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RESEARCHING THE INTERACTION OF DIFFERENT PRINTED MATERIALS TYPES WITH LIQUIDS

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Досліджено взаємодію паперів та плівок з тестовою рідиною. Проведено вимірювання крайового кута змочування залежно від виду субстрату та його морфології. Визначено лінійні розміри паперу при зволоженні зразків дистильованою водою, а також досліджено динаміку проникнення води в структуру паперу. Виконано контроль якості всотування рідини паперами. Дослідження позначених показників є необхідним при створенні принципово нових матеріалів для друку. Такі вимірювання дозволяють визначити можливість використання існуючих матеріалів в конкретному технологічному процесі виготовлення поліграфічної продукції.

Встановлено взаємозв'язок між ступенем зволоження задруковуваного матеріалу та його друкарсько-технічними властивостями. Зпрогнозовано взаємодію системи «задруковуваний матеріал – рідина». Визначено вплив пар компонентів на друкарські процеси. Досліджено придатність матеріалів до задруковування струминним способом і можливість їх використання в плоскому офсетному друці зі зволоженням друкарських форм. При цьому враховувалася можливість забезпечення нормованих значень колірних характеристик відбитків.

Проведена перевірка висунутих гіпотез на відповідність математико-статистичним твердженням достовірності. Проведено розрахунок величин кореляції і встановлення кореляційних зв'язків. Математично доведено, що найбільший опір проникненню води залежить від показника пористості і поверхневого об'єму води. А також значно сильніше залежить від змочування поверхні паперу, ніж від виміряного поверхневого об'єму води. Тобто при виборі задруковуваних матеріалів, потрібно обов'язково враховувати пористість субстрату, ступінь його змочування рідиною. Дані, отримані шляхом вимірювання таких показників, дозволяють прийняти рішення про можливість задруковування матеріалу різними способами. Результати дослідження дозволять забезпечити стабільність технологічного процесу і отримання репродукцій з нормованими показниками оптичної густини і колірними відмінностями не більше 5 одиниць

Ключові слова: задруковуваний матеріал, поліграфічна продукція, струминний друк, крайовий кут, змочування поверхні

1. Introduction

The interaction of the printed surface with the liquids is a must in many technological processes of printing. Here are the cases: applying the dampening solution, printing with the ink-water emulsion in offset printing [1], using the inks in inkjet printing [2], water-soluble inks in the flexographic printing, etc. Selection of the technological process

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determines the way how the components of the technological environment of a printed contact would interact and sets the specifics of imprint formation [3]. However, the change of liquid absorbing by a substrate is influential in the case of low-viscous inks (inkjet inks). The interaction of printed material with the liquid is happening in a short notice time, while the surface morphology and the technological environment define the availability or absence of the defects onto the produced imprints, so set the stability of the printing process and color reproduction [4].

So, onto the imprint's quality major influence is done by printed surface type and wetting of its surface. Especially the process of creation of the ink film onto the porous surface is connected with the physical phenomena of the dyeing substance diffusion into the printed material structure, and it requires rather good wetting, which is necessary to get the non-defect ink film in the end [5].

In the case of using the non-absorbing printed surfaces, the phenomena of molecular interaction between the contact systems, as well as rheological and printing parameters of inks, are important. In the process of achieving the accepted good quality of printing there may be obstacles such as static electricity gained onto the printed surface, and the gained inertia of the surface itself [6]. The non-absorbing printing materials, films, plastics, some designer material have got the low surface energy, which is not enough for a decent ink wetting or other wetting, so they require additional treatment by various means to improve the adhesive properties [7].

The requirements to the quality of consumables, semi-products, and final printed products are getting higher in time. This means it is required to perform the constant search of methods and means to improve the technology, which is going to lead to set the stable ink transfer onto the printed surface, to get the reproduction, to obtain the normalized color parameters of imprints.

Issues while printing may arise while the printed surface and the liquid interact, also when the liquid (ink-water emulsion [8], inks, etc.) is being transferred (absorbed) into the printed material internal layers. That is why it is required to research the interaction of the various printed materials with liquids in a way of experimental research and to digest the possibility of their usage in different technological reproduction processes, which becomes the actual scientific-technical task.

2. Literature review and problem statement

Onto the printed surface a liquid (ink) volume is transferred, and it can be described as the function $y=f(h_i, S_{ef})$, where (h_i) – is the ink volume applied onto the printed surface; (S_{ef}) – is the effective contact surface area between the printed material and ink, which depends on the surface type and on the mechanical-structural parameters of the printed material, rheological liquid parameters, printing speed [6, 9]. Many factors of the printed contact are influencing on the thickness and the evenness of the ink film. Normalized rheological, adhesion, and wetting parameters of the ink, as well as correspondence of the surface morphology to the printed material – all these and also some other factors are influencing onto getting the even, seamless layer on the imprint.

In the paper [10], the change of printed material roughness while printing is researched and the completeness of rough elements fill-in by the ink in the flexographic printing is shown. In the paper [11], the adhesion parameters of films are researched by means of determining their surface energy and thermodynamic work of the ink adhesion to this film's surface. The influence of the paper compound onto its parameters is thoroughly studied by the authors of the paper [12]. For example, the system «raw material – paper – imprint» was researched via the proposed algorithm of complex imprint quality grading. Adding the secondary fiber materials to the paper compound allowed to reduce the time of the preliminary ink fixation on the imprint. With that, the optical density parameters are kept as per the standard. However, the possibility to use the material to get the reproductions by other means and with the absolutely different «printed material – imprint» system's parameters was not studied.

Texture parameters of the printing paper and cardboard types, determination of them with taking into account liquid absorbtion kinetics data is studied in the paper [13]. In details, the kinetics of white-spirit absorbtion is researched and the volumetric constants of absorption speed were determined, as well as the existence of 6 main kinetic dependancies was discovered. The factors influencing the transfer process and imprint formation are shown in the paper [14], where the most influential are the printed material type and the availability of the coating protective layer. The influence of the paper parameters onto the quality of digital imprints also was many times studied by the scientists. For example, the influence of papermaking technology onto the imprint's quality in the case of inkjet printing was researched in the paper [15]. Coating the paper basis with specific components allowed achieving the rigid inkjet imprint with a wider color gamut; however, the ability to use the suggested material in the other printing technologies was not studied [16].

With the help of microscopy, densitometry, and spectrophotometry the imprints digitally printed in the same conditions were studied, while varying the substrates. The results had shown that the roughness reduction resulted in optical density gain, so the quality improved [17]. In the paper [18], however, it was figured out that the ink selection for the inkjet printing does not impact on the liquid absorbtion time in the internal substrate's structure. What is influencing on it – it's the outer external pressure caused by the ink droplets influence onto the surface tension of the substrate. The proposed mathematical model [19] allows calculating the maximum diameter of the droplet being absorbed by the substrate. However, the model takes into account only the hydrodynamic parameters of the ink droplet and the physical parameters of the paper substrate. The model can't be used in the other printing techniques, for example, for the paper used in the offset printing [19].

The details of the changes nature happening into the printing contact, proposed means to improve the technological process are showing only some of the aspects. But it's not clarified enough on the causes of the issue appearance while the printed substrates and liquids interact, and while liquids are transferred into the substrate's internal structure.

Based on that, the issues to determine the systems' components while working with «printed substrate – imprint», issues to control the liquid transfer into the printed substrate's structure while printing happens, issues of paper/films interaction exist and require further study and clarification. So, the means to prevent the increased linear substrate deformation and to control the dynamics of liquid penetration into the substrate have got the room for improvement.

3. The aim and objectives of the study

The main goal lies in the experimental research of various printed substrates with liquids interaction, and how the structural parameters and the surface morphology influence onto the final reproduction quality.

To meet the set goal the following tasks had been set up:

– to determine the wetting angle depending on the printed substrate and on its morphology;

– to determine the linear paper parameters while wetted by a distilled water;

– to determine the dynamics of water penetrating the paper's internal structure, to determine the quality control of paper being penetrated by water and get the correlation with the printing-technical material's properties;

– mathematically set the dependancies of the greatest water penetration resistance on the values of porosity and surface liquid volume.

4. Materials and methods of researching the printed substrates and liquids interaction

4. 1. Researched materials and means used in the experiment

To conduct the experimental research there were four types of printed substrates selected, they differ in composition and surface parameters from the porous, absorbing to non-absorbing structure. The process of material selection was conducted based on their possibilities of being applied in different technological processes of printed products manufacturing, with the usage of liquids as well. The selected materials with the correct technological process picked up compounds can be used in the most traditional printing technologies. These substrates were chosen: coated (glossy and matt) paper, offset paper of the various sqm weight, designer's metalized paper of several color tones and films (white and transparent) of the known manufacturers. The parameters of the substrates are shown in Table 1.

Table 1

Researched substrates

Substrates	Parameters	Manufacturer (supplier)
Coated paper – Arctic Paper	– Glossy: Researched weights – 130, 200, 250, 300 g/sqm. – Matt: Researched weights – 130, 250, 350, 400 g/sqm. Fluffiness – 1.13. Whiteness (CIE) – 145. Brightness (ISO 2470/D65 %) – 109. Roughness (Bendtsen, ml/min) – 150	– Arctic Paper (supplier in Ukraine – Arctic Paper)
Offset paper UPM Fine	Researched weights – 150, 170, 250 g/sqm. Fluffiness – 1.14; 1.10;1.10 correspondingly. Whiteness (CIE) – 150. Brightness – 103. Roughness – 230; 230; 250 correspondingly	– UPM (supplier in Ukraine – Serviceoptorg, LTD)
Designer's paper	– Cordenons Stardream splendor. – Cordenons Stardream opal. – Cordenons Stardream crystal Researched weights – 280 g/sqm	– Cordenons (supplier in Ukraine – August Trade, LTD)
Self-adhesive foils	– Ritrama RI – JET145 PVC GLOSS WHITE. – Ritrama RI–145/165/205. Thickness – 80 mkm.	– Ritrama (supplier in Ukraine – Service center Ritrama-Ukraine)

The research was conducted in a way of measuring the contact wetting angle, linear paper's parameters change while being wetted and while under dynamic absorbing (Table 2).

Table 2

Indicators and devices to measure them

Indicators	Devices (TM, manufacturer)	Device's parameters
Contact wetting angle	Goniometer, version PGX supplied by «Fibro Systems» (Sweden)	Built-in camera: 80 images/sec. (640×480 pixels). Built-in pump – provides the exact droplets with the 0.5 mkl steps. Automatic droplets addition – static and dynamic mode. Software built for 32-bit and 64-bit operating systems. Conforms with TAPPI T458, ASTM D-724, ASTM D-5946
Linear paper size	The analyzer of linear parameter increase for the paper while wetted Emtec WSD 02 (Germany)	Measurement range: widening up to 25 %, with no time limits. Getting data: approximately after 100 ms after contact with the liquid. Minimal sample size: 210×60 mm
Dynamics of water absorbtion into the paper's structure	Analyzer of dynamic absorbtion Emtec PEA.C 02 (Germany)	Sensor: horizontal line with 32 elements 1×1 mm. Working frequency: 1 MHz. Getting data: approximately after 40 ms after the contact with liquid. Testing liquids: any liquids of low and medium viscosity

The interaction of paper with the liquid under the printing pressure impulse happens in a very short period of time (microseconds/milliseconds). At that exact moment, the parameters of a future imprint are formed. The main surface parameter that determines the liquid absorbtion depth into the material's internal structure is porosity. In general, the printing equipment parameters are set for the exact printed substrate. Usage of materials with different porous structure leads to having issues while printing. As long as the dampening values set in the printing equipment can not be ok for many of the used substrates. That is why the usage of the instrumental control shown above is very important while selecting the technological process.

4. 2. Methodology of the research

Samples of printed substrates were cut into $a\times b$ stripes (a – length, mm, b – width, mm), according to the technical parameters of the devices (Table 2).

To measure the contact wetting angle, the goniometer of PGX version was used, which conforms with the industry standards Tappi T558 and ASTM D-5725, as well as with the ISO. The built-in CCD camera was registering the water droplets, which were further analyzed by the software for Windows'98/2000/XP. To determine the statistical contact angle, there were 5 different sectors of the substrate used. To register the geometrical droplet parameters (contact wetting angle, droplet contact diameter, and droplet's height), measurements were taken 10 times in a minute. The timeline used to illustrate it was picked to be 30 seconds. Starting droplet volume is about 2 mkl.

To study the linear parameters of paper while being wetted, the analyzer Emtec WSD 02 was used. The sheet of printed material was put into the frames and the load of 3.5 grams was applied. The sample got contacted by distilled water used as a testing liquid. Within 60 seconds the dynamics of the substrate's lengthening was measured while the substrate had a liquid applied to it.

To conduct the research, the analyzer of the dynamic absorbtion (Emtec PEA.C 02) had been used. The sheet of printed material was fit in a frame, and it was immersed in the testing liquid afterwards. After the contact with the liquid happened, the ultrasound was transmitting the high-frequency signal through the sample. When the liquid penetrated the sample's surface, the intensity of the signal changed. The uneven liquid absorbtion on the paper's surface modulated the transmitted signals in different ways. As a result, the 32 single curves were obtained, which had shown the measured differences on the paper/film surface. Each curve characterized the average pore structure set for the 1×1 mm area of the sensor element. Analysis of the obtained curves allowed studying the water penetration dynamics into the paper's structure and to qualify the printing-technical parameters of the substrate.

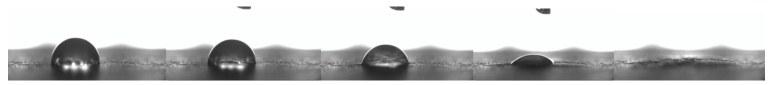

Fig. 1. Camera-recorded image of the droplet, applied onto the offset paper surface, 170 g/sqm

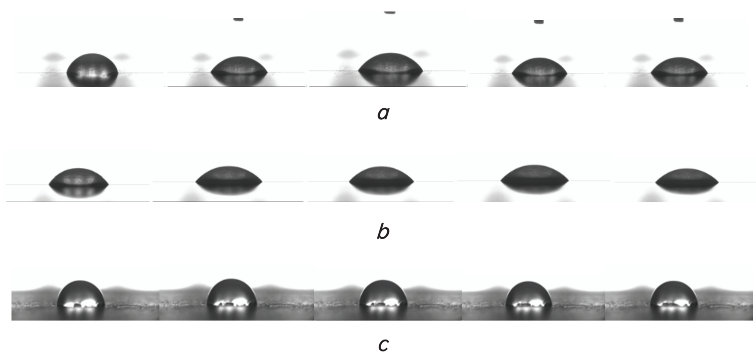

Fig. 2. Camera-recorded image of the droplet, applied onto the paper surface: *a* – matt coated paper, 400 g/sqm; *b* – glossy coated paper, 130 g/sqm; *c* – designer's paper No. 3, Cordenons Stardream crystal, 280 g/sqm

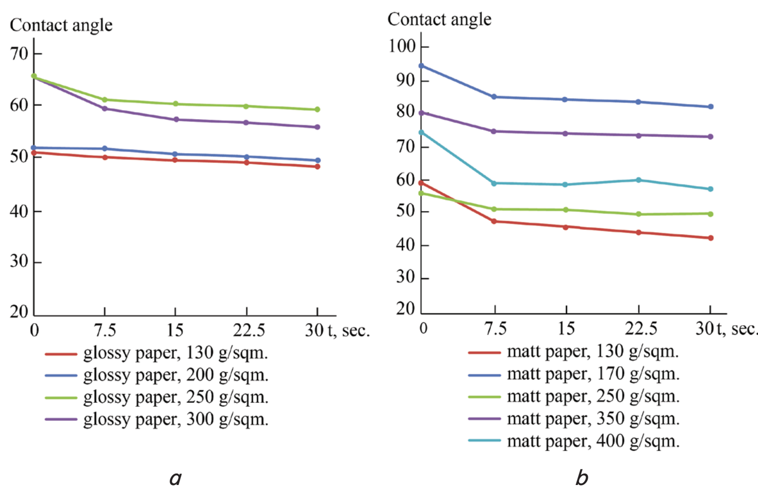

Fig. 3. Kinetics of contact wetting angle change while distilled water is applied when examining: *a* – glossy paper; *b* – matt paper

5. Research results of the main parameters in the «material – liquid» contact system

5. 1. Wetting contact angle determination depending on the printed substrate type

While conducting the research, the camera had taken images of the droplets, applied onto the printed substrate's surface. While measuring the contact wetting angle, the phenomenon of quick absorbtion of the droplet into the porous paper's structure was observed for the offset paper (Fig. 1) within the set timeline. In opposite, the designer's materials, films, and coated paper (Fig. 2, *a–c*) did not have the same dynamics, which is understandable and caused by the structural differences of the researched materials.

Fig. 3, *a, b* and Fig. 4, *a, b* graphically show the kinetics of wetting contact angle change while examining various substrates wetted by a distilled water. Fig. 5 shows the contact angle on the 30th second of the experiment.

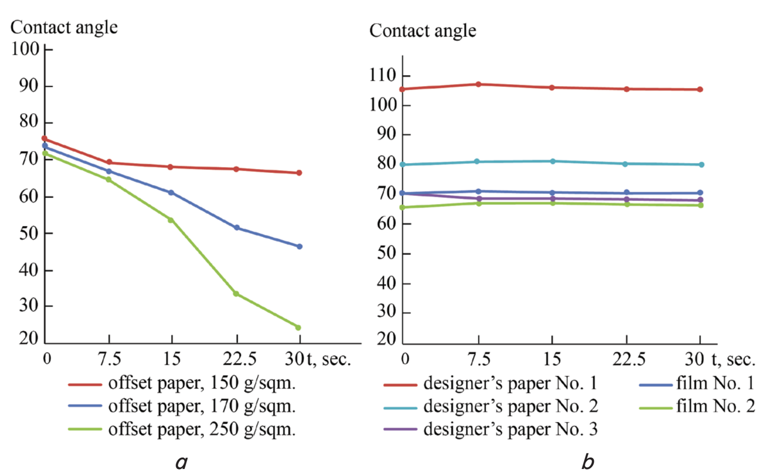

Fig. 4. Kinetics of contact wetting angle change while distilled water is applied when examining: *a* – offset paper; *b* – designer's paper and film

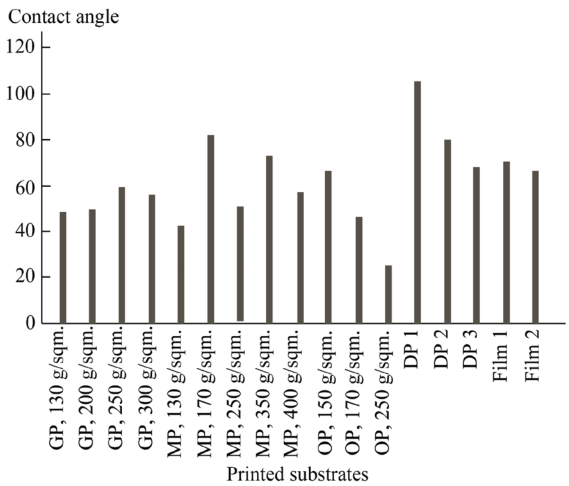

Fig. 5. Contact wetting angle of the samples on the 30th second of the experiment

The dynamics of wetting contact angle change on the paper's surface (considering the various paper coatings) allows to judge on the paper's ability to absorb water-based inks of the inkjet printer (wetting, capillarity). The examined glossy papers (Fig. 3, *a*) have got the surface tension if calculated in din/cm values in the range of 44–46. Matt coated papers, however, (Fig. 3, *b*) possess a wider range, 35–46 din/cm. But all the samples while printed by inkjet have got the tolerable range and can assure the accepted color parameters of imprints.

While examining the experimental research data, we can claim that the surface properties of the printed substrates are dependant on the composition and additives concentration in them.

From Fig. 3–5 it is visible that the water has better wetting and spreading on the surfaces of the offset paper (Fig. 4, *a*) and coated matt paper (Fig. 3, *b*).

To reach the printing inks adhesion, it is required to have the surface tension of the printed substrate not less than 38 din/cm. This value is the lowest acceptable one, and as confirmed practically values around 40–42 din/cm are used more often.

The researched films (Fig. 4, *b*) have got the surface treatment with the surface tension at 40–41 din/cm and so can immediately be used to print on them. However, high values of the contact angle and about linear dependency in their dynamics can cause problems with curing the inks on the imprint. In opposite, designer's paper 1 and 3 is not suitable at all for inkjet printing, because the ink curing, as well as the imprint quality, can be highly reduced – this can be explained by the metallic particles availability in the compound.

5. 2. Determining the linear size while wetting the samples with a testing liquid

Based on the results of linear parameters analysis of paper while wetted (conducted on the Emtec WSD 02 device), the dynamic distortion is happening on the samples of thin and more porous samples without coating (Fig. 6, *a, c*).

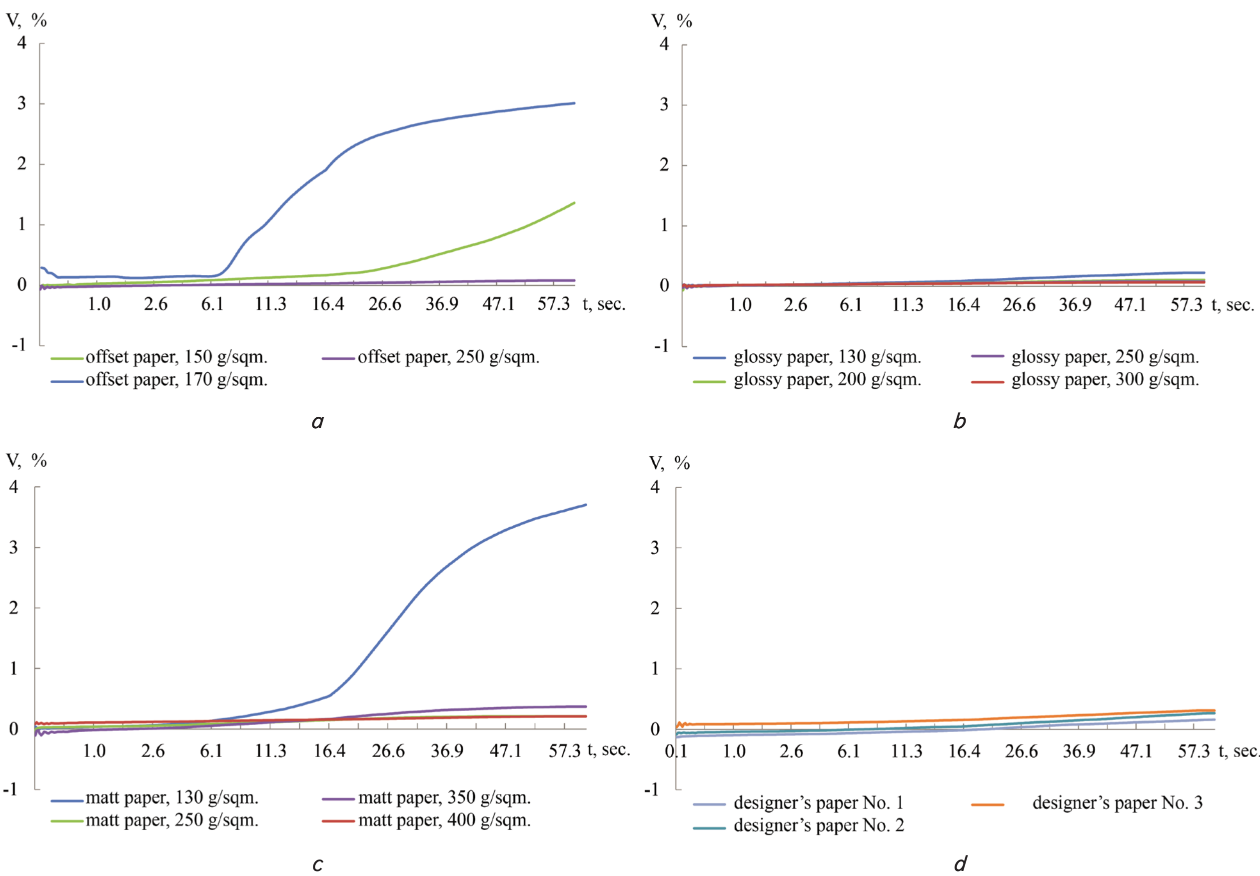

Fig. 6. Dynamic distortion while wetting by a distilled water:
a — offset paper; *b* — glossy coated; *c* — matt coated; *d* — designer's paper

5. 3. Determining the dynamics of water penetration into the sample's structure

Fig. 7 there shows the results of measuring the dynamics of absorbtion within the first 20 seconds for four types of printed substrates (coated, offset, and designer's paper and white film). The film is stably repellant to liquid absorption and is not suitable for being printed with the liquid inks without preliminary treatment. Problems with printing with the inkjet printing type can appear when the designer's paper is used.

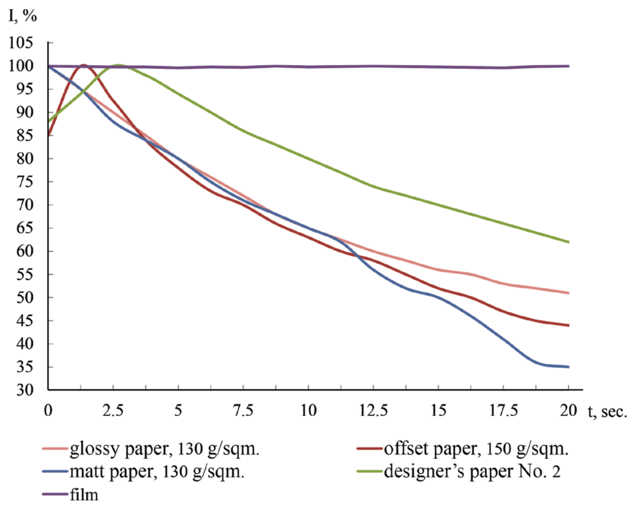

Fig. 7. Graphical dependancies from the PEA device

As seen from Fig. 7, the highest water repellency is observed in the designer's paper (the highest time T_{max}= =2.36–4.88), after it comes the offset paper (time T_{max}= =0.19–2.28). Coated papers are characterized by the zero wetting phase (W=0) and the maximum absorbtion happens immediately after draining them in water. Designer's materials are characterized by low liquid penetration into their structure, which can lead to bad ink curing on the imprint.

The most important parameters of the printed substrates that are checked before the printing starts are the results from PEA and WSD, and they are shown in Table 3.

Table 3

Measurement results of the main parameters of the printed substrates

Type PS	Weight, g/sqm	Paper's surface wetting, T_{95}, s	Surface liquid volume, W	T_{max}, s
1. Coated glossy paper				
No. 1	130	1.43	0.00	0.08
No. 2	200	1.18	0.00	0.08
No. 3	250	1.55	0.00	0.08
No. 4	300	3.56	0.00	0.08
2. Coated matt paper				
No. 1	130	1.43	0.00	0.08
No. 2	170	1.18	0.00	0.08
No. 3	250	1.77	0.00	0.08
No. 4	350	3.82	0.00	0.08
No. 5	400	3.61	0.00	0.08
3. Offset paper				
No. 1	150	0.99	0.16	2.28
No. 2	170	0.58	0.03	0.19
No. 3	250	0.66	0.04	0.19
4. Designer's paper				
No. 1	280	1.06	0.32	2.36
No. 2	280	4.69	6.13	3.01
No. 3	280	11.37	21.4	4.88

The inkjet ink viscosity correlates well with the combination of measurements: the porosity value via the dot (T95), (Tmax) is determined, as well as the surface paper volume (W). CIE Lab coordinates for about all the samples except the designer's are within the tolerance range according to ISO 12647-2, so the substrate's impact on the color deviations of the imprint would be minimal; however, the difference in the absorbtion capability can lead to distortions and color differences on the different material types.

As can be seen from Table 3 and partially from Fig. 7, by the parameter T_{95} offset papers have low internal gluing and high porosity. So, these samples from all the studied are the most usable for the inkjet printing. The acceptable values of color parameters can be achieved by the thin coated papers (up to 250 g/sqm) and the designer's paper without metallic particles. All other sample have got low liquids wetting capabilities and have troubles while printing inkjet on them.

6. Mathematical study on the experimental results

The hypothesis put forward should be thoroughly checked to reflect the mathematical-statistical certainty statements, e. g.: calculation of the correlation values and setting the correlation relations.

Let us research the dependence of the highest water penetration resistance T_{max} on the porosity parameter at the point (T_{95}) and the surface water volume W. Let us mark these values Z, X and Y correspondently. Let us pick up 6 paper types for the research: 3 types of offset and 3 types of designer's paper (numbers 1, 2, and 3). The measurement results for each are shown in Table 3. As known [20], when the researched object or phenomenon is characterized by more than 2 characteristics $X_1, X_2, ..., X_k$, the multiple dependancies have to be studied. To judge on the relationship between the characteristic X_i and all others, the *multiple correlation coefficient* is used, which is shown as R_j. Also, in the case when it is required to study the correlation connection between characteristics X_i and X_j, $i=1,...,k$, $j=1,...,k$, from the set of characteristics $X_1, X_2, ..., X_k$ of the studied object (phenomenon) which is pure from all the other characteristics, the *partial correlation coefficient* is calculated, which is shown as R_{ij}.

It is considered that for correct usage of multiple and partial correlation coefficients, it is required for the partial data to have the compatible normal distribution, however, checking this condition is not generally done practically, because of too complex calculations.

Let us figure out the strength of the relationship between Z and X and Y using the multiple correlation coefficient, also compare the strength of the relationship between Z and X and between Z and Y using the partial correlation coefficient.

From the mathematical point of view, as per the stated task for the object characterized by the three parameters X, Y та Z (k=3), we need to calculate [20] the multiple correlation coefficient R_Z and partial correlation coefficients R_{XZ} and R_{YZ} based on the 6 mutually connected threes of the selected data (x_i, y_i, z_i), $i=1,...,n$, $n=6$.

Let us build the matrix of the pair correlation coefficients r_{ij}, $i=1,...,k$ between the parameters X_i and X_j in the look:

$$A=\begin{pmatrix} 1 & r_{12} & \dots & r_{1k} \\ r_{21} & 1 & \dots & r_{2k} \\ \dots & \dots & \dots & \dots \\ r_{k1} & r_{k2} & \dots & r_{kk} \end{pmatrix}. \quad (1)$$

In the case of the ungrouped data r_{ij}, $i=1,..., k$ ($r_{ij}=r_{ji}$) is calculated by the formula:

$$r=\frac{n\sum_{i=1}^{n}x_iy_i-\left(\sum_{i=1}^{n}x_i\right)\left(\sum_{i=1}^{n}y_i\right)}{\sqrt{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2}\sqrt{n\sum_{i=1}^{n}y_i^2-\left(\sum_{i=1}^{n}y_i\right)^2}}. \quad (2)$$

Calculations are listed in Table 4.

Table 4

Calculated table of the correlation coefficients

Calculated values of correlation coefficients							Σ
x_i	0.99	0.58	0.66	1.06	4.69	11.37	19.35
y_i	0.16	0.03	0.04	0.32	6.13	21.4	28.08
z_i	2.28	0.19	0.19	2.36	3.01	4.88	12.91
x_i^2	0.9801	0.3364	0.4356	1.1236	21.9961	129.2769	154.1487
y_i^2	0.0256	0.0009	0.0016	0.1024	37.5769	457.96	495.6674
z_i^2	5.1984	0.0361	0.0361	5.5696	9.0601	23.8144	43.7174
$x_i y_i$	0.1584	0.0174	0.0264	0.3392	28.7497	243.318	272.6091
$x_i z_i$	2.2572	0.1102	0.1254	2.5016	14.1169	55.4856	74.5969
$y_i z_i$	0.3648	0.0057	0.0076	0.7552	18.4513	104.432	124.0166

So, by the formula (2), we get:

$$r_{XY}=r_{YX}=$$
$$=\frac{6\cdot 272.6091-19.35\cdot 28.08}{\sqrt{6\cdot 154.1487-19.35^2}\sqrt{6\cdot 495.6674-28.08^2}}\approx 0.9959.$$

Similarly, for $r_{XZ}=r_{ZX}$ and $r_{YZ}=r_{ZY}$, we get:

$$r_{XZ}=r_{ZX}=\frac{n\sum_{i=1}^{n}x_iz_i-\left(\sum_{i=1}^{n}x_i\right)\left(\sum_{i=1}^{n}z_i\right)}{\sqrt{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2}\sqrt{n\sum_{i=1}^{n}z_i^2-\left(\sum_{i=1}^{n}z_i\right)^2}}\approx 0.862;$$

$$r_{YZ}=r_{ZY}=\frac{n\sum_{i=1}^{n}y_iz_i-\left(\sum_{i=1}^{n}y_i\right)\left(\sum_{i=1}^{n}z_i\right)}{\sqrt{n\sum_{i=1}^{n}y_i^2-\left(\sum_{i=1}^{n}y_i\right)^2}\sqrt{n\sum_{i=1}^{n}z_i^2-\left(\sum_{i=1}^{n}z_i\right)^2}}\approx 0.8347.$$

In this case, the correlation matrix gets this look:

$$A=\begin{pmatrix}1 & 0.9959 & 0.862\\ 0.9959 & 1 & 0.8347\\ 0.862 & 0.8347 & 1\end{pmatrix}.$$

Let us find the determinant $|A|$ of the matrix A (using Microsoft Excel methods) and algebraic addition $A_{zz}=A_{33}$.

$$|A|=\begin{vmatrix}1 & 0.9959 & 0.862\\ 0.9959 & 1 & 0.8347\\ 0.862 & 0.8347 & 1\end{vmatrix}=0.0156;$$

$$A_{ZZ}=A_{33}=(-1)^{3+3}\begin{vmatrix}1 & 0.9959\\ 0.9959 & 1\end{vmatrix}=$$
$$=1-0.9959^2\approx 0.0083.$$

Then, by the known [18] formula:

$$R_Z=R_3=\sqrt{1-\frac{|A|}{A_{33}}}=\sqrt{1-\frac{0.0156}{0.0083}}\approx 0.9008.$$

The value of the multiple correlation coefficient R_Z shows that Z is very strongly tied with X and Y.

Let us check the statistical significance of the multiple correlation coefficient R_Z. Let us find the t-statistics by the formula:

$$t=\frac{R^2(n-k)}{(1-R^2)(k-1)}=\frac{0.9008^2(6-3)}{(1-0.9008^2)(3-1)}\approx 6.45.$$

The calculated value of t-statistics is compared with the critical value F_{crit}. F_{crit} – table value of Fisher distribution (by the appendix-table of values) [20], which can also be found via the built-in statistical Excel function FINV (α; l_1; l_2), where α – selected by the researcher level of significance (generally for α values 0.01; 0.05; 0.1 are taken), l_1; l_2 – freedom degrees, $l_1=k-1$; $l_2=n-k$.

Let us find F_{crit}, considering that $l_1=k-1=3-1=2$, $l_2=n-k=6-3=3$. Let us choose the significance level $\alpha=0.085$. Then F_{crit}=FINV(0.085; 2; 3)=6.259. Because $t>F_{crit}$, the zero hypothesis about the correlation absence is declined, the multiple correlation coefficient R_Z is considered as statistically significant on the selected significance level (authentic connection trend).

To calculate the partial correlation coefficient we need: to build the matrix of paired correlation coefficients A; to find the algebraic additions A_{ii}, A_{jj}, A_{ij} for the elements r_{ii}, r_{jj}, r_{ij}, correspondently; to calculate the partial correlation coefficient [20] via the formula:

$$R_{ij}=\frac{-A_{ij}}{\sqrt{A_{ii}A_{jj}}}. \quad (3)$$

To check the statistical significance of the partial correlation coefficient, we need to use the t-statistics, which is calculated via the formula:

$$t=\frac{R_{ij}\sqrt{n-k+2}}{\sqrt{1-R_{ij}^{\ 2}}}, \quad (4)$$

where n is the number of mutually connected values of the characteristics X_i, $i=1, ..., k$.

The calculated value of t-statistics is compared with the critical value t_{crit}. T_{crit} – table value of Student's distribution, which can also be found with the help of built-in Excel function TINV (α; l), where α is the significance level selected by the researcher, l – freedom degree, $l=n-k+2$.

If the calculated t-statistics value is bigger than the critical $|t|>t_{crit}$, then the partial correlation coefficient is considered as significant on the selected level of significance α.

To calculate the partial correlation coefficients $R_{XZ}=R_{13}$ and $R_{YZ}=R_{23}$, let us find the needed algebraic additions: $A_{13}\approx -0.0308$; $A_{23}\approx 0.0238$; $A_{11}\approx 0.3032$; $A_{22}\approx 0.2569$.

Then by the formula (3), we get:

$$R_{13}=\frac{-A_{13}}{\sqrt{A_{11}A_{33}}}=\frac{-(-0.0308)}{\sqrt{0.3032\cdot 0.008}}\approx 0.615;$$

$$R_{23}=\frac{-A_{23}}{\sqrt{A_{22}A_{33}}}=\frac{-0.0238}{\sqrt{0.2569\cdot 0.008}}\approx -0.5158.$$

The values of partial correlation coefficients show that the value Z is connected with the value X stronger, than with the value Y.

Checking the statistical significance, t-statistics via the formula (4) gives:

$$t_1=\frac{R_{13}\sqrt{n-k+2}}{\sqrt{1-R_{13}^{2}}}=\frac{0.615\cdot\sqrt{6-3+2}}{\sqrt{1-0.615^{2}}}\approx 1.744;$$

$$t_2\approx -1.346.$$

Let us find the critical value t_{crit}, select significance levels α=0.05 and α=0.01. Then t_{crit}=TINV(0.05; 5)=2.57 and, correspondently, t_{crit}=TINV(0.01; 5)=4.03. Because the calculated values of t-statistics for R_{13} and R_{23} are lower than the critical $|t|<t_{crit}$, it means that partial correlation coefficients aren't significant on the selected levels of significance. However, for α=0.25 t_{crit}=TINV(0.25; 5)=1.3, $|t|>t_{crit}$, so the partial correlation coefficients R_{13} and R_{23} are significant on the significance levels of α=0.25, and we have a slight correlation.

Calculations of the correlation values and setting up the correlations confirm the experimental dependency of the T_{max} parameter on the T_{95} parameter. The water repellant resistance also has the mutual connection with the W parameter, although to a lesser extent. All the connection powers, t-statistics, are statistically significant while setting the corresponding level of significance. So paper surface wetting has to be definitely examined before adding any substrates in the printing production process. This is going to allow making a correct decision in the process of selections done in the «printed substrate – imprint» system, as long as the surface glueing of the material, internal glueing or the non-absorbing surface of films is going to be water-repellant and so impact the imprint's quality.

7. Discussion of the research results of how printed substrates and liquids interact

The obtained research results can be used while setting up the rational technological process in the printshops, and the testing methodology can be used while creating new samples of printed substrates on the papermaking mills.

The proposed methodology of testing the consumables allows avoiding mistakes while selecting the components of the system «printed substrate – imprint», and so reduce the waste percentage. Before the items are meant to be used in the technological process of printed product manufacturing for the substrates the preliminary check of its surface with liquid wetting is required, especially in the cases when principally new materials are going to be used for printing. Determining the wetting parameter of the material's surface allows stating its applicability in the inkjet or offset printing, where there is the highest liquid-substrate interaction. In the case of significant linear deformations, the high-quality imprint can be achieved using other printing types: screen printing, electrophotography, etc. Determination of the contact wetting angle allows getting the ink adhesion to the substrate defined and make a decision about using liquid or toner-based systems in the process of imprints production.

Further research effort is going to be put on studying the interaction of the printed substrates not with the testing liquid, but with the real ones, used in the technological process of printing production. For example, coated and offset papers can be used not only in the offset printing, where we have a contact of a substrate with the dampening solution and where the material confronts the linear deformation forces. These substrates can be printed with inkjet as well, where a liquid ink as a toning agent is used, which possesses similar properties to the testing liquid used. Designer's papers and films are a wonderful material to get the exclusive product printed digitally, or via classical printing types with the usage of UV inks. With that, they remain useful for the offset printing as well, and the interaction with the dampening solution does not cause any unwanted linear deformations and color deviations on the imprint. However, according to the research results, using the inkjet for the just mentioned materials will not guarantee getting high-quality reproductions as there will be complications with ink curing.

8. Conclusions

1. Consumables testing methodology was proposed for their rational selection in the technological printing process. In details, determining the absorbtion ability, linear deformation, contact angle before starting their actual usage will lead to the correct selection in the «printed substrate – imprint» system, and will reduce the percentage of production waste.

2. Studying the linear paper parameters while wetting the substrates with distilled water confirmed that dynamic distortion is more applicable to thin and porous papers without coating. So it is required to thoroughly control the liquid supply in the technological process of printed products manufacturing in order to avoid the linear deformation of a substrate and the reproduction distortions.

3. It can be stated that coated and offset papers can be used to get reproductions made via inkjet printing. Using designer's papers and films can make the process of ink curing complicated, thus lowering the possibility to obtain a high-quality imprint. The determination of the dynamics for the water penetration into the substrate's internal structure assured that these materials should rather be used for toner-based printing, or printing with UV or foil inks depending on the product's characteristics and on the printrun.

4. The proposed hypothesis about the interaction of various types of printed substrates with the liquids was checked with the help of calculating the correlation values and setting the correlations. It was confirmed that the highest resistance to water penetration T_{max} strongly depends on the value of porosity at the point (T_{95}) and the surface liquid volume. Additionally, it depends on the paper surface wetting more than on the measured surface liquid volume.

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