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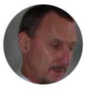
2 authors:

Veronika Tunakova
Technical University of Liberec



Jiri Militky
Technical University of Liberec

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Electromagnetic Field Shielding Fabrics with Increased Comfort Properties

Veronika Safarova[1, a] and Jiri Militky[1,b]
[1]Faculty of Textile Engineering, Technical University of Liberec, Studentska 1402/2
461 17 Liberec 1, Czech Republic
[a]veronika.safarova@tul.cz, [b]jiri.militky@tul.cz

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Abstract The expansion of the electronic industry and the extensive use of electronic equipment in communications, computations, automations, biomedicine, space, and other purposes have led to problems such as electromagnetic interference of electronic devices and health issues. For reasons given above, a demand for protection of human being, sensitive electronic and electrotechnic appliances against undesirable influence electromagnetic signals and troublesome charges raised. This paper presents the present state of a fabrication and characterization of multifunctional metal hybrid fabrics with increased resistivity to electromagnetic smog at conserving basic properties of textile structures designated for clothing purposes. The parameters influencing electromagnetic (EM) shielding properties of the hybrid fabrics were investigated. It was shown that the EM shielding effectiveness of the fabrics could be tailored by modifying the metal content, metal grid size and geometry. Furthermore, correlation between electrical properties and EM shielding effectiveness and comfort properties was studied.

Introduction

According to World Health Organization [1], exposure to electromagnetic fields is not a new phenomenon. However, during the 20th century, environmental exposure to man-made electromagnetic fields has been steadily increasing as growing electricity demand, ever-advancing technologies and changes in social behavior.

Everyone is exposed to a complex mix of weak electric and magnetic fields, both at home and at work. Sources of such emissions could include generation and transmission of electricity, domestic appliances and industrial equipment, telecommunications and broadcasting. If the electromagnetic waves are not isolated effectively, they will cause interference with each other and result in technical errors. If somebody gets exposed under the electromagnetic, radiate environment, physical harms may occur on human body [2,3].

Metal is considered to be the best electromagnetic shielding material due its conductivity and permeability, but it is expensive, heavy, and may also have thermal expansion and metal oxidation, or corrosion problems associated with its use. In contrast, most synthetic fabrics are electrically insulating and transparent to electromagnetic radiation [4].

In recent years, conductive fabrics have obtained increased attention for electromagnetic shielding and anti-electrostatic purposes. This is mainly due to their desirable flexibility and lightweight [5]. One way how conductive fabrics can be created is by using minute electrically conductive fibers. They can be produced in filament or staple lengths and can be incorporate with traditional non-conductive fibers to create yarns that possess varying degrees of conductivity. Another way represents conductive coatings which can transform substrates into electrically conductive materials without significantly altering the existing substrate properties. They can be applied to the surface of fibers, yarns or fabrics. The most common are metal and conductive polymer coatings.

In this paper, a hybrid electromagnetic shielding fabrics with different structure (woven, knitted) are introduced. The parameters influencing electromagnetic shielding characteristics (content and placing of conductive component, geometry of textile structure) and dependence between electric conductivity and EM shielding efficiency were investigated. At the same time, comfort properties of designed fabric were evaluated.

Theory on Shielding of Electromagnetic Interference

An electromagnetic field is built up from various electric E and magnetic field H components. An electric field is created by a voltage difference and magnetic field is created by a moving charge, i.e. by a current. Every current is thus accompanied by both an electric and a magnetic field. Electromagnetic radiation consists of waves.

EMI shielding consists of two regions, the near field shielding region and far field shielding region. The amount of attenuation due to shield depends on the electromagnetic waves reflection from the shield surface, absorption of the waves into the shield and the multiple reflections of the waves at various surfaces or interfaces in the shield. The multiple reflections require the presence of large surface area (porous or foam) or interface area (composite material containing fillers with large surface area) in the shields. The loss connected with multiple reflections can be neglected when the distance between the reflecting surfaces or an interface is large compared to the skin depth δ [m] (the penetration depth) defined as:

$$\sigma = \frac{1}{\sqrt{\pi \varphi \mu K}} \tag{1}$$

where f [Hz] is the frequency, μ is the magnetic permeability equal to $\mu_0 . \mu_r$, μ_0 is the absolute permeability of free space (air = $4.\pi.10^{-7}$) and K [$S.m^{-1}$] is the electrical conductivity. An electric field at a high frequency penetrates only the near surface region of a conductor. The amplitude of the wave decreases exponentially as the wave penetrates the conductor. The depth at which the amplitude is decreased to 1/e of the value at the surface is called the "skin depth," and the phenomenon is known as the "skin effect" [6]. Efficiency of electromagnetic shields is commonly expressed by the total shielding effectiveness S_T [dB], which represents the ratio between power P_2 [W] received with the shield is present and power P_1 received without the shield is present:

$$S_T = -10 \log\left(\frac{P_2}{P_1}\right) \tag{2}$$

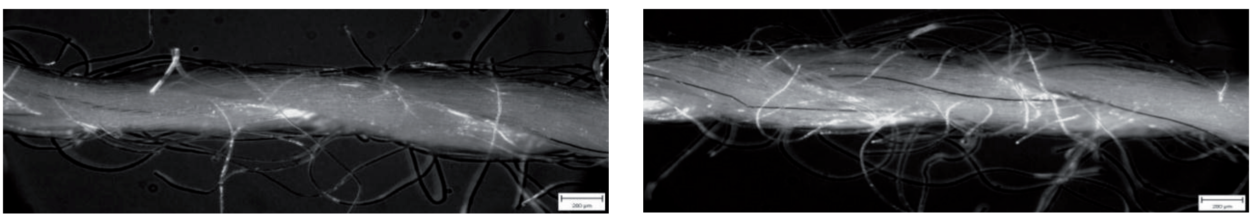
where log(x) is decimal logarithm.

The electromagnetic shielding efficiency of element is characterized by its electric conductivity, permittivity, and permeability, parameters of source and properties of ambient surrounding. Basic proposed numerical models of fabrics S_T are based either on electrical properties (especially volume conductivity) of element [6,7,8,10,11,12] or on analysis of leakage through of opening in textile [9]. Determining the level of attenuation of an EMI shield can be complex and the methods often vary according to the particular shield application. The more common techniques for testing shielding strength include Open Field Test, Coaxial Transmission Line Test [13,14], Shielded Box Test and Shielded Room Test [15].

Experimental Part

Hybrid yarns

Hybrid yarns were composed of polypropylene and different content of staple stainless steel metal fiber (1 - 75 %). The aspect ratio (length/diameter ratio, l/d) of the SS is 6250 used in this study, since the diameter of the SS is 8 μm and the fiber length of the SS is 50 mm. The yarn was designed at two levels of fineness: 25 and 51 tex. See Fig. 1 for microscopic image of hybrid yarn.



(a) (b)

Fig. 1 Microscopic images of chosen hybrid yarns containing: (a) 1% of stainless steel fibre, (b) 5% of stainless steel fibre.

Hybrid fabrics

Extensive set of fabrics with different structure (woven, knitted) were designed. First group of samples were twill weaves with weft and warp fineness 51 tex - warp sett 20 1/cm, weft sett 19 1/cm made of the hybrid yarn containing different portion of conductive phase. Second group of samples were twill weaves with identical structure containing so-called conductive grid made of hybrid yarn with constant portion of conductive phase and different grid openness. So-called nonconductive bottom is formed by 100% Co yarn. Third group of samples were twill weaves with identical structure containing so-called conductive grid made with constant grid openness made of hybrid yarns containing different portion of metal fiber. Fourth group of samples were flat stitch fabrics (yarn fineness 25 tex, conductive component content 1 – 20%). The characteristics of the resulting metal composite fabrics are listed in Table 1.

Table 1 Characteristics of metal composite fabrics.

Group of samples no.	Composition	Structure	Hybrid yarn placement	Mass per unit area [g.m^{-2}]	Thickness [mm]
1	99% PP/ 1% SS - 25% PP/75% SS	Twill 2/2	100%	220	0.77
2	95% PP/ 5% SS + 100% Co	Twill 2/2	5x5 mm*	220	0.66
	95% PP/ 5% SS + 100% Co	Twill 2/2	4x4 mm*	220	0.67
	95% PP/ 5% SS + 100% Co	Twill 2/2	3x3 mm*	220	0.65
3	99% PP/ 1% SS - 80% PP/20% SS	Twill 2/2	5x5 mm*	220	0.83
4	99% PP/ 1% SS - 80% PP/20% SS	Flat Stitch Fabrics	100%	182	0.64

Note: * warp and weft grid opening

Sample Characterization

<u>Volume resistivity</u> was measured according to the standard ČSN 34 1382, at the temperature T = 22,3°C and relative humidity RH = 40,7 %. Volume resistivity is measured by applying a voltage potential across opposite sides of the sample and measuring the resultant current through sample. Volume resistivity ρ_V [Ω.cm] was calculated from relation:

$$\rho_V = R_V \frac{S}{h} \tag{3}$$

where R_V [Ω] is volume resistance reading, h is thickness of fabric [cm], S is surface area of electrodes [cm^2].

<u>Electromagnetic shielding</u> was characterized by the attenuation of electromagnetic field power density by using of simple device (see Fig. 2).

Basic parts of device are two waveguides. One waveguide is connected with receiving wire (antenna). Textile sample is placed on the entrance of second waveguide. The end of this waveguide is filled by foam saturated by carbon absorbing the electromagnetic field passed through sample. Sample is oriented perpendicularly the electromagnetic waves. Transmitting antenna is placed in front of first waveguide input. As source of electromagnetic field the ZigBee module working at frequency 2.4 GHz and 1.8 GHz is used. The total shielding effectiveness SE [dB], is calculated from (2) where P_1 [W.m^{-2}] is input power density and power P_2 is power density after passing through sample.

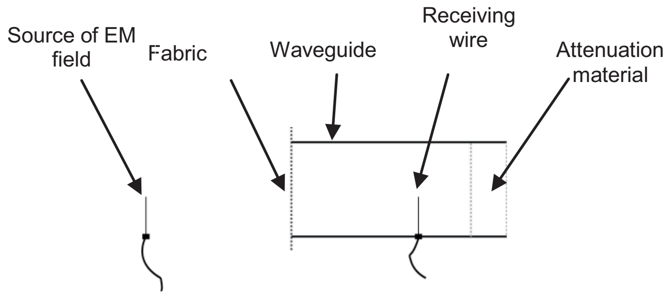


Fig. 2 Scheme of device of measurement of electromagnetic shielding efficiency.

Chosen comfort properties were represented by bending rigidity, crease durability, drapability, abrasion resistance, thermal characteristics, air permeability and water vapor permeability. Characteristics mentioned above were studied by the help of conventional measuring techniques..

Results and discussion

Electromagnetic shielding efficiency of samples

The dependence of total shielding effectiveness *SE* on the percentage of conductive component *P* or opening size of conductive grid for single groups of samples is shown in Fig. 3.

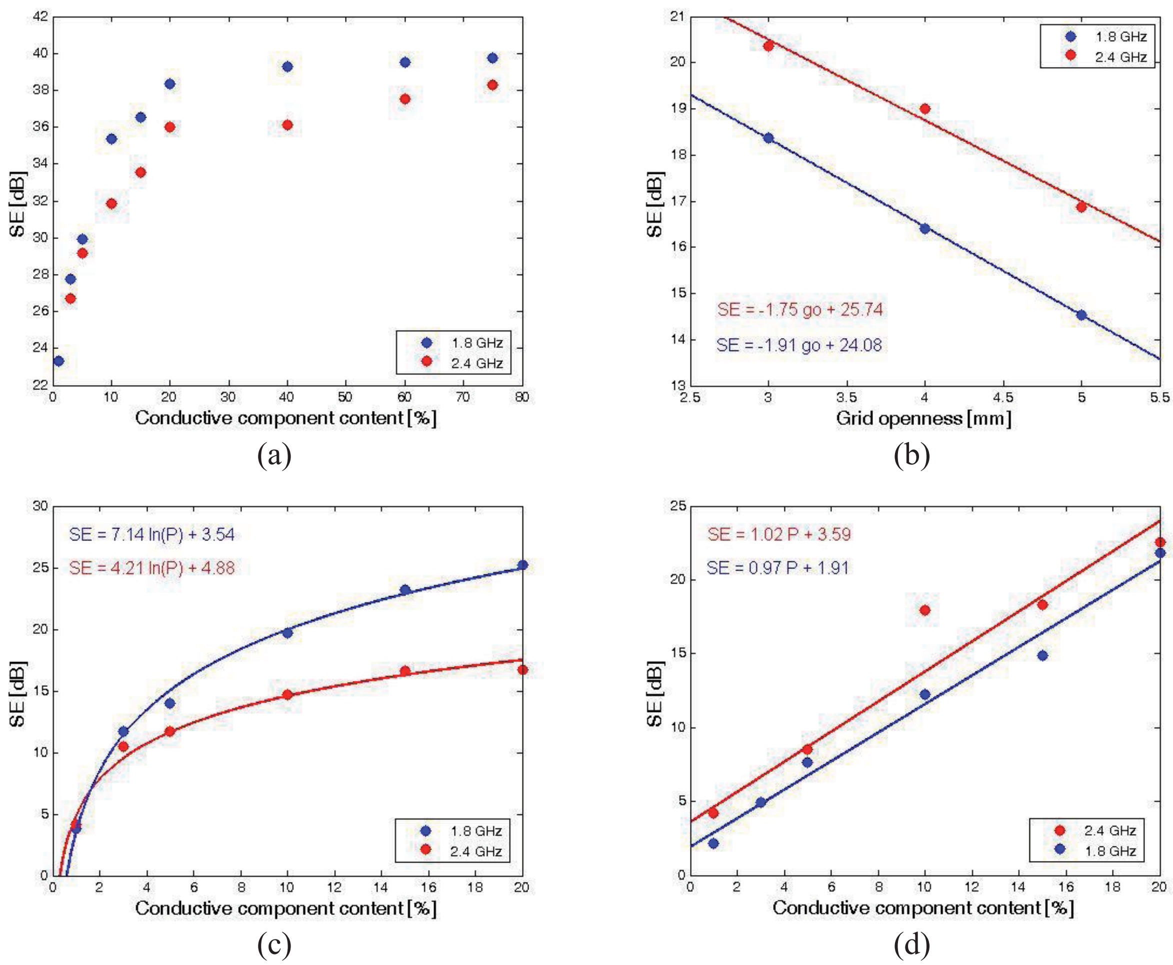


Fig. 3: The dependence of total shielding effectiveness *SE* on the percentage of conductive component *P* or opening size of conductive grid for: (a) group no. 1, (b) group no. 2, (c) group no. 3, (d) group no. 4.

Effect of Metal Content

The dependence of total shielding effectiveness (*SE*) on the metal content is shown in Fig. 3(a),(c). It is clear that SE increased logarithmically with metal content. Samples with 40% content of metal fiber (Fig. 3 (a)) already reach very satisfactory results (*SE* about 35 – 40 dB), which exceeded specified requirements on electromagnetic shielding textiles for general usage [16]. We can observe percolation threshold in area about 3-5% conductive component. The results showed that the SE is greater for lower frequency. This phenomenon could be probably caused by higher attenuation of incident EM field energy by reflection on conductive interface containing e.g. metal at lower frequencies.

Effect of Grid Openness

The dependence of total shielding effectiveness *SE* on opening size of conductive grid in weft and warp is shown in Fig. 3(b). Fabrics with smaller metal grids showed higher SE. The dependence is possible to approximate by linear function.

Effect of Structure

In Fig. 3(d) there is the dependence of total shielding effectiveness (*SE*) on the metal content for flat stitch fabrics. When compare woven and knitted samples, it clear that knitted samples reach at the same content of metal fiber content dramatically lower values of EM shielding. This phenomenon is caused by more open structure of knitted fabric, usage of finer hybrid yarn and lower mass per unit area.

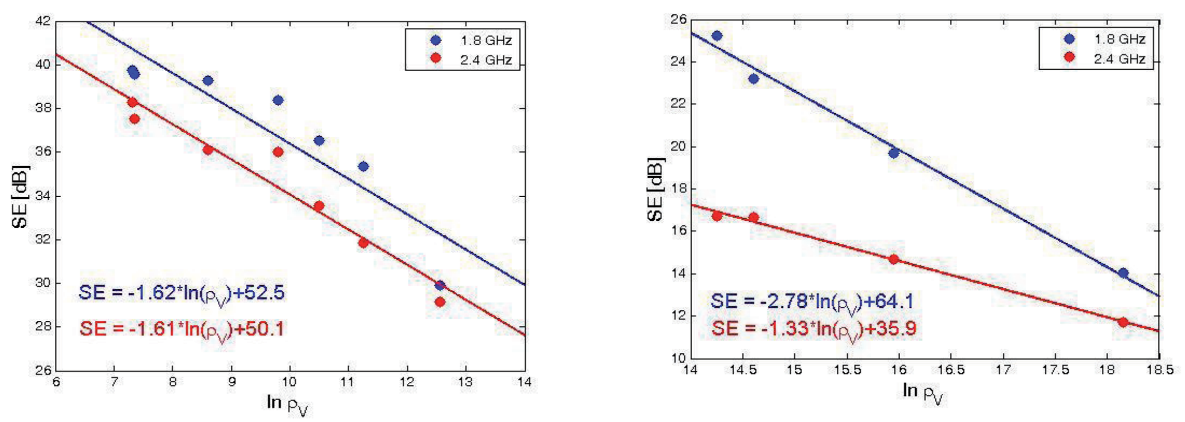
Correlation between electric conductivity and shielding effectiveness

The electromagnetic interference shielding efficiency needs to use special devices. Simpler are measurements of surface or volume resistivity. It is known from theory that at sufficiently high frequencies it is possible to measure characteristics of electrical part of electromagnetic field only and therefore it should be mathematical relation between total shielding effectiveness *SE* [dB] and fabric resistivity or conductivity.

Based on extensive experiments it was found out that there is a statistical dependence between *SE* and electrical resistivity of samples. We can observe two areas: area below percolation threshold and area above percolation threshold (for sufficiently high content of conductive component). The most suitable (for samples formed by 100% hybrid yarn) is prediction based on volume resistivity by this model:

$$SE = K_1 . ln(\rho_V) + K_2 \tag{4}$$

where K_1 and K_2 are constants dependent on frequency, sample structure (woven, knitted) and material composition, see Fig. 4. The prediction ability of this linear model is restricted to the higher content of conductive component above conductivity percolation threshold.

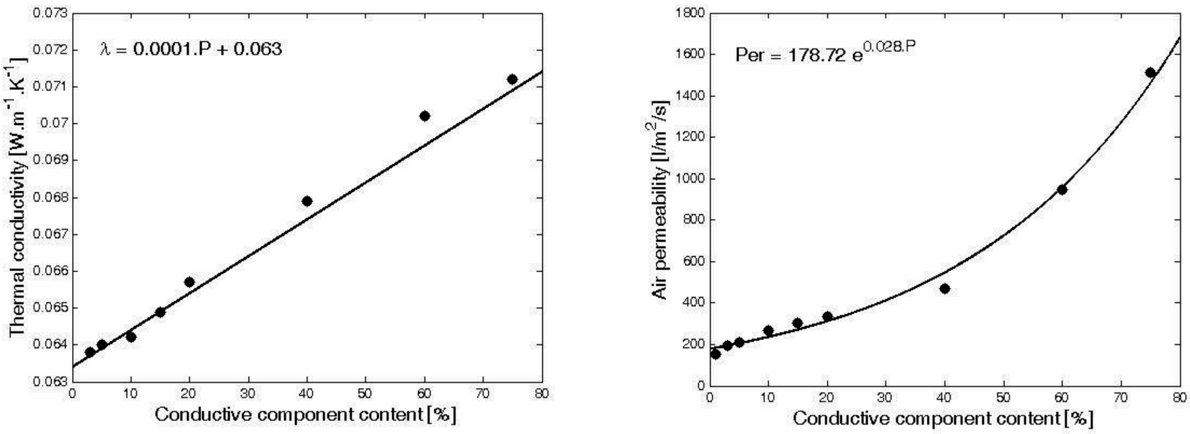


(a) (b)

Fig. 4 The dependence of *SE* on natural logarithm of volume resistivity for: (a) group no. 1, (b) group no. 3.

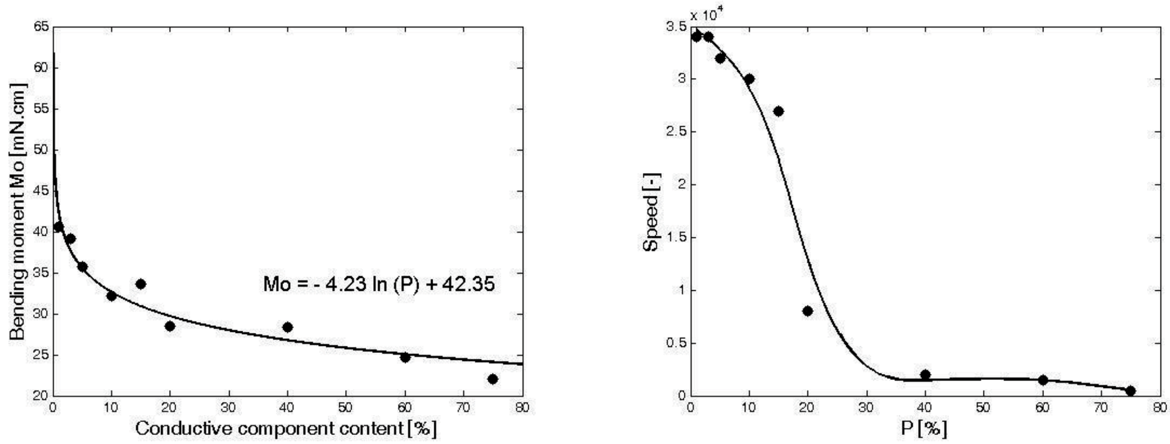
Comfort properties

Aim of this experimental investigation was to find out how increased content of metal fiber affects chosen comfort and usable characteristics of samples. It was found that thermal conductivity of samples (group no. 1) increases with increased content of conductive component; see Fig. 5(a). Identical behavior is possible to observe for parameter thermal absorptivity. Air permeability and water vapor permeability increases with increased metal fiber content for both woven (group no. 1) and knitted (group no. 4) samples, see Fig. 5(b). This phenomenon causes the fact that metal fibers are finer than polypropylene fibers and therefore yarn with higher content of metal fiber embodies lower diameter. Hence higher pores are formed in fabric which allows easier passing of both air (air permeability) and water vapor (water vapor permeability). It was confirmed that a group of knitted samples has higher air permeability and water vapor permeability compared to woven samples.
Bending rigidity (see Fig. 6(a)) and crease durability were decreased by increasing conductive phase in sample. Therefore, drapability was enhanced. Abrasion resistance became worse with increasing content of metal fiber in sample; see Fig. 6(b).



a. b.

Fig. 5 The dependence of (a) thermal conductivity, (b) air permeability on conductive component content for samples of group no. 1.



a. b.

Fig. 6 The dependence of (a) bending moment – measured along the weft, b) speed to first binding point failure for samples of group no. 1.

Summary

Low cost conductive fabrics with sufficient electromagnetic shielding efficiency conserving the main properties, e.g. comfort properties, drapability and process ability characteristics were created.
Fabrics with diverse structure, different portion and different placement of hybrid yarn containing extremely fine metal fibers were studied. Hybrid yarns forming weaves and knitted fabrics were composed of polypropylene and staple stainless steel fiber. Samples were characterized by its volume resistivity (standardized method) and its electromagnetic shielding efficiency was measured by means of simple waveguide type device on frequency 2.4 GHz and 1.8 GHz.
So called percolation threshold, dependence of total shielding effectiveness *SE* on the amount of conductive component P in hybrid yarn or opening size of conductive grid and dependence of total shielding effectiveness *SE* on volume resistivity was examined.
It is clear, that the portion of conductive component has a significant effect on increasing conductivity (decreasing resistivity) and improvement of electromagnetic shielding efficiency. Fabrics with smaller metal grids showed higher *SE*. Woven fabric exceeded better electro-smog resistivity due to its compact structure and finer yarn used.
Dependence between volume resistivity and *SE* for samples made of 100% hybrid yarn with content of metal fiber above percolation threshold is possible to express by linear function.
It was experimentally verified that designed fabrics with increased resistivity to electromagnetic smog fulfill requirements for wearing thermo physiological comfort. Negative effect of addition of metal fiber causes decrease of abrasion resistance of fabric.

Acknowledgement

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