

A REVIEW OF TEXTILES REFLECTING FIR PRODUCED BY THE HUMAN BODY

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Abstract:

The human body constantly produces thermal electromagnetic radiation with a maximum of about 10 μm . This thermal radiation has a number of positive effects on the human body and, in addition, allows the insulation under clothing to be improved under extreme climatic conditions, causing a significant reduction in ambient temperature. With so-called far-infrared (FIR) textiles, it is possible to ensure the reflection of thermal radiation back to the human body. In the first part of this review, the generation of heat by the human body and its propagation by radiation through the skin are comprehensively explained. The thermal characteristics of the individual skin layers as an emitter of infrared radiation are given. The second part discusses the basic preparation methods of FIR textiles. Suitable particle systems are described based on metals and their oxides, porous carbon, and special ceramics. Modification of the fiber phase (especially the fineness of the fibers and the porosity of the fabric) in combination with the surface coating of metals is also used for their health-promoting effects. The main manufacturers of FIR textiles and their typical products are mentioned.

Keywords:

Far infrared, reflection, infrared radiation, heat transfer, thermal radiation, emissivity, FIR textiles

1. Introduction

Standard textiles act as an insulator of thermal conduction and convection but with very limited ability for thermal radiation reflection. A few textiles can realize efficient reflection of far-infrared (FIR) produced by the human body, but they have some limitations [1]. The FIR textiles are designed to retro-reflect thermal radiation back to the human body. Infrared (IR) radiation emitted by the human body is not the most effective for localized human body heating. There is also a discrepancy between optimal radiative heating performance and comfort. FIR textiles are a category of functional textiles that have presumptive health and well-being functionality. Molecules are impacted by the rotational and vibrational forces of FIR [1]. FIR textiles are designed to transform the energy into radiation with a wavelength of 4–14 μm and reflect it back to the human body. Fabrics with the FIR function can therefore offer thermal retention.

Clothing that safeguard from low (0°) to extremely low (–15°) temperatures are required in industrial and sporting activities. This is necessary to avoid external and internal risks associated with extreme temperatures. Common solutions for protective clothing against low to extremely low ambient temperatures are based on thick clothing thermal insulation layers, limiting the wearer's mobility during the activity and increasing the overall weight of the clothing. Clothing with thick insulating layers also does not absorb heat generated by the human body effectively. During physical exertion, at least 30% of body heat radiates through the outer layers

of clothing and subsequently released to the surrounding. Aluminum foil is used as a reflective layer in thermal clothing. It helps in the prevention of thermal radiation escaping into the environment. However, such arrangements result in challenges with water vapor transport, which affects the comfort of the wearer. Accumulation of water vapor at low ambient temperatures may result in hypothermia. Sometimes perforated reflective foil addresses this issue, but it results in large openings, which reduce thermal insulation properties [1]. Therefore, the better solution is to only use the porous textile layers with a surface reflective layer [2–7].

This study explores contemporary possibilities to create thermal insulation fabric that can retroreflect IR radiation in the wavelength range of 4–14 μm while maintaining sufficient breathability and eliminating or at least reducing the disadvantages of the reflective foil and increasing the comfort of clothing for users. The prediction of radiation from the human body depends on ambient conditions and metabolic rate.

2. Heat produced by the human body

The human body generates heat due to basal metabolism, specific activities, and ambient temperature/humidity conditions. The power of heat generated by the human body ranges from about 75 W while sleeping to about 1,000 W during extreme physical exertion. The skin dissipates up to 85% of the heat. In case of an air gap between the human body and clothing, heat is propagated through radiation at wavelengths from 4.4 μm to a



maximum of $9.4\ \mu\text{m}$ (FIR) under ambient conditions. Even indoors and in a sedentary state, 50% of the heat generated by the human body is dissipated through radiation [1]. FIR thermal energy is found to have positive effects on the body [3,8]. The heat balance influences the thermal state of a person. It is the relationship between the amount of heat produced by the organism and the amount of heat removed from the organism to the surroundings [1]. In the case of thermal equilibrium, when there is no accumulation of heat in the body, the heat produced by the body is dissipated in various forms, namely, radiation, flow, conduction, evaporation, and respiration.

Heat transfer modes generally depend on the ambient temperature and fibrous material porosity (Figure 1) [9]. Based on real experiments, it was found that the loss of heat from the body is influenced by the surrounding temperature [4]. In the “neutral zone” ($30\text{--}32^\circ\text{C}$), the heat loss is equal to heat produced.

The heat loss increased under both colder and warmer conditions. Under colder conditions, heat loss is proportional to a decrease in ambient temperature at the rate of approximately $12.5\ \text{J}\ ^\circ\text{C}^{-1}$ because of increased convection and radiation [9]. Radiation depends on the difference between skin and ambient temperature, and it changes from $274\ \text{J}\ \text{h}^{-1}$ at 23°C to zero at 35°C . Convection varies considerably and has a definite trend

only when the skin and air temperatures become nearly the same. It approaches zero at 34.7°C . Evaporation loss is uniform up to 30°C [8] (Figure 2).

Under warmer conditions (over 30°C), evaporation increases rapidly, and at 34.7°C , nearly all body heat is dissipated by this mechanism. Body heat loss regulation is governed by a combination of increased blood flow to the skin and evaporation [9].

For a typical skin temperature of 35°C , according to the Wiener Shift Law, the maximum radiated energy occurs at wavelength $\lambda = 2.8983/(273.15 + 35) = 9.4\ \mu\text{m}$ (FIR range). As the skin temperature increases, the maximum radiated energy shifts very slightly to lower wavelengths (Figure 3).

The human body has mechanisms to regulate heat-moisture processes affecting skin temperature [12]. It is necessary to investigate complex transport processes in the system:

- Human (heat produced by metabolic processes, M ; mechanical work, W ; body core temperature, T_{co}).
- Skin (skin temperature, T_s ; water vapor partial pressure, P_s).
- Clothing (clothing temperature, T_c ; water vapor partial pressure, P_c).

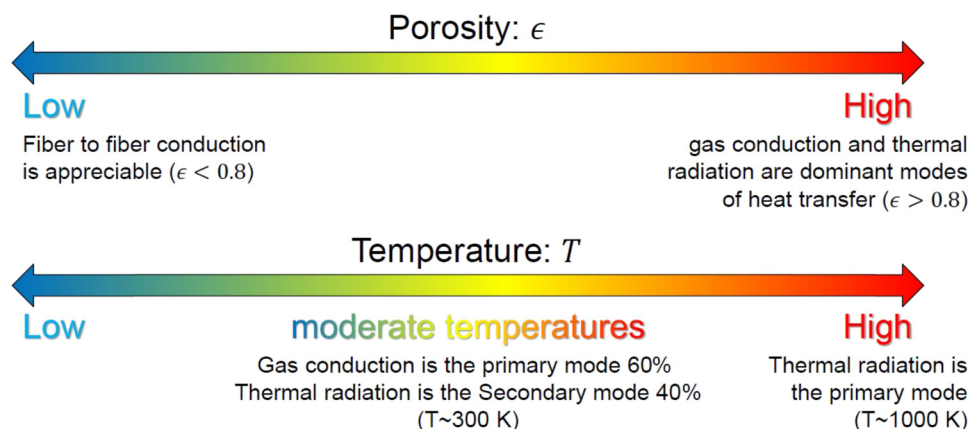


Figure 1. Influence of porosity and temperature of the fibrous material on heat transfer modes [10].

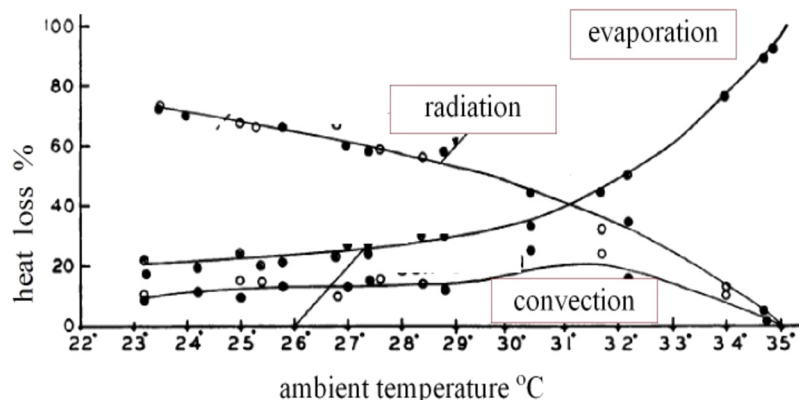


Figure 2. Percentage of heat loss due to radiation, evaporation, and convection, as a function of ambient temperature (adapted from ref. [11]).

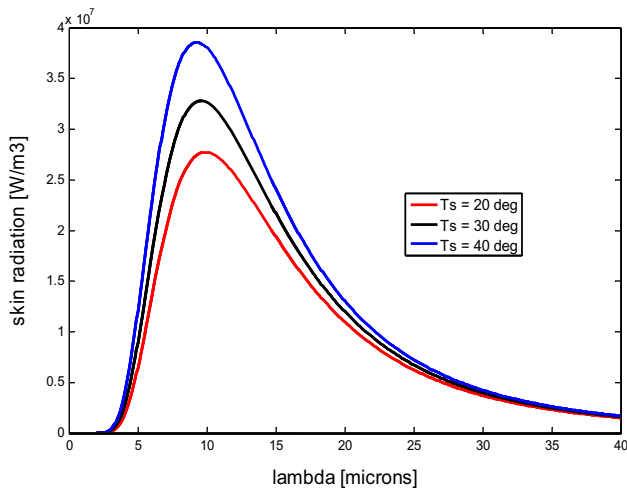


Figure 3. The intensity of heat radiation from human skin at different skin temperatures T_s .

- Surroundings (temperature, T_a ; water vapor partial pressure, P_a ; air velocity, v).

These processes are based on the thermal balance of humans depending on their body dimensions and physical activity: simulation of heat transfer components from the human body by convection (when the fabric touches the skin), conduction in the air phase, and radiation (Figure 4). It is interesting to determine what proportion of FIR radiated by the human body can reflect from the surface of specially treated fabrics back to the skin and possibly penetrate its subsurface layers.

The intermediate layer thickness between skin and clothing is estimated from 1 to 5 mm. The outer boundary layer of air where the temperature of the fabric is not equal to the ambient temperature depends on the temperature difference. For an ambient temperature of 21°C and a fabric temperature of 34°C, this thickness is estimated to be about 4 cm.

3. Skin radiation

The skin provides the first barrier between the organism and its surroundings. It regulates local humidity and temperature flows depending on ambient conditions. It also contains complex

vascular systems and sweat glands that allow humans to respond by changes of conductivity to the thermoregulatory requirements of the body.

However, the thermal sensitivity of the skin varies in different parts of the body. Humans automatically maintain body temperatures within certain temperature limits. Under normal conditions of heat generation and output equilibrium, temperatures in other parts of the body are kept at constant values, but they vary in size. However, changing 1–2°C from these values is enough to give a sense of discomfort. Skin temperature T_s is dependent on where it is measured. In general, the average skin temperature is around 36°C, dependent on ambient temperature [13–15].

The skin comprises three layers, namely, the thick epidermis (0.1 mm), thick dermis (1.5 mm), and thick subcutaneous fat layer (4.4 mm) (Figure 5) [10].

Blood flow is found only in the dermis layer, but metabolic heat is generated in all three layers. Of the total incident heat energy, 21% is reflected by the surface; 66% penetrates to the corneum; 50% penetrates to the subcutaneous tissue; and 99% of the total radiation is absorbed within 3 mm of the surface [5]. For good penetration, the maximum radiation shall fall at 1.2 μm [16–18]. Basic parameters of individual skin layers are given in Table 1.

Human skin is an emitter of IR radiation whose characteristics depend on the skin temperature T_s and its emissivity ε (usually 0.99) [6,7,9]. Thus, the skin can be considered approximately a black body with a spectral distribution of monochromatic radiation according to Planck's law [19]. Skin's real radiation starts from about 3 μm , where sunlight no longer emits [20]. In the area where the skin emits significantly, it has low reflectance and transmittance [17]. At a wavelength of 2 μm , the skin reflectance is only about 7% and further decreases monotonically above this wavelength. Above a wavelength of 6.5–7.5 μm , the skin reflectance is zero [13]. IR transmittance through the skin is small. About 95% of FIR is absorbed within 2 mm of the skin surface and 99% within 3 mm [1,17,18].

To calculate the areal radiation intensity of FIR emitted from skin I_s , the Stefan–Boltzmann law can be used

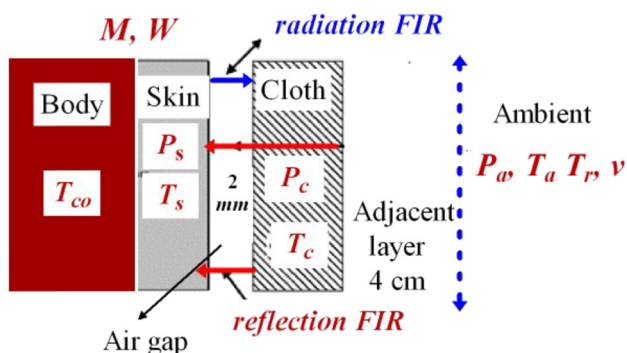


Figure 4. Heat flows in the system human-clothing surroundings.

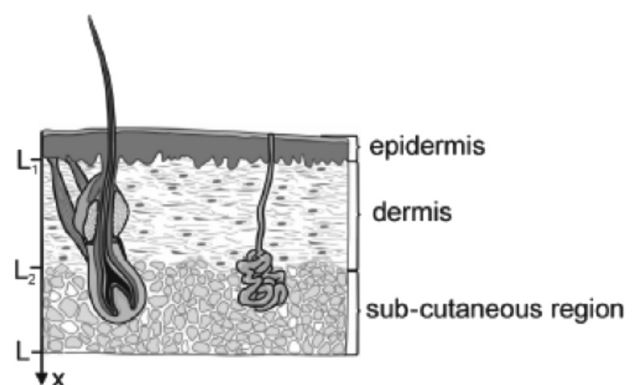


Figure 5. Composition of human skin [9].

Table 1. Basic characteristics of skin layers [9]

Parameter	Epidermis	Dermis	Subcutaneous
Density (kg m^{-3})	1,190	1,116	971
Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	0.235	0.445	0.185
Specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)	3,600	3,300	2,700
Metabolic heat/generated (W m^{-2})	368.1	368.1	368.3
Thickness (mm)	0.1	1.5	4.4

$$I_s = \varepsilon \sigma T_s^4, \quad (1)$$

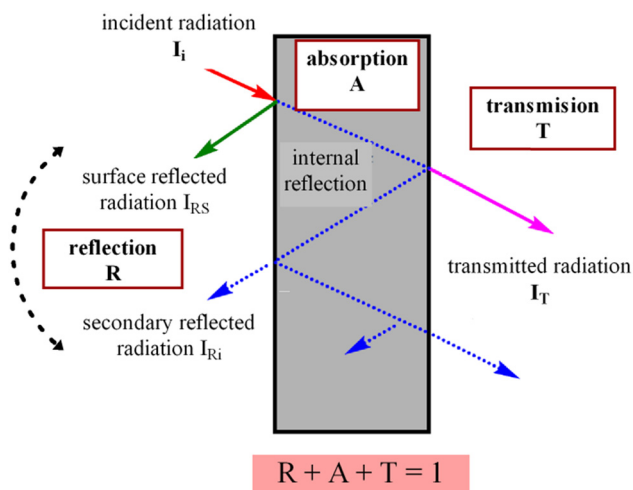
where ε is the skin emissivity (usually 0.99), and $\sigma = 5.669 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan–Boltzmann constant. For skin temperature $T_s = 20^\circ\text{C}$, $I_s = 414.48 \text{ (W m}^{-2}\text{)}$; for $T_s = 30^\circ\text{C}$, $I_s = 473.99 \text{ (W m}^{-2}\text{)}$; and for $T_s = 40^\circ\text{C}$, $I_s = 539.70 \text{ (W m}^{-2}\text{)}$. The total radiated heat per unit time QR (W) is then determined by multiplying I_s by the total skin area. From knowledge of skin temperature T_s and ambient temperature T_a , it is possible to determine heat loss by radiation QR (W) [11].

4. Textiles and IR radiation

The different types of interactions of electromagnetic radiation with the object are shown in Figure 6.

Based on the internal structure and optical properties of the object, incident radiation (heat intensity $I_i \text{ (W m}^{-2}\text{)}$) at a selected wavelength is split into three components, i.e., reflected radiation (IR), absorbed radiation (IA), and transmitted radiation (IT). It is simple to define relative dimensionless characteristics as transmittance T , absorbance A , and reflectance R as portions.

The reflection loss is attributed to the disparity between the incident signal and the surface blockage of the shield. The absorption loss is related to the physical characteristics of shield material, and, unlike reflection loss, it is independent of the type of source field.

**Figure 6.** Interaction of electromagnetic radiation with object.

For opaque materials, is transmittance equal to zero, and then reflectance is

$$R = 1 - A = 1 - \varepsilon, \quad (2)$$

where ε is the emissivity (characterizing the tendency to emit radiation from an object), the ideal black body is $\varepsilon = 1$, and incident heat intensity is equal to absorption intensity. The black body is therefore emitting maximum heat intensity. For the gray body, emissivity is less than one but independent of the wavelength of radiation λ . The emitted heat is lower. Emissivity is then the percentage of IR energy emitted by an object at any given temperature compared to the IR energy emitted by a black body at the same temperature. Typically, the opaque materials with a reasonably high emissivity value (over reflective, so emissivity 0.7) are gray body materials. Therefore, practically all-natural and chemical fibers belong to this category. Non-gray materials are characterized by no constant emissivity ε (λ) dependent on radiation wavelength. The emissivity value of a body is influenced by the chemical composition of material (presence of some typical groups), surface condition, reflectivity, and opacity. Some synthetic fibers belong to this group. The emissivity of highly reflective materials is generally higher at shorter wavelengths λ than at longer wavelengths.

The emissivity of fibrous materials can be tuned by a suitable choice of fiber type, fiber diameter d , and fiber packing density [21]. Radiative transfer in the fibrous material is expressed in terms of scattering and absorption coefficients. According to the scattering properties of the fibrous material, two different criteria of fiber diameters are considered separately as follows:

1. Coarse (non-scattering criteria) where $(\pi d/\lambda) \gg 1$,
2. Fine (scattering criteria) where $(\pi d/\lambda) \ll 1$,

An expression for the absorption and scattering coefficients was developed in ref. [21].

5. Materials for FIR textiles

Reflection of FIR heat can be promoted by selecting special particles embedded in fibers or deposited on their surface [22]. Another possibility is to use a sandwich structure containing a high reflective surface as metal foils or metal-coated surfaces.

5.1. FIR reflective materials

FIR reflection is supported by ceramic particles (mica, tourmaline, and basalt), activated carbon particles, metal oxides (Al_2O_3 , SiO_2 , ZnO , MgO , ZrO_2 , TiO_2 , CuO , and Cu_2O), and metals (Fe, Ag, Cu, Zn, and Ni) or metal particles. There are also selected systems containing bonded metal cations, porous carbon particles (such as bamboo stems [23]), and natural materials (tourmaline and clamshells) that have a positive effect on FIR back reflection [24].

The challenge is finding a suitable and economically advantageous combination of particles of different chemical compositions and sizes to achieve maximum FIR absorption and back reflection (emission). In particular, metals appear to be potential materials for this purpose. The reflection of electromagnetic radiation by reflection R is a function of the electrical conductivity/magnetic permeability ratio. At the same time, absorption attenuation A is a function of the product of electrical conductivity and magnetic permeability. Materials such as silver, copper, gold, and aluminum are suitable for electromagnetic field reflection due to their high electrical conductivity, and, for example, nickel and stainless steel are suitable electromagnetic radiation absorbers due to their high magnetic permeability (Table 2).

It is known that the loss of electromagnetic radiation at high frequencies due to reflection is the function of the ratio of σ_r/μ_r , and loss due to absorption is a function of product $\sigma_r\mu_r$, where σ_r is the relative electrical conductivity and μ_r is the magnetic permeability. The metallic reflectance is directly related to the conductivity of the metal by the Hagen–Rubens equation [25], i.e., the higher conductive metals have higher reflectance. Copper generally has a low risk of deleterious effects on the skin. The advantage of CuO is that it can be used from bed linen, socks, and clothing textile to special technical and military textiles for its versatile antibacterial, antifungal, and racial effects associated with improving wound healing.

Ceramic and ceramic basalt particles contain metal oxides and positively affect FIR absorption and back reflection. TiO_2 and ZnO have a unique position among electrically conductive oxides, absorb UV radiation, are photocatalytically active, and can photo-oxidize chemical and biological structures. Therefore, it is also suitable for the preparation of antimicrobial, self-cleaning, UV-blocking, and antistatic fabrics. For example, it is possible

to combine nanoparticles of TiO_2 and MgO to perform a self-sterilizing function. Using photocatalysis in combination of TiO_2 or ZnO with SiO_2 particles and others is also realized by the effects of odor deactivation, the release of active oxygen, and active surface cleaning.

5.2. Modification of fibrous phase

It has been found that thermal radiation can account for 40–50% of the total heat transfer in fiber structures of high porosity at lower ambient temperatures. IR wavelengths range from 2 to 100 μm . Fiber diameters less than 600 nm will probably be too small to affect thermal radiation. However, fibers with diameters of about 3 μm can increase the thermal resistance of polymer fiber insulation materials. The finer fibers generally exhibit less radiation heat transfer and higher heat radiation absorption. Therefore, selecting a microfibrillar structure as a functional textile backing layer is desirable. Other requirements for this structure are good dimensional stability, low planar weight, and low thickness.

The promising way to prepare FIR reflective surfaces is surface metallization (via fusing of metal nanoparticles). This approach was selected to design the FIR textile layer based on light-weight nonwoven Milife coated by copper nanoparticles [26]. Copper-coated Milife has enhanced reflectance in the FIR region, and untreated Milife is sufficiently transparent for the near-infrared radiation (NIR) range (sun radiation) [26]. Copper-coated Milife is shown in Figure 7.

There were also prepared multiple layers with dual modes of cooling and heating functionalities [11]. In heating mode, it is advisable to have the inner layer with high reflectivity (low emissivity) in FIR, enabling FIR reflectance, and the outer layer with low reflectivity (high emissivity) in NIR, enabling NIR emission to the human body. In cooling mode, it is necessary to flip over the active layers [27]. Apart from FIR transmittance and NIR reflectance of textiles (cooling effects from inside and outside), the surface emissivity of textiles plays an important role [1]. By increasing the emissivity of the surface of the textile, the radiation heat flux will increase, and the radiative cooling effect will be achieved. For obtaining high emissivity levels on the outer surface of textiles, a highly porous layer of carbon material (4–9 μm) was proposed [1,11].

Table 2. Relative electrical conductivity and magnetic permeability of selected metals

Metal	σ_r	μ_r	$\sigma_r\mu_r$	σ_r/μ_r
Silver	1.05	1	1.05	1.05
Copper	1	1	1	1
Gold	0.7	1	0.7	0.7
Aluminum	0.61	1	0.61	0.61
Nickel	0.2	100	20	2.10–3
Stainless steel	0.02	500	10	4.10–5

6. FIR textiles

FIR radiation (3–1,000 μm) consists of invisible electromagnetic waves with wavelengths longer than visible light. It is the major heat-transmitting radiation at wavelengths of 3 μm to 1 mm, as defined by the international commission on illumination (1987). Particularly in the range of 8–14 μm , FIR was supposed to have many biological effects [28,29]. This spectrum of wavelength transfers energy that thermoreceptors in the skin perceive as heat. In previous years, people had believed that the optimal wavelength most effective for life is between 8 and 14 μm [30,31]. Numerous medical studies used

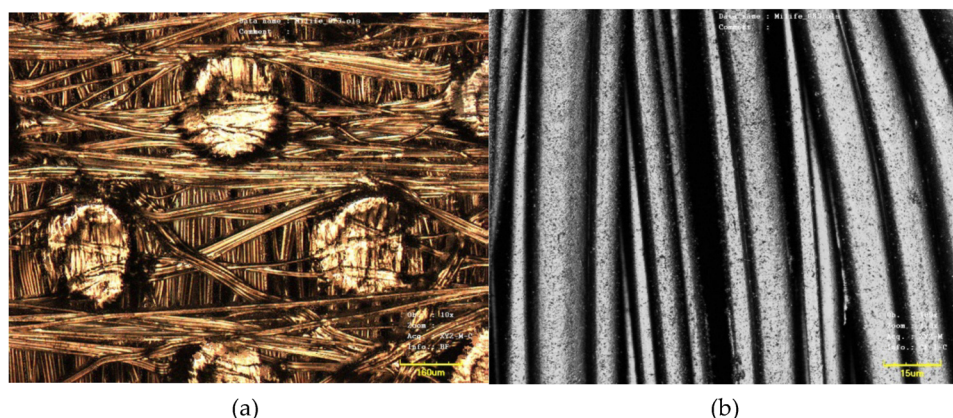


Figure 7. (a) Surface and (b) longitudinal view of copper-coated Milife.

FIR with an external heat supply source to demonstrate that the FIR wavelength increases skin microcirculation, improves blood flow of arteriovenous fistulas in hemodialysis patients, extends survival of skin grafts, and has other health-promoting effects [1]. Since the mid-1980s, patents about FIR fabric have emerged in Japan, forming a development boom. The “Masonic” fiber of the Zhong Fang company was made by adding FIR ceramic powder into nylon or polyacrylonitrile or coating on the surface of the fiber and then spun yarn. Kuraray’s “Ron Weip” was a fiber that blends FIR ceramic powder into polyester; Asahi Kasei Corporation developed the new nylon thermal fabric “SOLAR-V” coated with zirconia ceramic solution and was mainly used for ski jackets. Toray and ESN jointly developed the polyester coated fabric, “Mekka Coulomb,” coated with heat-sensitive coatings. At present, these materials are not produced. The FIR polyester fabrics “Louvro” and “Ohdus” and acrylic fabrics CERAM® introduced by Toyobo Co., Ltd. have excellent drape, good touch, and elegant color [32].

The development of FIR fabrics in China began in the early 1990s. Representative products included FIR polyester staple fiber developed by Jiangsu Textile Research Institute; the 1.67dtex × 38 mm FIR polyester short fiber jointly developed by East China University of Science and Technology and Shanghai Chemical Fiber Factory, FIR polypropylene developed by Tianjin Polytechnic University (with good moisture permeability, low-cost, light-weight, anti-bacterial, and anti-mite), FIR acrylic and fine-denier polyester (or wool) blended knitting yarn and knitting products jointly developed by Donghua University and Shanghai Jinshan Petrochemical Acrylic Fiber Factory [5,9].

In Asian garment markets, an increasing number of products containing fiber additives, such as bamboo charcoal and mineral ores, which the manufacturers claim can promote health when worn on the body, are offered. Garments composed of bamboo charcoal have putative health-promoting functions. Although the authors cannot deny the health benefits of these products in maintaining warmth, observing physiological responses to the fabrics in clinical practice has indicated that these products cannot be defined as actual health-promoting materials [6]. Similar features have products implemented in several branded versions in Europe and the USA in the last

10 years. Examples are Celliant® [33], Emana®, Resistex Bioceramic® [34], Welltex®, and Nilit® Innergy, which are in the form of fibers; Trinomax In® in the form of a hybrid yarn [35]; Gold Reflect Line® in the form of a ceramic filled PUR membrane [30]; and Schoeller, which is in the form of fabric treatments [36]. The production of textiles with the effect of back reflection of the FIR produced by the human body using mainly ceramic active particles embedded in textile fibers or surface mounted on the textile surface is already realized by a number of companies such as Schoeller (technology Energear [29]), Hologenix LLC [37], and LIBOLON [37].

Some home furnishing textiles use selected systems comprising bound metal cations, ceramic particles, porous carbon particles (e.g., from bamboo stems), and natural materials (tourmaline and shell shells), which have a positive effect on FIR reflection [38,39]. Materials enabling the FIR reflection can be used to create heating textiles with highly conductive metallic surface coatings to use the heat generated by the human body [1] as metals silver and copper are promising. In previous studies [26,27], a bilayer nanophotonic structure textile composed of an IR-reflective metallic layer and an IR-transparent polyethylene (PE) layer with embedded nanopores in both layers to simultaneously have minimal IR emissivity and good breathability was proposed. In this nanoporous metalized PE design, the embedded nanopores in the metallic layer were smaller than the IR wavelength but larger than the water molecules [3].

7. Conclusions

With the improvement of people’s living standards, the demands for light, warm, comfortable, and healthy clothing are becoming stronger and stronger. The research and development of FIR fibers conform to people’s needs [41]. These fabrics can also significantly affect localized heating or cooling of the human body under given indoor conditions. Lowering indoor heating is one important source of suppressing global energy consumption. The preparation of FIR functional fabrics needs to properly select surface modification or particulate systems as fillers for obtaining reflection of FIR generated by the human body. The benefit is to use materials with low fiber diameters,

good shape stability, and comfort-related properties. One promising candidate is composite nonwoven fabric Milife with a surface covered by a particulate-based copper layer.

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