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DEFINING FEATURES OF DECORATING SANITARY-HYGIENIC PRODUCTS BY THE METHOD OF FLEXOGRAPHIC AND DIGITAL PRINTING

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The intensive use of tissue products encourages manufacturers to search for new technologies for their decoration and researchers to study the factors influencing the quality of finished products.

Flexographic printing is used to decorate sanitary and hygienic products, which is effective for large print runs. Digital printing is recommended for producing tissue products with small print runs. Therefore, the object of this study was flexographic and digital ink-jet imprints. As a result of the research, it was found that in the range from 50 to 100 % of the printed control scale, the optical density of all CMYK colors on a flexographic imprint is twice as high as in digital printing. The optical density of digital imprints increases in proportion to the color saturation.

The optimal amount of luminophore that provides the luminescence effect of printed images on flexographic imprints has been determined. In the process of printing, tissue paper is exposed to temperature conditions. Thermogravimetric studies of printing inks with luminophore additives and corresponding imprints were conducted. Initial thermo-oxidative processes in the ink composition begin to develop at temperatures above 187 °C. A slight loss of mass (1.1 %) of the composition is observed in the range of 187–236 °C, which is accompanied by a deviation of the DTA channel into the region of exothermic effects due to the thermal oxidation of the luminophore.

The influence of tissue products' structure and printing area on punching resistance has been shown. Using the Kendall concordance coefficient, the degree of consistency of experts' opinions regarding the priority of factors influencing the quality of tissue products was determined

Keywords: sanitary and hygienic products, flexographic and digital printing, luminescent impurities, quality of imprints

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1. Introduction

In recent years, tissue products have become increasingly popular all over the world. Currently, it is difficult to imagine a person who would not use paper napkins, towels, tablecloths, etc. in everyday life. Statistics speak eloquently about this: in the USA, the consumption of paper napkins and toilet paper is 40 %. On average, in the world, consumption of paper napkins and toilet paper accounts for 52 %, towels – 12 %, napkins and handkerchiefs – 31 % [1]. Analysts forecast growth in demand for tissue products until 2035: in Western Europe – up to 18–20 kg per person (1.5 % per year), Eastern Europe by 3.3 %, China – up to 4.5 %, South America – about 24–25 kg per person one person (up to 3 % per year), other Asian countries – 3.3 % per year [2].

The quality of tissue products depends on the choice of technology and production techniques at all stages, as well as storage conditions. Tissue paper is made from cellulose pulp and usually has a crepe structure. This special type of paper is absorbent, lint-free, and meets special rupture resistance requirements. Such paper can be divided into two main categories: toilet paper and table decorations.

The modern consumer puts forward higher requirements for the decoration of tissue products. Therefore, one can often see such decorations as embossing, printing, cutting, perforation, etc. on napkins. The usual way is to apply an image on paper products by flexographic, screen or digital (inkjet) printing, to provide not only decorative but also advertising functions, in particular, the placement of company logos and emblems. The most widespread in the world is the flexographic technique of printing on tissue products. The speed of flexographic printing on tissue products is more than 600 m/min, which can lead to increased formation of paper dust, which must be dealt with. Such machines use a knife system of the NOVA XLS type, a special water-based paint feeding system, such as the EPQ 200.

Printed images can be various: personalized, thematic, ornamental, etc., which can cover the entire area of the product or only its part. To print images on tissue products, special water-based paints are used that meet certification requirements [3]. The authors emphasize such characteristics of tissue products as the number of layers, surface type, presence of perforations, embossing, flavoring, etc. Such properties of tissue paper are important for obtaining high-quality printed images, but they were left out of the study in this work.

Our review of modern technologies for printing and decoration of tissue products demonstrates that flexographic and digital printing are the most popular so far. Therefore, research on the improvement of methods for decorating tissue products is relevant in order to meet the modern demands of the most demanding consumers and improve production efficiency.

2. Literature review and problem statement

Our review of the literature reveals that much of the attention of researchers is focused on finding ways to improve the technological processes of decorating sanitary-hygienic products with polygraphic technologies. For example, paper [4] investigates the physicochemical characteristics of tissue paper for cigarettes, which negatively affect the possibility of printing. The attention of the authors is focused on determining such parameters of paper as air permeability and surface roughness. It has been studied that tissue paper has high porosity and air permeability, which leads to too strong ink penetration and low print quality. The authors recommend applying a thin layer of coating on paper based on kaolin pigment, which, in their opinion, can improve the structure of the paper and the quality of offset printing. However, the influence on the quality of prints of flexographic and digital printing, which is mainly used today to decorate tissue products, has not been investigated.

Determination of the absorbent properties of tissue paper is described in [5]. It has been confirmed that water absorption is a key property of such thin materials as tissue paper. The kinetics of liquid spreading in cigarette paper were studied. It was found that water absorption is influenced by the presence of embossing in the structure. The results show that the "micro" embossing process promoted volumetric and porous structures, increasing the water absorption capacity and capillary rise properties Klem. However, the authors do not investigate the quality of image formation with ink in the process of digital printing on tissue products.

Work [6] emphasizes the fact that ensuring product quality is always the main task of the production process. It is important to reduce the level of product defects. To solve this problem, the authors suggest using the 8D method. The 8D troubleshooting steps include using root cause analysis to identify, verify, and determine the root cause of intaglio printing defects on tissue paper. The authors performed a failure mode and effects analysis (FMEA), constructed an Ishikawa diagram, and control charts to streamline the problems. Suggested improvements to reduce defects relate to the following causes – insufficient experience and inattention of operators of rotary gravure printing machines and cutting machines. It is emphasized that the recommendations reduced the percentage of defects to the level corresponding to the company's standard (less than 2 %). However, the authors associate the problems of low product quality only with the features of gravure printing machines and the experience of operators, which makes these studies incomplete. After all, prints on tissue paper are obtained with other technologies that are used by other machines, a different mechanism for fixing the paint on the print. Therefore, it is appropriate to study the impact of flexographic and digital printing techniques on the quality of prints.

In work [7], the authors determine some optical properties – the brightness and whiteness of sanitary-hygienic products, in particular napkins, paper towels of five different companies. Weight, moisture content, crepe, volume, density, tensile strength, thickness, water retention value, and water absorption time were investigated and compared. All the above studies refer to tissue paper and do not take into account the impact of printing methods on ensuring the promotion of products in the consumer market. Paper [8] emphasizes the importance of the tissue drying process, which is very energy-consuming and determines the operational quality of the product. The technical characteristics of the Intelli Tissue energy-saving machine, which allows limiting CO_2 emissions, are described. However, the authors do not cite research on the influence of temperature regimes on the quality of tissue products.

Paper [9] examines the technology of manufacturing 5-layer tissue paper and making ready-made cigarette products from it. The authors aim to evaluate the influence of the paper conversion conditions on the surface structure and the final softness of the products. Embossing processes during paper production and their influence on softness are analyzed. A proposed scale for evaluating the tactility of paper based on the feeling of touch. The authors found that the softer and more pleasant touch paper had an HF of 75.3 units, while the other was rougher and less pleasant, with a total HF value of 68.0 units. With the help of an optical system, the finished products were analyzed and the reasons for the resulting differences in the softness of paper layers were revealed. However, decorative elements created by printing technologies are also important on tissue products. Therefore, the research of factors affecting the quality of printed images by the method of flexographic and digital printing and their influence on the consumer properties of sanitary and hygienic products is relevant.

Study [10] presents a numerical model for evaluating the quality of toilet paper, developed based on the results of laboratory studies of physical quantities characterizing the properties of this paper. Based on the research of nine types of paper, 28 features of those products were identified. The quality of paper was evaluated taking into account the maximum values of the specified feature, which was assigned number 1. According to this model, the quality of the paper can theoretically be characterized by numbers from 0 to 1. The quality of the tested paper ranged from 0.64 to 0.94 [11]. However, it is interesting and relevant to study the factors affecting the consumer properties of tissue products, taking into account the quality of images printed on them by flexographic and digital printing.

Our review of the above studies demonstrates that the quality of tissue paper products is affected by many technological factors that require in-depth research. In particular, the influence of the surface and internal structure of the substrate, its hydrophilic properties, as well as the method and area of printing, on the consumer properties of tissue products remains incompletely studied.

3. The aim and objectives of the study

The purpose of our study is to determine the factors influencing the quality of flexographic and digital printing imprints. This will make it possible to choose the optimal method for decorating sanitary and hygienic products.

To achieve the goal, the following tasks were set:

– to determine and compare densitometric and colorimetric indicators of imprints formed by various methods of printing on tissue products;

– to conduct a thermogravimetric analysis of imprints on tissue paper, formed by ink with luminescent impurities in order to assess the feasibility of their use in flexographic printing;

– to investigate the surface structure of imprints after punching;

– with the help of the coefficient of multiple rank correlation, to reveal the consistency of the opinions of experts on the factors influencing the consumer indicators of sanitary-hygienic products.

4. The study materials and methods

4. 1. Test materials and equipment used in the experiment

Imprints on Huchtemeier Papier Gmbh tissue paper, which is made of 100 % cellulose, were selected for research.

The characteristics of the paper are given in Table 1.

Eco-friendly water-soluble inks from Aquaflex Plus (viscosity 15–20 seconds) were used for flexographic printing. Hewlett Packard HP pigment inks were used to obtain imprints by digital printing.

For research, imprints on two-layer napkins were obtained by flexographic printing under production conditions on an OMET TV 503 Lecco (Italy) machine [12].

Digital printing imprints on three-layer napkins were made on a Ticab machine (Poland). The technical characteristics of the printing machines are given in Table 2 [13].

Table 1

Paper characteristics

	Test method	
Tensile strength MD P	900–1000–800	SCAN P 44:81
Tensile strength CO P	450–500	SCAN P 44:81
Weight	18.5±0.5	ISO 536
Thickness	2 ply	SCAN P 66
Color	White	–
Creeping, %	17	On machince
Humidity, %	5.5	On machince

Table 2

Technical characteristics of printing machines

Flexographic printing machine model OMET TV 503 Lecco	Digital printing machine, model Ticad
Working width: 500 mm (20″), 600 mm (23″)	Print from 1 unit to 50 units per minute
Number of tracks: 1	Low cost per copy – 0.01 euro per unit
Flexographic section: 1–4 printed sections	Versatility – printing on a variety of surfaces: paper bags, cardboard, assembled and envelopes, textiles, wood
Max. roll diameter: 1.800 mm (72″)	Does not require preparatory work: clichés, molds, stencils
Materials: 1 and multilayer fabric, paper, non-woven fabrics	Simple operation, in-house development – printer management program
Fold Type: N, M, C, Double Bend, WM, or Book	
Open format max: 18×18 cm (7′×7″)	
Open format min.: 50×50 cm (20″×20″)	
Mechanical speed: 850 m/min (2800 fpm)	
Max. continuous output: 2.800 pieces/min	

To study the process of decorating napkins with flexographic inks with luminophore additives, the Flexiproof 100 RK (PrintCoat Instruments Ltd) probe printing machine with FLX100.02 ceramic anilox roller was used.

4. 2. Methodology for the study of densitometric and colorimetric indicators of tissue imprints

A GRETAG SPM50 spectrophotometer was used to measure the optical density of the printed image. A GRETAG SPM50 spectrophotometer was used to measure the optical density of the printed image. The principle of operation of the device implies the reaction of the photoreceptor to the reflected beam and the creation of an electric charge proportional to its intensity. The optical density of the background and dies is calculated from the amount of the charge. In addition, it is possible to determine such indicators as decompression of raster elements, trapping, gray balance, uniformity, and contrast of printing.

Standardized viewing angles of 2° and 10° are used for colorimetric measurements of images observed from different distances.

a

b *c*

Fig. 1. General view of the test image for conducting experimental studies on an imprint: *a* – flexographic printing; *b*, *c* – digital printing

The study of the quality of reproduction of line thicknesses on imprints was carried out using an optical microscope "Intel Pla" (China) with a micrometric nozzle with a division price of 0.01 mm.

The height of the font strokes was determined using a control scale (Fig. 2).

To determine the resolution (Lc, Lm, Ly, Lb), reproduction of small details of the image, separately placed strokes, as well as accurately transfer images of strokes of different sizes: 5; 10; 20; 30; 40; 50; 60 microns.

The resolution (Lc, Lm, Ly, Lb) of small details of the image was determined on a scale with different stroke sizes: 5; 10; 20; 30; 40; 50; 60 µm (Fig. 3).

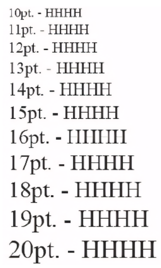


Fig. 2. Control scale of the image quality of the height of the fonts on the imprint

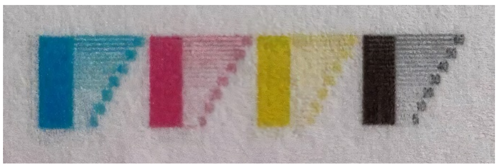


Fig. 3. A scale for determining the resolution of digital printing images

Control over the combination of colors on the imprint, when printing multi-color images, was carried out using the control elements of the driving crosses of thin lines intersecting perpendicularly.

An optical microscope "Intel Pla" and a desktop digital USB microscope 1600 Digital Microscope (China) were used to study the quality of imprints (Fig. 4) [14].

a *b*

Fig. 4. General view of microscopes:
a – "Intel Pla"; *b* – USB 1600 Digital Microscope

The determination of the resolution of the printed image, or the number of points contained in a unit of length, was carried out using the Siemens star, which consists of 72 pairs of black and white lines placed in a circle from one central point of contact.

4. 3. Research methodology for the thermogravimetric analysis of samples of tissue products before and after applying printed images

Thermogravimetric studies of samples of paper and ink composition with a luminophore admixture were performed on a Q-1500D derivatograph, the Paulik-Paulik-Erdei system, with registration of the analytical signal of mass loss and thermal effects using a computer. The samples were analyzed under a dynamic mode with a heating rate of 5 °C/min in air. The weight of the samples was 50 mg, the reference substance was aluminum oxide Al_2O_3.

4. 4. Methodology for researching the organoleptic indicators of tissue products

To determine the organoleptic indicators of tissue products, a series of observations were conducted in accordance with DSTU 8862:2019 "Paper products for sanitary, hygienic, and household purposes. Technical conditions" (ISO 12625-1:2019 Tissue paper and tissue products).

Conducting organoleptic indicators of sanitary-hygienic products took place in the laboratory at the Department of Polygraphic Media Technologies and Packaging. The organoleptic examination was carried out by the inspection method, in daylight, each sample separately. When conducting research, attention was paid to the appearance, color, and smell of products that were made from 100 % cellulose and secondary raw materials. First of all, the appearance, color, smell, and composition of the napkins were evaluated [15].

The methodology for conducting organoleptic tests involved the selection of six samples, 20.0±0.2×10.0±0.2 cm in size, with a total surface area of 400±12 cm^2 (the area is determined on both sides of the paper).

The test begins with a visual inspection of dry paper samples, assessing the condition of the surface and its color.

To determine the smell, water extracts from paper are used, three containers (50–100) cm^3 were prepared. Distilled water (control samples) is placed in two containers, and water extract from the test sample is placed in the third. During the test, tasters are exposed to the smell of a control sample in one container, and then – closed with two other samples by lightly inhaling air from them, pre-shaking (agitating) the contents of each container [16].

To determine paper clogging, the number of side inclusions on a sheet with an area of 1 m^2 is taken into account or the area of these inclusions is measured. According to DSTU standard EN ISO 15755:2005 Paper and cardboard. Determination of undesirable impurities.

Clogging of paper is characterized by the presence of contrasting side inclusions of various shades, unwanted impurities, dots in the paper, which are visible to the naked eye in the light that passes through it. Clogging negatively affects the appearance of paper, reduces its aesthetic properties, and complicates the printing process.

4. 5. Methodology for determining the degree of consistency of experts' opinions

The research methodology involved taking into account the opinions of 11 experts, ranking factors by importance and assigning them ranks from 1 to 9.

To determine the degree of consistency of experts' opinions, the Kendall concordance coefficient was used:

$$W = \frac{12S}{m^2\left(n^3 - n\right)}, \qquad (1)$$

where m is the number of experts in the group; n – number of factors; S is the sum of squares of rank differences (deviations from the average. The sum of the squares of the rank differences (S) can be found using any of the following formulas:

$$S = \sum_{i-1}^{n}\left(\sum_{j-1}^{m} R_{ij}\right)^2 - \frac{\left(\sum_{i-1}^{n}\sum_{j-1}^{m} R_{ij}\right)^2}{n}, \qquad (2)$$

$$S = \sum_{j-1}^{n}\left(\sum_{i-1}^{m} A_{ij} - \frac{1}{2}m\left(n+1\right)\right)^2. \qquad (3)$$

The concordance coefficient W varies in the range from 0 to 1 – $0 \leq W \leq 1$: when $W=0$ there is complete inconsistency, when $W=1$ – complete unity of expert opinions. If $W<0.2$–0.4, it means weak agreement of experts; if $W>0.6$–0.8, then agreement of experts is strong. $W=0.6$ indicates a moderate degree of consistency of experts' opinions).

Weak agreement is usually the result of the following reasons: there is no commonality of opinion in the considered group of experts; within the group there are coalitions with high consensus of opinion, however, the generalized opinions of the coalitions are opposite.

To determine the concordance coefficient, the opinions of 11 experts were taken into account regarding the priority of 9 important factors that affect the quality of printed images [17].

For the reliability of our results of experimental studies, 3–5 parallel measurements were carried out. Statistical processing of the research results was carried out using statistical methods implemented in the STATISTICA v.10 software package.

5. Results of studies on the quality of decoration of sanitary-hygienic products by the method of flexographic and digital printing

5. 1. Study of densitometric and colorimetric indicators of imprints

Based on the results of our research on flexographic print impressions, the dependence plots of the optical density indicators of printed full-color images on color saturation were constructed (Fig. 5). The more saturated the color, the more ink is contained on the surface of the print. This leads to an increase in the optical density of the printed image. Thus, saturated colors are more vivid on the printing print. In the range from 50 to 100 %, the optical density of the printed image almost doubles for all CMYK colors. In particular, for black ink, the optical density in the indicated range increases from 0.52 to 1.26 relative units, for ink Y – from 0.42 to 0.9 relative units, for ink C – from 0.48 to 1.08 relative units, for ink M – from 0.4 to 1.0 relative units.

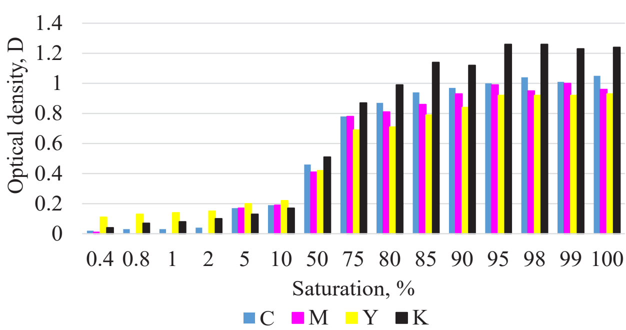


Fig. 5. Optical density diagrams of a full-color print of flexographic printing on tissue paper

Fig. 6 shows diagrams of the dependence of the optical density of digital print imprints on color saturation. As the analysis of the diagrams reveals, the resulting dependence of the optical density of the digital print impression increases in proportion to the color saturation. The more saturated the color of the paint (100 %), the greater the optical density of the imprint with unchanged substrate structure and printing modes.

Analysis of dependences reveals that the imprint of flexographic printing is richer compared to digital printing. The optical density on a flexographic print imprint is 21 % higher than on a digital print imprint. This is especially noticeable at 100 percent saturation for all CMYK colors. Thus, it has been confirmed that flexographic printing increases the brightness of the image on the imprint.

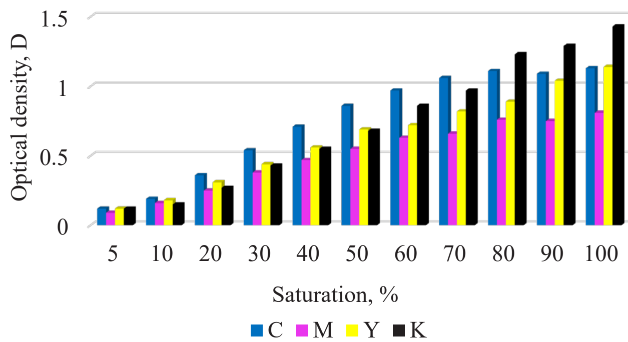
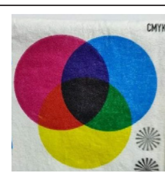


Fig. 6. Optical density diagrams of a full-color digital imprint

Analysis of densitometric studies confirmed that the optical density of the printing imprint changes depending on the type of printing and the saturation of the image. Table 3 gives values of the color difference ΔE of the printed images on the investigated imprints.

Table 3

The difference in CMYK colors formed by sequential application of inks on the imprint (at 100 % image saturation)

Flexographic printing	Digital printing
ΔE C=2.26	ΔE C=1.22
ΔE M=4.48	ΔE M=2.13
ΔE Y=2.62	ΔE Y=1.17
ΔE K=1.09	ΔE K=2.06
	

As studies show, the color difference on the digital print imprint increases from ink Y (1.17 %) to ink M (2.13 %). A somewhat different picture is characteristic of the flexographic print – the increase in color difference is observed from ink K (1.09 %) to ink M (4.48 %).

Table 4 gives the results of measuring the $L^*a^*b^*$ color coordinates on flexographic and digital Ink-Jet imprints. The quality of digital printing imprints was compared according to the ISO 12647 standard by analogy with offset printing.

Diagrams of color coverage of imprints on paper napkins are shown in Fig. 7.

The study of the color coverage of all tested samples showed that their color coordinates are within the normative range according to the ISO 12647 standard. From Fig. 7, it can be seen that the area of the circle of color coverage on the imprint of flexographic printing is much larger than the area of the color gamut of digital printing. The wider the color gamut, the greater the value of L^*a^* and b^*.

Table 4

*L*a*b** color coordinates on imprints

Materials for printing	Color coordinates	Color characteristics						
		skyblue	blue	purple	red	yellow	green	skyblue
Two-layer paper napkin (flexographic printing)	a	–24.97	13.44	68.3	59.9	–8.86	–52.45	–24.97
	b	–47.75	–34.66	–4.46	44.15	87.68	17.02	–47.75
Three-layer paper napkins (digital printing)	a	–29.87	–12.84	58.02	58.37	–5.86	–52.15	–29.87
	b	–42.44	–30.67	8.69	29.02	89.24	17.39	–42.44

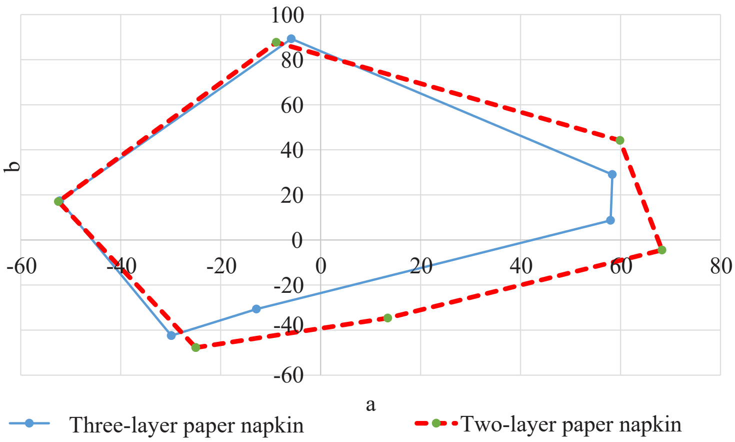
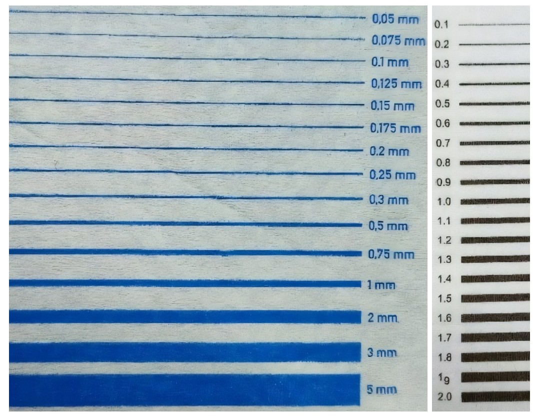


Fig. 7. *L*a*b** color gamut chart of flexographic and digital imprints



a *b*

Fig. 8. Control scale of the image quality of the stroke width in dark areas on the imprint: *a* — flexographic; *b* — digital imprint

Colorimetric tolerances for triad and special inks show that the permissible deviation for black is within the limits: $L<5$, for cyan $L<3$, for magenta and yellow – $L<6$. For all CMYK colors, the change in deviations is $\Delta E\ E_{2000}<2$.

The results of the line thickness values on the printed scale in the dark areas of the image on the flexographic and digital imprints are given in Table 5.

Fig. 8 shows the imprints of the control scale, according to which the width of the printed strokes was determined by the method of flexographic and digital printing.

Analysis of the reproduction of font elements on the investigated tissue products revealed that the line thicknesses reproduced by flexographic printing have smaller deviations from the norms than on digital printing imprints. This is obviously related to the different mechanism of fixing water-soluble inks for flexoprinting and inks for digital printing on paper.

Fig. 9 shows the images printed on the imprints, according to which the reproduction of the height and clarity of the strokes on the tissue products was studied.

The minimum font size (size in points) in both printing techniques is unreadable and does not have a clear reproduction, which is evidenced by the presence of "distorted" elements and letter breaks.

Table 5

Value of the thickness of lines on imprints (mm)

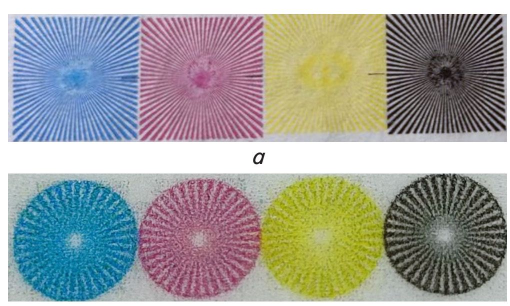
Flexographic printing									
0.1	0.2	0.25	0.3	0.5	0.75	1.0	2.0	3.0	5.0
White base									
0.14	0.22	0.37	0.47	0.54	0.84	1.02	2.07	3.34	5.35

Digital printing												
0.1	0.2	0.3	0.4	0.5	0.7	0.9	1.0	1.2	1.5	1.8	1.9	2.0
White base												
0.12	0.26	0.36	0.46	0.52	0.74	0.9	1.03	1.20	1.52	1.82	1.91	2.1

a *b*

Fig. 9. Reproduction of the height and clarity of the strokes on tissue products: *a* — digital; *b* — flexographic printing

Fig. 10 shows the imprint of the scale for determining the resolution of the image, obtained by flexographic (*a*) and digital (*b*) printing.



a

b

Fig. 10. Microscopic image of the scale for determining the resolution of the printed image on imprints: *a* — flexographic; *b* — digital printing

Therefore, our densitometric studies confirm that the color reproduction of images is influenced by the printing technique.

5. 2. Thermogravimetric analysis of samples of sanitary and hygienic products

The results of comprehensive thermal analysis of the samples are represented in the form of thermograms (Fig. 11–13) and in Table 6.

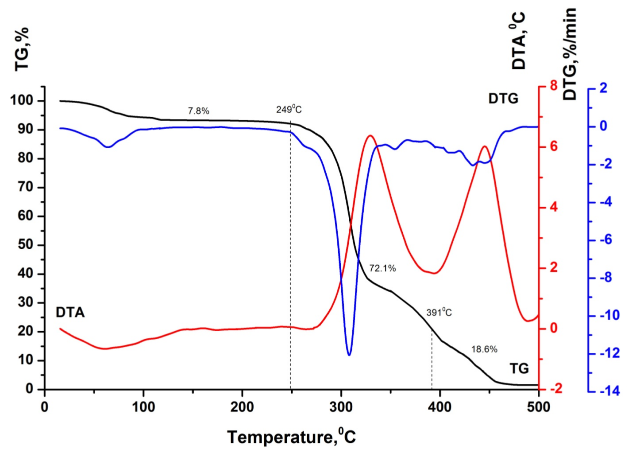


Fig. 11. Thermogram of a napkin sample

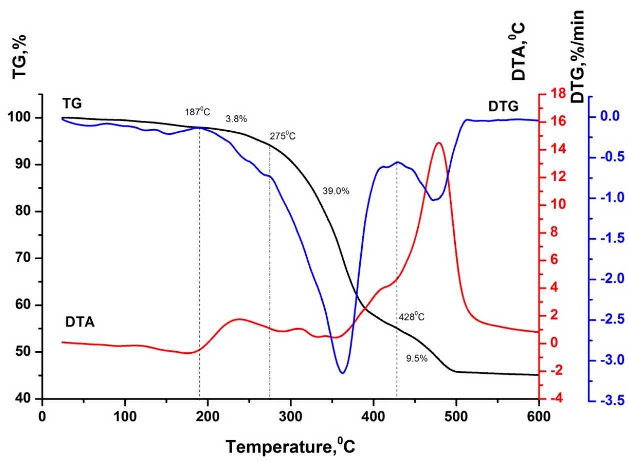


Fig. 12. Thermogram of luminophore

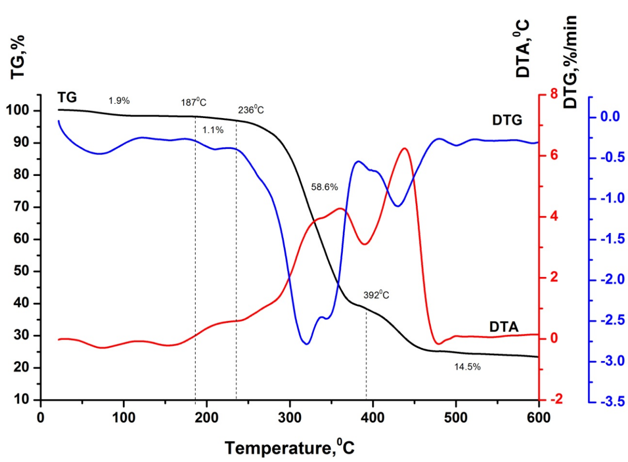


Fig. 13. Thermogram of a printing composition with an admixture of luminophore

Table 6

Results of thermal analysis of the napkin sample

Sample	Temperature interval, °C	Mass loss, %
Napkin	20–249	7.8
	249–391	72.1
	391–500	18.6
Luminophore	20–187	2.1
	187–275	3.9
	275–428	39.0
	428–600	9.5
Printing ink with an admixture of luminophore	20–187	1.9
	187–236	1.1
	236–392	58.6
	392–600	14.5

According to the data of the comprehensive thermal analysis, in the temperature range of 20–195 °C, volatile components of the napkin sample are released (7.8 %). This process is accompanied by the appearance of an endothermic effect on the DTA curve, with a maximum at a temperature of 60 °C.

Deep destructive processes in the napkin sample begin to occur at temperatures higher than 249 °C. The intense loss of the mass of the sample (72.1 %) in the temperature range of 249–391 °C corresponds to active destructive, thermo-oxidative processes and combustion of the remnants of the destruction of the sample. This process is accompanied by a high exothermic effect on the DTA curve, with a maximum at a temperature of 330 °C, and the appearance of a sharp extremum on the DTG curve. The temperature of 308 °C corresponds to the maximum speed (12 %/min) of sample mass loss.

In the temperature range of 391–500 °C, combustion of the pyrolytic residue of the sample occurs. This process corresponds to a significant exoeffect on the DTA curve, with a maximum at a temperature of 446 °C. Mass loss at this stage is 18.6 %.

A slight mass loss (2.1 %) of the luminophore sample in the temperature range of 20–187 °C corresponds to the release of volatile components present in the sample. This process is accompanied by the deviation of the DTA channel into the region of endothermic effects.

In the temperature range of 187–275 °C, destructive and thermooxidative processes begin to develop in the luminophore sample. This is evidenced by the gradual loss of sample mass (3.8 %) and the appearance of an exothermic effect on the DTA curve.

Deep destructive and thermo-oxidative processes in the luminophore impurity occur in the temperature range of 275–428 °C. They correspond to an intensive mass loss (39 %) of the sample and a deep extremum on the DTG curve, with a maximum at a temperature of 362 °C.

In the range of temperatures of 428–600 °C, combustion of the organic residue of the sample occurs. This is evidenced by the appearance of a rapid exothermic effect on the DTA curve, with a maximum at a temperature of 480 °C, and a loss of sample mass (9.8 %).

A slight loss of mass (1.9 %) of the ink sample with a luminophore admixture in the temperature range of 20–187 °C corresponds to the release of volatile components of the sample. This is evidenced by the deviation of the DTA channel into the region of endothermic effects.

The initial thermo-oxidative processes in the ink composition sample begin to develop at temperatures higher than 187 °C.

A slight loss of mass (1.1 %) of the composition sample in the temperature range of 187–236 °C, which is accompanied by the deviation of the DTA channel into the region of exothermic effects, is due to the thermal oxidation of the luminophore.

Deep destructive and thermo-oxidative processes in the ink composition sample begin to develop at temperatures higher than 236 °C. Intensive mass loss (58.6 %) of the composition sample in the temperature range of 236–392 °C is due to decomposition and combustion of destruction products. This process is accompanied by a sharp extremum on the DTG curve, with a maximum at temperatures of 320 °C and 345 °C, and a sharp extremum on the DTA curve. The temperature of 308 °C corresponds to the maximum speed (2.8 %/min) of sample mass loss.

At temperatures higher than 392 °C, combustion of the organic residue of the composition sample occurs.

According to the results of our research, it should be noted that among the components of the composition, the luminophore has the lowest thermal stability. Decomposition and thermal oxidation of this component cause the initial mass loss of the composition at a temperature of 187 °C.

5. 3. Results of investigating the surface structure of imprints after pressing

Fig. 14 shows photomicrographs of imprints on two– and three-layer napkins.

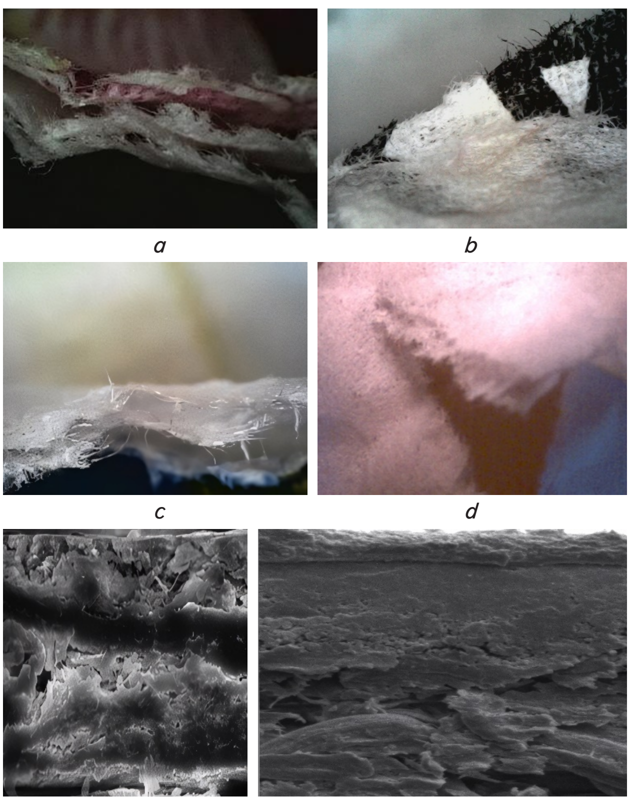


Fig. 14. Optical (magnification 60x) and electron microscopy (magnification 1000x) photographs of napkins after punching: *a* — imprints of digital printing on a three-layer paper napkin; *b* — imprints of flexographic printing on a two-layer napkin; *c* — unprinted three-layer napkin; *d* — unprinted two-layer napkin; *e* — electron microscopy (1000x magnification) of a fragment of the destroyed structure of a three-layer napkin; *f* — electron microscopy (magnification 1000x) of a fragment of the destroyed structure of a two-layer napkin

As one knows, tissue paper is a thin, soft, and porous material with a low density. Its structure gives it unique properties, including high absorption capacity. Cellulose fibers, as the main component of paper, form a kind of frame. The absence of wood pulp fibers in the composition of tissue paper gives the products softness. To increase strength and absorbency, tissue paper is often made multi-layered. Each layer can have a different density and composition. Microscopy studies show that the presence of an additional third layer in napkins makes them stronger and more resistant to punching.

So, our microscopic studies confirm that the printing technique has an impact not only on quality indicators but also on the strength characteristics of tissue products. In addition, the resistance to punching napkins is directly proportional to the number of connected layers of tissue paper and depends on the structure of the material.

Fig. 15 shows microphotographs of imprints of the main colors, formed by water-soluble flexo printing inks with the addition of luminophore.

As visual analysis of the imprints reveals, the most effective is a fluorescent imprint made with yellow ink with the addition of luminophore (15 %). So, the luminescence effect is obviously influenced by the ink pigment.

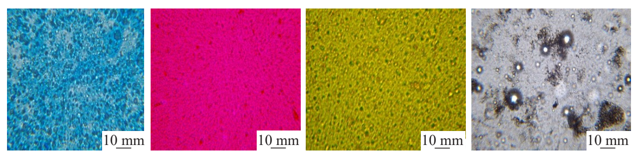


Fig. 15. Photomicrographs of imprints made with flexographic ink with luminescent impurities

5. 4. Results of investigating the organoleptic indicators of flexographic and digital printing products

The results of our study on organoleptic indicators are given in Table 7.

The organoleptic evaluation of these samples of tissue products revealed that in five samples out of six in each of the three experiments carried out, they did not have any smell, and only one that was made from secondary raw materials had a smell.

The appearance and characteristics of sanitary-hygienic paper are determining factors of their aesthetic quality, namely color, shade, clogging, artistic decoration, and other indicators.

The degree of agreement of experts' opinions was determined by Kendall's concordance coefficient. The quality of tissue products is influenced by many factors that were identified as a result of our review of scientific sources, conducted experimental studies, and analyzed by experts according to a certain number of points. Therefore, the following factors were chosen to determine the degree of consistency of experts' opinions:

1 – type of tissue product (napkins, towels, tablecloths, etc.);

2 – structure of tissue material (one-, two-, three-layer);

3 – appearance (decorated with and without embossing, with and without a printed image, colorless, colored);

4 – printing technique (flexographic, digital ink-jet printing);

5 – percentage of the printed surface (fragmentary image, solidly printed surface of the product);

6 – quality of the printed image (densitometric and colorimetric characteristics);

7 – type of processing of tissue products (calendered, non-calendered, dry, wet, flavored, antiseptic, etc.);

8 – operating conditions (resistance to tearing, crushing, moisture absorption);

9 – environmental influence (temperature, humidity).

Table 7

Results of organoleptic indicators of tissue products

Product color	Decoration	Smell	Appearance	Napkin samples	Number of experiments
Grey	With printed embossing	Barely noticeable	Sometimes folds were found	1-layer	3×6
White	With printed embossing	Odorless	According to DSTU 8862:2019	1-layer	3×6
White	With printed embossing	Odorless	According to DSTU 8862:2019	2-layer	3×6
White	With frame embossing and printing	Odorless	According to DSTU 8862:2019	2-layer	3×6
White	With frame embossing and continuous printing	Odorless	Sometimes folds were found	3-layer	3×6
White	Without decoration	Odorless	According to DSTU 8862:2019	3-layer	3×6

Table 8 gives the results of studies of factors influencing the quality of sanitary and hygienic products, taking into account the opinions of experts.

Table 8

Determining the ranks of groups of influence factors

Factor/Expert	1	2	3	4	5	6	7	8	9	Total
1	3	4	7	2	5	6	8	9	1	45
2	2	5	7	3	4	6	9	8	1	45
3	4	5	6	1	3	8	7	9	2	45
4	2	5	6	4	3	8	7	9	1	45
5	1	4	7	3	5	6	9	8	2	45
6	5	1	9	2	4	6	7	8	3	45
7	6	5	4	3	2	9	8	7	1	45
8	2	5	6	3	4	8	7	9	1	45
9	2	6	5	4	3	8	9	7	1	45
10	3	5	7	1	4	6	8	9	2	45
11	3	2	6	4	5	9	7	8	1	45

To agree on the group opinion of experts, the method of average arithmetic ranks can be applied – the sum of the ranks given by experts to each group of factors is calculated, the sum is divided by the number of experts, and the average arithmetic and final ranks are obtained (Table 9).

The results of determining the final rank of groups of influence factors showed the following result:

1 – type of tissue product (napkins, towels, tablecloths, etc.);

2 – structure of tissue material (one-, two-, three-layer);

3 – appearance (decorated with and without embossing, with a printed image, colorless, colored);

4 – printing technique (flexographic, digital ink-jet printing);

5 – percentage of the printed surface (fragmentary image, solidly printed surface of the product);

6 – type of processing of tissue products (calendered, non-calendered, dry, wet, flavored, antiseptic, etc.);

7 – quality of the printed image (densitometric and colorimetric characteristics);

8 – operating conditions (resistance to tearing, crushing, moisture absorption);

9 – environmental influence (temperature, humidity).

After determining the final opinion of the working group of experts, it is necessary to determine the degree of consistency of the opinions of m experts. Kendall's concordance coefficient is used to determine the degree of consistency of experts' opinions.

The concordance coefficient W varies in the range from 0 to 1 – $0 \leq W \leq 1$: when $W=0$ there is complete inconsistency, when $W=1$ – complete unity of expert opinions. If $W<0.2–0.4$, it means weak agreement of experts; if $W>0.6–0.8$, then agreement of experts is strong. $W=0.6$ indicates a moderate degree of consistency of experts' opinions).

Poor consistency is usually the result of the following reasons:

– there is really no commonality of opinion in the considered group of experts;

– within the group there are coalitions with high consistency of opinions, however, the generalized opinions of the coalitions are opposite.

Kendall's coefficient of concordance, or in other words, the coefficient of multiple rank correlation, is needed to reveal the agreement of experts' opinions on several factors.

Table 10 gives the results of calculating the Kendall coefficient, taking into account factors affecting the quality of tissue products, determined by experts.

After performing calculations according to formulae (2), (3), we get $S=5.980$.

Table 9

Determining the final rank of groups of influence factors

Factors	1	2	3	4	5	6	7	8	9	Total
Sum of ranks	33	47	70	30	42	80	86	91	16	495
Average Arithmetic rank	3	4.27	6.36	2.72	3.82	7.27	7.81	8.27	1.45	45
Final rank	3	5	6	2	4	7	8	9	1	45

Table 10

Determination of Kendall's concordance coefficient

Factor/Expert	1	2	3	4	5	6	7	8	9	
1	3	4	7	2	5	6	8	9	1	
2	2	5	7	3	4	6	9	8	1	
3	4	5	6	1	3	8	7	9	2	
4	2	5	6	4	3	8	7	9	1	
5	1	4	7	3	5	6	9	8	2	
6	5	1	9	2	4	6	7	8	3	
7	6	5	4	3	2	9	8	7	1	
8	2	5	6	3	4	8	7	9	1	
9	2	6	5	4	3	8	9	7	1	
10	3	5	7	1	4	6	8	9	2	
11	3	2	6	4	5	9	7	8	1	
Total	33	47	70	30	42	80	86	91	16	495
Sum square	1.089	2.209	4.900	900	1.764	6.400	7.396	8.281	256	3.3195

Then Kendall's concordance coefficient calculated from formula (1) is $W = 0.82$, which indicates a strong agreement among experts.

6. Discussion of results of investigating the quality of imprints of flexographic and digital printing on sanitary and hygienic products

The results of densitometric studies (Fig. 5) showed that the optical density of the image on the imprint of flexographic printing in the range from 50 to 100 % for all CMYK colors increases almost twice. Experiments have shown that imprints of digital printing are richer compared to flexographic ones. The optical density on the print of digital printing (Fig. 6) is 21 % higher than on the imprint of flexographic printing. Analysis of densitometric studies confirmed that the optical density of the image on the imprints varies depending on the printing method and image saturation.

The study of the color reproduction indicator (Fig. 7) shows that a much larger area of the circle of color coverage is achieved on the imprint of flexographic printing than on the imprint of digital printing. The wider the color gamut, the greater the value of the color coordinates L^*, a^* and b^*. Experiments have shown that for all CMYK colors, the change in deviations is $\Delta E\ E_{2000} < 2$.

Studies on the quality of reproduction of font elements on tissue products have shown (Fig. 8) that line thicknesses on flexographic printing imprints have smaller deviations from norms than on digital printing imprints.

In both printing techniques, the minimum font size (size in points) does not have a clear reproduction, is unreadable (Fig. 9), there are "distorted" elements and breaks in letters on the imprints.

Microscopic analysis of the printed image (Fig. 10) reveals that the resolution of the strokes of the test scale is much higher on the flexographic imprint than on the digital imprint.

Works [5, 9] investigate the importance of the tissue drying process, which is very energy-consuming and determines the operational quality of the product and paper-making processes. However, the authors do not cite studies on the influence of temperature regimes on the quality of tissue products. Unlike them, in this work the results of thermal studies of tissue paper and imprints on them have confirmed the sensitivity of these materials to temperature changes, which confirms the endo- and exo-effects present on the thermograms (Fig. 11–13).

It has been confirmed that the resistance of tissue products to punching (Fig. 14) depends on the number of interconnected layers. Increasing the layers of paper increases its strength but reduces softness and elasticity.

In contrast to works [4, 7], in which the authors focus on determining the impact on imprint quality of air permeability and surface roughness of paper, paper composition, indicators of mechanical strength of paper, in this study the influence of the technique and area of printing of sanitary-hygienic products on densitometric and colorimetric indicators of imprints.

According to the results of experimental studies, it was established that to ensure the quality of printed images on imprints, it is advisable to use flexographic printing with water-soluble inks with luminophore admixtures (Fig. 15).

In contrast to work [10, 11], which presents a numerical model for evaluating the quality of toilet paper, which characterizes its properties, we conducted an organoleptic evaluation of tissue products with the involvement of a group of experts. And on the basis of the coefficient of multiple rank correlation, the consistency of the opinions of experts regarding the factors affecting the quality of sanitary and hygienic products was revealed (Tables 8–10). Therefore, flexographic and digital printing can be used to decorate sanitary-hygienic products on tissue paper.

The research is limited to the use in the testing process of only one type of tissue paper for digital ink-jet printing and flexographic printing. It is recommended to expand the range of tissue paper for printing with these technologies, in particular, to study the strength to punching, taking into account the number of layers glued together.

For the reliability of influencing factors on the organoleptic assessment of sanitary-hygienic products, it is advisable to divide expert groups into categories taking into account age and gender, employees of the medical and cosmetology industries, the service sector, etc.

The shortcoming of the study is the surface analysis of electron microscopic photographs of the destroyed structure of tissue products. For in-depth research, it is recommended to study at the micro level the destruction of cellulose fibers of the main composition and auxiliary, which would help study more deeply the deformation processes of this material during operation in order to meet the needs of the most demanding consumers.

Our research data might be used in the production process for the manufacture of sanitary and hygienic products for selecting a specific printing method. In addition, these findings may form the basis of an expanded classification of factors affecting the quality of tissue products.

The testing methodologies that have been used could be improved by adding new testing methods. Further research may be aimed at identifying the influence of the type of inks in flexoprinting and inks in digital printing on densitometric and colorimetric indicators. It is also recommended to pay attention to the use of interactive technologies for decorating tissue products.

7. Conclusions

1. Our experimental studies of printing imprints showed differences between the quality indicators of printed images by flexographic and digital printing on tissue products. Flexographic printing imprints have brighter and richer colors, greater optical density.

2. According to the data from comprehensive thermal analysis, it was determined that in the temperature range of 20–195 °C volatile components of the napkin sample are released (7.8 %). This process is accompanied by the appearance of an endothermic effect on the DTA curve, with a maximum at a temperature of 60 °C.

3. Our microscopic studies have confirmed the influence of the printing technique not only on quality indicators but also on the strength characteristics of tissue products. It was found that the resistance to punching of napkins is directly proportional to the number of connected layers of tissue paper and depends on the structure of the material. A rational amount of luminophore (10–15 %) was determined to be added to the composition of the printing ink to ensure the

luminescent effect. It was experimentally established that the maximum glow is observed when a luminophore is introduced into yellow ink.

4. Factors influencing the organoleptic indicators of tissue products have been determined using the expert method. The calculated Kendall concordance coefficient $W=0.82$ indicates a strong agreement of the experts' opinions.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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