Impact of Air Jet Impingement Technology on the Strength of Tissue Paper

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Impinging air jets can be used to dewater, heat, and dry the web of tissue paper. High velocities of the air jets degrade the paper, and appropriate adjustments to the jet velocity and the distance of the nozzle from the surface of the wet web are crucial to obtain the highest quality product. This work investigated the correlation between the velocity of the air jet and the strength of paper subjected to the impingement method. Papers with an initial moisture content of 20% and various pulp mixes were tested, and the physical properties of papers were explored. After impinging an air jet, different tensile strength limits were obtained in the machine and cross directions. The paper had lower apparent density and higher roughness compared to classical pressing. The dependence of tensile strength and roughness on the fibers composition also was determined. Increasing the amount of eucalyptus fibers in impingement dewatered paper resulted in a decrease in its tensile strength and roughness. The value of elongation before breaking was the highest for softwood papers after the impingement method. The maximum velocity of an air jet that can be used to dewater or dry paper without the risk of damage to the papers was determined.

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INTRODUCTION

Tissue papers belong to the group of hygienic and sanitary papers. Their most desirable features are softness, adequate absorbency (porosity), and low apparent density. Obtaining the desired paper properties depends on both the type of cellulose fibers used and the production technology. The hardwoods and softwoods fibres are used to produce tissue paper, which gives the product appropriate strength (softwoods long fibers) and softness (hardwoods short fibers) (Loebker and Sheehan 2011; De Assis *et al.* 2018, 2019; Fiserova *et al.* 2019).

The strength of the paper is influenced by few factors, including the type of interaction between the surfaces of adjacent fibres (interdiffusion, mechanical blocking and capillary bridges) (Persson 2008; Hubbe 2013; Hirn and Schennach 2017) and the strength and arrangement of the fibers in the network. Generally, refining and wet pressing improve the bonding between fibers. Higher strength of paper can be obtained by using long fibers, because they can form bonds with many other fibres. The formation of a well bonded structure depends on the number of fibres, their width and wet elasticity, external fibrillation, and fine particles. A good fit results in a large number of bonds per unit area (de Assis *et al.* 2018).

Tensile failure in paper products occurs when the fiber-to-fiber bond breaks or the fiber becomes damaged. In tissue products where the bond between the fibers are fewer or are weaker (in comparing with, *e.g.*, printing papers) the most probable is their breaking rather than damage of the fibres (Borch *et al.* 2002; Mark 2002; Kullander *et al.* 2012; de Assis 2018). Therefore, wet pressing improves the strength of the paper by better fitting the fibers. The use of an air impingement method to dry a wet web may break up the loose network of fibers constituting its structure. In turn, to achieve low apparent density of paper, appropriate production technology must be used. Producing highly porosity tissue papers with low apparent density is difficult to achieve when using conventional technology.

A conventional tissue machine (dry creped tissue, DCT) uses a process that involves pressing the web before drying it. A Yankee cylinder and a dryer hood are used to dry the web. Typically, a high linear load from the press is used to dry the web as far as possible before the drying zone, thus reducing the thermal energy consumption (Karlsson 2000).

Mechanical pressing of the fibrous web, which occurs in the contact area between the press and the drying cylinder, causes a partially permanent densification of the fibrous structure. This leads to both a strengthening of the web structure and a significant reduction in its porosity. The use of a conventional web pressing and drying system is not an optimal solution for the production of porous papers with high bulk, as the process of pressing the web increases its apparent density, thus limiting its softness and absorbency (He *et al.* 2003).

To replace (or reduce) the need for mechanical pressing of the web, a convection drying method can be used in the production process. This method allows a higher drying rate to be obtained (the amount of water evaporated per hour per unit area of drying surface), and better softness and absorbency of the paper compared to conventional (DCT) technology. However, this solution increases the consumption of thermal energy used to produce the paper (Kullander *et al.* 2012).

TAD air drying technology is also used to produce tissue paper. The machine does not have a press section, which allows the production of paper with low apparent density. The web with a dryness of 20 to 25% is introduced into the drying area consisting of a perforated drying cylinder. The web lying on the TAD cylinder is blown with hot air. Depending on the solution, hot air flows through the paper structure from inside or outside the cylinder. The advantage of this technology is the production of papers characterized by high bulk, softness, and absorbency. Unfortunately, the paper production process using a TAD machine involves higher investment costs and energy consumption (Kullander *et al.* 2012; De Assis *et al.* 2018; Reczulski *et al.* 2023).

Impinging air jets are commonly used as part of the paper production process (Keränen 2011), as these can dewater, heat, or dry the paper web. The use of this method results in high heat and mass transfer coefficients in the impinging area. In addition, the use of an impingement system enables a low apparent density to be achieved for the paper. The technologies used in the production of tissue paper use hot impingement air jets to dry or heat paper with a wide range of initial levels of dryness (10 to 55%) (Chitsazan *et al.* 2021).

The most well-known process that uses an impingement system is the convection drying of tissue paper in machines with a Yankee cylinder. The use of impinging air jets in this case allows for a high drying rate of the paper. Tissue paper is dried ("dry creped") using a Yankee drying cylinder and a high-performance dryer hood, with jets of hot air flowing from the nozzles located in the Yankee hood directly onto the surface of the web. The high level of dryness of the web obtained after pressing allows for the use of high-velocity impingement air jets in the hood of up to 150 m/s, without the risk of damaging the structure of the paper. The use of a conventional DCT solution to produce tissue paper results in a decrease in its softness and absorbency (De Assis *et al.* 2018).

Another example of the use of impingement jets to dry a web is air-dried tissue (ADT) technology, where a pressing stage is optional. This approach uses low velocities for the hot air to avoid damaging the structure of the web. The initial dryness of the web entering the dryer is 20 to 25%. In the forming part of the machine, a special structural wire is used to shape the topography of the wet web surface. In this way, the web is given suitable structural properties (low apparent density, high absorbency, *etc*.) (Graf 2013; Klepaczka 2007).

A hot air impingement system is also used before the press in paper machines with crescent former units and an extended nip press. A wet web with a dryness of 10 to 12% is transported on the felt and heated with hot air jets (150 to 200 °C) in the suction roll in front of the press with an extended nip press. This action reduces the viscosity of water in the web, thus reducing the resistance to water flow during pressing (Deventer 1997).

Impingement drying is often used in the production of tissue paper; however, different velocities of air jets are needed due to the varying amounts of water in the paper structure. The higher the water content of the paper, the lower its strength, requiring the use of air jets with lower velocity. The high-velocity air that flows from the nozzles can often cause product degradation if the tensile strength of the paper is low, although higher velocities allow for a higher heat transfer coefficient. It is therefore important to make appropriate adjustments to the jet velocity and the distance of the nozzle from the web surface to obtain the highest quality product with the lowest possible energy consumption (Etemoglu *et al*. 2010).

Obtaining the optimal heat transfer coefficient for the impact area of the air jets involves finding an appropriate shape and size for the nozzles, and suitable values for the distance between the nozzles and the web surface, the velocity and temperature of the air jets, the number of nozzles, and the distance between nozzles. Extensive research in this area has been conducted by Etemoglu *et al.* (2010). Tawfek (1996) determined the heat transfer characteristics of a round jet impinging on an isothermal plate, while Gulati *et al.* (2009) determined the influence of the nozzle shape, the distance between the nozzle and the material, and the Reynolds number on the local heat transfer characteristics. Three different nozzle cross-sections were considered: round, square, and rectangular. Many publications (Aust *et al.* 1997; Gabbrielli *et al.* 2016; Martín *et al.* 2021) have considered modelling processes for the drying section of a paper machine using an impingement system.

This article presents research on the physical and strength properties of wet paper samples subjected to the impingement method. The aim was to explore the extent to which the air jets (*i.e.* their velocity) were destructive to wet tissue papers made of various fibre pulps. Jets of unheated impingement air were used, as the wet paper samples were not sensitive to heat, *i.e.* the heat did not degrade the paper. Additives that increase the wet strength of paper were not used in this study, as these can inhibit the swelling of fibres and prevent their separation.

The high velocities of hot air used in the impingement method allow for a high heat transfer coefficient, but the fast-moving air can also damage the structure of the paper. Adjusting the velocity of the impinging air jets and the distance of the nozzles from the web surface is not a simple task, especially since the strength of the paper in the wet state varies depending on the production processes, stock composition, chemicals, *etc*.

The main factor that determines the air impingement velocity is the water content in the paper structure: the more water in the paper, the lower its strength, requiring the use of air jets with lower velocity. In this study, the upper limit on the value of the air velocity was determined by the appearance of defects in the paper sample. To obtain defect-free paper with the highest possible heat transfer coefficient, the impingement air velocities are typically adjusted in production plants by trial and error, which is often associated with large production and energy losses.

Research on this topic was therefore undertaken to expand the current knowledge of this subject. In addition to the tensile strength of the samples, the Bendtsen roughness number and the apparent density, which are important properties of tissue papers, were also studied.

The article describes the strength behavior of tissue paper subjected to the impingement drying method. The strength of paper subjected to impingement with various air velocities was tested. The article draws attention to the danger of breaking the loose network of fibers with high air velocities during drying. These dangers can be counteracted by reducing the velocity of air or increasing the distance of the nozzles from the web surface. Unfortunately, this results in under-drying of the web and, consequently, a decrease in the performance of the machine. In addition to the breaking force of the samples, the Bendtsen roughness number and the apparent density, which are important properties of tissue papers, were also studied.

EXPERIMENTAL

Samples Characterization

This research consisted of three series of experiments. The first series of studies (S1) involved dewatering paper samples with an unheated air jet, while in the second series (S2), the samples were pressed in a two-roll press, and the third series (S3) involved a combination of both dewatering techniques. The S1 research reflects the impingement drying process of a wet web with a dryness of 20% without the pressing process. The second series (S2) of research concerns the production process, which involves pressing the web before convection drying. A third series (S3) of research was also performed, according to the process in which the web is subjected to impingement heating before the pressing zone and then pressed and convection dried. The second and third series of tests were additionally performed for comparison purposes with the S1 research.

Paper samples with a basis weight of 30 g/m^2 were formed from commercial bleached softwood pine kraft pulp (BSK) and bleached hardwood eucalyptus kraft pulp (BHK). The paper samples under study were made of 100% long-fibre pine pulp (referred to here as type A), 50% long-fibre pulp and 50% short-fibre eucalyptus pulp (type B), and 30% long-fibre pulp and 70% short fibre pulp (type C). The average moisture content of the paper pulp was approximately 4.3%.

The adjustable parameter was the percentage composition of the initial paper pulp used to form the paper. The pine pulp was refined to a level of 25 °SR in a laboratory Hollander beater, while the eucalyptus pulp was defibrated in a laboratory centrifugal defibrator (14°SR). The SR freeness of the pulp was analyzed in accordance with the ISO 5267-1:1999 standard (L&W Schopper–Riegler freeness tester, Sweden), and the fibre length was measured using a Kajaani FS-200 tester. The long-fibre pulp had an average fibre length of 1.53 mm, whereas the short fibre pulp had an average fibre length of 0.6 mm (see the Supplementary Information). Wet paper samples with dryness of 20±2% were studied.

Before the strength studies were carried out, the samples were subjected to a preliminary preparation process. After dewatering with an impinging jet, the samples were dried between two heating plates to 93 to 95% dryness (moisture content 0.075 to 0.0526 kg water/kg fibre). Drying the samples between two heating plates at 150 °C with a drying felt prevented the formation of wrinkles on the surface of the paper. In the next stage, the paper samples were conditioned according to the ISO 187:1990 standard. The thickness and apparent density were analysed based on the ISO 12625-3 standard, while the roughness of the paper was analysed based on ISO 8791-2:1990 (Bendtsen Roughness Tester, TMI Testing Machines Inc., USA).

Tensile strength was determined based on the PN-EN ISO 12625-4:2023-02 standard. Due to the method of preparation and the specific nature of the samples, their other dimensions were used (150x25) and the measurement parameters were modified. The width of the sample was limited by the width of the head of the device. The prepared samples were subjected to strength tests in a Zwick Z010 measuring device. The measurements were conducted in a room with the same climatic conditions as when the samples were air-conditioned. A standard testing machine equipped with a 500 N force measuring head with handles intended for tissue samples was used for the measurements. An initial force of 1 N and a testing speed of 50 mm/min were used. Test span, *i.e.* the distance between the clamping lines, was 100 mm.

Forming of Paper Sheets

Wet paper samples were formed using an Allimand device, which can form a sheet of paper with properties similar to those obtained from a paper machine. In this device, the speed of the wire and the flow velocity of pulp from the outlet nozzle can be adjusted. There are therefore conditions for using any jet-to-wire ratio.

The paper sheet was formed by injecting a stream of paper pulp (from an outlet nozzle) onto a synthetic wire placed inside a cylindrical perforated drum. The drum rotated around a vertical axis at a speed of 1000 rpm. The prepared paper mass with a concentration of 0.15% and a volume of 10 l was passed through an outlet nozzle with appropriate pressure. In this way, the appropriate pulp flow rate was achieved. The nozzle made reciprocating movements in the vertical direction while forming the sheet (figure in supplementary information).

When a sheet with dimensions of 220 × 880 mm had been formed, it was removed from the drum and cut into samples with dimensions (150 × 35 mm) determined by the width of the head and the dimensions of the running frame.

The samples were cut in both the longitudinal (MD) and transverse (CD) directions of the formed sheet, as this is important for tests of the tensile strength of paper. The parameters of the forming device were selected in such a way as to obtain a jet-to-wire ratio of 0.95. After forming the sheet, its dryness and grammage was checked, and any sheet that did not meet the assumed level was rejected. Wet samples cut from the sheet were transferred to the research stand under constant air humidity (70%) and at a temperature of 23 °C.

Dewatering with Impinging Air Jets

In the first series of studies (S1), paper samples of types A, B and C were subjected to the air jet impingement method. The tests were divided into three stages based on various values for the air flow rates through the nozzle (outflow slot). At each stage, 10 samples cut from the formed sheet in the MD and CD directions were studied. Based on the test results, the standard deviation was calculated.

In the first set of tests making up series S1, the velocity of the air jet flowing from the nozzle was set to 4.8 m/s (referred to here as series V_{A1}), whereas in the second, this was set to 5.6 m/s (series V_{B1}), and in the third to 6.4 m/s (series V_{C1}). To compare the effects of the air jet impingement method with the conventional pressing method, a second set of studies were conducted (S2), in which the samples were pressed in a laboratory press at an average pressing pressure of 2 MPa and a press speed of 4 m/s.

In series S3, a combination of the methods described above was used. The samples were first subjected to dewatering with an impinging jet, and then pressed. These tests used the same velocities for the air jet as in series S1 and the same pressing parameters as in series S2.

Low air velocities were used in this research due to the low strength of the wet samples. The minimum air velocity was determined based on the initial decrease in the breaking force of the samples, while the maximum air velocity was determined by the appearance of defects in the paper.

Impingement System

The paper web drying/heating devices found in industry usually have certain design limitations due to the excessive numbers of design variables and device operating parameters. The design of these devices is limited by the regulation of one or more of the important parameters that affect the drying rate of the web (such as the temperature and the velocity of the air jets flowing from the nozzles).

Choosing the right guidelines for a project in order to ensure optimal operation in terms of energy consumption, production capacity, and product quality is extremely difficult. Other desirable aspects are ease of regulation of the process and predictable operation of the device when its operating parameters are changed.

Most industrial solutions are based on procedures for the construction of drying/heating devices that are developed through trial and error. Therefore they are based on practical experience. The choice of nozzle geometry and nozzle configuration for the entire system (multi-nozzle system) has a significant impact on the cost of the device, its operation, and the quality of the product (*e.g.*, an uneven web moisture profile in the CD direction).

Drying systems are usually composed of several similar nozzle boxes that are arranged in a modular fashion, with appropriately placed outlet holes. Fume extraction systems must be designed to minimise any unevenness in heat distribution across the machine. It is therefore important to use an appropriate nozzle system. Two basic types of nozzle are used in industry: round and slotted.

An experimental stand was developed for this research, as shown in Fig. 1. The research stand consisted of two main systems: an adjustable head, to which compressed air was connected, and a system with a trolley for the placement of a paper sample. The wet paper sample was fixed onto the trolley, on a bronze wire that was tensioned with a constant force of 4 kN/m using a system of springs. The trolley moved on guides, and it was driven by a pneumatic system with adjustable pressure. The speed of the trolley was determined by measuring the distance travelled and the time, determined using motion sensors. The experiments were conducted at the maximum achievable trolley speed of 4 m/s. An energy absorption system for the trolley was also installed, based on a pneumatic system.

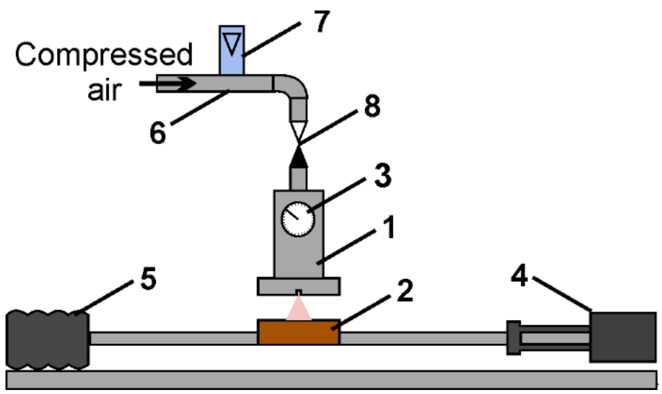

Fig. 1. Schematic diagram of the research stand. 1 - head, 2 - trolley with sample, 3 - manometer, 4 - drive system, 5 - trolley energy absorption system, 6 - pipeline, 7 – rotameter, 8 – valve

The head of the device was positioned in relation to the moving trolley at an angle of 90°, to ensure that the air jet hit the sample surface perpendicularly. The vertical adjustment of the head allowed for precise determination of the distance between the slot nozzle and the sample surface. A plate with a slot nozzle of width B = 1 mm was installed in the head, where the distance from the nozzle to the surface of the paper sample was Z = 8 mm. Following research by Etemoglu *et al*. (2010), the optimal ratio (in terms of energy) between the distance of the nozzle from the paper surface (Z) and the width of the nozzle (B) was assumed to be equal to eight. Compressed air was supplied to the head from a tank connected to the compressor. To determine the flow rate and velocity of air outflow from the head nozzle, a PS31 rotameter from Tecfluid was installed on the research stand. The location at which the air flow was measured is marked in Fig. 1. During the experiments, the operating parameters of the stand were controlled, such as the air flow rate, the speed of the trolley, the tension of the wire, and the air temperature and humidity in the chamber of the head. The air jet between the nozzle and the paper surface had the form of a pyramid, with a rectangular base and an apex angle α of 30° (Fig. 2), resulting from the geometry of the nozzle in the head. In the experiments, a slot was used that was perpendicular to the plate surface, without rounded edges.

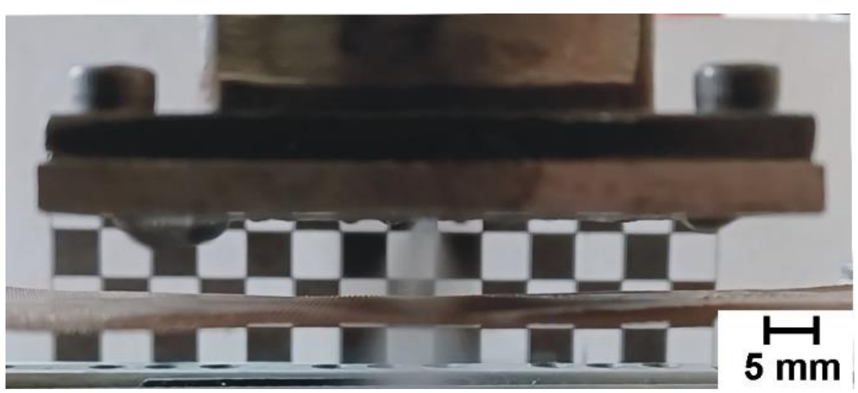

Fig. 2. Photograph showing the shape of the air jet flowing from the nozzle of the head

RESULTS AND DISCUSSION

Paper Tensile Strength

Paper samples of types A, B, and C were subjected to an impingement study using different air velocities. The decrease in the tensile strength for the paper and the appearance of defects determined the range of air velocities used. For all samples that contained eucalyptus pulp, a decrease in the tensile strength in the paper began to occur at an impinging velocity of 4.8 m/s, while for papers made of 100% pine pulp, this value was 5.2 m/s. The air velocity was increased until damage appeared in the paper, which was determined visually. For samples that included eucalyptus mass, the air velocity that destroyed the sample was 6.4 m/s, whereas for samples made of pine mass, destruction occurred at 8 m/s. Air velocities that were too high caused defects to appear on the surface in the form of white transverse stripes, as well as tears and perforations (Fig. 3). This applied to samples cut in both the MD and CD directions, and these samples were rejected for further strength tests. Not all of the samples dewatered at destructive air velocities showed visible defects. Breaking the loose network of fibers occurred most often during impingement dewatering of papers containing eucalyptus pulp at air jet velocities of above 4.8 m/s. Strength studies revealed these cases in the form of a much lower tensile force until the sample broke.

Fig. 3. Photograph of a destroyed sample

Table 1 and Figs. 4 and 5 present the results for the tensile strength of the papers.

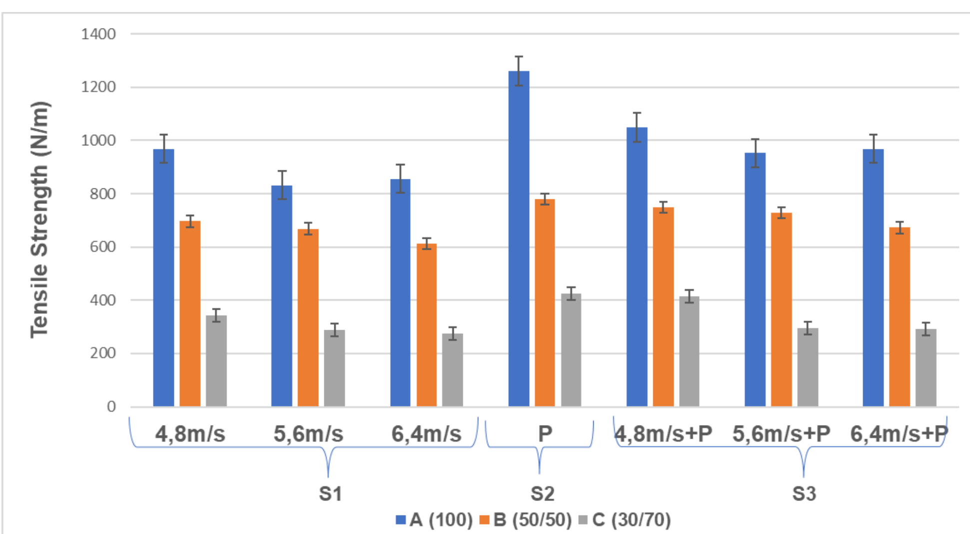

Fig. 4. Tensile strength for samples cut from a formed sheet in the MD direction, for all study series

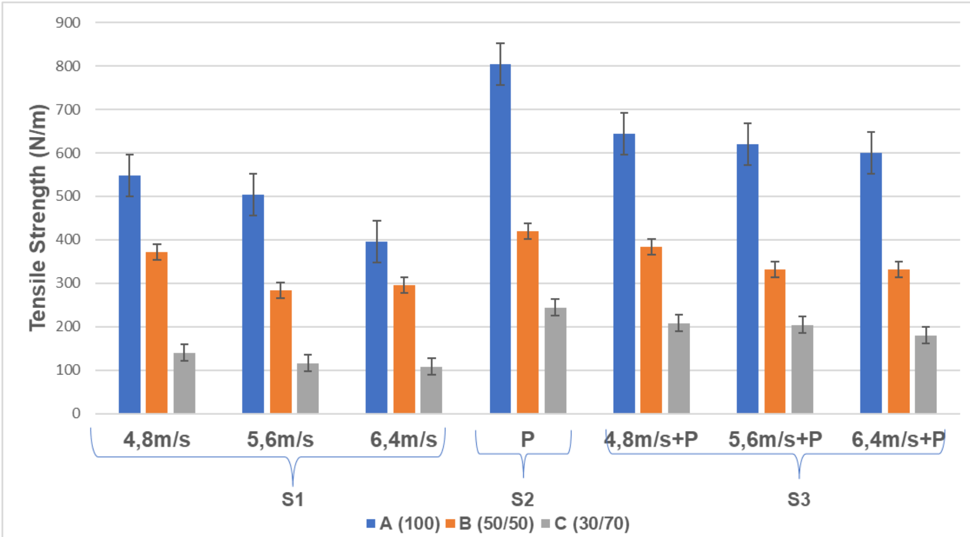

Fig. 5. Tensile strength for samples cut from a formed sheet in the CD direction, for all study series

Table 1. Summary of Results for the Tensile Strength for the Studied Papers

Paper samples	Series of studies		Tensile strength (CD), N/m	Elongation at break (CD), %	Tensile strength (MD), N/m	Elongation at break (MD), %
A (100%)	S1	(V_{A1}) 4.8 m/s	548 (52)	8.6 (0.8)	968 (88)	5.2 (0.7)
		(V_{B1}) 5.6 m/s	504 (72)	8.7 (1.4)	832 (104)	4.8 (0.9)
		(V_{C1}) 6.4 m/s	396 (80)	8.1 (1.2)	856 (116)	4.9 (1.1)
	S2	Pressing (P)	804 (108)	7.5 (0.5)	1260 (104)	4.6 (0.3)
	S3	(V_{A3}) 4.8 m/s +P	644 (28)	7.5 (0.3)	1048 (84)	4.6 (0.4)
		(V_{B3}) 5.6 m/s +P	620 (44)	7.9 (0.6)	952 (88)	4.5 (0.1)
		(V_{C3}) 6.4 m/s +P	600 (60)	7.3 (0.8)	968 (76)	4.6 (0.2)
B (50/50%)	S1	(V_{A1}) 4.8 m/s	372 (44)	2.5 (0.2)	696 (80)	2.2 (0.3)
		(V_{B1}) 5.6 m/s	284 (40)	2.0 (0.3)	668 (60)	1.9 (0.2)
		(V_{C1}) 6.4 m/s	296 (60)	1.6 (0.2)	612 (60)	1.8 (0.2)
	S2	Pressing (P)	420 (32)	3.2 (0.2)	780 (88)	2.5 (0.2)
	S3	(V_{A3}) 4.8 m/s +P	384 (44)	3.2 (0.2)	748 (72)	2.5 (0.2)
		(V_{B3}) 5.6 m/s +P	332 (24)	3.0 (0.2)	728 (80)	2.2 (0.1)
		(V_{C3}) 6.4 m/s +P	332 (56)	2.5 (0.3)	672 (104)	2.1 (0.2)
C (30/70%)	S1	(V_{A1}) 4.8 m/s	140 (8)	1.0 (0.2)	344 (64)	1.1 (0.1)
		(V_{B1}) 5.6 m/s	116 (16)	1.1 (0.1)	288 (88)	1.0 (0.3)
		(V_{C1}) 6.4 m/s	108 (8)	0.9 (0.1)	276 (68)	0.8 (0.1)
	S2	Pressing (P)	244 (4)	1.2 (0.2)	424 (68)	0.9 (0.1)
	S3	(V_{A3}) 4.8 m/s +P	208 (16)	1.4 (0.4)	416 (84)	1.2 (0.2)
		(V_{B3}) 5.6 m/s +P	204 (12)	1.3 (0.1)	296 (64)	1.1 (0.1)
		(V_{C3}) 6.4 m/s +P	180 (12)	1.1 (0.2)	292 (72)	0.9 (0.1)

Standard error of the mean shown in parentheses

Studies were carried out to determine the tensile strength for the samples and the elongation at breaking. All paper samples (A, B and C) were studied in both the MD and CD directions. Figure 4 shows graphs of the tensile strength in the MD direction for all study series (S1, S2, S3), while Fig. 5 shows graphs for all samples cut in the CD direction.

The results of strength tests for samples cut in the MD and CD directions were compared, and it was found that all samples showed a higher value for the tensile strength in the MD direction than in the CD direction, for all three study series (S1, S2, and S3). After pressing, the tensile strength of paper sample A in the machine direction (MD) was almost 60% higher than in the CD direction, whereas for samples B and C, increases of approximately 85% and 75% were seen, respectively. In series S3, which involved a combined method, the tensile strength for paper sample A in the machine direction (MD) was 55 to 60% higher than for the sample cut in the CD direction. For samples B and C, the increases were 95 to 120% and 45 to 100%, respectively. Sample A papers had the highest tensile strength. As can be seen from Figs. 4 and 5, the lower the content of pine cellulose fibres in the paper, the lower its tensile strength in both the MD and CD directions. The most beneficial effects were obtained after the pressing process; in these studies, the tensile strength was found to be higher than for samples subjected to the impinging jet (S1) methods. This applied to papers cut in both the CD and MD directions.

Too high impinging air velocities used to dry/heat the web may cause breaking of the loose fiber network or destruction of its structure. In studies S1 and S3, as the velocity of the impinging air jet increased, the paper structure weakened and, consequently, its tensile strength decreased. For sample A papers cut in the CD direction, increasing the velocity of the air jet from 4.8 m/s to 5.6 m/s (series A/S1), reduced the average value of the tensile strength of the sample by almost 9%, while in the MD direction the reduction was approximately 16% of the average value. Increasing the velocity of the air jet to 6.4 m/s resulted in a decrease in the average value of the tensile strength by approximately 38% (CD) and 17.5% (MD). For papers B and C, an increase in the velocity of the impinging air jet from 4.8 m/s to 6.4 m/s resulted in a decrease in the average value of the tensile strength by 15 to 30%. This applied to both MD and CD cut samples. The reason for this decrease in the tensile strength was the destruction of the fibre bonds in the paper structure by the air jets during impinging.

Analyzing the above data, it should be noted that in all series the measurement errors for air stream velocities of 4.8 and 5.6 m/s overlap. It is therefore difficult to draw clear conclusions. However, considering only the data obtained from impingement tests with air velocities of 4.8 and 6.4 m/s, the measurement errors do not overlap. In this case, a decrease in tensile strength of paper can be concluded as the air speed increases.

The results for the tensile strength for the samples in the S3 studies were compared with those for the S1 and S2 series. The aim of this research was to determine the extent to which the process of consolidating the paper by pressing strengthened its structure after the impinging jet.

Compared to the strength results for the A samples subjected to pressing (A/S2 series), there was a decrease in the average value of the tensile strength from applying the combined method (A/S3/V_{A3} series) of 5.3% in the MD direction and 4% in the CD direction. For the A/S3/V_{B3} and A/S3/V_{C3} series (*i.e.* after increasing the impinging jet velocity), samples cut in the MD and CD direction had even lower strength, with a decrease in the average value of the tensile strength of 30 to 35%). The B samples subjected to the combined B/S3 method also had a lower breaking strength compared to those undergoing the B/S2 method. The decrease in the average value of the tensile strength was 5 to 25%. An even higher decrease was recorded for the C papers, with values of 35 to 45%.

The study results for samples subjected to both the impinging jet and pressing (A/S3) were compared with those for the samples undergoing the impinging jet only (A/S1). After applying the combined method, there was an increase in the average value of the tensile strength for the paper in both the MD and CD directions, in all three series of studies and for all papers. For the series A/S3/V_{A3}, there was an increase of approximately 8 to 17%. An increase in the average value of the tensile strength was also achieved for the other two series, A/S3/V_{B3} and A/S3/V_{C3}: for the A/S3/V_{B3} series, this was an increase of 14 to 23%, whereas for the A/S3/V_{C3} series, an increase of 18 to 52% was seen. The B samples that were subjected to a impinging air jet and then pressing (B/S3) showed an increase in the average value of the tensile strength compared to the B/S1 series of 3 to 17%, while for the C samples this reached 75%.

Elongation at Breaking

Figure 6 shows the results for the elongation at breaking for the dried samples. Elongation at breaking decreased with the content of pine pulp in the formed paper. Elongation at breaking is a measurement that shows how much a material can be stretched before it breaks, as a percentage of its original dimensions, and this applies to both MD and CD cut paper samples. Greater the average value of the elongation of the samples was recorded for papers cut in the CD direction than in the MD direction. The A samples cut in the CD direction and subjected to an impinging air jet (for all air velocities) showed the greatest the average value of the elongation at breaking of 8.1 to 8.7%. After pressing (A/S3 for CD), the papers showed slightly lower the average value of the elongation at breaking of 7.3 to 7.9%. A similar relationship was noted for the A samples cut in the MD direction. In this case, after the impinging jet, the average values of the elongation at breaking for the samples were 4.8 to 5.2%, while after pressing (S3), these values were 4.5 to 4.6%. Similar the average values for the elongation at breaking were recorded for the studies using the S2 and S3 methods. In the analysis, attention should be paid to measurement errors, which sometimes amounted to more than 1%.

After pressing of samples A, B, and C, slight differences in the average value of the elongation at breaking were visible. The situation was different in the case of impingement dewatered samples. A significant difference was observed in the elongation at breaking of paper samples A compared to B and C in both the MD and CD directions; it was also noted that the average value of the elongation at breaking was similar for all C samples, after both pressing and after impact dewatering, and was in the range 0.8 to 1.4%. The maximum measurement error in this set of results was 0.4%. For A samples cut in the MD and CD directions, a significant increase in the average value of the elongation at breaking after impingement dewatering was visible compared to after pressing; this tendency was not visible for the other papers, B and C.

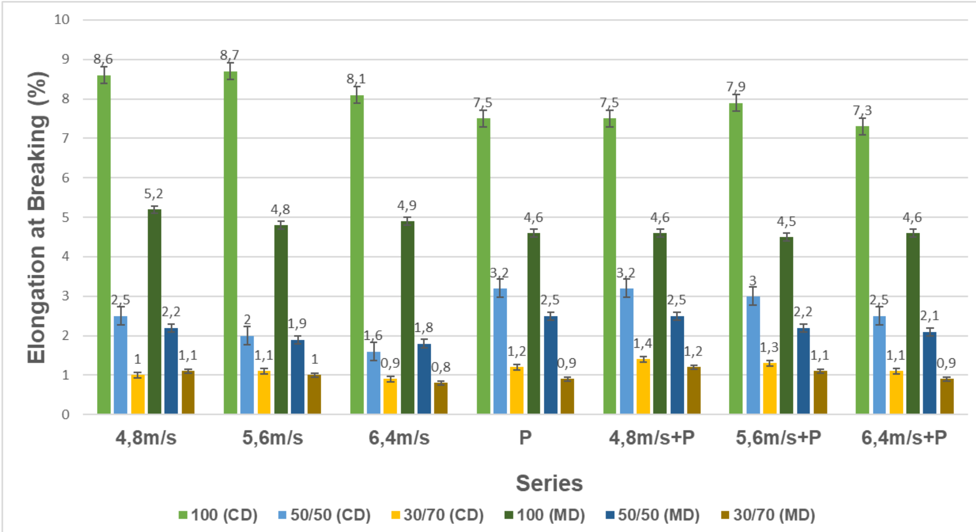

Fig. 6. Elongation at breaking of samples

Apparent Density and Bendtsen Roughness Number

Producers of tissue paper strive to produce papers with the highest possible porosity and bulk density. To demonstrate the significant difference in the apparent density of the papers after the pressing process and after the impinging jet, a series of studies was performed for the three types of paper, A, B, and C. The results are shown in Fig. 7.

The average value of the apparent density of papers A, B, and C after pressing (S3 series) was higher by 10 to 55% compared to papers dewatered using the impingement dewatering method (S1) (Fig. 7). The average value of the apparent density of the papers after impingement dewatering was in the range 0.24 to 0.32 g/m^3.

After pressing, all papers had a similar apparent density. However, after dewatering using the S1 method, the B and C samples showed a slightly higher the average value of the apparent density than the A samples. Adding eucalyptus pulp to the initial pulp increased the bulk of the paper. A comparison of samples after pressing (S2) and after the combined method (S3) showed no significant differences in the apparent density of the papers. Pressing the samples resulted in partial densification of their structure compared to the impingement method.

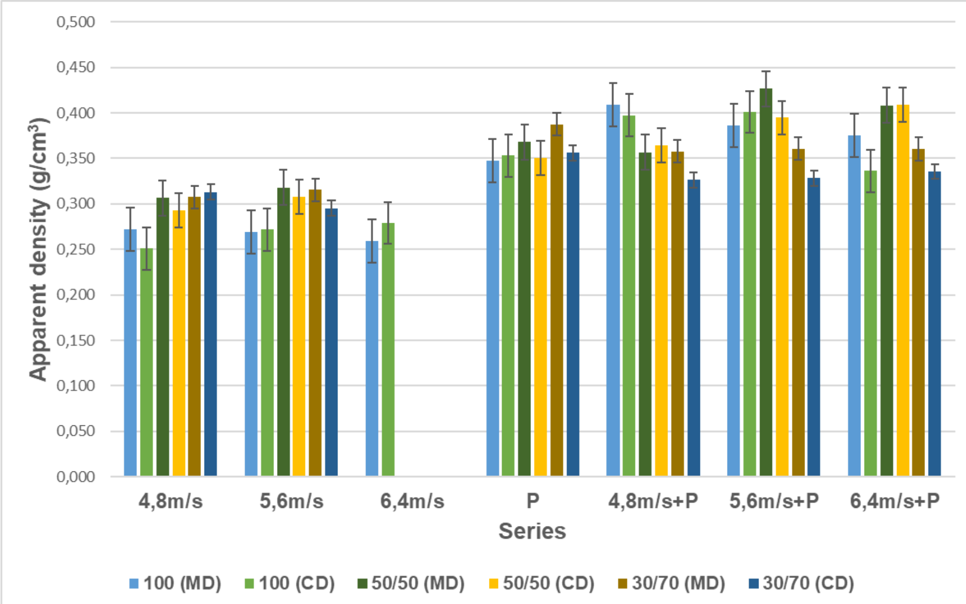

Fig. 7. Apparent density of the studied papers

The softness of tissue paper is often considered one of its most important properties (Wang *et al*. 2019). A number of production technologies have been designed to increase softness of tissue paper. Many of these focus on the pressing and drying aspects to prevent the densification that occurs in conventional papermaking. The analysis of paper softness is difficult, as this property is hard to estimate (Pawlak *et al.* 2022). In addition to a subjective assessment of softness by touch, mechanical methods are also used (*e.g.* tissue softness analysers). However, due to the size of the tested samples, this type of device could not be used in our study.

Subjective assessments of softness based on touch differed between samples A, B, and C (not very soft, medium soft, and very soft, respectively), but it was not possible to use this approach to assess the changes between samples with different impingement velocities of air-jets.

The Bendtsen roughness measurement was used to describe changes in surface uniformity (Fig. 8 and Supplementary Information). When the impingement method was used to dewater samples, it was noticed that with an increase in the air stream velocity, the roughness of the papers increased or remained constant. For papers with the addition of eucalyptus fibres at the highest impinging velocity (samples V_{C1}), this value was beyond the measurement capabilities of the device, indicating a high degree of deformation of the paper surface under the influence of the air stream. It was interesting to note that in several cases, pressing the paper after impingement at the highest air jet velocity resulted in a reduction in roughness to below the value of other samples from the S3 series.

Differences in the roughness of the tested papers were also observed depending on the percentage composition of both partial pulps used to form the paper. The highest roughness values were observed for the A samples, and an increase in the amount of eucalyptus fibres in the initial pulp resulted in a decrease in paper roughness. Compared to papers made only from pine fibres, B papers had a decrease in the average value of the roughness of up to 90%, while for C papers, this decrease was 170%. An analysis of paper samples after pressing showed a similar tendency, although these differences were not as large as for the samples subjected to impinging air jets. The sample pressing method used in the research resulted in a decrease in the average value of the roughness compared to the impingement method of up to 130%.

The roughness of the papers tested using the S3 method was similar to or higher than for the S2 method, except for the B-MD system. When comparing the roughness of MD and CD cut papers subjected to impact/pressing, some differences were noted: for the A papers, samples cut in the MD direction showed higher roughness, whereas for the B and C papers, samples cut in the CD direction were rougher in most cases.

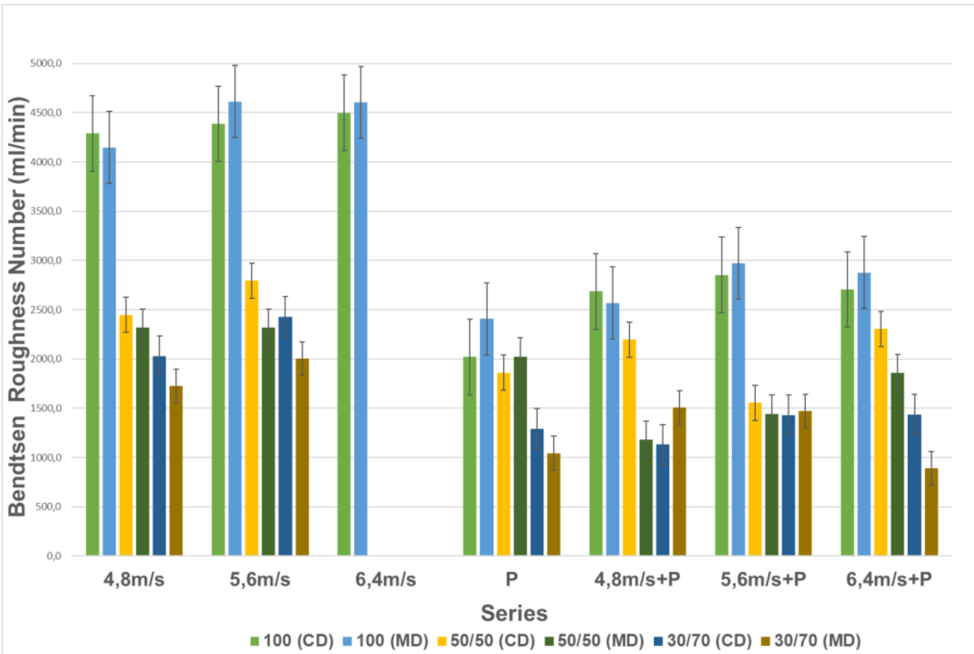

Fig. 8. Bendtsen roughness number for each of the studied papers

CONCLUSIONS

1. The use of an inappropriately high value for the air jet velocity in the impinging method may break the loose network of fibers of the paper (reduce its tensile strength) or even destroy it. Each wet paper has a certain limit with respect to the maximum air velocity that can be used to dewater/dry it without the risk of damage; when this limit is exceeded, the tensile strength of the sample decreases. From a study of three types of papers, different limits of their tensile strength were obtained in both directions (CD and MD). After applying an impingement method, all types of paper had much lower the average value of the tensile strength compared to pressed samples. All samples subjected to impinging followed by pressing (S3) showed an increase in the average value of the tensile strength in both the CD and MD directions compared to the impinging method alone (S1). The pressing process caused the paper structure, weakened by the impinging air-jet, to densify and become stronger.
2. The average value for elongation before breaking for papers made of pine pulp after impinging was higher than after pressing. Adding eucalyptus pulp to the paper and dewatering it by impinging air jet reduced its the average value of the elongation at breaking compared to papers made only from pine pulp. The elongation at breaking for samples with the addition of eucalyptus pulp was similar to those obtained after pressing and after the combined method.
3. Using the impinging method alone to dewater/dry the wet web without the pressing process resulted in a significant decrease in the apparent density of the paper, but at the expense of a decrease in tensile strength. The use of the impingement method before pressing the wet web did not reduce the apparent density of the paper compared to the conventional method (only pressing).
4. There was a visible increase in the Bendtsen roughness of the papers after impinging compared to the pressed samples. Increasing the amount of eucalyptus fibres in the initial pulp for paper production resulted in a decrease in the Bendtsen roughness. Unfortunately, as the impinging air velocity increased, the Bendtsen roughness of the paper also increased.

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APPENDIX
Supplementary Information

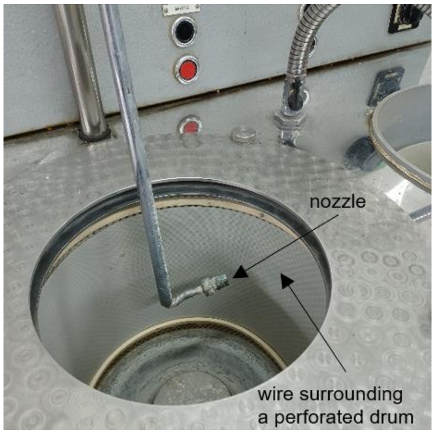

Fig. S1. Allimand paper former device

Table S1. Average Fibres Length for Used Pulps

Average Fibres Length (mm)	Refined (25°SR) bleached softwood pine kraft pulp (BSK)	Defibrated (14°SR) bleached hardwood eucalyptus kraft pulp (BHK)
Arithmetic mean	0.96	0.43
Geometric mean	1.53	0.60
Weighted mean	2.05	0.85

Table S2. Average Apparent Density and Roughness for Studied Paper Sheets

Paper Samples	Series of Studies		Apparent Density ([g/cm^3)		Roughness (mL/min)	
			CD	MD	CD	MD
A (100%)	S1	(V_{A1}) 4,8 m/s	0.251	0.272	4288.2	4148.1
		(V_{B1}) 5,6 m/s	0.272	0.269	4387.7	4614.0
		(V_{C1}) 6,4 m/s	0.279	0.260	4498.3	4605.3
	S2	Pressing (P)	0.353	0.347	2020.5	2408.3
	S3	(V_{A3}) 4,8 m/s +P	0.397	0.409	2684.8	2569.6
		(V_{B3}) 5,6 m/s +P	0.401	0.386	2852.7	2971.7
		(V_{C3}) 6,4 m/s +P	0.336	0.376	2706.8	2876.7
B (50/50%)	S1	(V_{A1}) 4,8 m/s	0.293	0.306	2447.0	2317.3
		(V_{B1}) 5,6 m/s	0.308	0.318	2795.5	2317.9
		(V_{C1}) 6,4 m/s				
	S2	Pressing (P)	0.351	0.368	1861.0	2025.3
	S3	(V_{A3}) 4,8 m/s +P	0.365	0.357	2196.8	1179.0
		(V_{B3}) 5,6 m/s +P	0.395	0.426	1555.6	1443.3
		(V_{C3}) 6,4 m/s +P	0.409	0.408	2304.1	1858.5
C (30/70%)	S1	(V_{A1}) 4,8 m/s	0.313	0.307	2031.4	1728.4
		(V_{B1}) 5,6 m/s	0.295	0.315	2429.5	2003.3
		(V_{C1}) 6,4 m/s				
	S2	Pressing (P)	0.356	0.387	1291.5	1045.4
	S3	(V_{A3}) 4,8 m/s +P	0.326	0.358	1132.6	1508.7
		(V_{B3}) 5,6 m/s +P	0328	0.360	1432.4	1472.5
		(V_{C3}) 6,4 m/s +P	0.335	0.360	1438.6	889.6