius (MWRB)</td></tr>
<tr><td>Intercept</td><td>1860.500</td><td>1</td><td>1860.500</td><td>465.1250</td><td>0.0000</td></tr>
<tr><td>SS variant</td><td>307.000</td><td>4</td><td>76.750</td><td>19.1875</td><td>0.0000</td></tr>
<tr><td>KF variant</td><td>40.500</td><td>1</td><td>40.500</td><td>10.1250</td><td>0.0028</td></tr>
<tr><td>SS * KF</td><td>57.000</td><td>4</td><td>14.250</td><td>3.5625</td><td>0.0141</td></tr>
<tr><td>Error</td><td>160.000</td><td>40</td><td>4.000</td><td></td><td></td></tr>
<tr><td colspan="6">Top Spreading Speed (SST)</td></tr>
<tr><td>Intercept</td><td>1.272587</td><td>1</td><td>1.272587</td><td>28.31474</td><td>0.0000</td></tr>
<tr><td>SS variant</td><td>0.186707</td><td>4</td><td>0.046677</td><td>1.03855</td><td>0.3994</td></tr>
<tr><td>KF variant</td><td>0.249331</td><td>1</td><td>0.249331</td><td>5.54755</td><td>0.0235</td></tr>
<tr><td>SS * KF</td><td>0.291694</td><td>4</td><td>0.072923</td><td>1.62253</td><td>0.1874</td></tr>
<tr><td>Error</td><td>1.797773</td><td>40</td><td>0.044944</td><td></td><td></td></tr>
<tr><td colspan="6">Bottom Spreading Speed (SSB)</td></tr>
<tr><td>Intercept</td><td>69.07755</td><td>1</td><td>69.07755</td><td>156.8801</td><td>0.0000</td></tr>
<tr><td>SS variant</td><td>18.06053</td><td>4</td><td>4.51513</td><td>10.2542</td><td>0.0000</td></tr>
<tr><td>KF variant</td><td>4.11036</td><td>1</td><td>4.11036</td><td>9.3349</td><td>0.0040</td></tr>
<tr><td>SS * KF</td><td>3.91752</td><td>4</td><td>0.97938</td><td>2.2242</td><td>0.0836</td></tr>
<tr><td>Error</td><td>17.61283</td><td>40</td><td>0.44032</td><td></td><td></td></tr>
<tr><td colspan="6">Accumulative One-way transport index (R)</td></tr>
<tr><td>Intercept</td><td>21109483</td><td>1</td><td>21109483</td><td>56.01793</td><td>0.0000</td></tr>
<tr><td>SS variant</td><td>5632509</td><td>4</td><td>1408127</td><td>3.73673</td><td>0.0113</td></tr>
<tr><td>KF variant</td><td>3482791</td><td>1</td><td>3482791</td><td>9.24223</td><td>0.0042</td></tr>
<tr><td>SS * KF</td><td>2769074</td><td>4</td><td>692269</td><td>1.83706</td><td>0.1407</td></tr>
<tr><td>Error</td><td>15073376</td><td>40</td><td>376834</td><td></td><td></td></tr>
</table>

Overall Moisture Management Capacity (OMMC)					
Intercept	16.07649	1	16.07649	341.1421	0.0000
SS variant	1.39154	4	0.34788	7.3821	0.0002
KF variant	0.50144	1	0.50144	10.6405	0.0023
SS * KF	0.32131	4	0.08033	1.7045	0.1680
Error	1.88502	40	0.04713		

Legend: SS – sum of squares, df – degree of freedom, MS – mean square of error, F – variable of F-distribution, p – significance level

The variant of knitted fabrics significantly influenced the following parameters: TAR, SSB, MWRB (Figure 7.8), R, and OMMC.

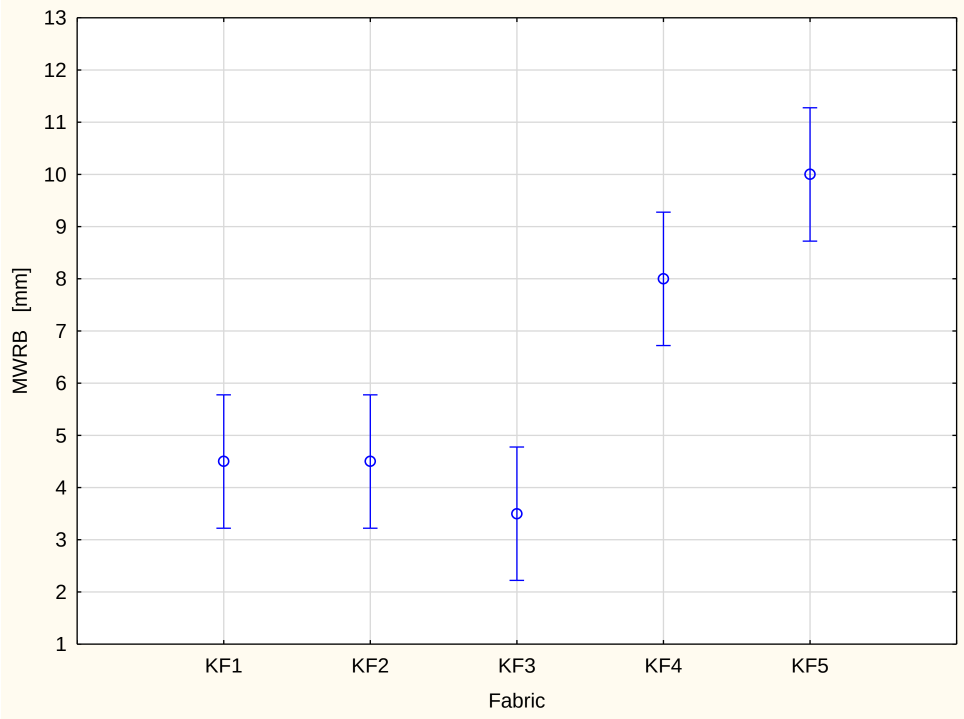

Fig. 7.8. *Influence of the fabric variant on the maximum wetted radius on the top surface*

The state (stretched/un-stretched) had a statistically significant influence on WTT, WTB, TAR (Figure 7.9), SST, SSB, MWRT, MWRB, R, and OMMC.

Only in the case of the BAR, the influence of both independent variables was statistically significant. The interaction between the independent variables was statistically significant only for two parameters: WTB, and MWRB (Figure 7.10)

In the majority of cases, the result of the ANOVA confirmed that both main factors, the variant of the fabric and stretching, have a statistically significant influence on the parameters characterizing the liquid moisture transport through the knitted fabric.

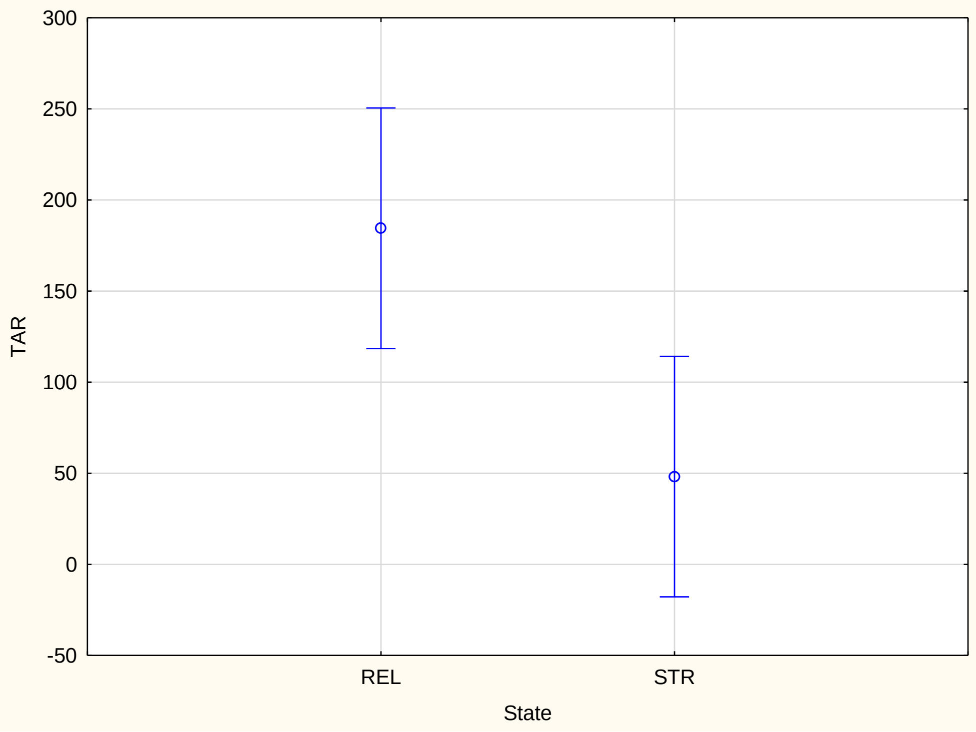

Fig. 7.9. *Influence of state on the absorption rate for the top surface: REL - relaxed (un-stretched) state, STR - stretched state*

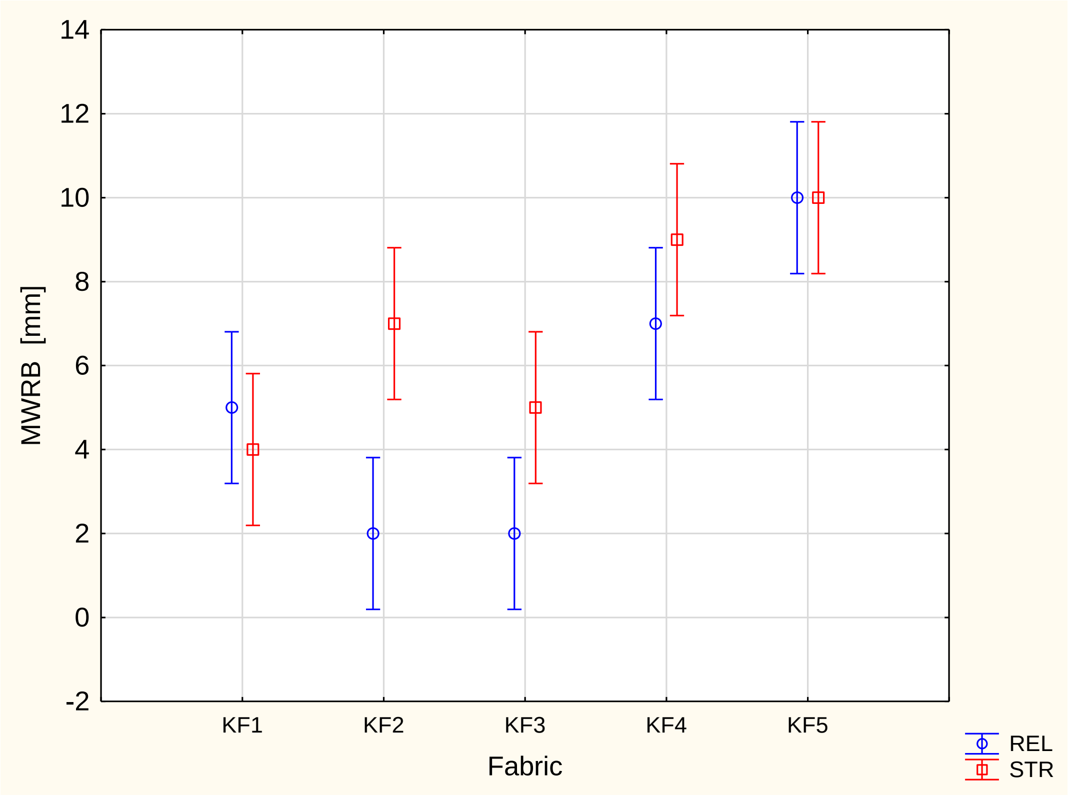

Figure 7.10. *Influence of the fabric variant and state on the maximum wetted radius for the bottom surface: REL- relaxed (un-stretched) state, ST- stretched state*

7.3. The liquid moisture transport of the firefighter’s protective assemblies made of the Sample Sets and knitted fabrics

The study properties of the textile packages and underwear materials under study were given the opportunity to be evaluated each of these objects. However, in practice, the FPC is worn with underwear on the inside. Therefore, it is important to study the parameters of the composite properties of the garment assembly layer. It is hypothesized that the liquid moisture transport properties of the FPC assemblies can be shaped by optimally selecting and bonding both the outer layer created by the protective clothing and the inner layer created by the underwear. The study of the liquid moisture transport properties of protective clothing assemblies for the firefighter was a work that should be done within the scope of the dissertation. Due to the fact, that the middle layers of the Sample Sets are not permeable to liquid sweat, the measurement of protective clothing assemblies for the firefighter’s outfit was created only by connecting the knitted fabrics for the underwear (7 variants) with the inner layer of the Sample Sets. In the presented research, the inner layers form 4 types of Sample Sets and 7 types of knitted fabrics have combined to create 28 variants of assemblies of protective clothing and have been measured using the Moisture Management Tester to assess their liquid moisture transport properties. The measurement results of the firefighter’s clothing assemblies are shown in the following tables (Tables 7.17-7.24).

Table 7.17. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 1 and knitted fabrics)*

Assembly			**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
SS1	KF1	Mean	35.76	62.13	270.42	25.96	4.00	5.00
		SD	47.20	47.05	234.54	16.82	2.24	3.54
		CV	1.32	0.76	0.87	0.65	0.56	0.71
	KF2	Mean	34.15	116.11	233.18	15.44	4.00	2.00
		SD	48.01	8.71	176.89	34.53	2.24	4.47
		CV	1.41	0.08	0.76	2.24	0.56	2.24
	KF3	Mean	10.90	120.00	275.26	0.00	6.00	0.00
		SD	2.10	0.00	188.57	0.00	2.24	0.00
		CV	0.19	0.00	0.69	0.00	0.37	0.00
	KF4	Mean	60.56	56.33	139.48	47.64	3.00	6.00
		SD	54.80	54.56	203.25	34.53	2.74	4.18
		CV	0.90	0.97	1.46	0.72	0.91	0.70
	KF5	Mean	35.89	120.00	349.44	0.00	4.00	0.00
		SD	47.06	0.00	257.00	0.00	2.24	0.00
		CV	1.31	0.00	0.74	0.00	0.56	0.00
	KF6	Mean	4.74	120.00	82.36	0.00	25.00	0.00
		SD	0.39	0.00	5.55	0.00	0.00	0.00
		CV	0.08	0.00	0.07	0.00	0.00	0.00
	KF7	Mean	25.83	57.44	290.64	31.48	5.00	5.00
		SD	36.49	57.23	173.47	33.51	0.00	5.00
		CV	1.41	1.00	0.60	1.06	0.00	1.00

Table 7.18. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 1 and knitted fabrics); continuation*

Assembly			**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
SS1	KF1	Mean	0.28	0.24	-515.92	0.17
		SD	0.17	0.32	711.25	0.24
		CV	0.62	1.37	1.38	1.36
	KF2	Mean	0.31	0.09	-642.66	0.07
		SD	0.18	0.21	412.87	0.16
		CV	0.57	2.24	0.64	2.24
	KF3	Mean	0.48	0.00	-931.32	0.00
		SD	0.10	0.00	63.36	0.00
		CV	0.21	0.00	0.07	0.00
	KF4	Mean	0.17	0.48	-53.71	0.37
		SD	0.17	0.58	748.29	0.26
		CV	1.04	1.21	13.93	0.70
	KF5	Mean	0.27	0.00	-696.98	0.01
		SD	0.16	0.00	398.06	0.02
		CV	0.59	0.00	0.57	2.24
	KF6	Mean	3.91	0.00	-1088.6	0.00
		SD	0.38	0.00	30.12	0.00
		CV	0.10	0.00	0.03	0.00
	KF7	Mean	0.44	0.62	-295.82	0.19
		SD	0.24	0.84	728.12	0.33
		CV	0.55	1.35	2.46	1.77

Table 7.19. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 2 and knitted fabrics)*

Assembly			**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
SS2	KF1	Mean	21.06	85.03	77.29	1.83	5.00	0.00
		SD	16.83	48.23	164.09	2.52	0.00	0.00
		CV	0.80	0.57	2.12	1.38	0.00	0.00
	KF2	Mean	60.30	120.00	47.93	0.00	5.00	0.00
		SD	23.01	0.00	98.60	0.00	0.00	0.00
		CV	0.38	0.00	2.06	0.00	0.00	0.00
	KF3	Mean	15.76	82.78	141.84	5.03	6.00	3.00
		SD	8.88	47.31	162.03	4.97	2.24	4.47
		CV	0.56	0.57	1.14	0.99	0.37	1.49
	KF4	Mean	12.75	77.34	58.31	3.31	11.00	1.00
		SD	4.97	58.47	19.23	5.26	2.24	2.24
		CV	0.39	0.76	0.33	1.59	0.20	2.24
	KF5	Mean	17.02	58.93	38.64	5.17	10.00	3.00
		SD	2.55	55.77	12.43	5.36	0.00	4.47
		CV	0.15	0.95	0.32	1.04	0.00	1.49
	KF6	Mean	5.00	99.76	54.84	1.20	15.00	0.00
		SD	0.16	45.25	3.70	2.69	0.00	0.00
		CV	0.03	0.45	0.07	2.24	0.00	0.00
	KF7	Mean	63.74	75.58	222.47	4.67	4.00	3.00
		SD	46.38	59.44	307.05	5.12	2.24	4.47
		CV	0.73	0.79	1.38	1.10	0.56	1.49

Table 7.20. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 2 and knitted fabrics); continuation*

Assembly			**SST (mm /sec)**	**SSB (mm /sec)**	**R (%)**	**OMMC (-)**
SS2	KF1	Mean	0.37	0.00	-158.1	0.02
		SD	0.24	0.00	256.47	0.02
		CV	0.65	0.00	1.62	1.52
	KF2	Mean	0.11	0.00	-27.03	0.04
		SD	0.08	0.00	50.31	0.02
		CV	0.74	0.00	1.86	0.56
	KF3	Mean	0.45	0.39	-438.7	0.02
		SD	0.18	0.84	311.10	0.04
		CV	0.40	2.17	0.71	2.24
	KF4	Mean	0.90	0.10	-484.9	0.00
		SD	0.43	0.22	196.00	0.00
		CV	0.48	2.24	0.40	2.24
	KF5	Mean	0.63	0.23	-257.3	0.00
		SD	0.09	0.39	46.41	0.00
		CV	0.15	1.68	0.18	2.24
	KF6	Mean	2.39	0.00	-712.7	0.00
		SD	0.18	0.00	40.21	0.00
		CV	0.08	0.00	0.06	0.00
	KF7	Mean	0.15	0.33	-297.5	0.07
		SD	0.16	0.53	473.26	0.08
		CV	1.04	1.61	1.59	1.08

Table 7.21. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 3 and knitted fabrics)*

Assembly			**WTT (s)**	**WTB (s)**	**TAR (%/s)**	**BAR (%/s)**	**MWRT (mm)**	**MWRB (mm)**
SS3	KF1	Mean	38.34	28.40	212.08	44.27	5.00	6.00
		SD	26.38	51.25	196.83	43.76	0.00	4.18
		CV	0.69	1.80	0.93	0.99	0.00	0.70
	KF2	Mean	33.73	53.41	257.42	24.91	5.00	8.00
		SD	31.62	61.03	231.60	24.10	0.00	10.37
		CV	0.94	1.14	0.90	0.97	0.00	1.30
	KF3	Mean	68.50	51.80	128.75	33.57	3.00	5.00
		SD	56.08	62.33	228.75	35.28	2.74	5.00
		CV	0.82	1.20	1.78	1.05	0.91	1.00
	KF4	Mean	21.40	4.06	38.42	44.82	9.00	6.00
		SD	5.39	1.51	17.96	22.29	4.18	2.24
		CV	0.25	0.37	0.47	0.50	0.46	0.37
	KF5	Mean	29.07	8.80	17.98	70.06	7.00	7.00
		SD	6.59	6.60	5.13	53.13	2.74	2.74
		CV	0.23	0.75	0.29	0.76	0.39	0.39
	KF6	Mean	4.44	101.17	67.45	1.81	20.00	1.00
		SD	0.33	37.68	2.02	2.50	0.00	2.24
		CV	0.07	0.37	0.03	1.38	0.00	2.24
	KF7	Mean	79.56	46.71	65.31	22.63	3.00	5.00
		SD	48.40	48.45	141.67	26.87	2.74	8.66
		CV	0.61	1.04	2.17	1.19	0.91	1.73

Table 7.22. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 3 and knitted fabrics); continuation*

Assembly			**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
SS3	KF1	Mean	0.19	0.91	312.39	0.38
		SD	0.10	0.69	694.81	0.23
		CV	0.55	0.75	2.22	0.62
	KF2	Mean	0.25	0.75	210.77	0.27
		SD	0.16	0.77	853.16	0.33
		CV	0.65	1.02	4.05	1.24
	KF3	Mean	0.23	1.19	366.10	0.43
		SD	0.29	1.42	1139.39	0.40
		CV	1.28	1.19	3.11	0.92
	KF4	Mean	0.41	1.36	211.24	0.42
		SD	0.19	0.59	423.33	0.30
		CV	0.48	0.44	2.00	0.72
	KF5	Mean	0.25	0.92	513.14	**0.62**
		SD	0.12	0.62	173.33	0.07
		CV	0.49	0.67	0.34	0.12
	KF6	Mean	3.26	0.03	-940.23	0.00
		SD	0.18	0.06	27.11	0.00
		CV	0.06	2.24	0.03	0.00
	KF7	Mean	0.09	0.29	142.41	0.28
		SD	0.11	0.42	458.17	0.31
		CV	1.21	1.44	3.22	1.09

Table 7.23. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 4 and knitted fabrics)*

Assembly			WTT (s)	WTB (s)	TAR (%/s)	BAR (%/s)	MWRT (mm)	MWRB (mm)
SS4	KF1	Mean	21.17	46.88	155.64	28.89	5.00	8.00
		SD	9.26	49.82	156.11	27.23	0.00	5.70
		CV	0.44	1.06	1.00	0.94	0.00	0.71
	KF2	Mean	30.79	11.76	4.14	57.33	5.00	11.00
		SD	14.65	3.37	0.28	8.95	0.00	2.24
		CV	0.48	0.29	0.07	0.16	0.00	0.20
	KF3	Mean	31.88	38.79	307.11	23.53	6.00	7.00
		SD	44.25	41.11	172.01	20.78	2.24	2.74
		CV	1.39	1.06	0.56	0.88	0.37	0.39
	KF4	Mean	50.26	10.80	6.66	73.64	9.00	10.00
		SD	18.82	4.07	2.73	23.28	2.24	0.00
		CV	0.37	0.38	0.41	0.32	0.25	0.00
	KF5	Mean	15.72	13.37	89.74	71.49	8.00	9.00
		SD	3.10	4.60	153.96	21.61	2.74	2.24
		CV	0.20	0.34	1.72	0.30	0.34	0.25
	KF6	Mean	4.47	93.71	60.98	2.33	20.00	0.00
		SD	0.26	40.88	1.59	2.13	0.00	0.00
		CV	0.06	0.44	0.03	0.91	0.00	0.00
	KF7	Mean	14.10	61.91	209.94	7.44	5.00	6.00
		SD	7.19	51.83	245.33	7.95	0.00	4.18
		CV	0.51	0.84	1.17	1.07	0.00	0.70

Table 7.24. *The liquid moisture transport properties of the firefighter's clothing assemblies (consisting of Sample Set 4 and knitted fabrics); continuation*

Assembly			**SST (mm/sec)**	**SSB (mm/sec)**	**R (%)**	**OMMC (-)**
SS4	KF1	Mean	0.27	0.91	-226.9	0.29
		SD	0.12	0.90	691.94	0.36
		CV	0.43	0.98	3.05	1.27
	KF2	Mean	0.18	1.20	416.42	0.62
		SD	0.06	0.21	92.18	0.04
		CV	0.34	0.17	0.22	0.06
	KF3	Mean	0.35	0.47	-289.5	0.15
		SD	0.18	0.59	583.12	0.26
		CV	0.51	1.25	2.01	1.70
	KF4	Mean	0.20	1.25	471.9	0.63
		SD	0.10	0.15	213.70	0.13
		CV	0.49	0.12	0.45	0.21
	KF5	Mean	0.46	1.15	197.82	0.47
		SD	0.08	0.45	38.71	0.09
		CV	0.17	0.39	0.20	0.18
	KF6	Mean	3.06	0.00	-745.3	0.00
		SD	0.09	0.00	21.86	0.00
		CV	0.03	0.00	0.03	0.00
	KF7	Mean	0.42	0.33	-332.9	0.05
		SD	0.19	0.40	404.51	0.11
		CV	0.45	1.21	1.21	2.18

Liquid moisture transport in the FPC multilayers can be influenced by two main factors: Sample Set type and knitted fabric type. As well as it is possible the interaction of these two main factors. In order to assess the influence of the Sample Set variant and variant of knitted fabrics on the liquid moisture transport properties of the firefighter's clothing assemblies the statistical analysis of the results has been performed by means of the two-factor (two-way) ANOVA. The results of the ANOVA testing are presented in Table 7.25 and the statistically significant relationships are marked in red color.

Table 7.25. *The results of the two-way ANOVA for the liquid moisture transport properties of the firefighter's clothing assemblies consisted of Sample Sets (SS) and knitted fabrics (KF)*

Wetting Time Top (WTT)					
Effect	**SS**	**df**	**MS**	**F**	***p***
Intercept	128074.8	1	128074.8	148.8554	0.0000
SS variant	4399.7	3	1466.6	1.7045	0.1702
KF variant	21209.2	6	3534.9	4.1084	0.0010
SS * KF	33489.3	18	1860.5	2.1624	0.0077
Error	96364.5	112	860.4		
Wetting Time Bottom (WTB)					
Intercept	593433.6	1	593433.6	347.3116	0.0000
SS variant	83631.2	3	27877.1	16.3153	0.0000
KF variant	55467.9	6	9244.6	5.4105	0.0001
SS * KF	48548.8	18	2697.2	1.5785	0.0777
Error	191368.7	112	1708.6		
Top Absorption Rate (TAR)					
Intercept	2721243	1	2721243	105.8190	0.0000
SS variant	435431	3	145144	5.6441	0.0012
KF variant	442161	6	73694	2.8657	0.0123
SS * KF	574888	18	31938	1.2420	0.2412
Error	2880194	112	25716		
Bottom Absorption Rate (BAR)					
Intercept	75092.24	1	75092.24	149.8722	0.0000
SS variant	27493.00	3	9164.33	18.2906	0.0000
KF variant	22704.31	6	3784.05	7.5524	0.0000
SS * KF	28073.73	18	1559.65	3.1128	0.0001
Error	56116.69	112	501.04		
Top Max Wetted Radius (MWRT)					
Intercept	8408.750	1	8408.750	2354.450	0.0000
SS variant	23.393	3	7.798	2.183	0.0939
KF variant	3737.500	6	622.917	174.417	0.0000
SS * KF	555.357	18	30.853	8.639	0.0000
Error	400.000	112	3.571		
Bottom Max Wetted Radius (MWRB)					
Intercept	2444.464	1	2444.464	152.1000	0.0000
SS variant	747.679	3	249.226	15.5074	0.0000
KF variant	404.286	6	67.381	4.1926	0.0008
SS * KF	428.571	18	23.810	1.4815	0.1099
Error	1800.000	112	16.071		

Top Spreading Speed (SST)					
Intercept	74.8831	1	74.88307	2075.039	0.0000
SS variant	0.5687	3	0.18958	5.253	0.0020
KF variant	137.5900	6	22.93166	635.445	0.0000
SS * KF	8.4260	18	0.46811	12.972	0.0000
Error	4.0418	112	0.03609		
Bottom Spreading Speed (SSB)					
Intercept	31.26240	1	31.26240	110.1939	0.0000
SS variant	12.29979	3	4.09993	14.4515	0.0000
KF variant	6.82955	6	1.13826	4.0121	0.0011
SS * KF	9.89822	18	0.54990	1.9383	0.0194
Error	31.77479	112	0.28370		
Accumulative One-way transport index (R)					
Intercept	7074130	1	7074130	31.29948	0.0000
SS variant	10370439	3	3456813	15.29466	0.0000
KF variant	11518278	6	1919713	8.49377	0.0000
SS * KF	6782325	18	376796	1.66713	0.0559
Error	25313604	112	226014		
Overall Moisture Management Capacity (OMMC)					
Intercept	5.532524	1	5.532524	151.6094	0.0000
SS variant	2.561325	3	0.853775	23.3963	0.0000
KF variant	1.555498	6	0.259250	7.1043	0.0000
SS * KF	2.183791	18	0.121322	3.3246	0.0001
Error	4.087099	112	0.036492		

Legend: SS – sum of squares, df – degree of freedom, MS – mean square of error, F – variable of F-distribution, p – significance level

The table shows, that the Sample Sets variant and the knitted fabric variant have a statistically significant influence on all analyzed liquid moisture transport parameters of assemblies. There are also statistically significant interactions between the main factors. This confirms the assumption that by properly selecting a Sample Set and underwear and combining them into a clothing package, it is possible to shape the most suitable version of the moisture transport properties of the firefighter’s clothing assemblies.

The influence of the Sample Set variant on the Accumulative One-way transport index (R) of created assemblies is shown in Fig.7.11. The highest R index was stated for the group of assemblies created on the basis of the

Sample Set SS3, and the lowest – for the assemblies created on the basis of the SS1 set.

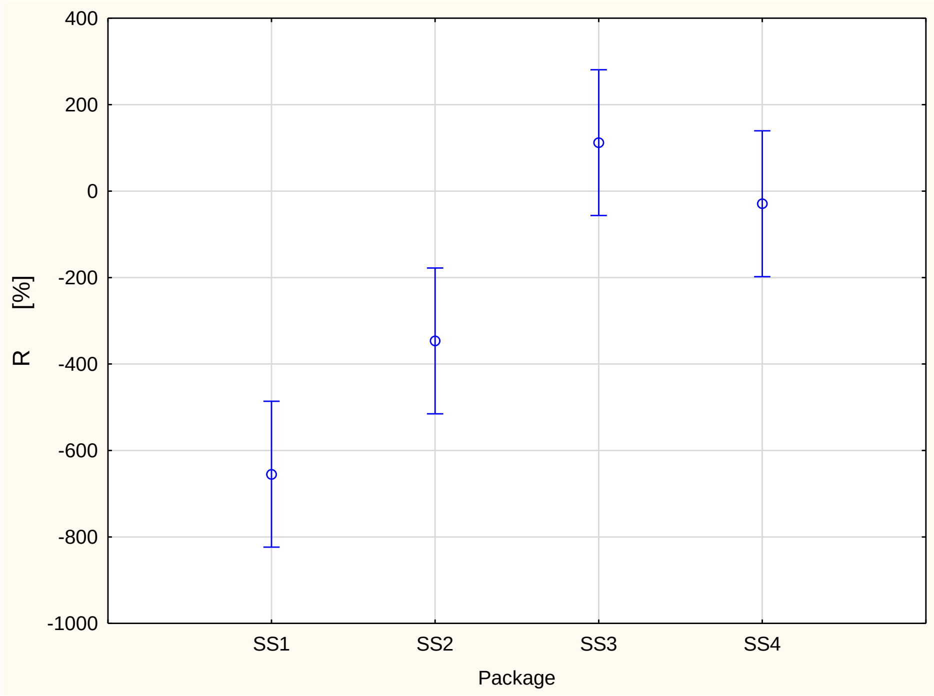

Fig. 7.11. *Influence of the Sample Set (SS) variant on the Accumulative One-way transport index of the multilayer clothing assembly*

The variant of knitted fabrics also influences the Accumulative One-way transport index R of the assemblies (Fig. 7.12). The highest R index was stated for the group of assemblies created with the KF4 variant, and the lowest - for the groups of assemblies created with the KF6 knitted fabric variants.

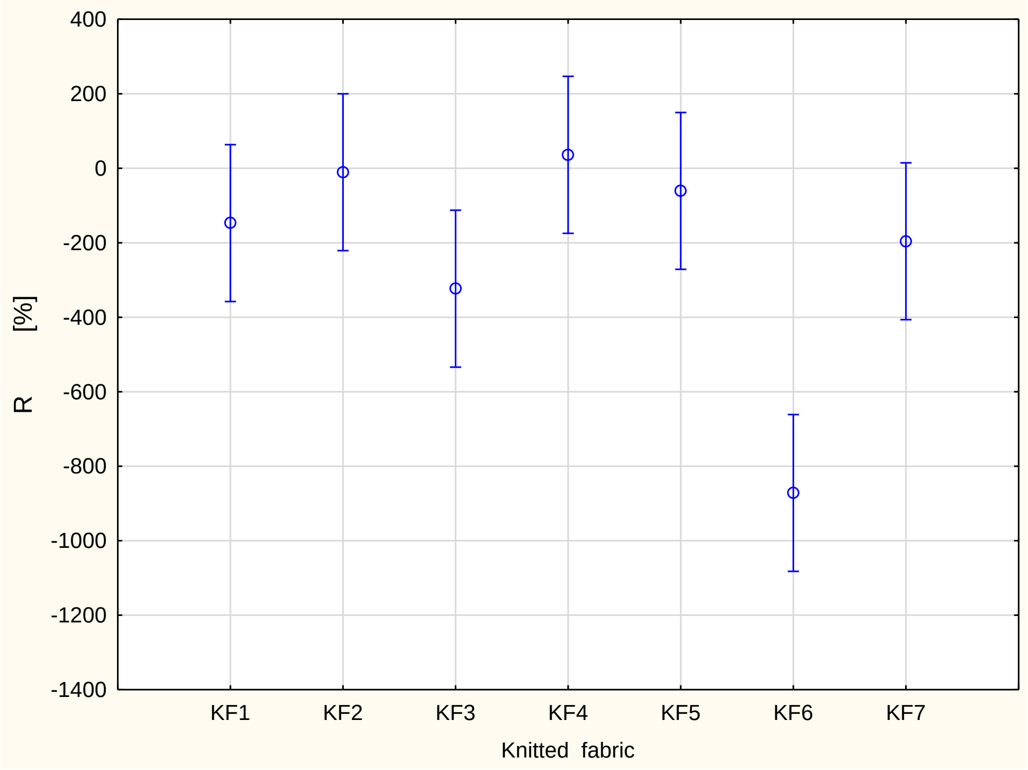

Fig. 7.12. *Influence of the knitted fabric (KF) variant on the Accumulative One-way transport index of the multilayer clothing assembly*

There is an interaction between the Sample Set variant and the knitted fabric variant (Fig. 7.13), but it is statistically insignificant (Table 7.25). Generally, the R index of the multilayer clothing assemblies created on the basis of the Sample Set 3 (SS3) has the highest and positive value in comparison to the assemblies created on the basis of the other Sample Sets. But when joining the Sample Set 3 with the KF6 knitted fabric a sharp decrease and negative value of the R index occurred. In addition, for the multilayer clothing assemblies containing the KF2, KF4, and KF5 knitted fabrics the positive values of the R index were stated for the assemblies created on the basis of the SS4 Sample Set variant. For assemblies created on the basis of the SS1, SS2 and all knitted fabrics their R index has a negative value stated for particular groups of multilayer clothing assemblies. It means that liquid moisture has not been transferred from the top surface to the bottom surface.

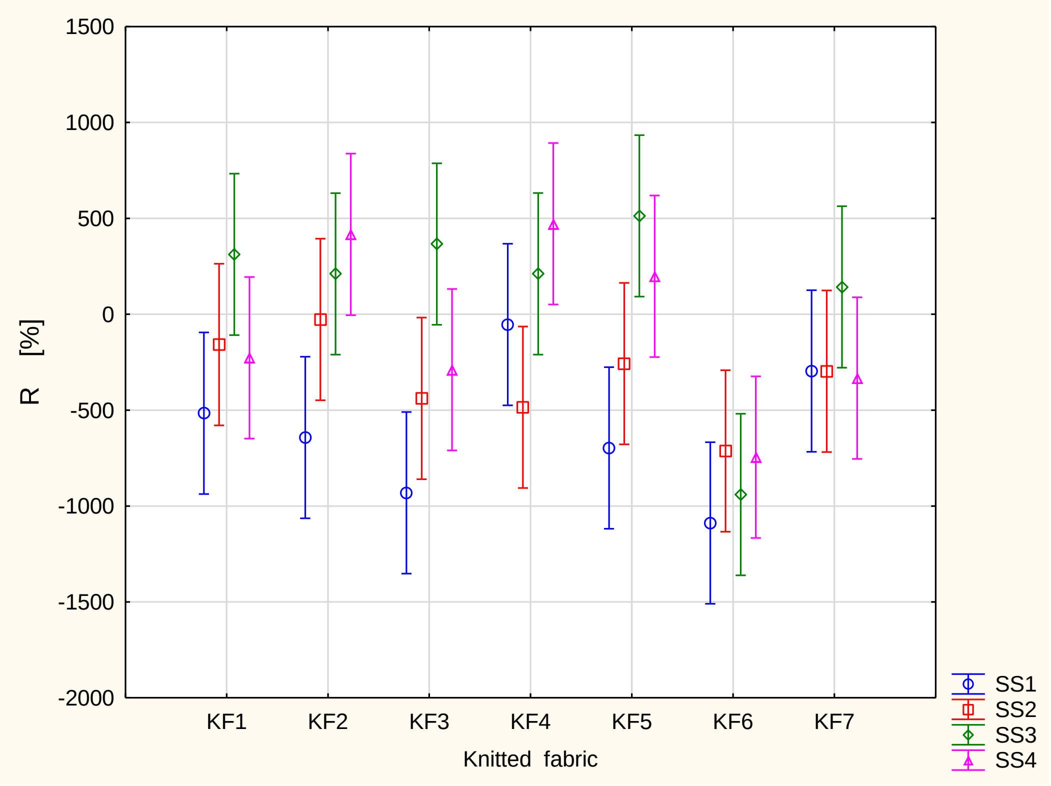

Fig. 7.13. *Influence of the Sample Set (SS) and knitted fabric (KF) variant on the Accumulative One-way transport index of the multilayer clothing assembly*

The Overall Moisture Management Capacity (OMMC) of created multilayer clothing assemblies varies significantly depending on the Sample Set variant applied in the assembly (Fig. 7.14). The highest value of the OMMC was stated for a group of assemblies created on the basis of the SS3 Sample Set. Then, the assemblies group based on the SS4 Sample Set shows the good value of the OMMC. The lowest value of the OMMC was stated for the group of assemblies created on the basis of the SS2 Sample Set. The influence of the Sample Set variant on the OMMC of the created multilayer clothing assemblies is statistically significant at the significance level of 0.05.

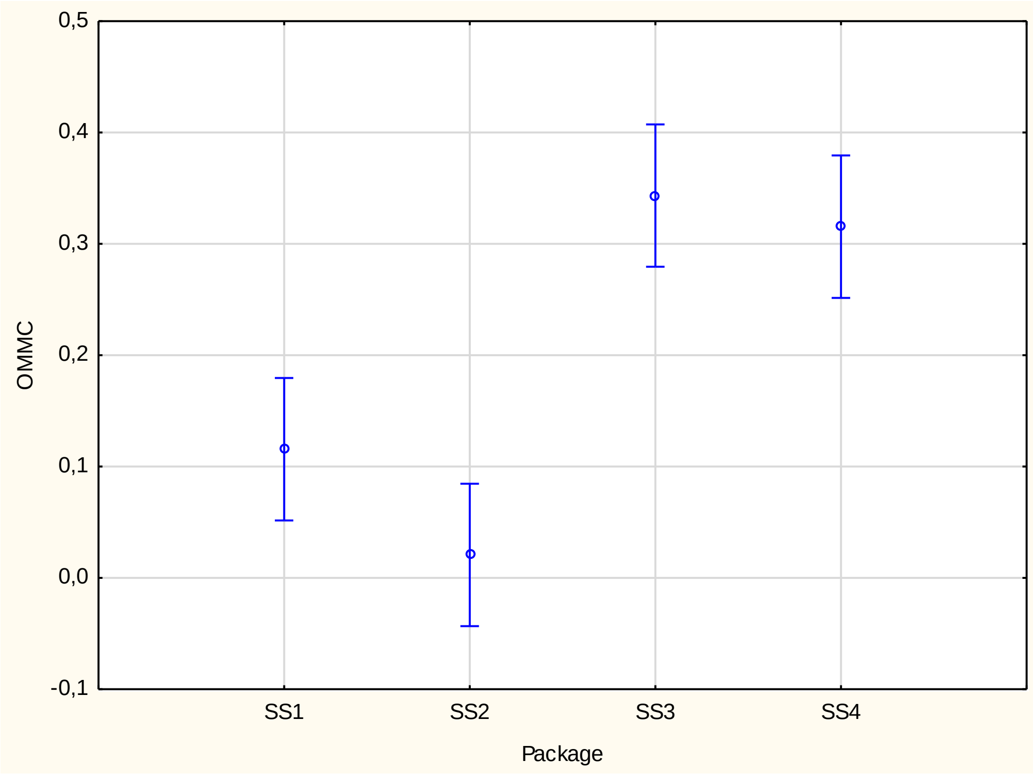

Fig. 7.14. *Influence of the Sample Set (SS) variant on the OMMC of the multilayer clothing assembly*

The influence of the knitted fabric variant on the OMMC of assemblies is statistically significant (Table 7.25). The highest OMMC was stated for the group of assemblies containing the KF4, and KF5 knitted fabric variants, and the lowest OMMC was stated for the group of assemblies containing the KF6 knitted fabric variant (Fig.7.15).

The interaction between the SS variant and the KF variant is statistically significant at the significance level of 0.05 (Table 7.25).

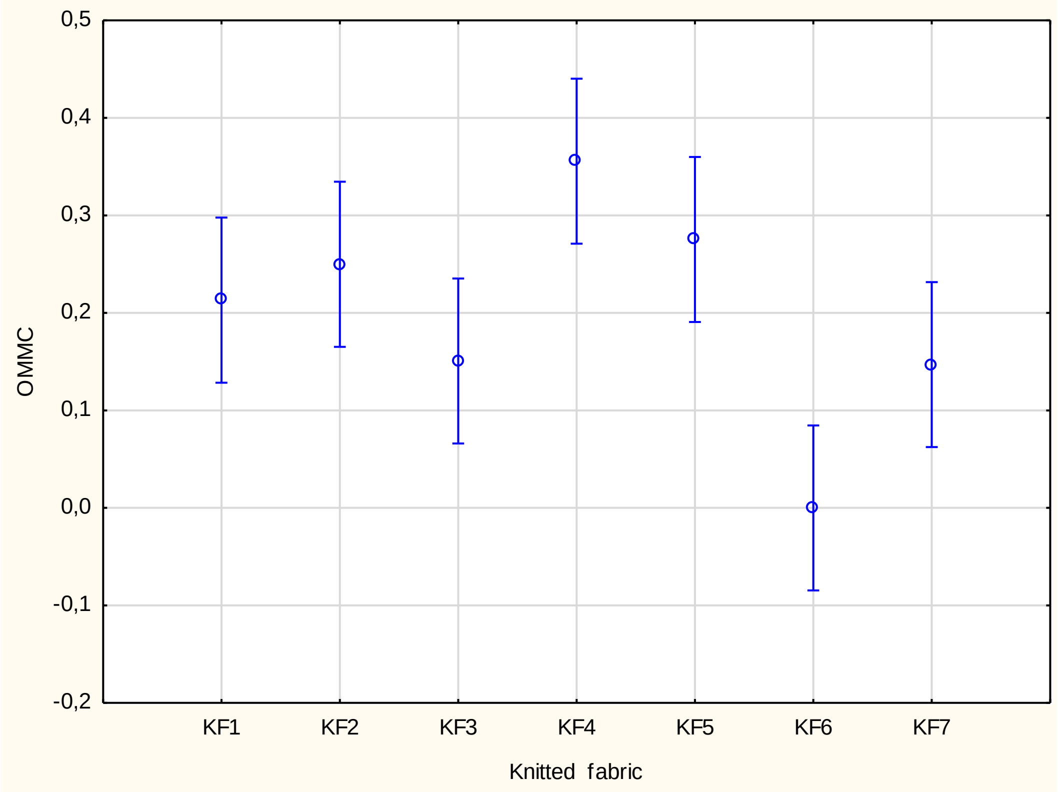

Fig. 7.15. *Influence of the knitted fabric (KF) variant on the OMMC of the multilayer clothing assembly*

On the basis of the results from the MMT (Fig.7.16), it observed that the highest OMMC is given by the following assemblies:

- SS4+KF4 (0.6305),
- SS3+KF5 (0.6201),
- SS4+KF2 (0.6197),
- SS3+KF3 (0.4330),
- SS3+KF4 (0.4218).

The lowest value of the OMMC is given by:

- SS1+KF3 (0.0000),
- SS1+KF6(0.0000),
- SS2+KF6 (0.000),
- SS3+KF6 (0.0000),
- SS4+KF6 (0.0000),

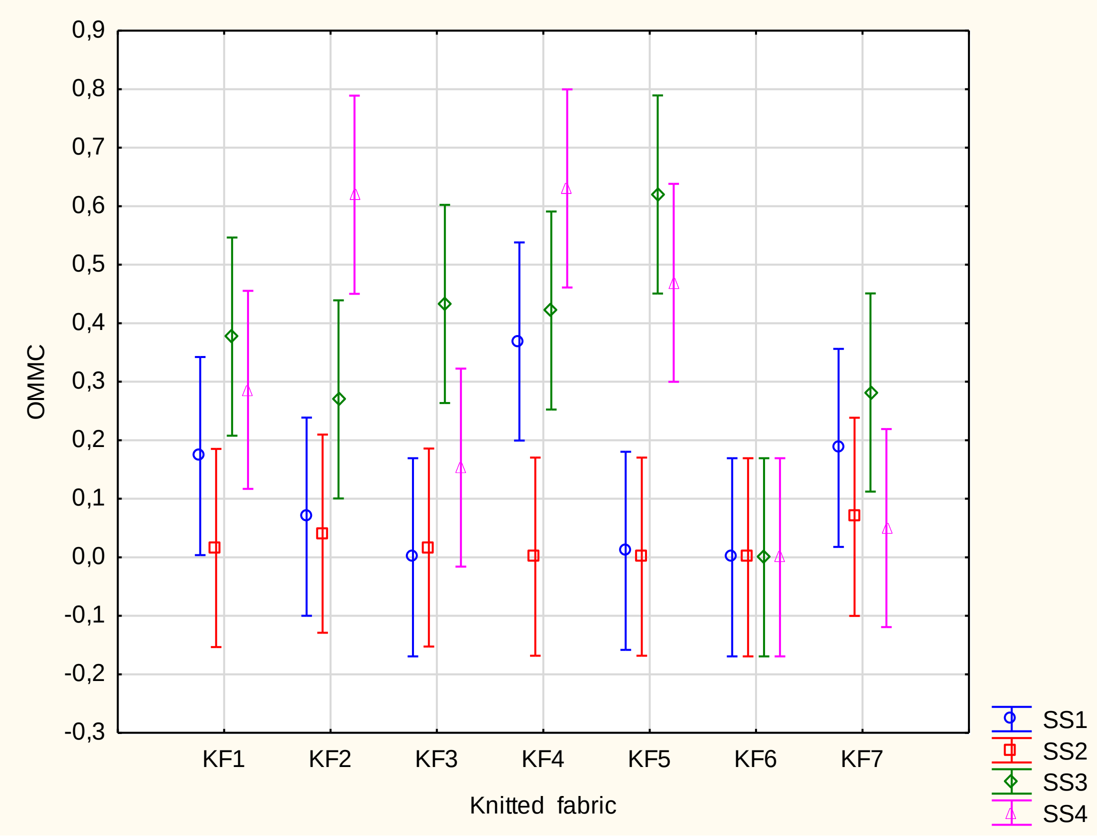

Fig. 7.16. *Influence of the knitted fabric (KF) variant and Sample Set (SS) variant on the OMMC of the multilayer clothing assembly*

7.4. Conclusion

Each variant of the Sample Set for the FPC and variant of knitted fabric for underwear have presented different results from each other in the range of liquid moisture transport properties for the respective group.

The liquid moisture has not been observed on the outer layer of the multilayer packages (SS) for the firefighter’s clothing. Liquid moisture transport has been observed only in the inner layer of the package. Liquid moisture remains in the inner layer of the package and accumulates during the use of the garment. The highest value of the OMMC occurred for the inner layer of the SS4 variant (0.21), and the lowest (0.01) for the inner layer of the SS2 variant.

For knitted fabrics for underwear, the liquid moisture transport varied depending on the individual properties of the knitted fabric. According to the OMMC value, there were ranked from the best one to the worst in the following order: KF5, KF4, KF1, KF6, KF2, KF3, and KF7.

On the other hand, the stretch of knitted fabrics for underwear has a significant influence on the liquid moisture transport properties and has been increased differently on each knitted fabric. The greatest improvement was shown for KF2 (OMMC = 0.27 → 0.72) and KF3 (OMMC = 0.18 → 0.50) knitted fabrics. It can be explained that during the stretching of the knitted fabric, its geometrical structure changes, and the distance between the stitching increases, which improves its moisture transport properties.

It was stated that both the Sample Set variant and the Knitted fabric variant in the components of the created multilayer clothing assembly had a statistically significant influence on the liquid moisture transport properties of the assembly, and there are statistically significant interactions between those two factors.

The highest liquid moisture transport properties of the created multilayer clothing assemblies are presented by the following assemblies: SS4+KF4 (0.6305), SS3+KF5 (0.6201), and SS4+KF2 (0.6197). The lowest value of the OMMC is given by: SS1+KF3 (0.0000), SS1+KF6 (0.0000), SS2+KF6 (0.000), SS3+KF6 (0.0000), and SS4+KF6 (0.0000). The difference between the variants of the highest and the lowest OMMC in the group of created clothing assemblies was 0.6.

The results have presented that by an optimal selection of the components of the clothing assemblies for the firefighter, it is possible to improve significantly the liquid moisture transport properties of the outfit and in the same way to improve the safety and comfort of the firefighter.

8. Quality assessment of the multilayer clothing assemblies

In the frame of the performed investigations 28 multilayer clothing assemblies for the firefighter’s protective outfit have been created. They were composed of multilayer textiles sets (Sample Sets) for the FPC and knitted fabrics for underwear. Measurements of the materials and obtained results showed that the Sample Sets, knitted fabrics, and assemblies made of them differ from each other in the range of all analyzed comfort-related properties.

As it was mentioned earlier, the protective properties are the crucial features of the FPC and its materials for it. In the dissertation, the protective properties of the multilayer textile sets for the FPC have not been assessed. The multilayer textile sets being the objects of the investigations have been received from the manufacturer. They were the commercially available multilayer sets of certified protective properties. The aim of the presented work was to show the possibility of shaping the comfort-related properties of the multilayer protective assemblies for the firefighter’s protective outfit.

In order to assess the quality of the created multilayer clothing assemblies containing the Sample Sets and knitted fabrics for underwear in the aspect of thermo-physiological comfort it is necessary to take into consideration all or selected comfort-related properties being analyzed. At the same time, you should be aware that some properties contradict each other.

In order to assess the created multilayer clothing assemblies we decided to apply the General Quality Index (GQI) formula [168, 169]. It is a numerical index representing the general value of the product in the aspect of its quality. It is a way of multi-criteria assessment of product quality. There are different formulas for quality indexes. Generally speaking, the general quality indexes characterize the quality of materials or objects from the point of view of a certain group of features.

In the presented work, in the first stage of the assessment, the General Quality Index was defined by the following formula:

$$GQI = \sum_{i=1}^{n} r_i \qquad (8.1)$$

Where:

r_i – the rank of the ith parameter taken into consideration,

n – the number of parameters under consideration.

The ranks of particular parameters have been established in such a way that a higher range corresponds to better performance, or the opposite – a higher range corresponds to a lower value of the parameter. It depends on the parameter and its influence on physiological comfort.

For instance, in the case of thermal resistance, the higher value means better protection of the user's body against heat loss in cold conditions and against heat in fire conditions. Due to this fact all created multilayer clothing assemblies were arranged in order from the lowest value of thermal resistance to the highest value of thermal resistance. Then, each sample was ranked from 1 (the lowest rank) to 28 (the highest rank). It is presented in Table 8.1.

In order to calculate the values of the General Quality Index the following comfort-related properties were taken into consideration:

- thermal resistance,
- water-vapor resistance,
- Overall Moisture Management Capacity.

In the case of thermal resistance and Overall Moisture Management Capacity, the samples were arranged from the lowest to the highest values of both parameters. In the case of the water-vapor resistance, the arrangement was in the opposite way because a lower value of water-vapor resistance means better performance of the material in the aspect of water-vapor transport. At the same time, it is better to transfer sweat produced by the human body.

Additionally, the water-vapor resistance of the created multilayer clothing assemblies was calculated as a sum of the water-vapor resistance of both the Sample Set and knitted fabric from which the assembly has been composed. In reality, it is difficult to tell how close the sum of the water-vapor resistance of particular layers is to the real (measured) water-vapor resistance of multilayer material. It was done in such a way because the Permetest failure made it impossible to measure the assemblies in this range. We used such an approach to illustrate the procedure for determining the General Quality Index. We are aware that the estimation result is only approximate.

Table 8.1. *The ranks of the multilayer clothing assemblies according to the value of thermal resistance*

Sample	R mK/Wm²	Rank
SS3+KF4	59.73	1
SS3+KF6	65.60	2
SS3+KF2	65.87	3
SS3+KF1	68.10	4
SS3+KF3	71.07	5
SS3+KF5	74.40	6
SS3+KF7	77.60	7
SS4+KF3	89.03	8
SS2+KF3	90.53	9
SS2+KF2	91.30	10
SS2+KF4	92.20	11
SS4+KF2	92.67	12
SS2+KF6	93.43	13
SS1+KF4	96.63	14
SS1+KF3	96.93	15
SS1+KF2	97.33	16
SS2+KF1	99.40	17
SS2+KF5	100.37	18
SS2+KF7	101.73	19
SS1+KF5	103.23	20
SS4+KF5	105.20	21
SS1+KF1	107.73	22
SS1+KF7	110.87	23
SS4+KF4	112.60	24
SS4+KF6	114.00	25
SS1+KF6	115.30	26
SS4+KF1	118.00	27
SS4+KF7	121.73	28

It was also assumed that the properties under consideration are equally significant.

The value of the General Quality Index was calculated according to the formula:

$$GQI = r_R + r_{Ret} + r_{OMMC} \qquad (8.2)$$

Where:

r_R – rank according to thermal resistance value,

r_{Ret} – rank according to water-vapor resistance value,

r_{OMMC} – rank according to the Overall Moisture Management Capacity value.

According to equation (8.2), the number of properties under consideration (3) and a number of assessed assemblies (28) causes the maximum value of the GQI can be 84. The minimum value can be 3. The values of the calculation are presented in Table 8.2. In the Table, the SS and KF columns are marked with different colors to mark the assemblies created based on particular SS variants and KF variants.

The highest value (66) of the General Quality Index was obtained for the SS4 +KF4 multilayer clothing assembly. It is characterized by the highest value of the Overall Moisture Management Capacity (0.68), fourth highest thermal resistance (112.6 mK/Wm²), and middle value of the calculated water vapor resistance (79.9 m^2PaW^{-1}). The lowest value of the General Quality Index was observed for the SS1+KF3 assembly. It is characterized by the middle thermal resistance (96.93 mK/Wm²) but the highest water-vapor resistance (121.8 m^2PaW^{-1}) and the lowest Overall Moisture Management Capacity (0). This assembly is practically impermeable for sweat in both forms vapor and liquid. It is exactly reflected in the proposed General Quality Index. It is seen that at the beginning of Table 8.2 – the lowest General Quality Index - are the assemblies created based on the SS1 Sample Set. The highest values of the General Quality Index occurred for the assemblies based on the SS4 and next – SS3 Sample Sets. In the case of the knitted fabrics, the situation is not so clear. It results from the fact that the Sample Sets are dominating in the created assemblies.

Table 8.2. *Quality assessment of the multilayer clothing assemblies using the General Quality Index formula*

No.	Sample	GQI	SS	KF	GQI$_{rel}$
1.	SS1+KF3	19	SS1	KF3	0.226
2.	SS1+KF5	30	SS1	KF5	0.357
3.	SS3+KF6	30	SS3	KF6	0.357
4.	SS4+KF3	31	SS4	KF3	0.369
5.	SS1+KF2	33	SS1	KF2	0.393
6.	SS1+KF6	33	SS1	KF6	0.393
7.	SS2+KF3	34	SS2	KF3	0.405
8.	SS2+KF6	34	SS2	KF6	0.405
9.	SS2+KF2	38	SS2	KF2	0.452
10.	SS2+KF4	38	SS2	KF4	0.452
11.	SS4+KF6	39	SS4	KF6	0.464
12.	SS2+KF5	41	SS2	KF5	0.488
13.	SS1+KF4	42	SS1	KF4	0.500
14.	SS1+KF1	44	SS1	KF1	0.524
15.	SS1+KF7	45	SS1	KF7	0.536
16.	SS3+KF2	45	SS3	KF2	0.536
17.	SS2+KF1	46	SS2	KF1	0.548
18.	SS4+KF2	48	SS4	KF2	0.571
19.	SS2+KF7	51	SS2	KF7	0.607
20.	SS3+KF3	51	SS3	KF3	0.607
21.	SS3+KF4	52	SS3	KF4	0.619
22.	SS3+KF7	52	SS3	KF7	0.619
23.	SS4+KF7	52	SS4	KF7	0.619
24.	SS3+KF1	53	SS3	KF1	0.631
25.	SS4+KF5	55	SS4	KF5	0.655
26.	SS3+KF5	56	SS3	KF5	0.667
27.	SS4+KF1	60	SS4	KF1	0.714
28.	SS4+KF4	66	SS4	KF4	0.786

To assess finally the Sample Sets and knitted fabrics in the aspect of their usefulness for application in the firefighter's clothing outfit the sum of values of the General Quality Index was calculated for the seven assemblies created based on each Sample Set variant and for four assemblies created on with each knitted fabric variant.

The highest sum of ranks occurred for SS4 (351), next SS3 (339), SS2 (282), and finally SS1 (246). In the case of the knitted fabrics, the highest sum of ranks was obtained for the KF1 (203), next KF7 (200), KF4 (198), KF5 (182), KF2 (162), KF6 (136), and KF3 (135).

The absolute values of the General Quality Index can be in the range from 3 to 84. For different numbers of assessed materials and properties under consideration, the values can be quite different. It is difficult to interpret the results presented in such a form. Much more convenient is to present the value of the General Quality Index as the relative value in the range from 0 to 1.

The relative value of the General Quality Index is defined by the following formula:

$$GQI_{rel} = \frac{r_R + r_{Ret} + r_{OMMC}}{84} \qquad (8.3)$$

Where:

GQI_{rel} – the relative value of the General Quality Index (in the range from 0 to 1),

r_R - rank according to the thermal resistance value,

r_{Ret} – rank according to water-vapor resistance value,

r_{OMMC} – rank according to the Overall Moisture Management Capacity value.

A higher relative value of the General Quality Index means better quality. GQI_{rel} equal to 1 means the ideal quality. The relative values of the General Quality Index are presented in Table 8.2.

Assessing the quality of the assemblies in the aspect of their ability to ensure physiological comfort other comfort-related properties can also be taken into consideration. In such a situation the number of the properties under consideration will be different which causes the change of the denominator of the equation (8.3).

The generalized formula of the relative value of the General Quality Index is the following:

$$GQI_{rel} = \frac{\sum_{i=1}^{n} r_i}{n * m} \qquad (8.4)$$

Where:

r_i – rank according to the i^{th} parameter (property), n – number of parameters taken for calculation,

m – number of assessed assemblies (materials).

In some cases, the importance of the properties under consideration is not equal. In such a situation, it is possible to assign appropriate weights to each parameter taken for the calculation.

The assemblies being assessed were composed of multilayer textile sets for the FPC (Sample Sets) and knitted fabrics for underwear. The underwear adheres directly to the human skin and affects the feeling of warmth to the touch. The warm/cool filling while first contacting the underwear with the human skin depends on the thermal absorptivity of the knitted fabric applied to the underwear. The FPC is thick and stiff. It has to be worn with the underwear. Due to this fact, while assessing the multilayer assemblies containing the knitted fabric for underwear, it is advisable to take into consideration the thermal absorptivity of the assembly while calculating the General Quality Index. Moreover, in the majority of cases, the assembly is not permeable to liquid sweat due to the moisture barrier content. In order to assess the assembly from the point of view of the liquid transport and physiological comfort taking into account the wetting time for the top surface (WTT parameter from the MMT) seems to be reasonable. This parameter illustrates how quickly the inner surface of the garment will absorb liquid sweat.

Taking the above into consideration we proposed another equation for calculation of the General Quality Index. It is based on a bigger number of comfort-related parameters:

- thermal resistance,
- thermal absorptivity,
- water-vapor resistance,
- Overall Moisture Management Capacity,
- wetting time for the top surface.

It is reasonable because a new formula does not require any additional measurements. Thermal absorptivity is determined using the Alambeta simultaneously with the thermal resistance, in the same test. The wetting time for the top surface is determined by the MMT simultaneously with the OMMC and other parameters. Having the values of the aforementioned parameters it makes sense to use them while assessing the material.

However, in our opinion, the significance of the thermal absorptivity is not equal to the significance of the thermal resistance. Similarly, the significance of the wetting time for the top surface is not equal to the significance of the Overall Moisture Management Capacity. Due to this fact, appropriate weights (degree of importance) were assigned to individual parameters under consideration. The weights were expressed in decimals in such a way that the sum of weights is 1. The value of the extended relative General Quality index was calculated according to the formula:

$$GQI_{ext} = \frac{0.3r_R + 0.1r_b + 0.3r_{Ret} + 0.2r_{OMMC} + 0.1r_{WTT}}{28} \qquad (8.5)$$

Where:

GQI_{ext} – relative General Quality Index extended to 5 properties under consideration,

r_b – rank according to the thermal absorptivity value,

r_{WTT} – rank according to the WTT value.

The values of the extended General Quality Index calculated based on the equation (8.5) are presented in table 8.3. In the table, the assemblies being assessed are arranged according to the increasing value of the General Quality Index.

An assessment according to the extended value of the General Quality Index is similar to the assessment according to the first formula – equation (8.1). In both cases, the best quality was stated for the assemblies SS4+KF4 and SS4 +KF1, and the worst – for the SS1+KF3 and SS1+KF5.

In the middle of tables 8.2 and 8.3, there are some differences.

An appropriate selection of the parameters taken for an assessment of the quality and assignation of appropriate weights / degrees of importance is crucial while assessing the quality of the textile assemblies based on several properties.

Table 8.3. *The quality assessment of the multilayer clothing assemblies according to the extended formula of the General Quality Index*

No.	Assembly	GQI_{ext}
1.	SS1+KF3	0.379
2.	SS1+KF5	0.379
3.	SS2+KF2	0.404
4.	SS2+KF6	0.418
5.	SS3+KF6	0.421
6.	SS4+KF3	0.429
7.	SS1+KF2	0.439
8.	SS2+KF3	0.461
9.	SS1+KF6	0.475
10.	SS2+KF4	0.479
11.	SS2+KF5	0.482
12.	SS3+KF7	0.486
13.	SS2+KF7	0.496
14.	SS4+KF6	0.500
15.	SS1+KF4	0.511
16.	SS3+KF2	0.511
17.	SS1+KF7	0.529
18.	SS1+KF1	0.532
19.	SS2+KF1	0.539
20.	SS3+KF3	0.571
21.	SS3+KF1	0.582
22.	SS4+KF2	0.582
23.	SS3+KF5	0.589
24.	SS4+KF7	0.596
25.	SS3+KF4	0.614
26.	SS4+KF5	0.646
27.	SS4+KF1	0.725
28.	SS4+KF4	0.725

The generalized formula of the extended General Quality Index is as follows:

$$GQI_{ext}\frac{\sum_{i=1}^{n} t_i r_i}{m} \quad (8.6)$$

Where:

GQI_{ext} – the relative value of the General Quality Index extended to the bigger number of properties under consideration (in the range from 0 to 1),

t_i – degree of importance of i^{th} property expressed as a decimal, where:

$$\sum_{i=1}^{n} t_i = 1 \qquad (8.7)$$

8.1. Conclusion

On the basis of the quality assessment of created multilayer clothing assemblies for the firefighter’s protective outfit are the following:

- Quality assessment of the multilayer firefighter’s protective assemblies should be performed based on several parameters characterizing the assemblies in the aspect of their heat and moisture transport performance.
- General Quality Index idea (method) can be applied in multicriteria quality assessment of the multilayer clothing assemblies.
- In the literature there are different formulas of the General Quality Index. The selection of appropriate formula for multicriteria quality assessment depends of the properties under consideration and the correlation on the parameters’ value with the quality level.
- In the quality assessment using the General Quality Index the most important aspect is to select appropriate properties taken for calculation and assumption of appropriate degree of significance of particular parameters under consideration.
- For the analyzed group of assemblies, the highest quality from the point of view of physiological comfort was stated for the SS4+KF4 and SS4+KF1 assemblies.
- The low quality of the assemblies created based on the KF6 knitted fabric was surprising because the KF6 fabric was manufactured using special patented technology designed to improve the comfort-related properties of cotton fabrics.

Final conclusion

Evaluation of properties such as thermal insulation properties, water vapor, and liquid moisture transport capabilities of materials related to the comfort of multi-layer clothing packages for the firefighter' protective clothing (FPC) was carried out. In addition, the comfort-related properties of each layer that make up the clothing assembly were analyzed and evaluated. The following conclusions are made within the scope of the research work.

- For the evaluated properties, thermal insulation properties, water vapor, and liquid moisture transport are the main properties that can fully express clothing comfort.
- The equipment used to measure the parameters of the thermo-physiological comfort properties of clothing materials and clothing was advanced and innovative, cooperating with specialized software enabling the determination of all relevant parameters.
- The multi-layered textile sets of the firefighter's protective clothing analyzed are the materials used in production, approved by appropriate standards, and the selected knitted fabrics for underwear are the materials widely used in practice. With these materials, 28 variants of multi-layer textile assemblies for FPC were created, which proved to be sufficient data for testing and analysis.
- It has been proven that the optimal and appropriate selection of materials in the assembly for the FPC can significantly improve the comfort and protective properties of the clothing and improve the safety and comfort of the firefighter wearing protective clothing.
- The assessment of assembly quality for FPC using the General Quality Index (GQI) is based on a theoretically developed method, and in the future, it is possible to evaluate the quality of other clothing with this method.
- The dissertation can serve as a reference guide for those researching clothing quality assessment and clothing comfort properties.

- It is considered that the aim of the Ph.D. thesis has been achieved. It was proved that by appropriate selection of the materials creating particular layers of the protective clothing outfit for the firefighters, it is possible to shape the comfort performance of the firefighter’s clothing assembly. In the same way, the safety of the firefighters can be improved.

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