THE INFLUENCE OF LOW-TEMPERATURE PLASMA ON PERMANENCE OF ANTIMICROBIAL NANO-FINISH

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ABSTRACT

This paper describes the effect of low-temperature plasma on increasing permanence of surface finish of textile materials using an antimicrobial nanosol. Selected textile materials (polyester and polyamide woven fabrics, polypropylene non-woven fabric) were pre-treated by surface activation with low-temperature plasma at atmospheric pressure and subsequently finished using an antimicrobial (AMB) nanosol with a concentration of 60 ppm Ag^+, 120 ppm Ag^+ in the application solution. The goal was to increase the permanence of AMB nano-coating of textiles after washing and drying. To verify the effect of low-temperature plasma on increasing the permanence of the nanolayer, washing and drying was performed in accordance with the STN EN ISO 6330 standard. To determine antibacterial activity and effectiveness of the nano-coated textile materials, a quantitative test method was used in accordance with the technical standard AATCC TM 100. Evaluation of the antibacterial activity of the textile materials was performed before washing and after 20 washing cycles.

KEYWORDS

Antibacterial effectiveness; Antimicrobial nanosol; Antibacterial textiles; Low-temperature plasma.

INTRODUCTION

Plasma treatments are gaining popularity in the textile industry due to many advantages over traditional wet finishing technologies. However, plasma can be used also in combination with wet finishing technologies, enabling to achieve new or modified properties, or to increase or extend desired properties of the application [1].

Low-temperature plasma treatment belongs to the environmentally friendly technologies used to modify the surface properties of polymer materials. Interactions between the plasma and the polymer surface lead to surface phenomena such as etching, cross-linking and activation [2]. Atmospheric plasma pre-treatment can add a large number of functional groups to the polymer surface depending on the processing gas in the plasma reactor. Plasma techniques offer far-reaching possibilities, but the technical effort is relatively high, as the processes often have to be carried out at reduced pressure [3]. Diffuse coplanar surface barrier discharge (DCSBD) plasma-based processes in atmospheric air provide sufficient modification of textiles. After plasma treatment, free radicals which settled on the surface of the material, immediately react with atmospheric oxygen to form hydroperoxides [4]. Plasma treatment causes not only chemical but also physical changes. The physical effect of plasma treatment is disruption of the fiber surface, which becomes larger and contains more places for physical connection. Plasma treatment is reported to be an effective technique for surface treatment of textiles to improve their wettability and adhesion [5]. Plasma technology changes the cost structure of textile processing by reducing energy consumption, environmental waste and the amount of chemicals used. The application of atmospheric discharge plasma offers higher production speed, better products as well as better surface finishes on the textiles [6].

Polyester fabrics belong to the most commonly produced fabrics in the textile industry. Polyester polymers have few polar oxygen groups. Low-pressure plasma treatments were designed to modify their surface properties (hydrophobicity and wettability) by introducing polar groups or by increasing surface roughness [7, 8].

Polypropylene textile materials are an interesting field of research as well. Surfaces of these materials are practically free of polar groups and therefore hydrophobic ones. There are many methods for surface treatment of polypropylene textiles, including the low-temperature plasma processing. This

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Table 1. Basic structural parameters of the input textile materials.

Designation of the textile materials	Woven fabrics		Non-woven fabric
	PES	PA	PP
Material composition	100% polyester	100% polyamide	100% polypropylene
Colour	white	white	white
Weave	canvas	twill 2/2	-
Mass per unit area [g/m^2]	106	99.7	40
Thickness [mm]	0.95	0.89	0.38

modification method is becoming more and more popular because it does not require a large amount of conventional chemicals, what is beneficial not only for the economy but also for the environment [9]. Currently, the results of finishing polypropylene non-woven fabric produced by spunbond technology with hydrogen fluoride using plasma are known as well. It was found that a fabric modified this way shows 99,04 % bacterial reduction, representing an effective barrier against penetration of the micro-organisms [10].

In recent years, an increased interest in antibacterial finish of fibers and textiles for practical application has been observed. Most textile materials used, e.g. in hospitals, can cause transmission of diseases caused by bacteria. Textile materials made from natural fibers provide an excellent environment for the growth of micro-organisms due to their large surface area and ability to retain moisture [11]. Today, the textile users demand textiles showing a number of performance characteristics, regardless of whether they are intended for the production of clothing, home textiles or materials for outdoor use. The decision to use them is often based on functional aspects of the fabric. Antimicrobial finish can offer added value to many different types of textiles [12]. Bacteria and fungi can degrade textiles in several ways, their decomposition causes odors especially in underwear and sportswear, they multiply especially in medical environment and are responsible for deterioration of a product due to its decomposition. The growth of microbes affects negatively also some other properties of textiles, such as change in color and/or permanent degradation of, for example, awnings, tents, etc. [13].

The aim of the paper is to verify the effect of low-temperature plasma on the permanence of antimicrobial nano-finish applied to the surface of selected textiles, pre-treated with low-temperature plasma under atmospheric pressure and subsequently finished with antimicrobial nanosol AMB-9. Antibacterial activity of these textiles was evaluated against selected strains of bacteria before and after washing [14].

EXPERIMENTAL PART

The experimental part describes pre-treatment of selected textile materials - polyester woven fabric (PES), woven fabric made from polyamide 6 (PA) and polypropylene non-woven fabric (PP) using the progressive technology of applying low-temperature plasma under atmospheric pressure and subsequent application of AMB nanosol. Consequently, their antibacterial activity and permanence of the AMB finish after washing were evaluated.

Specification of the input textile materials

Basic structural parameters of the input textile materials used in the experimental part are listed in the Table 1.

Activation of the textile material surface with low-temperature plasma

As part of the research, conditions for activating the surface of textiles with low-temperature plasma under atmospheric pressure were verified. Surface of the textile material was activated by low-temperature plasma with DCSBD (Diffuse Coplanar Barrier Discharge) on a quarter-operation finishing line ZUP 400 (Figure 1) under specific conditions as follows:

- power of plasma electrodes: 350 W,
- time of plasma surface activation: 150 s,
- line shift speed: 0,98 m.min^{-1}.

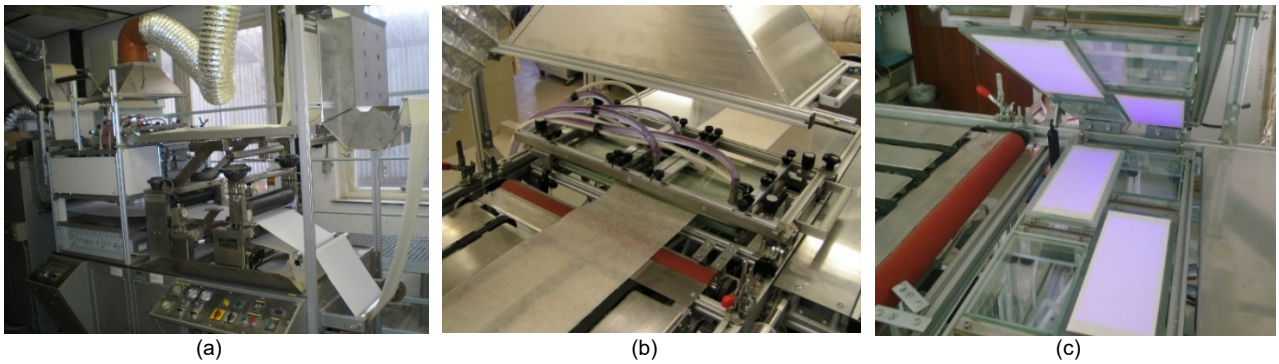
ZUP 400 device is designed for double-sided continuous treatment of textile materials; it enables the interconnection of activation of textile surfaces with low-temperature plasma under atmospheric pressure and subsequent chemical finishing of the textile materials. The device has 4 electron systems located on both sides in a working width of 400 mm with the possibility of setting the working speed from 0.67 m/min to 14.7 m/min and the power of the electrode systems 4x 400 W.

Pre-treatment of the textiles with low-temperature plasma under the specified conditions was problem free, passage of the textile materials through the plasma electrodes was smooth, no phenomena appeared during plasma treatment that would negatively affect the technological process of pre-treatment of the textiles.

Application of AMB nanosol to the textiles

The AMB nanosol was applied to textile materials pre-treated with low-temperature plasma, as well as to textile materials without pre-treatment with low-temperature plasma, in order to create an antimicrobial coating (Table 2).

Application solutions of AMB nanosol with a concentration of 60 ppm Ag^+, 120 ppm Ag^+ in the solution were used for treatment. The excess solution was removed from the finished fabrics by wringing on Fulard VFM Werner - Mathis AG device. The nanocoated textiles were dried and heat-set under the same conditions in Werner-Mathis AG dryer at a temperature of 100 °C for 2 min.



(a) (b) (c)

Figure 1. ZUP 400 quarter-operation processing equipment (a), surface activation of a fabric (b), plasma sources in working mode (c).

Table 2. Identification of textiles from PES, PA and PP to verify antibacterial effectiveness, permanence of the nano-coating.

Description of textile samples	woven fabric		non-woven fabric
fabric finished with an **AMB** nanosol application solution with a concentration of **60 ppm Ag^+**	PES/AMB_{60}	PA/AMB_{60}	PP/AMB_{60}
fabric finished with an **AMB** nanosol application solution with a concentration of **120 ppm Ag^+**	PES/AMB_{120}	PA/AMB_{120}	PP/AMB_{120}
fabric finished with plasma, application solution of **AMB** nanosol with a concentration of **60 ppm Ag^+**	PES/150s/AMB_{60}	PA/150s/AMB_{60}	PP/150s/AMB_{60}
fabric finished with plasma, application solution of **AMB** nanosol with a concentration of **120 ppm Ag^+**	PES/150s/AMB_{120}	PA/150s/AMB_{120}	PP/150s/AMB_{120}

In order to verify changes in surface macrostructure of the AMB finished textile material and prove the presence of the AMB nano-finish, SEM (Scanning Electron Microscopy) analysis of the surface of the PP non-woven fabric was performed with a magnification of 1000 times and 15 000 times respectively (Figure 2, 3). A compact layer of the AMB nano-coating is visible on the surface of PP fibers in the Figure 3.

The modified textile samples (Table 2) were subjected to washing and drying according to the STN EN ISO 6330: 2022 standard by the 4N washing procedure with water temperature of (40±3) °C using a commercial detergent, drying was carried out by the C procedure, i.e. drying in a horizontal position on a flat surface (laid out flat).

Evaluation of antibacterial activity of the AMB nano-coated textiles

Evaluation of antibacterial finishes applied to the textile materials is determined by degree of antibacterial activity required when using such materials. If bactericidal activity is required or assumed, quantitative assesment is necessary. Quantitative assesment will also create a clearer picture of possible applications of the modified textile materials. To determine the requirements for antimicrobial nano-coated textile materials, test method was used in accordance with the technical standard AATCC 100-2019 "Assessment of antibacterial finishes on textile materials" [14].

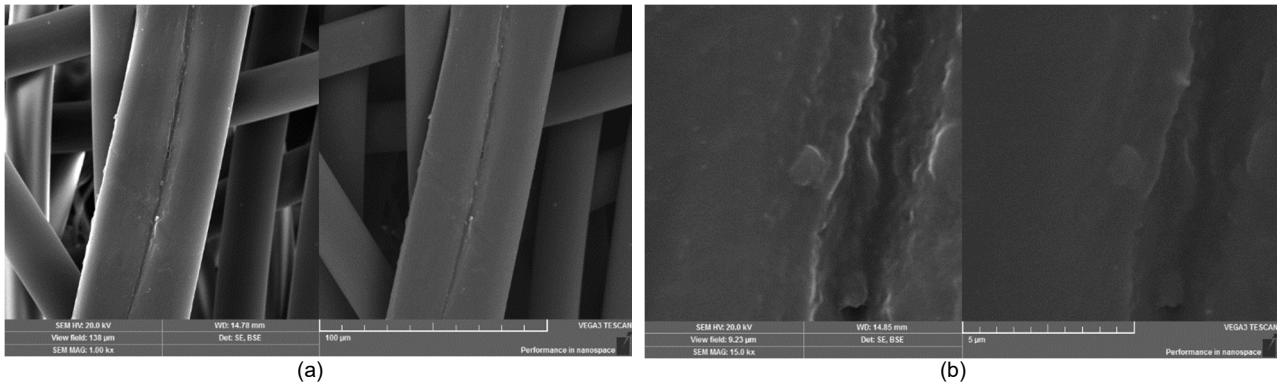
AATCC TM 100 – 2019 test method evaluation conditions:

- test micro-organism:
  a) gram positive bacterium Staphylococcus aureus CCM 4516,
  b) gram negative bacterium Klebsiella pneumoniae CCM 8853,
- bacterial concentration achieved: 1.0 x 10^5 – 3.0 x 10^5 CFU/ml;
- size and quantity of samples used: circle – shaped samples with a diameter of (4.8 ± 0.1) cm and with a weight of (1.0 ± 0,1) g are cut out of a test fabric;
- amount of inoculum per sample: (1.0 ± 0.1) ml;
- test conditions: 24 h, (37 ± 2) °C, nutrient used: Nutrient Agar pH 6.8.

This test method is a quantitative procedure for comparison and evaluation of the degree of antibacterial effectiveness after 24-hour exposure to the test bacteria on a textile sample. After incubation, the bacteria are eluted from the textile samples and total bacterial number is determined. The method involves actual bacterial counts, with results reported as a percentage or logarithmic reduction in contamination levels. Bacterial reduction of the test sample is calculated in percentages according to the following equation:

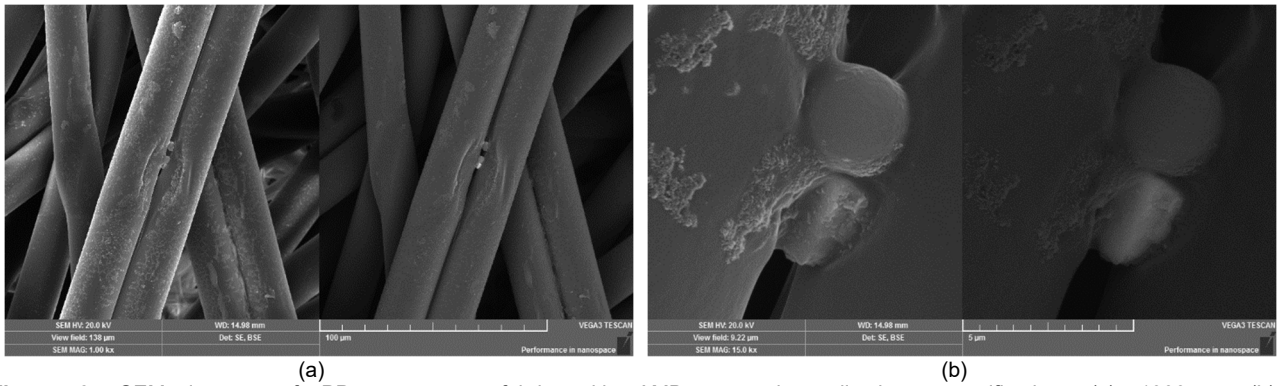
$$100\ (C - A) / C = R, \qquad (1)$$

where: R is the bacterial reduction in percentages; C is the number of bacteria recovered from the inoculated finished test samples in the vessel, immediately after vaccination (in “0” contact time); A is the number of bacteria recovered from the inoculated finished test samples in the vessel, incubated for 24 h contact time.



(a) (b)

Figure 2. SEM images of the PP non-woven fabric without application of AMB nanosol, maginication: (a) 1000 x, (b) magnification 15 000 x.



(a) (b)

Figure 3. SEM images of PP non-woven fabric with AMB nanosol application, magnification: (a) 1000 x, (b) magnification 15 000 x.

Table 3. Results of the antibacterial effectiveness of PES fabrics before and after washing against the bacterium Staphylococcus aureus CCM 4516.

Bacterial reduction *R* [%]					
Number of washing cycles	**0**	**5**	**10**	**15**	**20**
PES/AMB_{60}	98.84	24.90	9.09	0.00	0.00
PES/150s/AMB_{60}	99.67	99.45	93.17	89.52	83.33
PES/AMB_{120}	99.73	54.74	25.00	10.35	0.00
PES/150s/AMB_{120}	99.95	99.71	98.27	97.82	91.80

Table 4. Results of the antibacterial effectiveness of PA fabrics before and after washing against the bacterium Staphylococcus aureus CCM 4516.

Bacterial reduction *R* [%]					
Number of washing cycles	**0**	**5**	**10**	**15**	**20**
PA/AMB_{60}	99.64	98.69	98.37	98.27	98.09
PA/150s/AMB_{60}	99.83	99.65	99.31	98.64	98.89
PA/AMB_{120}	99.80	99.73	99.74	98.49	98.40
PA/150s/AMB_{120}	99.90	99.69	99.43	99.30	99.17

RESULTS AND DISCUSSION

Antibacterial effectiveness of the finished textiles was evaluated before and after washing and drying (in Tables 3-8).

Antibacterial effectiveness of the nano-coated textiles

On samples of textile materials made of 100% PES, 100% PA and 100% PP with AMB nano-coating (with/without plasma pre-treatment), the antibacterial effectiveness was evaluated before and after washing in accordance with the AATCC Test Method 100-2019 using the test micro-organisms Staphylococcus aureus CCM 4516 (Tables 3-5, Figures 4-6) and Klebsiella pneumoniae CCM 8853 (Tables 6-8, Figures 7-9), under the above-mentioned test conditions.

From the results presented in the Tables 3-4, it can be concluded that by application of AMB nanosol in a concentration of 60 ppm Ag^+ as well as in a concentration of 120 ppm Ag^+, a high antibacterial effectiveness (R > 99%) was achieved on the

Table 5. Results of the antibacterial effectiveness of PP fabrics before and after washing against the bacterium Staphylococcus aureus CCM 451.

Bacterial reduction *R* [%]					
Number of washing cycles	**0**	**5**	**10**	**15**	**20**
PP/AMB$_{60}$	57,52	41.84	3.54	not evaluated	not evaluated
PP/150s/AMB$_{60}$	99.92	98.83	57.97	not evaluated	not evaluated
PP/AMB$_{120}$	70.59	60.00	16.67	not evaluated	not evaluated
PP/150s/AMB$_{120}$	99.92	99.78	58.46	not evaluated	not evaluated

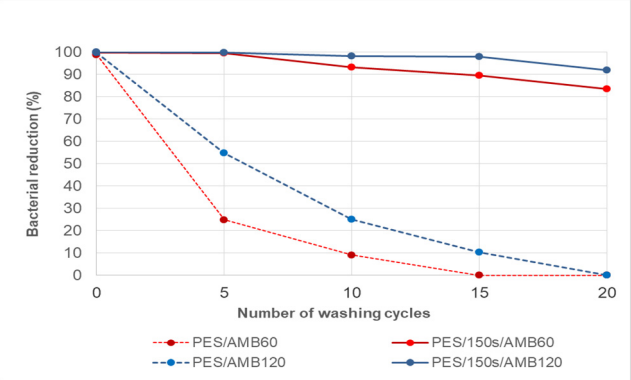


Figure 4. Influence of washing and drying on bacterial reduction of Staphyloccocus aureus CCM 4516 on the AMB finished PES woven fabric.

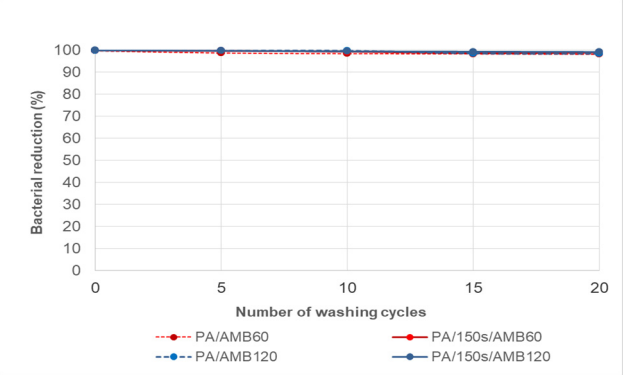


Figure 5. Influence of washing and drying on bacterial reduction of Staphyloccocus aureus CCM 4516 on the AMB finished PA woven fabric.

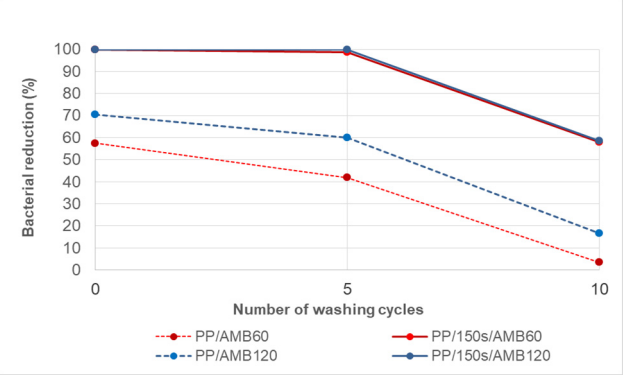


Figure 6. Influence of washing abd drying on bacterial reduction of Staphyloccocus aureus CCM 4516 on the AMB finished PP non-woven fabric.

samples of woven fabrics made from PES and PA before washing at the "bactericidal" level against the test micro-organism Staphylococcus aureus CCM 4516.

The same antibacterial effectiveness was achieved on the samples of woven fabrics with AMB nanosol application without plasma pre-treatment (PES/AMB$_{60}$, PES/AMB$_{120}$, PA/AMB$_{60}$, PA/AMB$_{120}$) as on the samples with AMB nanosol application with plasma pre-treatment and surface activation time of 150s (PES/150s/AMB$_{60}$, PES/150s/AMB$_{120}$, PA/150s/AMB$_{60}$, PA/150s/AMB$_{120}$). It can be seen from the results that time of surface activation with low-temperature plasma has no effect on final antibacterial effectiveness of these materials before washing (Tables 3, 4).

The same high bactericidal effect was achieved on the PP non-woven fabrics with applied solution of AMB nanosol and with surface activation by low-temperature plasma (PP/150s/AMB$_{60}$, PP/150s/AMB$_{120}$), before washing, at the level of bacterial reduction of Staphylococccus aureus CCM 4516 R > 99 % (Table 5). Antibacterial finish of the test samples without plasma activation PP/AMB$_{60}$ and PP/AMB$_{120}$ for the micro-organism Staphylococccus aureus CCM 4516, showed bacterial reduction at the level of approximately 60-70%.

In order to verify the effect of plasma on increasing the affinity of the nano-layer to the surface of the textile material, and/or permanence of the antibacterial finish, samples of nano-coated textile materials were subjected to 5-20 washing and drying cycles in accordance with STN EN ISO 6330: 2022 by the 4N washing procedure with water temperature of (40±3) °C using a commercial detergent. Drying was carried out by C procedure, i.e. drying in a horizontal position in a spread state on a flat surface (laid out flat) and then the antibacterial effectiveness was evaluated on them. From a practical point of view, it is important to what extent the applied surface finish of the textiles is stable (permanent), and therefore tests of the finished fabrics by washing and drying were carried out in the frame of the experiments as well. Samples of the material were subjected to 5-20 washing and drying cycles and subsequently their antibacterial effectiveness was re-evaluated to verify the effect of plasma on increasing the affinity of the nano-layer to the surface of the textile material, and/or permanence of the nano-coating on the textile materials. Results of the tests

are shown in the Tables 3-5. The non-woven fabric made of 100 % PP was losing its shape after the 10th washing cycle, therefore washing of the PP fabric was not continued.

From the results shown in the Table 4 it can be concluded that the application of AMB nanosol on PA fabric without/with surface activation by low-temperature showed a high antibacterial effect (approx. 99%) even after 20 washing cycles. Neither effect of low-temperature plasma, nor concentration of AMB nanosol on the antibacterial effectiveness was observed on the PA woven fabric, as bacterial reduction on the PA woven fabric with/without pre-treatment with low-temperature plasma was the same.

A positive effect of low-temperature plasma on the permanence of AMB nano-coating was found both on PES woven fabric and PP non-woven fabric already after the 5th washing and drying cycle. The bacterial reduction of these fabrics, regardless of the concentration of AMB nanosol, was at the level of 99% on the low-temperature plasma pretreated materials (PES/150s/AMB_{60}, PES/150s/AMB_{120}, PP/150s/AMB_{60}, PP/150s/AMB_{120}). Bacterial reduction on samples of the fabrics without low-temperature plasma pre-treatment (PES/AMB_{120}, PP/AMB_{120}), finished using AMB nanosol with a concentration of 120 ppm Ag^+ in the application solution, compared to textiles pre-treated with low-temperature plasma (PES/150s/AMB_{120}, PP/150s/AMB_{120}) decreased by approx. 40 - 45 %. A more pronounced decrease was recorded for textiles without low-temperature plasma pre-treatment (PES/AMB_{60}, PP/AMB_{60}) finished using AMB nanosol with a concentration of 60 ppm Ag^+ in the application solution, which was at the level of approximately cca 60–75 %.

After the 10th washing and drying cycle, the sample of PES woven fabric PES/AMB_{60}, compared to the PES/AMB_{60} sample before washing, showed a significant decrease in bacterial reduction to the level of about 90%. A somewhat lower decrease was recorded with the sample PES/AMB_{120}, where bacterial reduction after washing decreased by 75% (Table 3). The same course of decrease in antibacterial effectiveness after washing was also recorded for samples of PP fabrics, where bacterial reduction after washing decreased by approx. 95% (PP/AMB_{60}) and approx. 75% (PP/AMB_{120}). From the results regarding the mentioned PES and PP samples finished with AMB nanosol after plasma pre-treatment of the surface (PES/150s/AMB_{60}, PES/150s/AMB_{120}, PP/150s/AMB_{60}, PP/150s/AMB_{120}), it can be seen that in this case time of surface activation of the material by plasma has a positive effect on the resulting antibacterial effectiveness.

A positive effect of low-temperature plasma was demonstrated on PES textile samples even after 15-20 washing and drying cycles. While the bacterial reduction in the PES fabric PES/AMB_{60} and/or PES/AMB_{120} without plasma treatment already after the 15th washing and drying cycle dropped to 0% and/or approx. 10%, bacterial reduction on the PES fabric PES/150s/AMB_{60} and/or PES/150s/AMB_{120} pre-treated with low-temperature plasma was at the level of approx. 90-98%. While after the 20th washing cycle the PES textile samples at both concentrations of AMB nanosol without plasma pre-treatment (PES/AMB_{60}, PES/AMB_{120}) lost their antibacterial effectiveness (bacterial reduction of these textiles dropped to the level of 0%), bacterial reduction of the PES textile samples with both concentrations of AMB nanosol, with plasma pre-treatment (PES/150s/AMB_{60}, PES/150s/AMB_{120}) decreased by only about 10 - 20%.

In general, it can be concluded that the highest antibacterial effectiveness after 20 washing cycles was achieved on the sample of PA woven fabric (PA/150s/AMB_{120}) finished with an application solution of the antimicrobial nanosol containing 120 ppm Ag^+, whose bacterial reduction for the test micro-organism Staphylococccus aureus CCM 4516 was approx. 99,17% (Table 4).

The performance characteristic - antibacterial effectiveness - was evaluated on the prepared nano-coated samples of PP and/or PA woven fabric and PP non-woven fabric using the test micro-organism Klebsiella pneumoniae CCM 8853. Results of the evaluation are shown in Tables 6-8, Figures 7-9.

The antibacterial effectiveness of PP, PES and PA fabrics against the bacterium Klebsiella pneumoniae was comparable to that of the bacterium Staphylococcus aureus.

PA fabrics pre-treated with low-temperature plasma (PA/150s/AMB_{60}, PA/150s/AMB_{120}) showed the highest resistance against the bacterium Klebsiella pneumoniae. Their bacterial reduction, regardless of the concentration of AMB nanosol, was even after 20 washing cycles at the level of R > 95 % (Table 7). Despite a small decrease in the reduction of PA fabrics without low-temperature plasma pre-treatment (PP/AMB_{60}, PP/AMB_{120}) to the level of approx. 80-90%, we do not consider this decrease to be significant. Even with the bacterium Klebsiella pneumoniae, it was confirmed that plasma pre-treatment is not unavoidable for PA fabrics to ensure permanence of the surface AMB finish. By evaluating the antibacterial effectiveness the effectiveness of the nano-coating was again demonstrated, without demonstrating the effect of plasma on the affinity of the nano-coating.

The antibacterial effect of both application solutions of the prepared AMB nanosol without low-temperature plasma pre-treatment as well as with low-temperature plasma pre-treatment was equally high on the PES woven fabric.

Table 6. Results of the antibacterial effectiveness of PES textiles before and after washing against the bacterium Klebsiella pneumoniae CCM 8853.

Bacterial reduction *R* [%]					
Number of washing cycles	**0**	**5**	**10**	**15**	**20**
PES/AMB_{60}	99.74	22.90	8.85	0.00	0.00
PES/150s/AMB_{60}	99.89	88.33	42.92	18.02	0.00
PES/AMB_{120}	99.96	56.93	16.53	0.00	0.00
PES/150s/AMB_{120}	99.96	92.86	61.88	39.02	7.86

Table 7. Results of the antibacterial effectiveness of PA textiles before and after washing against the bacterium Klebsiella pneumoniae CCM 8853.

Bacterial reduction *R* [%]					
Number of washing cycles	**0**	**5**	**10**	**15**	**20**
PA/AMB_{60}	99.31	96.68	90.13	88.39	83.95
PA/150s/AMB_{60}	99.88	99.35	98.27	97.84	95.38
PA/AMB_{120}	99.70	99.26	97.84	96.12	93.03
PA/150s/AMB_{120}	99.93	99.81	99.30	98.71	97.96

Table 8. Results of the antibacterial effectiveness of PP textiles before and after washing against the bacterium Klebsiella pneumoniae CCM 8853.

Bacterial reduction *R* [%]					
Number of washing cycles	**0**	**5**	**10**	**15**	**20**
PP/AMB_{60}	45.31	26.32	0.00	not evaluated	not evaluated
PP/150s/AMB_{60}	99.96	96.31	20.00	not evaluated	not evaluated
PP/AMB_{120}	63.82	34.97	6.19	not evaluated	not evaluated
PP/150s/AMB_{120}	99.95	99.61	37.00	not evaluated	not evaluated

Bacterial reduction on the PES woven fabric before washing was >99% (Table 6). The effect of low-temperature plasma was demonstrated on the PES woven fabric (PES/150s/AMB_{120}) after 5 washing cycles, when the antibacterial effectiveness was at the level of bacterial reduction of approx. 93% and after 10 washing cycles with the bacterial reduction at the level of 62%. AMB nano-coated PES fabric with plasma pre-treatment (PES/150s/AMB_{120}) after 20 washing cycles shows very low antibacterial effectiveness against the test micro-organism Klebsiella pneumoniae CCM 8853, namely at the level of bacterial reduction <8%. Antibacterial activity of the nano-coated textile materials after 20 washing and drying cycles was not demonstrated on the sample pre-treated with plasma (PES/150s/AMB_{60}), on two samples without plasma pre-treatment (PES/AMB_{60}, PES/AMB_{120}).

Results of antibacterial effectiveness of the non-woven fabric from PP with surface activation by low-temperature plasma before washing are comparable to the results measured on the samples of woven fabrics from PES and PA for the two above mentioned test micro-organisms (> 99%, Tables 3-8).

By applying AMB nanosol to PP non-woven fabric activated by low-temperature plasma (PP/150s/AMB_{60}), (PP/150s/AMB_{120}), AMB effectiveness compared to the non-woven fabric without low-temperature plasma activation (PP/AMB_{60}, PP/AMB_{120}) achieved bacterial reduction of Klebsiella pneumoniae CCM 8853 more than 99,9 % (Table 8). The positive effect of low-temperature plasma was demonstrated on PP non-woven fabric (PP/150s/AMB_{120}) after 5 washing cycles, when the antibacterial effectiveness was at the level of bacterial reduction more than 99% and after 10 washing cycles the bacterial reduction was at the level of 37%. The AMB effectiveness of PP textiles for the Klebsiella pneumoniae strain is nevertheless lower than it was for the Staphylococcus aureus strain. In the PP/AMB_{60} sample, after the 10th washing cycle, the antibacterial effectiveness of the nano-coated non-woven fabric without surface activation by low-temperature plasma was lost. The sample PP/AMB_{120} achieved bacterial reduction of 6.19%, which was compared to the sample PP/AMB_{120} before washing a decrease of about 90%.

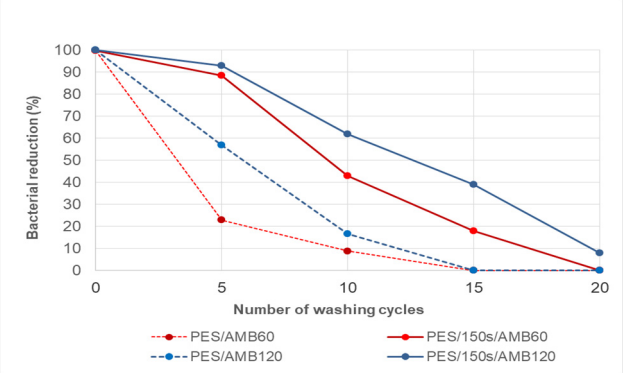


Figure 7. Effect of washing and drying on the reduction of bacteria Klebsiella pneumoniae CCM 8853 of AMB modified PES fabric.

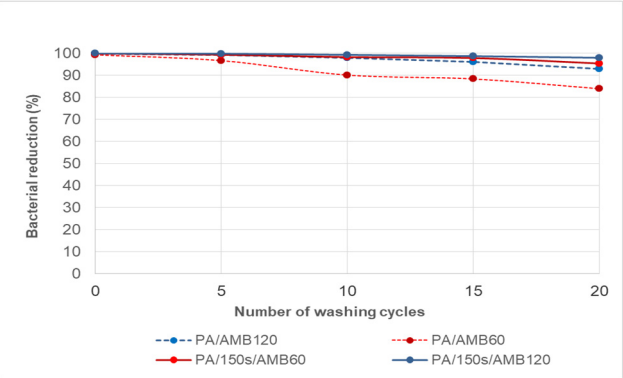


Figure 8. Effect of washing and drying on the reduction of bacteria Klebsiella pneumoniae CCM 8853 of AMB modified PA fabric.

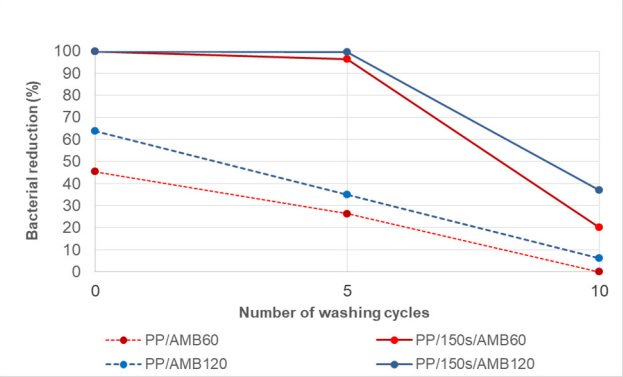


Figure 9. Effect of washing and drying on the reduction of bacteria Klebsiella pneumoniae CCM 8853 of AMB modified PP fabric.

CONCLUSION

Subject of the research was study and investigation of the relationships between the effects induced by low-temperature plasma on the initiated surface of textile materials made of synthetic fibers and the applied type of surface finish of the fabric using AMB nanosol, in order to create the prerequisites for increasing the permanence of the nano-coating of textiles using the antimicrobial nanosol after washing. In the frame of the research aimed at development of antimicrobial nano-coated textiles, the permanence of the AMB nano-coating on PES, PA fabric after 20 washing cycles and on PP non-woven fabric after a maximum of 10 washing cycles has been verified. Conclusions from the achieved results are as follows:

- the highest bactericidal effectiveness with a high degree of reduction according to the AATCC TM 100 – 2019 method after 20 washing cycles was achieved with the textile sample from 100% PA woven fabric for both test micro-organisms Staphylococcus aureus and Klebsiella pneumoniae,
- the highest antibacterial effectiveness of the antimicrobial nano-coating was achieved on the sample of PA fabric finished with the application solution containing 120 ppm Ag^+, where bacterial reduction of the test micro-organism Staphylococcus aureus as well as Klebsiella pneumoniae was even after 20 washing and drying cycles at the level of approx. 99%,
- results of the antibacterial effectiveness of the PA woven fabric do not confirm positive effect of low-temperature plasma on increasing affinity of the AMB nano-coating to the surface of the fabric from 100% PA. Bacterial reduction (Staphylococcus aureus, Klebsiella pneumoniae) of both pre-treated samples without/with plasma surface activation and with subsequent application of AMB nanosol (60 ppm Ag^+ and 120 ppm Ag^+) is also at the level of bactericidal effectiveness even after 20 washing cycles.
- with an increasing number of washing cycles, there is a decrease in the antibacterial effectiveness of the PES woven fabric finished with AMB nanosol without plasma surface activation. A higher antibacterial effectiveness after washing and drying was achieved on the sample of PES fabric with plasma surface activation finished with an application solution of AMB nanosol containing 120 ppm Ag^+, whose bacterial reduction of the test micro-organism Staphylococcus aureus was even after 20 washing and drying cycles at the level of approx. 92%. A positive effect of surface activation of the PES fabric with low-temperature plasma was demonstrated by increasing the affinity of the AMB nanocoating to the surface of the fabric compared to the fabric finished with AMB nanosol under the same conditions without surface activation with low-temperature plasma.
- AMB nano-coated PES fabrics with plasma surface activation achieve antibacterial properties with bacterial reduction of 83-92% for the test micro-organism Staphylococcus aureus, compared to the antimicrobially finished PES woven fabric without plasma surface activation, where bacterial reduction is at the level of 0%. A positive influence of the low-temperature plasma on the increased affinity of the AMB nano-layer to the surface of the textile material made from 100% PES can be noted from the above results,
- for the test micro-organism Klebsiella pneumoniae, a bacterial reduction of only about 8% was demonstrated on the antimicrobially nano-coated PES woven fabric with nanosol concentration of 120 ppm Ag^+. No antibacterial properties were detected on PES woven fabric with AMB nanosol application without plasma surface activation. Bacterial reduction was not demonstrated even in the case of the sample with surface activation by low-temperature plasma with a concentration of AMB nanosol of 60 ppm Ag^+, no positive effect of plasma was demonstrated in this case.
- Based on the above results, it is possible to state a positive effect of low-temperature plasma on

increasing the affinity of AMB nano-coating to the surface of textile material made from 100% PES compared to a fabric without surface activation by low-temperature plasma,

- nano-coated PP non-woven fabric with surface activation by low-temperature plasma shows antibacterial effectiveness at the bactericidal level against the test micro-organism Staphylococcus aureus and antibacterial effectiveness at the bacteriostatic level against the test micro-organism Klebsiella pneumoniae compared to the PP non-woven fabric without surface activation by low-temperature plasma. The PES and PA woven fabrics clearly retain higher antibacterial efficiency even after the 10th washing and drying cycle.

Research in the field of antibacterial effectiveness continues and, in the future, will be focused on PP woven fabrics modified by AMB nanosol with/without low-temperature plasma pre-treatment to exclude the influence of fabric construction on the antibacterial effectiveness.

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