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THE ANALYSIS OF THE CONSOLIDATION PROCESS OF THE PAPER WEB IN THE AIR PRESS

Theoretical analysis of the dewatering and consolidation process of the wet paper web with the air through- blowing technique is presented in this study. This kind of process takes place in a new (patented) device called the air press.

The results of theoretical considerations are experimentally verified. The experimental research was conducted on a specially designed experimental stand with the use of three kinds of paper used for oil and air filtration.

It was proven that the air through-blowing process of the fibrous web dewatering can be considered as unidirectional consolidation with the linear relationship of dehydration and deformation.

A new system of devices was suggested for the continuous production of high quality filter papers, with the air press as its basic element.

1. Introduction

The consolidation of the wet paper web is achieved in the paper machine through introducing the web, together with the felt on which it lies, into the nip between two press rolls pressed to one another with an appropriate force.

Paper pressing causes partial removal of the water from the paper (dewatering) and densification of the fibrous material; it results in an increase in the mechanical strength of the paper web and also the deterioration of its porosity and absorbency. This situation is not always beneficial. Especially, in the case of the production of sanitary papers (towel paper, toilet paper, etc.), or filter papers (for filtration of air, engine oils, natural oils etc.), it is necessary to conduct the dewatering process in order to retain the paper's permeability and absorbency at sufficiently high levels.

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A very important property of filter papers, which is significant in determining their quality, is the uniformity of the sheet structure. To achieve the paper properties required, an appropriately prepared suspension of long fibres with the required additives has to be poured out on the wire of the paper machine with a sufficiently low consistency of those fibres in the water. This consistency can sometimes be as low as 0,01%, which is many times lower than that usually applied. The consistency is directly related to the requirement of draining a very large amount of water on the paper machine's wire, whilst simultaneously eliminating the intensive densification of the fibrous web being dewatered; a well known fact in such conditions. This requirement can be sufficiently fulfilled with air through-blowing devices, in which the paper web is dewatered with the use of airflow.

From 1974 to 1994, we were working, together with a group of co-workers, on the conceptual designs for these types of devices; we constructed their semi-industrial the models and then undertook studies on dewatering process in these devices using different kinds of fibrous webs. The results of this research were published in Poland and abroad [1], [2], [3], [4], [5], [6], [7], [8], [9], [10].

One of the more important results of the research carried out was the elaboration of the concept and construction of the air press [2]. The scheme of the air press is shown in Figure 1.

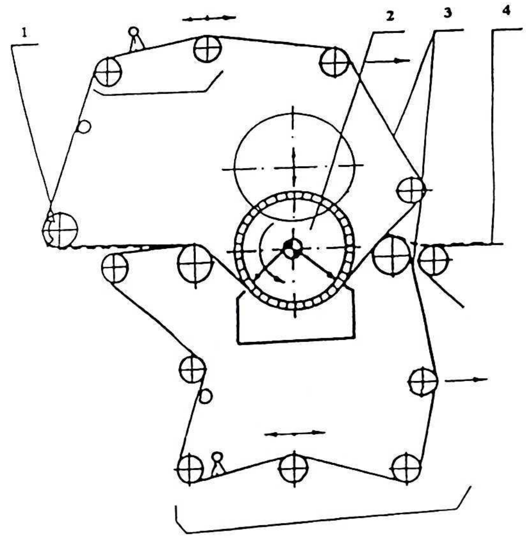

Fig. 1 Scheme of the air press: 1 - suction roll (pick-up type); 2 - proposed air press; 3 - wire; 4 - web transporter (felt)

In a contrast to mechanical presses used to date, this new device - which works on the basis of using air masses under pressure - provides intensive dewatering of the paper web without changing its structure (web densification).

In this study, we undertake an attempt of the elaborated mathematical model's description of fibrous web dewatering process, with the use of air through-blowing technique [1]. So far, several researchers of fibrous web consolidation (dewatering) in paper machines were attempting to describe this process using relations derived from Darcy-Weisbach and Kozeny-Carman equations. However, their work can be mostly used to study general trends only, as most of the results were obtained for water flow in capillaries with a specified hydraulic radius r. Paper is a material of such a complex structure that this parameter, which is also variable in time, can not be precisely described. On the other hand, the filtration coefficient, according to Darcy, can provide a mathematical description of the water flow process through fibrous paper webs. Such a model can be of a high practical value for paper machine manufactures optimising their design. The attempts to describe the water and airflow through webs with a Navier-Stockes equation led to very complicated relationships. After the simplifications required for practical utilization, these relationships gave results that were inconsistent with those of experimental measurements.

The description of web dewatering process as a two-phase fluid flow through a deformable porous environment, using the Euler's method with the incorporation of Darcy's equation, seems practically possible. It is proven by the described studies.

2. Characteristics of the air through-blow dewatering of the fibrous web

Typical wet fibrous web, as can be found in pulp and paper, contains both the so called free water and constrained water. Free water is mostly concentrated in spaces between fibers and, on a smaller scale, in fiber lumens and larger pores. Mechanical dewatering is a most commonly used procedure to remove this type of water. On the other hand, the constrained water forms a chemical connection with the elements of the pulp. There are several different mechanisms holding this type of water inside the pulp: a gel swelling, capillary condensation, and surface absorption to mention just a few.

As to the constrained water, we also describe water residing in the fiber micropores created by a fiber fibridation process as well as water that is calosed in the fiber lumens. Although theoretically possible, in practice it is very difficult to remove such water with mechanical means. In some cases, it is even impossible. Jayme at al. [11] proposed a standard procedure to measure volume of the constrained water by removing the free water in a high speed centrifugal machine working with commonly used specifications: 86.7 RPS and 900 sec of mixing time.

With the above technique, it is possible to describe the sheet dryness without the free water, a so-called theoretical sheet dryness s_T [11]. This theoretical sheet parameter depends on physical properties of the pulp used in the fibrous web and it can be calculated from the following relation

$$s_T = 100 - WRV/[1 + WRV/100][\%], \qquad (1)$$

where WRV is an experimental coefficient obtained with the Jayme procedure.

Dewatering or drying of the sheet below s_T usually leads to its shrinkage. Thereby, the sheet theoretical dryness constitutes a practical borderline between dewatering and drying process.

As it was mentioned before, the technique of the air through-blow dewatering of the fibrous webs is a preferred method for producing filter papers and cardboards. Those types of grades should be manufactured from long fibers in the aqueous mixtures at a very low consistency of 0.1% or lower, using special incline headboxes. The characteristic feature of these systems is that of a process of sheet forming that starts inside the headbox resulting in a very uniform, isotropic structure with practically the same properties in all dimensions. It is a perfect solution for the filter papers.

The theoretical description of a dewatering process of such isotropic fibrous structures is a subject of this paper. For the purpose of this study, we can describe this web as an isotropic, deformable porous body consisting of three phases: solid phase (fibers), liquid phase (water) and gas phase (air). Volumetric ratio between these three phases can be calculated using appropriate relations.

Porosity of a wet sheet can be obtained from the following equations:

$$\varepsilon = V_{por} / V_f \quad \text{and} \quad \varepsilon_l = V_{por} / V_t$$

where:

V_{por} – total volume of the porous area inside the web,

V_f – volume of the wet fibers of density q_f in the web of theoretical dryness s_T,

V_t – total web volume.

Let us assume that a fibrous web structure, at the theoretical dryness s_T, consist of the wet fibers with constrained water and a porous area between fibers filled with air only. With web dryness lower than s_T, the porous area is filled with a water-air mixture or water only (i.e. web with a critical wetness). Volumetric ratios of water, n_w, and air, n_p, in the porous area can be described as

$$n_w = \frac{V_w}{V_{por}} \quad \text{and} \quad n_p = \frac{V_p}{V_{por}}$$

where:

V_w – total volume of the free water in a porous area,

V_p – total volume of air in the web.

Accordingly, volumetric ratio of wet fibers in the web, n_{wl}, can be described as $n_{wl} = \frac{V_{wl}}{V_l}$.

The process of air through-blow dewatering of fibrous webs can be described as a mechanical removal of the free water by through-blowing cold, unheated air at a small pressure drop, $\Delta p < 100\,\text{kPa}$. Therefore, it is a process of web consolidation caused by a through flow of the air of higher density. Such a flow has an undersonic character, with the Mach number ranging from 0 to 1, thus it does not significantly affect the air density. Air is blown from the pressure chamber, through the fibrous web and forming wire, to an underwire chamber at atmospheric pressure, removing the free water from the web only. However, some water is still left in the micropores inside the web and some water is absorbed as a thin film on the surface of the fibers. Longer through-blowing can lead to a vaporization of this water but it is not, at this point, an economically sound process, as only cold, unheated air is used. Thus, the air through-blow dewatering process ends when a fibrous web arrives at its theoretical dryness s_T. With further air through-blowing we begin the drying process associated with a different dehydration phenomena and typical sheet shrinkage. Air through-blow dewatering is a process of mechanical removal of the free water from a web that can be described as a process of filtration of air and water in the deformable porous structure.

In response to this deformation, sheet caliper decreases from initial thickness b_p to b_k. The method of the air through-blow dewatering of the fibrous webs can be practically used for sheets with dryness higher than 10% in order to avoid excessive fiber loss (fibers blown off through the wire).

Our previous study [1] indicates that for the optimal range of process conditions ($s_i \geq 10\%$, $s_f \leq s_T$, $\Delta p < 100\,\mathrm{kPa}$) sheet deformation can be directly related to the amount of removed water. Air through-flow has a less significant effect. After removing the free water (i.e. arriving at the theoretical dryness s_t), sheet caliper stabilizes at a certain level t_f, and longer air through-blowing does not cause further thickness decrease until the beginning of the process of constrained water vaporization. Accordingly, for filter papers, we can assume that in the described range of sheet dryness the following relation can be used

$$b(t) = b_k + \Psi V_w(t) \qquad (2)$$

where:

- Ψ – experimental deformation coefficient that dependents on a fiber elastic module,
- V_w – relative volume of free water in porous area of the web [m^3/m^2].

3. Mathematical model of the paper dewatering process in the air press

The process of the air through-blow dewatering of any fibrous web in the air press can be described as the airflow through the wet fibrous web of a unit area and a thickness b, Fig. 2. Air flows from the pressure chamber with a higher than atmospheric pressure, located just over the web, to a zone at atmospheric pressure located just under the web, with its total through-blow time computed as

$$t_c = \frac{L}{V_s}$$

The web is supported by a stiff but permeable support (wire) with a negligible hydraulic resistance. Upper web surface can move freely downward in response to the applied pressure drop $\Delta p = p_a - p_0$. However, web sides are constrained, and are not permeable (pressure chamber walls). Thereby, the web can be deformed in the z-direction (thickness direction), coupled with dewatering, but it cannot deform in neither MD nor CD direction.

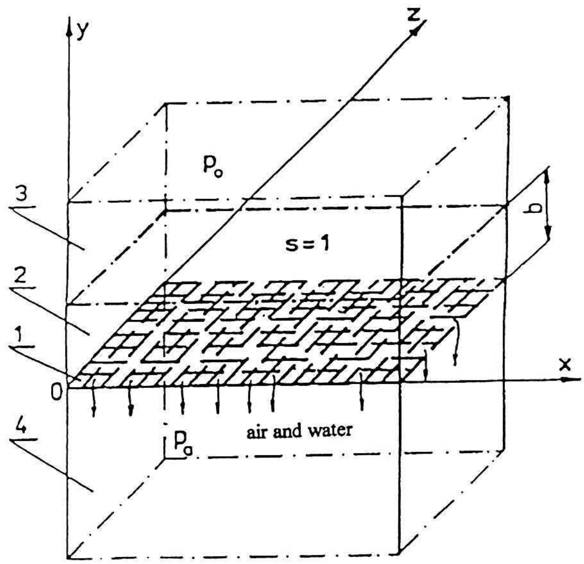

Fig. 2 Overall model of the air through-blow dewatering of a fibrous web, s=1 m^2: 1 - wire; 2 - sample of a fibrous web; 3 - pressure chamber; 4 - atmospheric chamber

In order to provide the analytical description of the above process, the following conditions are assumed:

1. Any individual fiber is nondeformable – it means that for the pressure range investigated, it cannot change its volume. However, fibrous structure (web) composed of such fibers is fully deformable in the y-direction (thickness direction). Web deformation in either MD or CD direction is negligible.
2. Web dewatering is caused by water filtration in all directions (x, y, and z) and by web deformation in the z-direction.
3. Air and water flow inside porous area between fibers obeys Darcy law [12], [13].
4. For simplicity, the hydraulic resistance of the wire is assumed to be negligible compared to the resistance force encountered by the flowing air and water inside the web.
5. Fiber loss due to air through-blowing is negligible.
6. All three phases (water, air and fibers) are distributed uniformly in the y-direction (thickness direction)

$$\frac{\partial n_w}{\partial y} = \frac{\partial n_p}{\partial y} = \frac{\partial n_{wl}}{\partial y} = 0 .$$

7. Both air and water flows are isothermal.
8. Centrifugal force affecting the dewatered element of the paper web is negligible; in this case, this force slightly enhances dewatering forces generated by the airflow through the web.
9. Affect of the centrifugal force on the dewatered paper web is negligible; this centrifugal force is balanced by the web tension forces of the web.

From the basic relations for a continuous flow of water and air through the porous area between fibers within the web and a flow of the fibers, in response to web deformation, the following relationship for the air through-blow dewatering can be obtained for a fibrous web by applying Darcy law

$$[\Phi(t)+Jp]\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}\right)+J\left[\left(\frac{\partial p}{\partial x}\right)^2+\left(\frac{\partial p}{\partial y}\right)^2+\left(\frac{\partial p}{\partial z}\right)^2\right]= \\ =R(t)p+N(t) \tag{3}$$

where:

$\Phi(t)$, $R(t)$, $N(t)$ are time dependent coefficients [1] obtained for a time t ranging from $t=0$ to t_0,

J is a constant that can be expressed as $J=\dfrac{\pi C_p \tau}{\eta}$.

The above equation has boundary conditions in the area:

$\Omega = \{(x,y,z): 0 \le x \le a: 0 \le y \le b: 0 \le z \le 1\}, 0 \le t \le \infty:$

$$\left.\begin{aligned}
&\left.\frac{\partial p}{\partial x}\right|_{(0,y,z,t)}=0=\left.\frac{\partial p}{\partial x}\right|_{(a,y,z,t)}, \\
&\left.\frac{\partial p}{\partial z}\right|_{(x,y,0,t)}=0=\left.\frac{\partial p}{\partial z}\right|_{(x,y,l,t)}, \\
&p(x,0,z,t)=p_a, \\
&p(x,b,z,t)=p_0, \\
&p(x,y,z,0)=p_a
\end{aligned}\right\} \tag{4}$$

Equation (3) describes a distribution of the dewatering pressure within the fibrous web: $p(x,y,z,t)$.

With the boundary conditions (4) it can be proved [1] that the above parameter p is independent on x and z, and dependent on y and t only.

Equation (3) can be then simplified as

$$\frac{\partial}{\partial y}\left[(1+\lambda_p)\frac{\partial p}{\partial y}\right]=\beta^2 p+\gamma \tag{3a}$$

where: $\lambda=\dfrac{J}{\Phi(t)}$, $\beta^2=\dfrac{R(t)}{\Phi(t)}$, $\gamma=\dfrac{N(t)}{\Phi(t)}$.

The generic description of the solution is the following relation

$$p(y,\lambda) = \upsilon_0(y) + \sum_{r=1}^{\infty}\left[\sum_{k=0}^{\infty} C_r^{(k)}\lambda^k\right]\Phi_r(y), \tag{5}$$

where: $r \to r = 1,......,r_0$,

$k \to k = 0,1,...,k_0$.

$C_r^{(k)}$ is a computational coefficient whose subsequent terms are given [1] in the detailed solution of the above equation.

Whereas:

$$\upsilon_0 = p_a + \frac{(p_0 - p_a)}{b(t)}y,$$
$$\varphi_r(y) = \sqrt{\frac{2}{b(t)}}\left(\sin\frac{\pi r}{b(t)}y\right). \tag{6}$$

Solution of the Equation (3) can also be given in the form

$$p(y,\lambda) = p_a + (p_0 - p_a)\frac{y}{b(t)} + H(y), \tag{7}$$

where function H(y) is described by the following relation

$$H(y) = \sqrt{\frac{2}{b(t)}}\left\{\begin{matrix} \sin\frac{\pi}{b(t)}y\left[\lambda^0 C_1^{(0)} + ... + \lambda^{k_0} C_1^{(k_0)}\right] + ... \\ ...... + \sin\frac{r_0\pi}{b(t)}y\left[\lambda^0 C_{r_0}^{(0)} + ... + \lambda^{k_0} C_{r_0}^{(k_0)}\right] \end{matrix}\right\}. \tag{8}$$

From numeric computation it was found that

$$C_1^{(0)} >> \lambda C_1^{(1)} > \lambda C_1^{(2)}.$$

Thereby, in the subsequent discussion we can presume that

$$r = 1,$$
$$k = 0.$$

With the above assumptions, the relations (7) and (8) can be simplified as follows

$$H(y) = \sqrt{\frac{2}{b(t)}}\sin\frac{\pi}{b(t)}yC_1^{(0)}, \tag{8a}$$

$$p(y) = p_a + (p_0 - p_a)\frac{y}{b(t)} + \sqrt{\frac{2}{b(t)}}\sin\frac{\pi}{b(t)}yC_1^{(0)}, \tag{9}$$

where:

$$C_1^{(0)} = -\frac{\sqrt{2b}}{\pi}\frac{2\gamma + \beta^2(p_a + p_0)}{\left(\frac{\pi}{b}\right)^2 + \beta^2}. \tag{10}$$

4. Fundamental parameters and indicators of the through-blow dewatering of a fibrous web

Dewatering efficiency Q_w (amount of removed water) and thickness of dewatering web b(t)

Amount of water displaced from a fibrous web, Q_w`, for a through-blowing device that was mathematically described by Equation (3) and boundary conditions (4), can be obtained from

$$Q_w = S\int_0^t u_{wy}\Big|_{y=0} dt, \tag{11}$$

where the function u_{wy} can be computed from the modified Darcy equation [1]

$$u_{wy} = -\frac{k_w n_w \pi}{\rho_w g}\frac{\partial p}{\partial y} + \varepsilon_2 u_{wly}. \tag{12}$$

The module for water in pores of a fibrous web, n_w, can be obtained [1] from the following relation

$$n_w(t) = n_{wp} e^{-\frac{t}{A}}, \tag{13}$$

where n_{wp} is an initial value of the term n_w for $t = 0$, which is a known value given by

$$n_{wp} = \frac{\dfrac{q10^2}{\rho_w}\left(\dfrac{1}{s_p} - \dfrac{1}{s_T}\right)}{b_p - \dfrac{q10^2}{\rho_w s_T}}. \tag{13a}$$

Coefficient A is a dewatering constant described as

$$A = \frac{b_{sr}^2 \varepsilon_{sr} \rho_w g}{k_{w\_sr}(p_0 - p_a)}. \tag{14}$$

For Equation (12), the parameter ε_2 is given by

$$\varepsilon_2 = \varepsilon_1 \frac{n_w}{n_{wl}}. \tag{12a}$$

Pressure drop in the Equation (12) can be computed from a derivative of Equation (5) around parameter t

$$\frac{\partial p}{\partial y} = \frac{p_0 - p_a}{b} + \sqrt{\frac{2}{b}}\frac{\pi}{b}\cos\left(\frac{\pi}{b}y\right)C_1^{(0)}, \tag{15}$$

where for $y = 0$:

$$\frac{\partial p}{\partial y}\Big|_{y=0} = \frac{p_0 - p_a}{b} + \sqrt{\frac{2}{b}}\frac{\pi}{b}C_1^{(0)}. \tag{15a}$$

After introduction of the constants:

$$F_1 = s_T\rho_{w1}(b_k s_T \rho_{w1} - q10^2),$$
$$F_2 = -\psi n_{wp} s_T \rho_{w1}(b_k s_T \rho_{w1} - q10^2),$$

the function u_{wy} introduced in Equation (11) can be transformed to the following form

$$u_{wy}\Big|_{y=0} = \left[\frac{p_0 - p_a}{b} + \sqrt{\frac{2}{b}\frac{\pi}{b}}C_1^{(0)}\right]\frac{F_1 k_{w1} n_{wp}}{F_1 e^{\frac{t}{A}} + F_2}. \qquad (16)$$

Thus, total amount of the displaced water from a fibrous web in a given time t is

$$Q_w = \frac{F_1 k_{wT} n_{wp} S}{\rho_w g}\int_0^t \frac{1}{F_1 e^{\frac{t}{A}} + F_2}\left[\frac{p_0 - p_a}{b} + \sqrt{\frac{2}{b}\frac{\pi}{b}}C_1^{(0)}\right]dt. \qquad (17)$$

Accordingly, dryness of the dewatered web s, at any specific time t, can be computed as

$$s = \frac{s_p}{1 - \frac{s_p \rho_w Q_w}{Sq10^2}}. \qquad (18)$$

Knowing the variable $Q_w(t)$, we can compute the corresponding values for b(t) from the following relation

$$b(t) = b_k + \Psi\left[\frac{q10^2}{\rho_w}\left(\frac{1}{s_p} - \frac{1}{s_k}\right) - \frac{Q_w(t)}{S}\right] \qquad (19)$$

using Equation (2) and a relation for $V_w(t)$ given as

$$V_w(t) = \frac{Q_w(t)}{St}.$$

Air consumption Q_p

The amount of the air that flows through a dewatered fibrous web in a given time t can be described as

$$Q_p = S\int_0^t u_{py}\Big|_{y=0} dt, \qquad (20)$$

where the following relation can be derived from the Darcy equation [1]

$$u_{py} = -\frac{C_p}{\mu}(1 - n_w)\frac{\partial p}{\partial y}. \qquad (21)$$

The ratio δp/δy has already been described by Equation (13).

Following similar transformations as those shown in the previous paragraph, the air consumption Q_p can be computed from the following relation

$$Q_p = -\frac{C_{pT} F_1 S}{\mu}\int_0^t \left\{\frac{e^{\frac{t}{A}} - n_{wp}}{F_1 e^{\frac{t}{A}} + F_2}\left[\frac{p_0 - p_a}{b(t)} + \sqrt{\frac{2}{b(t)}\frac{\pi}{b(t)}}C_1^{(0)}\right]\right\}dt. \qquad (22)$$

5. Theoretical predictions of the through -air dewatering

The theoretical relations describing the through-air dewatering process of a fibrous web were used for numerical computation of three key parameters of this process: $Q_w = f(t)$, $b = f(t)$ and $W_p = f(t)$ for three different types of a fibrous web and varying values of pressure gradient (drop) on both sides of the web, Figures 3 to 11. Initial values used in this exercise are listed in Table 1.

Table 1

Initial values used for the numerical computation

Parameter			Parameter value for a specific type of grade		
			A	B	C
1	q	$[kg_{sm}/m^2]$	0.190	0.323	0.133
2	s_p	[%]	10.0	10.0	10.0
3	s_T	[%]	41.0	45.0	59.0
4	b_k	[m]	2.17×10^{-3}	3.10×10^{-3}	1.11×10^{-3}
5	Ψ		0.45	0.37	0.41
6	ρ_{wl}	$[kg/m^3]$	1.160×10^3	1.175×10^3	1.305×10^3
7	k_{wT}	[m/s]	5.4×10^{-6}	5.2×10^{-6}	6.6×10^{-6}
8	C_{pT}	$[m^2]$	0.9×10^{-12}	0.6×10^{-12}	0.7×10^{-12}
9	ρ_w	$[kg/m^3]$	1.0×10^3		
10	μ	[kg/(ms)]	17.85×10^{-6}		
11	$\wp$	$[kg/(m^3Pa)]$	12.0×10^{-6}		
12	p_a	[Pa]	1.0×10^5		
13	g	$[m/s^2]$	9.81		
14	s	$[m^2]$	1.0		

Theoretical predictions were derived for the following three types of a fibrous web:

A – filter paper (for filtration of engine oils), 190 g/m^2, s_T=41%,

B – filter board KF-17, 323 g/m^2 (dust absorbing board), s_T=45%,

C – specialty filter paper containing a certain amount of fiber glass, OF, 133 g/m^2, s_T=59%.

Initial values for the particular parameters required for numerical simulations were obtained during the initial phase of the project [1].

Based on these basic data, an experimental facility for through air-dewatering process was designed, constructed, and commissioned. This complex research facility was used for a precise experimental measurement of this unique dewatering process.

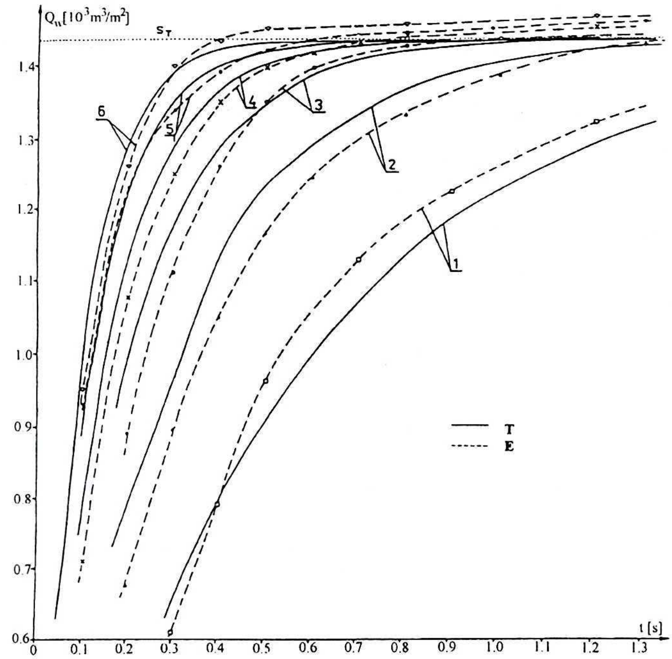

Fig. 3 Theoretical prediction and experimental curves: Q_w=f(t) for an oil filter paper A
1 - $\Delta p = 10$ kPa , 2 - $\Delta p = 20$ kPa , 3 - $\Delta p = 30$ kPa ,
4 - $\Delta p = 40$ kPa , 5 - $\Delta p = 50$ kPa , 6 - $\Delta p = 60$ kPa

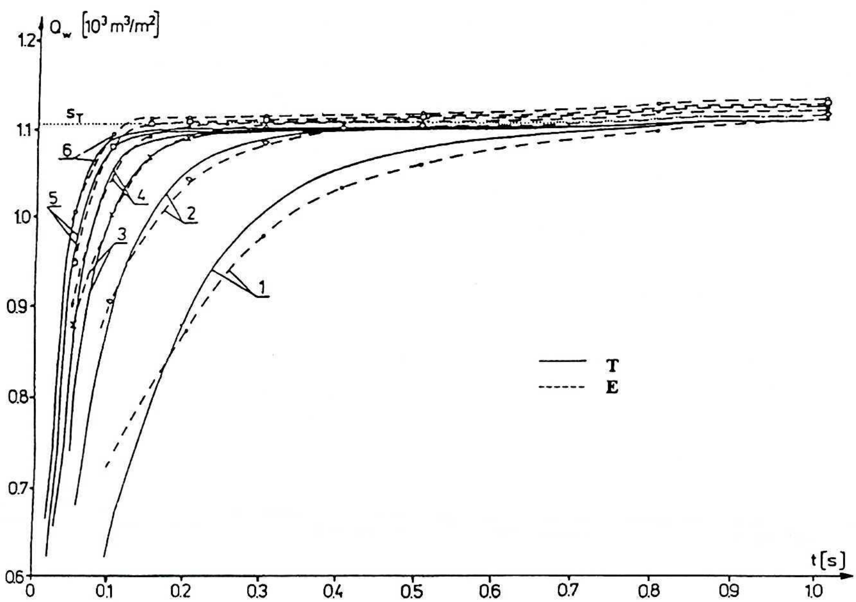

Fig. 4 Theoretical prediction and experimental curve: Q_w=f(t) for filter paper C
1 - $\Delta p = 10$ kPa , 2 - $\Delta p = 20$ kPa , 3 - $\Delta p = 30$ kPa ,
4 - $\Delta p = 40$ kPa , 5 - $\Delta p = 50$ kPa , 6 - $\Delta p = 60$ kPa

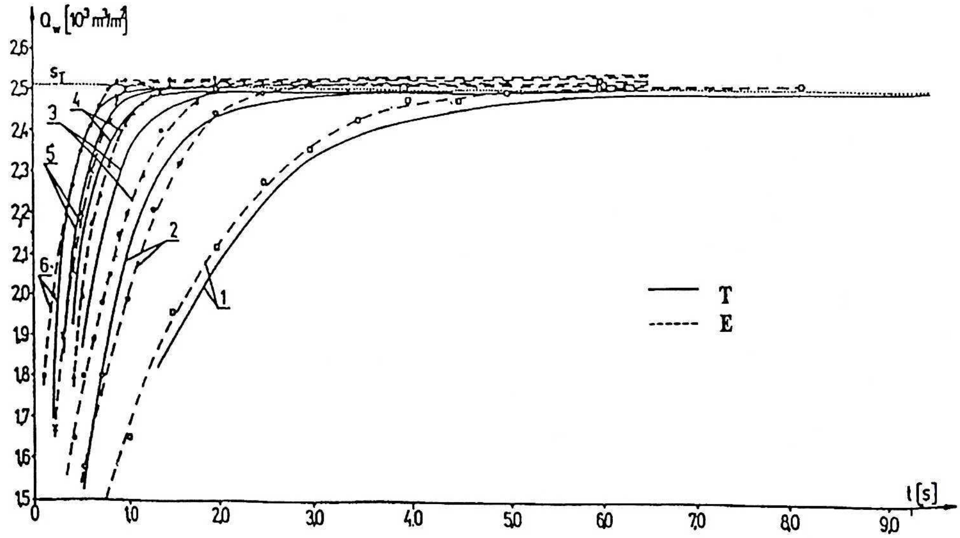

Fig. 5 Theoretical prediction and experimental curve: Q_w=f(t) for an oil filter cardboard B
1 - $\Delta p = 10\,kPa$, 2 - $\Delta p = 20\,kPa$, 3 - $\Delta p = 30\,kPa$,
4 - $\Delta p = 40\,kPa$, 5 - $\Delta p = 50\,kPa$, 6 - $\Delta p = 60\,kPa$

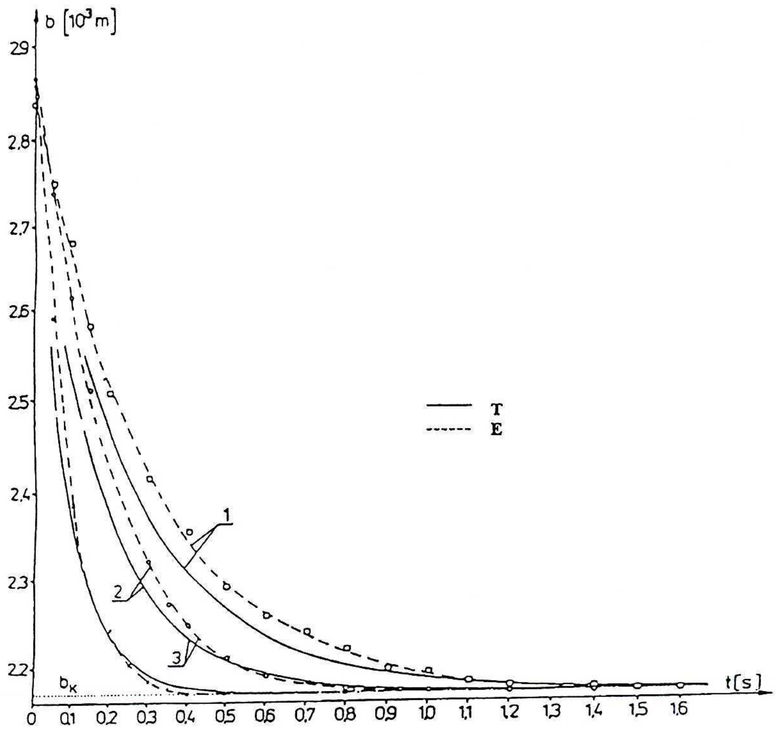

Fig. 6 Theoretical prediction and experimental curves: b=f(t) for an filter paper A
1 - $\Delta p = 10\,kPa$, 2 - $\Delta p = 30\,kPa$, 3 - $\Delta p = 60\,kPa$

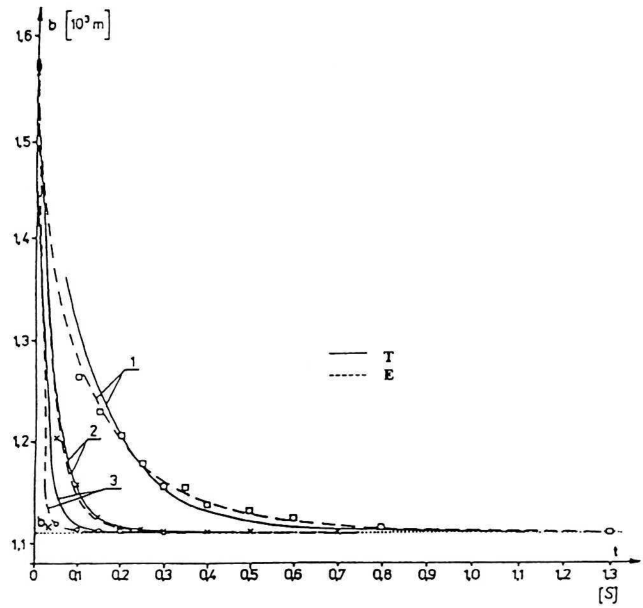

Fig. 7 Theoretical prediction and experimental curves: b=f(t) for an filter paper C
1 - Δp = 10 kPa , 2 - Δp = 30 kPa , 3 - Δp = 60 kPa

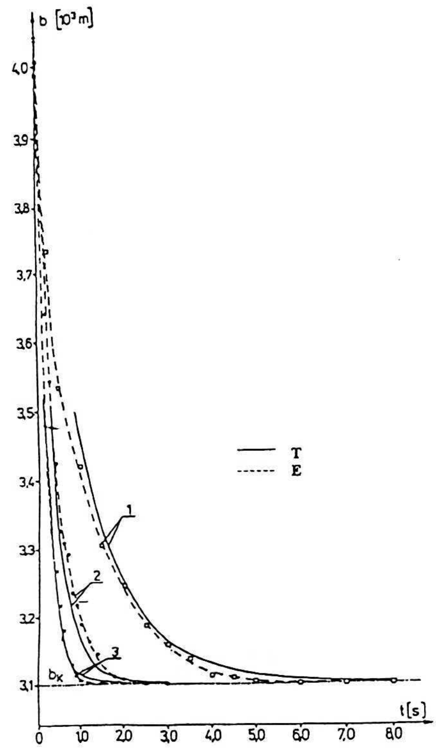

Fig. 8 Theoretical prediction and experimental curve: b=f(t) for an oil filter cardboard B
1 - Δp = 10 kPa , 2 - Δp = 30 kPa , 3 - Δp = 60 kPa

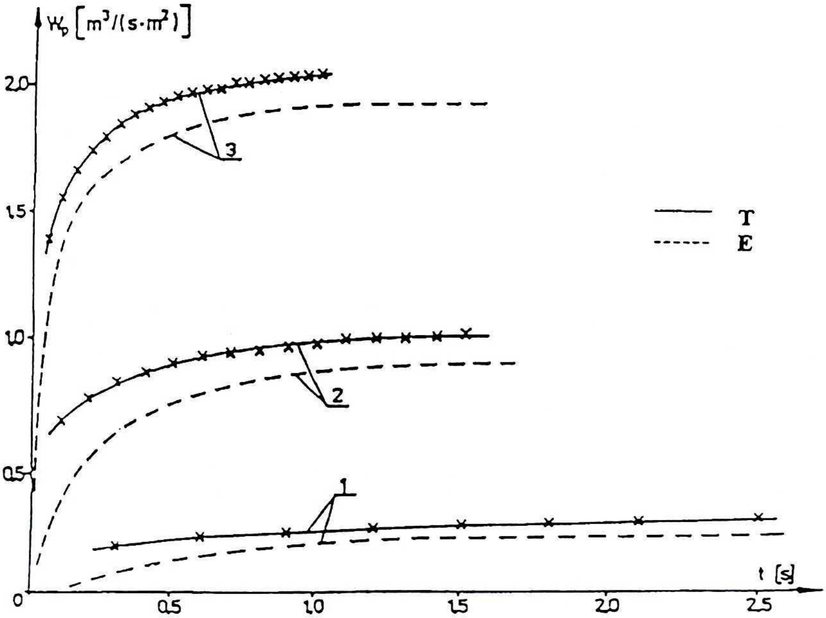

Fig. 9 Theoretical prediction and experimental curve: W_p=f(t) for an oil filter paper A
1 - $\Delta p = 10\,kPa$, 2 - $\Delta p = 30\,kPa$, 3 - $\Delta p = 60\,kPa$

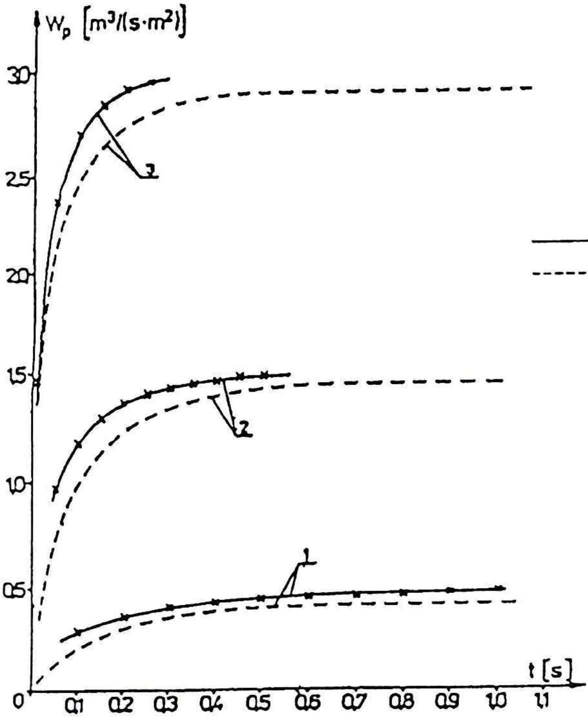

Fig. 10 Theoretical prediction and experimental curve: W_p=f(t) for filter paper C
1 - $\Delta p = 10\,kPa$, 2 - $\Delta p = 30\,kPa$, 3 - $\Delta p = 60\,kPa$

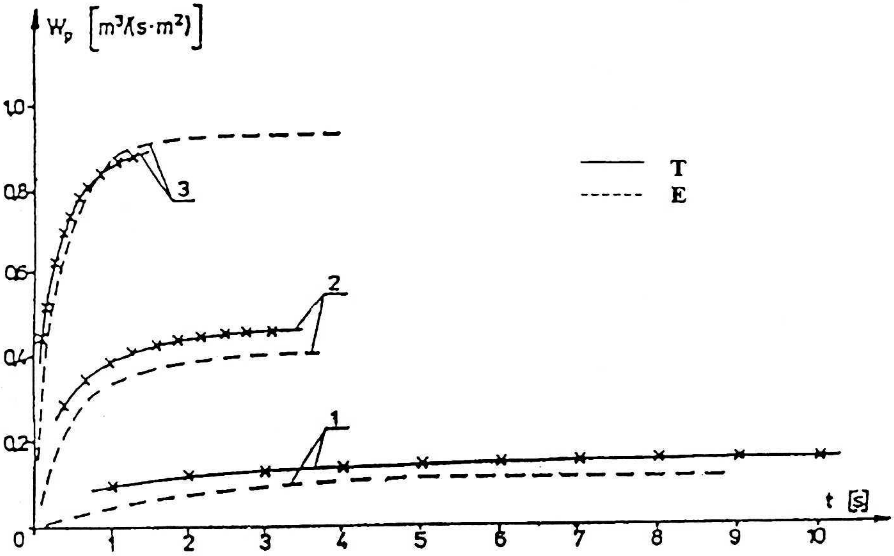

Fig. 11 Theoretical prediction and experimental curve: W_p=f(t) for filter cardboard B
1 - $\Delta p = 10\,kPa$, 2 - $\Delta p = 30\,kPa$, 3 - $\Delta p = 60\,kPa$

6. Experimental analysis of the air through-blow dewatering process

A specific feature of the experimental facility for air through-blow dewatering is the possibility of precise measurements of the amount of water removed from samples while recording changes in the thickness of those samples during the entire process. Samples, 94 mm by 142 mm in size, were carefully cut from a master wet sheet, 220 mm by 880 mm in size, formed on a Type ctp 18 forming device from Allimans. After cutting, each sample was placed on a permeable wire mounted in a special movable frame. Design of the experimental air through-blowing facility allows this wire frame to act, for a very specific time, as a bottom wall of a pressure chamber where each sample was treated with through-blowing air at a specific pressure. Additional samples cut from the same master sheet were used to measure initial sample dryness s_p and thickness b_p.

The amount of the removed water was continuously monitored and recorded during the entire air through-blow dewatering for each sample. At the same time, special equipment was also used to film sample deformation in order to measure changes in sample thickness in the course of the dewatering process.

The experimental facility for air through-blow dewatering consist of the following six major components:

– through-blow dewatering device, an "air press" type, with instrumentation,
– pressure chamber, 3.5 m^3 volume and 600 kPa max pressure, with the air compressor and adsorption dehumidifier,

- special piping with instrumentation containing closing valve, ZRC Z5 type reducer, and ZE 435 type valves with bypass controlled by an electronic timer in the range 0 to 10 sec,
- Pentazet movie camera, with 16 mm tape and special 125 mm lenses, capable of taking from 300 to 3000 pictures/sec, used for monitoring sample deformation (thickness changes) in response to a dewatering intensity,
- microwave moisture sensor, M/K Systems 400R, installed just at the outlet from the pressure chamber, which was used for an continuous monitoring and recording of the amount of removed water,
- control and recording system.

For the sake of simplicity and conciseness, a detailed description of the experimental procedure and the experimental facility for air through-blow dewatering, including all necessary schematics, is given in [1].

7. Experimental conditions and sample preparations procedure

A very important property of filter papers and cardboards is uniformity of sheet structure. To achieve required sheet uniformity, a complex mixture of long fibres and additives in the aqueous suspension have to be distributed, disposed and intermixed on the wire of the forming machine at a very low consistency level, of 0,1% or lower, using special papermaking machines with an incline headbox. The characteristic feature of these systems is that the process of sheet forming starts inside the headbox allowing for a much longer retention time. In such a process, highly dispersed fibers are laid in layers, and it results in a very uniform, almost isotropic structure.

In the present study, the laboratory-scale Allimant Ctp 18 type forming machine, capable of forming high quality filter paper, was used to prepare the master sheets.

Experimental conditions assumed in this process are:

- fiber consistency in a mixing tank: 0.05%,
- drum linear speed: 9.0 m/s,
- ratio of pulp stream speed to drum linear speed: 1.15.

With the above conditions, the 220 mm by 880 mm master sheets were formed with an approximately 10% dryness. From each master sheet, 92 mm by 142 mm samples were later cut for the air through-blow dewatering study on the experimental dewatering facility. In order to prevent any moisture changes, samples were kept in a desiccator.

Three types of paper were used in the experimental part of this study:

A – filter paper (for filtration of engine oils), 190 g/m^2, s_T=41%,

B – filter board KF-17, 323 g/m^2 (dust absorbing board), s_T=45%,

C – specialty filter paper containing a certain amount of fiber glass, OF, 133 g/m^2, s_T=59%.

Specifications for preparation of the above papers, including pulp, were provided by the Warszawskie Zakłady Papiernicze (Warsaw Paper Mill) in Konstancin-Jeziorna, Poland, and Główny Instytut Górnictwa in Katowice, Poland, under a special confidentiality agreement (some specifications are listed in Table I in the first part of this paper [1]). Therefore, the experimental papers used in the present study are very similar to the commercial papers, however, laboratory conditions made it possible to obtain more uniform, close to isotropic sheets.

All air through-blow dewatering experiments were performed in controlled and fixed environment conditions. Air temperature and air humidity in the research laboratory were maintained at 20 $\pm 1^0$C and 65 $\pm 1\%$ humidity during entire dewatering study.

The pressure chamber of the air through-blow dewatering facility was supplied with an unheated air at the pressure p_0 ranging from 110 to 160 kPa. This pressure range allowed us to obtain from 10 to 60 kPa pressure gradient (drop) on both sides of the sample as pressure on the exit side was not controlled and was equal to an atmospheric pressure.

In order to create water flow inside the porous areas of the fibrous web, the pressure drop has to be higher than the critical pressure p_m given by

$$p_m = \frac{\delta \cos\alpha}{r_h},$$

where: δ - surface tension, N/m,

α - wetting angle,

r_h - hydraulic radius of porous in the fibrous web, m.

For all filter papers and cardboard investigated, the hydraulic radius is from 5 to 50×10^{-6} m [1], thus the lower limit for pressure p_0 was set at 110 kPa. The upper limit for this parameter was chosen to prevent any damage to the sheet structure from the water flowing at the elevated velocity inside the porous area.

8. Preparation procedure for the experimental facility

To ensure the optimal conditions for the air through-blow dewatering, a series of preliminary measurements were performed prior to the main experiments. Sheet samples used for that preliminary study were prepared with exactly the same procedure as the experimental samples. Preliminary data indicated that, during any given experiment, the volumetric ratio for air contained in the air chamber to air actually flowing through the sample was high enough to ensure a constant pressure level of the air just over the sample, regardless of the changing permeability of the sample. Value of pressure p_0 was found to decrease by approximately 1,5% of the initial value during 5 to 10 seconds after the beginning of the experiment.

Air pressure in the pressure chamber of the air through-blow dewatering facility, p_0, was measured over the range 0 to 200 kPa with less than 0.2 kPa error with a special pressure device produced by Kistler utilizing a piezoelectric sensor located inside the chamber. The above device allows for a very precise measurement of the actual air pressure with about 1% precision.

The air pressure pulsation was also measured just over the sample surface for varying conditions (different papers and air pressure p_0) using a 55M type thermoanemometric device from DISA. For a fixed flow of the air, flow speed over the airflow area approximately 10 mm over the sample surface was also characterized for different experimental papers. For airflow speed ranging 0.3 to 3,0 m/s, the data obtained during preliminary measurements indicate that, for a fixed airflow, values of actual airflow speed were practically identical at different locations in the pressure chambers for all types of paper investigated. Speed variations of the airflow never exceeded 5% of the nominal value. Therefore, we can assume that the speed field of the fixed airflow through the sheet sample is practically uniform.

Since dehydration process affects porosity and permeability of the wet paper and cardboard samples, speed of the air through-flow varies significantly. Variations in a through-flow speed were also registered using a measuring device from DISA with a specific frequency of 20 kHz.

Temperature and humidity of the air was measured in the pressure chamber by special dry and wet thermocouple.

9. Experimental results

Analysis of the dewatering characteristics: $Q_w = f(t)$

Results of measurements of the amount of water removed by the air through-blow dewatering technique are given in Figures 3 to 5 as a function of the pressure drop Δp for all types of paper investigated. Experimental curves shown in the above Figures illustrate trends in the amount of the water removed from the sheet by a through-blow technique for an area of 1 m^2.

The experimental results shown here indicate that the total amount of water removed by air through-blowing increases significantly with time, than it reaches plateau, approximately constant for a given type of paper, with a definite end of the through- blowing process. The time required to reach this plateau depends on the pressure drop Δp and generally increases with the lower air pressure p_0 (air in the pressure chamber). Similar characteristics of the through-blow dewatering were also predicted by the theoretical description of this process proposed in the first part of this study [1] and shown here as solid lines.

The largest impact on the intensity of the dewatering process, defined as $\Delta Q_w / \Delta t$, is caused by the pressure drop Δp. However, the dewatering intensity was found to decrease with the increase of theoretical sheet dryness s_T, up to a point when the theoretical dryness approaches the final dryness s_k. At this point, dewatering intensity approaches zero.

For a sheet of the initial dryness s_p ranging from 0% to s_T and pressure drop varying 10 to 60 kPa, the average dewatering intensities of the investigated papers are:

0.60×10^{-3} to 1.82×10^{-3} $m^3/(m^2 s)$ for oil filter paper A,
1.36×10^{-3} to 7.40×10^{-3} $m^3/(m^2 s)$ for specialty filter paper C,
0.50×10^{-3} to 2.52×10^{-3} $m^3/(m^2 s)$ for filter cardboard B.

In the commercial process on a conventional papermaking machine [1], the dewatering intensity of the same types of paper was found to be lower than $0,5 \times 10^{-4}\ m^3/(m^2 s)$. The major reason for higher values of the dewatering intensities obtained experimentally with the air through-blowing technique is the use of air with higher density and the lack of web rewetting process typical in the commercial machines.

This experimental study also shows that, for a pressure drop ranging from 10 to 60 kPa, it is possible to totally remove the free water from the investigated papers. However, both required and sufficient time for the air through-blow dewatering of a wet paper depends on the type of paper and pressure drop Δp. Values of this time are key parameters highly affecting the final design of the air through-blow systems.

Taking into account the excellent agreement between experimental results and theoretical predictions curves $Q_w = f(t)$, one can obtain optimal value for the time t_0 from the appropriate relations given in the first part of this paper. Average speed at which water is removed from the fibrous web can be calculated from the following equation

$$u_{w\_sr} = \int_0^{t_0} u_w \big|_{y=0} dt \tag{24}$$

at the same time

$$u_{w\_sr} = \frac{q\left(\dfrac{1}{s_p} - \dfrac{1}{s_k}\right)}{\rho_w t_0} 10^2 \tag{25}$$

The above two equations, together with Equation (16), can be used to obtain the parameter t_0 for any given value of air pressure p_0. It is a very practical method to find an optimal value for t_0.

Analysis of deformation characteristics: b = f(t)

One aspect that distinguishes the filter papers and cardboards from other papers is their normalized thickness, not basis weight. Thus, uniformity of thickness is another key factor affecting quality of filter papers that depends highly on the dewatering process.

Figures 6 and 8 show the experimental results of sheet y-direction deformation in response to a through-blow dewatering for all types of paper investigated. Theoretical prediction curves $b = f(t)$, given by Equation (19), are also shown for comparison. We can see an excellent agreement between experimental data and theoretical prediction.

The obtained data indicate that the experimental curves $b = f(t)$ have just opposite trends to the $Q_w = f(t)$ curves discussed in the previous paragraph. Web caliper dramatically decreases from the initial thickness b_p up to a certain value b_k which again is constant for a specific grade. After reaching b_k, the following deformation process stabilizes.

Time t_0 required to stabilize the deformation process increases with the decrease in pressure drop Δp, a similar trend to the dewatering characteristic $Q_w = f(t)$. For each particular value of Δp investigated, it is possible to reach the final, grade dependent thickness b_k. Again, time t_0 required to reach the final thickness b_k was found to be grade dependent. Particular values for the required time t_0 for both dewatering and deformation processes are practically the same for a given grade. This experimentally found agreement supports the previously suggested assumption that the amount of the free water removed from a sample and the final sample thickness are highly correlated.

Moreover, an excellent agreement between experimental data and theoretically predicted curves $b = f(t)$ provides the necessary validation for the earlier assumption that the relation $b = f(v_w)$ is linear.

Sample thickness was also recorded with a standard caliper meter each time the particular sample was periodically removed from the air through-blowing facility to measure its dryness as a function of air through-blow dewatering time. Comparison of the caliper obtained in the pressure chamber (from the recorded film) and that measured with a standard off-line caliper meter suggests that there is no elastic recovery of the thickness, thus there is no elastic deformation of the paper during the air through-blow dewatering.

After sample reaches its final dryness $s_k \geq s_T$, it has a fixed final caliper b_k which depends only on the type of paper used. This suggests that further airflow through a porous area of the sheet at a dryness $s_k \approx s_T$ does not affect its thickness until the beginning of the drying process associated with a typical sheet shrinkage.

The above conclusions suggest that deformation of the wet paper in response to the air through-blow dewatering has different characteristics than deformation experienced by paper in the press section, when paper passes through the high loaded nips formed by press cylinders.

The overall deformation of the paper in a typical press section, at very high loads, comes from the mechanical deformation of the individual fibers, associated with change in their volume, and from fibers being shifted inside the fibrous web. In the case of air through-blow dewatering, there is not deformation of individual fibers, and thus their volume remains unchanged during this process. For the entire dewatering process, fibers dryness is equal the theoretical paper dryness s_T. In the typical dewatering, only free water contained in the porous area of the web is removed. Sheet y-direction deformation comes from wet fibers being shifted to fill out space freed up by the removed water. During this process, fiber shape is frequently changed, with the amount of this change depending on elasticity of the individual fiber. This behaviour explains the correlation between sheet y-direction deformation caused by dewatering and the amount of water removed during this process.

Analysis of deformation characteristics: $W_p = f(t)$

Volumetric intensity of the air through-flow, for a time of 1 sec and at 1 m^2 area, was also measured for all types of paper investigated. These measurements were performed inside the pressure chamber by recording the speed of airflow just over the sample surface [1]. Since the speed of the airflow was found during preliminary measurements to be practically uniform throughout the entire cross-section of the pressure chamber, at a certain level just over the surface of a sample, values of airflow speed were measured at the centreline of the pressure chamber only. Thermoanemometric probe was used to record these data.

Figures 9 to 11 show the experimental results for the air flow speed intensity as a function of time, $W_p = f(t)$, for all three types of paper investigated. Again for comparison, the theoretically predicted curves $W_p = f(t)$ are also drawn as solid lines.

Again, an excellent agreement found between the experimental data and the theoretical prediction obviously validates accuracy and precision of the mathematical model of air through-blow dewatering proposed in the first part of this paper. As an example, values of the above parameters for oil filter paper being dewatered for t = 1.5 seconds at the pressure drop of Δp = 30 kPa are: 1.0, 0.9, and 0.8 $m^3/(m^2s)$, thus relative difference between these three data points is less than 10%.

A study of the dewatering characteristics, $W_p = f(t)$ and $Q_w = f(t)$, obtained for a specific type of paper indicates that the same increase in sheet dryness ($\Delta s = \text{const}$) can be achieved with different combination of key dewatering variables Δp and t_0 at a fixed air consumption Q_p ($Q_p = \text{const}$). For example, at a fixed air consumption $Q_p = 0.55$ m, 28% dryness of the oil filter paper sample can be obtained with any set of the following conditions:

1. Δp = 60 kPa and t_0 = 0.3 sec,
2. Δp = 30 kPa and t_0 = 0.6 sec,
3. Δp = 10 kPa and t_0 = 1.8 sec.

The flexibility of the air through-blow dewatering is a very important characteristic of this process allowing its successful introduction to different types of papermaking machines working with varying speeds.

10. Conclusions

The theoretically obtained mathematical model of the air through-blow dewatering was validated with very difficult experimental measurements. An excellent agreement between experimental and theoretically predicted values of the key characteristics of this process makes this model a very valuable tool in optimising both the through blowing process and the design of the air through-blow dewatering equipment for a successful application in commercial papermaking machines. Based on the theoretical predictions and the experimental measurements, the following conclusions can be drawn:

1. Air through-blow dewatering of filter papers and cardboards can be described as two-phase process of the air and water flow through a deformable fibrous structure with a linear relationship between paper y-direction deformation (change in thickness) and paper dehydration (change in volume of free water contained in a fibrous web). Therefore, dewatering process can also be described as a one-way isotropic consolidation of a fibrous web with a linear deformation-dehydration relation theoretically shown in Equation (3).
2. Caliper of paper web being dewatered with air through-blowing technique changes according to Equation (2) with deformation coefficient Ψ being dependent mostly on fiber elasticity. Values of the Ψ coefficient were found to vary from 0.37 to 0.45 for all three types of paper investigated.
3. Experimental measurements indicate that, for pressure drop not higher than 60 kPa, air through-blow dewatering does not cause any elastic deformation of the filter papers and cardboard. There is no measurable deformation recovery after through-blow process (sample does not swell). Deformation of the web being dewatered is mostly due to fiber shifting inside the fibrous structure. Individual wet fibers change their shape, but their volume remains unchanged until the beginning of a shrinkage process associated with a typical drying process of fibrous webs.
4. Thickness of a dewatered paper increases with decreasing speed of the process. Initially high dewatering speed slowly decreases with higher sheet dryness and starts approaching zero when paper dryness approaches the theoretical dryness s_T, with the thickness decreasing to a constant, grade dependent, final thickness b_k regardless of pressure drop Δp.
5. Intensity of the air through-blow dewatering decreases with the increase in dryness of investigated types of paper. Regardless of the pressure drop Δp used in this process, dewatering intensity reaches its minimum at the same level of dryness $s_k \approx s_T$. The increase in pressure drop affects the average value of the dewatering intensity.
6. Unheated air can be successfully used in through-blow dewatering technique to completely remove free water from the fibrous web when sheet

arrives at its theoretical dryness s_T. Values of theoretical dryness can be practically obtained for a particular type of paper from the Jamye's procedure. Required and sufficient time t_0 for the through-blow dewatering can be computed from Equations (24) and (25) by means of Equation (16).

7. The amount of water removed from a web, at any given time t, can be calculated from Equation (17). Equation (22) can be used to compute the air consumption Q_p at a given pressure p_0 required for the through blowing process. It was found that, for a fixed increase in sheet dryness $\Delta s = s_k - s_T = \text{constant}$, Q_p is practically constant. Thus, to achieve the same increase in dryness, different values of the term $\Delta p t_0$ can be used according to different technological requirements.
8. Experimentally measured dewatering intensity of the air through-blow dewatering, which depends on type of paper and the used ranges of Δp from 0.5×10^{-3} to 7.5×10^{-3} $m^3/(m^2{\cdot}s)$, were found to be one order of magnitude larger than those found for commercially used dewatering techniques. These high values of the dewatering intensity allow for producing filter paper and cardboards at optimal conditions, i.e. low stock consistency in the range of 0.05% that guarantees a high quality and uniformity of the end product. The use of air at a higher density, and elimination of the rewetting process, ensure high efficiency of the through-blowing technique of paper and cardboard dewatering. The dewatering model proposed by Wahlström proved insufficient in this case.
9. The data obtained in the present study provide a valuable information for designing the new improved systems for filter paper and cardboard dewatering, utilizing the "air press" concept, applicable to commercial papermaking machines [2].

Nomenclature

a	-	sheet length in x-direction [m],
A	-	dewatering constant,
b	-	sheet thickness [m],
C_p	-	air flow (permeability) indicator [m_2],
g	-	earth gravity (attraction) [m/s^2],
k_w, k_p	-	coefficients for water and air flow through the sheet [m/s],
L	-	length of the web in the through air zone (length of the air through-blow dewatering zone) [m],
n_w, n_p	-	modules of water and air in the sheet pores,
n_{w1}	-	module of fibers in the sheet,
p	-	dewatering pressure [Pa]
p_a	-	atmospheric pressure [Pa],
p_0	-	air pressure over the web (in the pressure chamber) [Pa],
r_h	-	hydraulic radius of pore in the fibrous web [m],

s	-	sheet dryness [%],
S	-	sheet area in the through air dewatering zone [m^2],
t	-	time [s],
t_0	-	optimal time for free water removal by air through-blowing [s],
u_w, u_p, u_{w1}	-	water, air and fiber speeds [m/s],
W_p	-	air flow indicator [$m^3/(m^2s)$],
v_s	-	wire and sheet speed [m/s],
q	-	sheet basis weight at 100% dryness [g/m^2],
Q_p	-	air consumption [m^3],
Q_w	-	amount of water displaced from the web [m^3],
α	-	wetting angle,
ε, ε_1	-	sheet porosity coefficients,
Δp	-	pressure drop [Pa or kPa],
$\wp$	-	proportionality constant [kg/\(m^{3}Pa)]'
μ	-	air absolute (dynamic) viscosity [Ns/m^3],
ρ_w, ρ_p	-	water and air densities [kg/m^3],
ρ_{w1}	-	density of wet fibers in the web at dryness of s_T [kg/m^3],
δ	-	surface tension, N/m,
ψ	-	deformation coefficient [$m/(m^3/m^2)$],
τ	-	air temperature [^0C].

Indexes for given symbols:

p, k, sr	-	initial, final and average values,
T	-	values for the web at the theoretical dryness.

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REFERENCES

[1] Kawka W.: Consolidation of the absorptive fibrous webs in paper – making machines at the air flow. Politechnika Łódzka, Zeszyty Naukowe – Rozprawy habilitacyjne 1985, No 75, pp. 7÷182 (in polish).

[2] Kawka W., Ingielewicz H., i in: Patent PRL No 141560, 1990r.

[3] Kawka W.: Consolidation of a fibrous web by means of through air. TAPPI, 2001, Vol. 84, No 2, pp. 2÷30.

[4] Kawka W., Ingielewicz H.: Formation and Consolidation of Filter Papers and Paperboards. PROGRESS, 1993, Vol. 1, No 1, pp. 421÷437.

[5] Kawka W., Ingielewicz H., Stępień K.: Formation and Consolidation of Absorbent Papers from Noncellulosic fibres., Przegląd Papierniczy, 1995/1996, Special Issue, pp. 60÷65.

[6] Kawka W., Szwarcsztajn E.: Nouvelle Technique D'eqoutags des Papier Poreux. Revue ATIP, 1974, Vol. 28, No 8, pp. 385÷389.

[7] Kawka W., Ingielewicz H.: Investigation on Intensive Dewatering and Drying of Porous Papers. Paper, 1979, Vol. 191, No 10, pp. 618÷622.

[8] Haas L.: Poland Improves Drainage. Pulp and Paper International, 1974, Vol. 16, No 12, pp. 51÷52.

[9] Kawka W., Szwarcsztajn E.: New Forming, Draining and Drying of Porous Papers. EUCEPA-74 in Paris, 1974, pp. 104÷109.

[10] Kawka W., Szwarcsztajn E.: Results of Investigations on the Equipment for Intensive Dewatering and Drying of Porous Papers. EUCEPA-79 in London, 1979, pp. 143÷149.

[11] Przybysz K.: Limiting and theoretical dryienes of a pressed paper web. Przegląd Papierniczy, 1982, Vol. 38, No 3, pp. 84÷86 (in polish).

[12] Paulapuro H.: Papermaking Part 1, Stock Preparation and Wet End. TAPP, 1999, pp. 285÷299.

[13] Новиков Н. Е.: Прессование бумажного полотна. Лесиая Промышленность. Москва 1972.

[14] Pohorecki R., Wroński S.: Kinetics and thermodynamic of processes in chemical engineering. WNT, Warszawa 1987 (in polish).

[15] Carson G., Lindström T., Florén T.: Permeability to Water of Compressed Pulp Fiber Mats. Svensk Papperstidn. 86, 12, R 128-R 134 (1983).

[16] Gardiner F.J.: How Air Through-flow Dewaters Porous Webs. Pulp a Pap. Mag. Canada, 79, 3, T115 (1978).

Analiza procesu konsolidacji wstęgi papieru w prasie powietrznej

Streszczenie

W pracy przedstawiono analizę teoretyczną procesu odwadniania i konsolidacji mokrej wstęgi papieru metodą przedmuchu powietrza. Taki proces zachodzi w nowym (opatentowanym) urządzeniu nazwanym prasą powietrzną. Wyniki rozważań teoretycznych zostały następnie zweryfikowane doświadczalnie. Badania eksperymentalne prowadzono na specjalnie zaprojektowanym stanowisku badawczym przy użyciu trzech rodzajów papierów przeznaczonych do filtracji oleju i powietrza. Udowodniono, że proces przedmuchowego odwadniania wstęg włóknistych można rozpatrywać jako jednokierunkową konsolidację przy liniowej zależności odwodnienia i odkształcenia. Zaproponowano nowy system urządzeń do ciągłego wytwarzania wysokojakościowych papierów filtracyjnych z prasą powietrzną jako podstawowym elementem.