ADAPTIVE, SELF-UNDERPRESSURIZING SUCTION ROLL FOR FAST WEB HANDLING CONCEPTS

by

M. Kurki[1] and P. Martihainen[2]
[1]Metso Paper, Inc.
[2]VTT Processes
FINLAND

ABSTRACT

In web handling one of the most demanding area is nip or pocket area for incoming or outgoing web. Depending on speed of web and rotating roll surfaces, boundary layers transport air causing negative or positive relative pressure difference between top and bottom sides of the web. Numerous publications and studies show that this effect causes web deflections, which can lead to web instabilities and deteriorations in web handing.

Pocket areas are also difficult from the viewpoint of fluid flow analysis since tangential points of the pocket geometry will lead to singularities in normal situation. This means that pressures are "infinite" and cannot be handled without "leakage effects" coming from surface roughness, or in this case, roll grooving.

Typically one possibility to avoid web handling problems in pocket areas is to increase substantially such "surface roughness" which can receive or convey air transported by viscous boundary layers. One form of this extra "surface roughness space" is roll grooving which is simply a helping duct or escape for air, especially in pocket areas.

In this paper we present a roll and a method not only to overcome pocket effects, but also a technique where boundary layers together with optimized roll groove structure can create a suction roll mechanism. This forms an underpressure between the roll and the web surface stabilizing the web.

Roll functioning is based on carefully designed but simple groove geometry where closing and opening pockets correspondingly create sealing and underpressurizing areas. Adequate and deep groove design ensures good air conveying utilizing air-surface friction forces. The roll arc covered by fabric is underpressurized as a whole.

Both CFD and experimental results show that underpressure develops adaptively according "Bernoulli's law", i.e. second power with roll surface speed. Roll is especially designed to work with supporting permeable fabrics. Since underpressurizing power is

coming from rotational speed and boundary layers, no external vacuum or suction devices are needed. Since whole wrap area is underpressurized from closing nip to opening nip, roll performance is ideal for such web handling situations where excessive web tensioning and web straining should be avoided.

In paper making industry with continuously increasing web speeds, more cost-effective web handling systems are needed. There, the web supporting is in essential position. With permeable, supporting paper making fabrics, web handling possibilities can be improved significantly when roll pocket effects can be controlled efficiently.

NOMENCLATURE

D = roll diameter, m,
M = molar mass, g/kmol,
p = pressure of gas, Pa,
r = radial distance from the roll centre-line, m,
R = general gas constant, 8.314 J/(mol K),
T = Kelvin temperature, K,
v = machine speed, surface velocity of the roll, m/s,
ρ = density of gas, kg/m^3,
φ = relative humidity, - ,
ω = angular velocity, rad/s

SUBSCRIPTS

a = air
w = water vapour

1. INTRODUCTION

Modern papermaking environment requires reliable and efficient high-speed processes in order to satisfy the efficiency needs targeted to the paper production line as a whole. It is obvious that with ever-increasing speeds stable web handling will be an increasingly important item. Higher web speeds are always causing higher aerodynamic effects on web handling via boundary layer behaviour (see Figure 2). Boundary layers, which origin lies in the fact that air is viscous media, are the major cause to the web handling difficulties.

Depending on the web surface, its permeability and structure, the boundary layer structure can vary a lot. Even in the case of hydraulically smooth surfaces boundary layers will develop and transport air into pocket areas formed by rolls and moving textile or web [2].

Transporting air will pack in to the pocket and forms overpressure, which causes deflections to web. In the case of fabric this overpressure detaches web from fabric which opens the contact. This new, revealed surface starts accumulate boundary layer immediately thus creating air flow to both sides of the web [7].

Finally, the air will be accumulated to the next pocket area where air will be pushed out creating new deflections, which deteriorate overall web handling rapidly [3, 4, 5]. For these reasons, web stability in paper machines requires constant, flawless web stabilization against supporting surfaces.

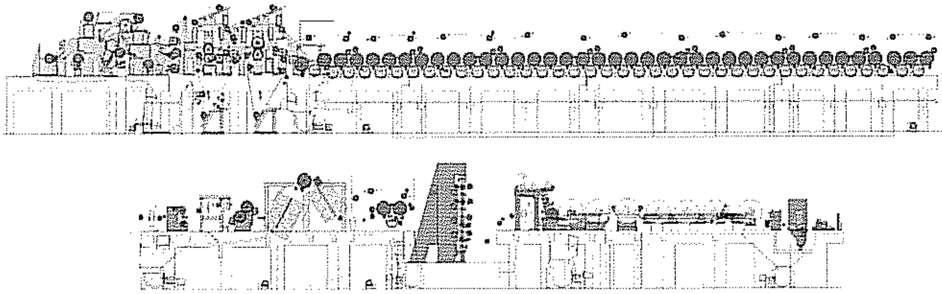


Figure 1 - On-line LWC paper machine JianXi Chenming, China.

Usual method to prevent these runnability disturbances is the installation of drilled or grooved bottom rolls. If drillings has been used, it is mandatory to use suction at high speeds in order to diminish overpressure effects, especially in closing pocket regions.

In this paper we present a roll which overcomes these problems providing not only passive air entrainment, but also using adaptively air flows creating stabilizing underpressure. This underpressure increases along with web speed manifesting the adaptive, self-correcting features of the roll.

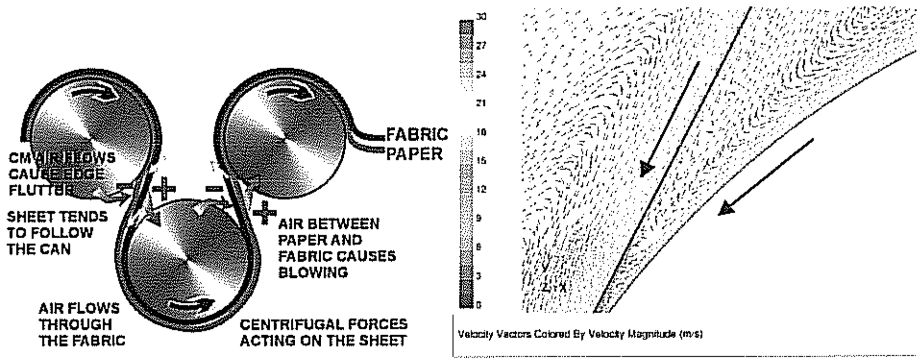


Figure 2 - a) Boundary-layer dependent web stabilization problems in paper machine dryer section, b) CFD air flow vectors from closing pocket region with permeable fabric and grooved suction roll [2].

2. NUMERICAL SIMULATION OF THE ROLL USING CFD

Roll performance was studied using CFD (Computational Fluid Dynamics). Especially in this case, fluid flow behaviour in the roll is very Euler-Bernoulli type and is difficult to analyze using analytical fluid flow models. Basic structure of this roll is a groove system where the groove depth is significantly greater than usual. This specified groove pattern creates flow-through situation where different kinematical and viscous contributors are creating needed underpressure. CFD simulations were performed in three dimensions. In this case, most advantageous CFD modelling method utilizes the symmetrical nature of the roll.

Figure 3 illustrates the CFD model, modelling constraints and boundary conditions. Fluid flow analysis only in x-y plane is not recommended since 3-d effects in z-direction (friction, angular velocity effect) must be taken into account. Textured area in Figure 3 describes flow area in z-direction, where periodical boundary conditions have been applied. Using these boundary conditions we assume the roll to be infinitely long in z-direction, but still it is possible to create necessary flow contribution between the grooves.

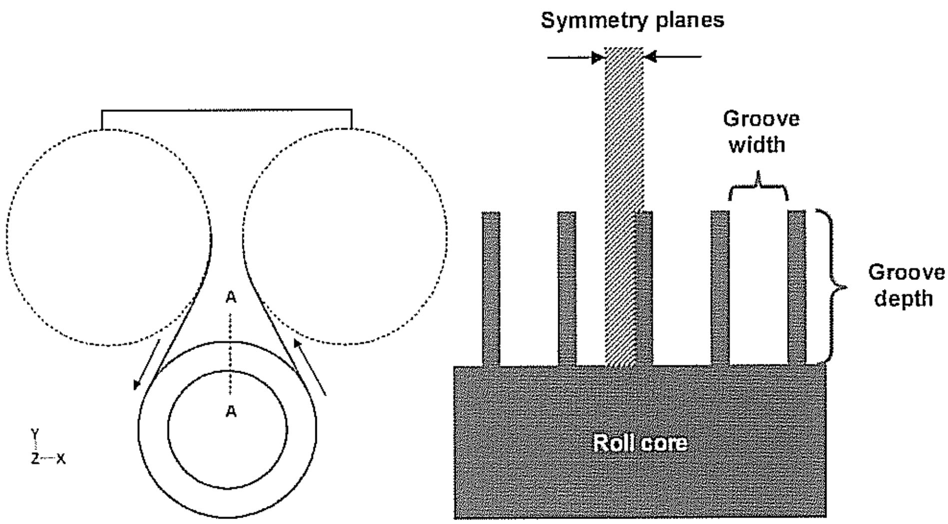


Figure 3 - a) CFD model area in x-y plane, b) schematic cross-directional section A-A and z-directional model dimension, textured area describes area modelled with CFD.

Several case examples were studied with CFD modelling, and the most graphic way to present roll behaviour is the rotational pressure curve. Same illustrations have been used also in real measurement cases presented in chapter 3.

Figure 4 presents results from CFD analysis performed in dryer section geometry, presented in Figure 3a. Paper web travels onto outer surface of the dryer fabric thus blocking the air permeation effects. High and respectively low efficiency curves describe the behaviour of an optimized and unoptimized roll structure. Point A is the closing nip contact point where fabric and roll surfaces attach. From point A to point B fabric and roll are in contact until they separate in nip B.

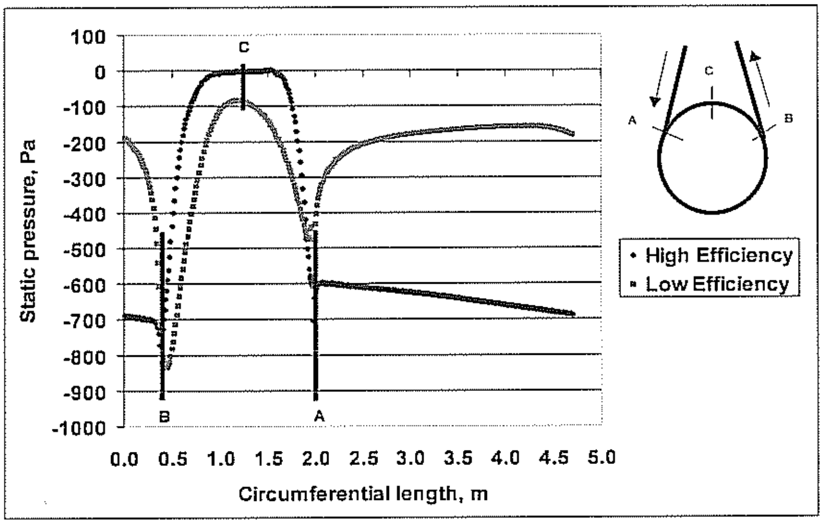


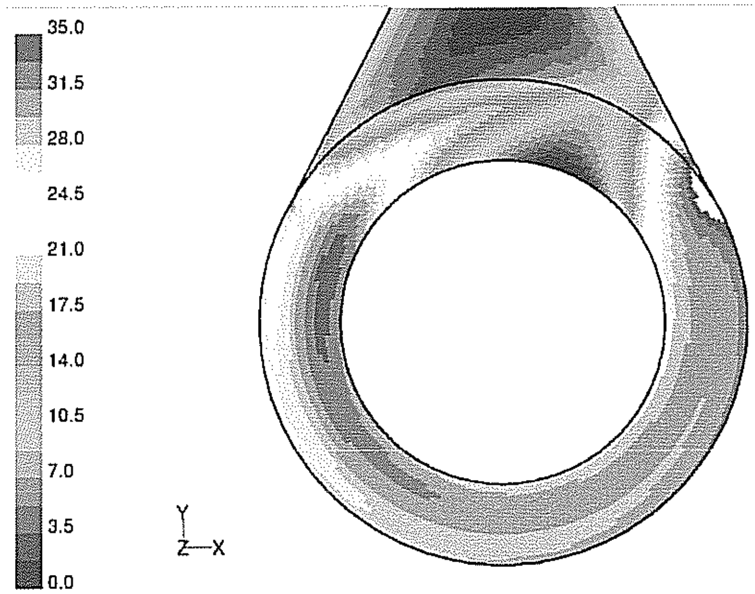
Figure 4 - One cycle of rotational pressure behaviour with impermeable paper web. Examples of high and low efficiency roll configurations, machine speed 2000 m/min (33 m/s)

Typical pressure behaviour in opening pocket region is shown in Figure 4. Due to rapid development of boundary layers, underpressure peak is appr. –850 Pa. However, closing pocket region near the roll does not exhibit normal closing pocket overpressure effect at all.

Roll behaviour is possible to examine from detailed pressure and flow velocity maps (Figures 5 and 6). From Figure 5 can be seen that incoming boundary layer on down-run side creates an area where the direction of impulse momentum of the air changes. This change is caused naturally by the closed surface area formed by roll outer surface. Flow decelerates on closing pocket region but surface friction accelerates it again. This can be seen as increased seed area on the bottom of the roll groove below closing pocket region.

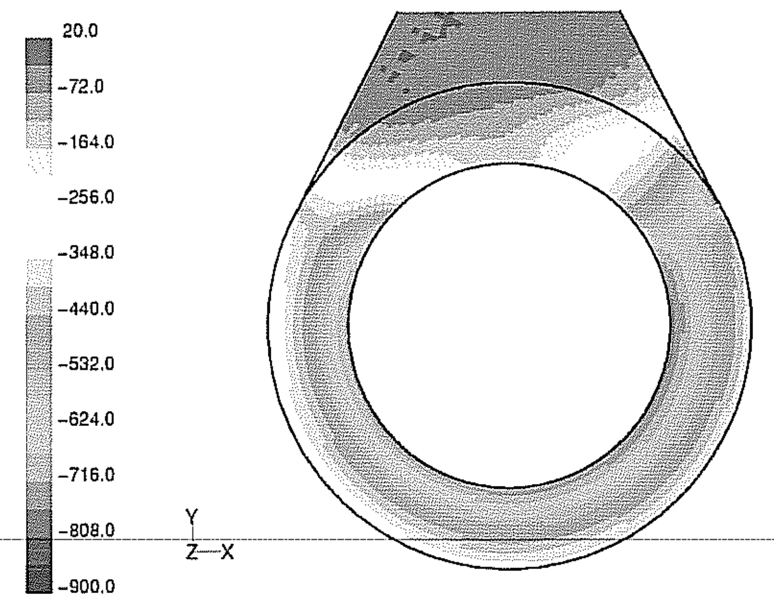
On the other hand, there are another air velocity lift-up in opening pocket region. Since the air is designed flow rather free in grooves, opening pocket on the right is another functional accelerator for the flow.

The outcome of this coupled velocity treatment can be seen in Figure 6. Deceleration and acceleration areas together with optimized groove design create underpressure region on the wrap area of the roll. Highest stabilizing underpressure is reached in opening pocket region where nip area is working as a "pump" removing air from the inside of the roll. The effect of centrifugal force can be seen clearly as an underpressure decrease (absolute pressure increases) when moving from the roll center surface to the roll outer surface.



Contours of Velocity Magnitude (m/s)

Figure 5 - Flow velocity resultants in x-y plane at 33 m/s web speed.



Contours of Static Pressure (pascal)

Figure 6 - Pressure in x-y plane at 33 m/s speed.

3. EXPERIMENTS

A prototype roll was manufactured and installed into a dryer group of a pilot machine. The prototype roll located perceptibly far from the cans of the dryer group (Figure 7). That was not good for machine runnability or web stability but convenient for the experimenter when making changes in devices or instrumentation in the roll or its close environment.

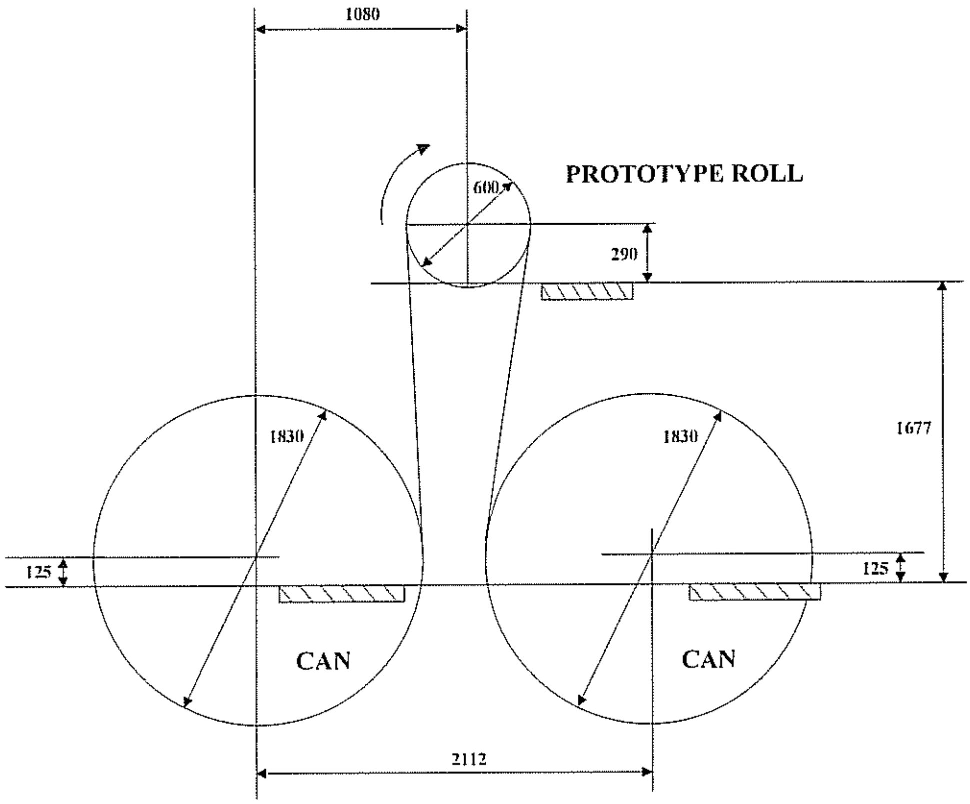


Figure 7 – The position of the prototype roll in a pilot machine.

Gas pressure and gas flows in roll grooves were the most important items of interest when function and aerodynamic efficiency of the prototype roll was studied. When measuring gas pressure in roll grooves, low-pressure sensors in differential pressure mode were utilized (± 2500 Pa, response time 500 μs). For that purpose, adequate pressure sensors of absolute mode were not easily available. Pressure sensors rotating with the roll were fixed 75 - 85 mm far from the roll surface in radial direction. Pressure under study was applied to the measuring port of a sensor with a thin silicone-plastic tube. The other port of a sensor was connected to the reference pressure, which was the atmosphere near the roll. Here, two types of reference arrangements could be used. The reference tubing could either end to the smooth roll head or pass through both the roll bearings and the sliding-ring assembly used for signal transfer and power supply for the sensors (Figure 8).

A pressure measurement point in a groove was typically in the distance of 3 - 4 mm from the roll surface (Figure 9). Thus, the measurement setup gave a rather good idea of the pressure variation a paper web was exposed to.

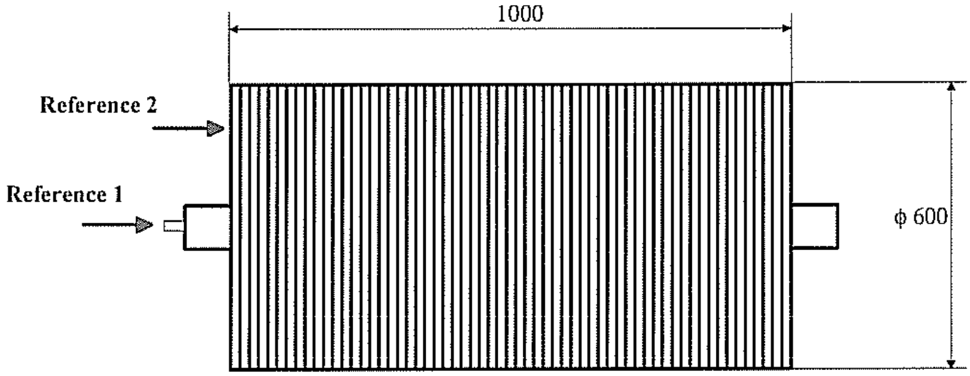


Figure 8 - Alternative reference points for pressure measurement.

In our measurement setup, pressure sensors were quite near to roll surface. When the roll rotates, a reference port will sense an excess pressure because of centrifugal force affecting to the gas column in the reference tubing. When rotating the roll, centrifugal force affects always in the same, radial direction. On the contrary, the effect of gravitation fluctuates regularly a function of the rotation angle. But at practical machine speeds, gravitation can be ignored without substantial loss in accuracy when compared to the centrifugal term.

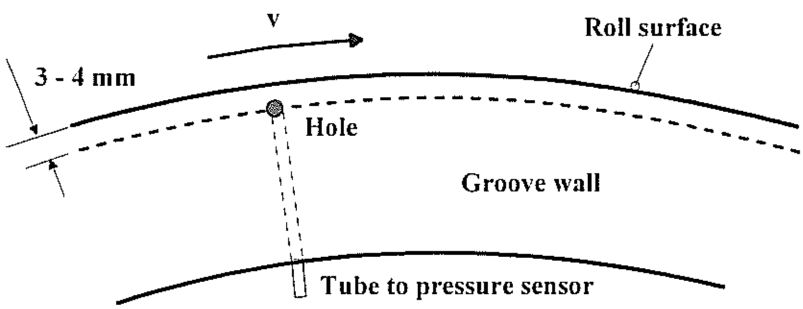


Figure 9 - A small hole perpendicular to the groove wall for pressure measurement.

In a rotating roll, the centrifugal force will increase pressure in a gas column in the radial direction as follows

$$\frac{\partial p}{\partial r} = \frac{p}{RT}\omega^2 r \quad \{1\}$$

where p = p(r), pressure of gas, Pa,

r = radial distance from the roll centre-line, m,

R = general gas constant, 8.314 J/(mol K),

T = Kelvin temperature, K,

ω = angular velocity, rad/s.

In a radial gas column, the relationship of the pressure values in two different points 1 and 2 can be expressed as

$$\ln(\frac{p_2}{p_1}) = \frac{\rho}{2p}\omega^2(r_2^2 - r_1^2) \quad \{2\}$$

where ρ = density of gas (kg/m^3).

Here, the ratio ρ/p is constant when applying ideal gas approximation at constant temperature. Let's assume that we are using the pressure reference 1 of Figure 8. The pressure sensor near roll surface will have an excess pressure Δp in its reference port

$$\Delta p \approx 2\rho_0\left(\frac{v}{D}\right)^2 r^2 \quad \{3\}$$

where ρ_0 = density of moist air in the research hall or in the machine hood, kg/m^3,

v = machine speed, surface velocity of the roll, m/s,

D = roll diameter, m,

r = position of the sensor reference port in the radial direction, m.

In the same way, the equation (2) can be applied in the tubing between the sensor and the real measurement point under study. Finally, when correcting the measured pressure signals, we have to know only, where the real point under study locates, and just to apply equations (2-3) to the real measurement point. The location of the pressure sensor is not crucial. Of course in order to avoid attenuation of high-frequency pressure fluctuations, short tubing between the sensor and the real measurement point is recommended. In addition, one should make sure that the sensor is so installed that high acceleration forces do not course any malfunction or distortion in the sensing elements of the sensor.

Density of moist air is a function pressure, temperature and some third thermodynamic variable, e.g. absolute moisture content (in units of kg water in kg dry air). Many appropriate thermodynamic programs and diagrams are available and can be utilized. But in many cases, the following rough approximation can be used.

$$\begin{aligned}\rho_0 &= \rho_a + \rho_w \\ &= \frac{p_a M_a}{RT} + \frac{p_w M_w}{RT} \\ &\approx \frac{p_{tot}}{RT}\left[M_a + \varphi(M_w - M_a)\exp\left(11.78\frac{T-372.79}{T-43.15}\right)\right]\end{aligned} \quad \{4\}$$

where p_a = partial pressure of dry air, Pa,
p_w = partial pressure of water vapour, Pa,
p_{tot} = pressure of moist air, Pa,
T = Kelvin temperature, K,
M_a = molar mass of dry air 0.02896 kg/mol,
M_w = molar mass of water 0.01802 kg/mol,
φ = relative humidity of air (0 – 100 %), $0 \leq \varphi \leq 1$.

It is worth mentioning that air pressure can vary so much that it should be taken into account in accurate measurements. For example, the extreme values of outdoor-pressure in Finland have been recorded to be 94.0 and 106.6 kPa. When measuring the gas pressure in roll grooves, the need of pressure correction as a function of machine speed is illustrated in Figure 10. Figure 10 depicts the situation at normal indoor conditions with temperature of 20 C and relative humidity of 30 %. The roll diameter is 600 mm. At high machine speed of 2400 m/s, pressure correction of over 900 Pa will be needed.

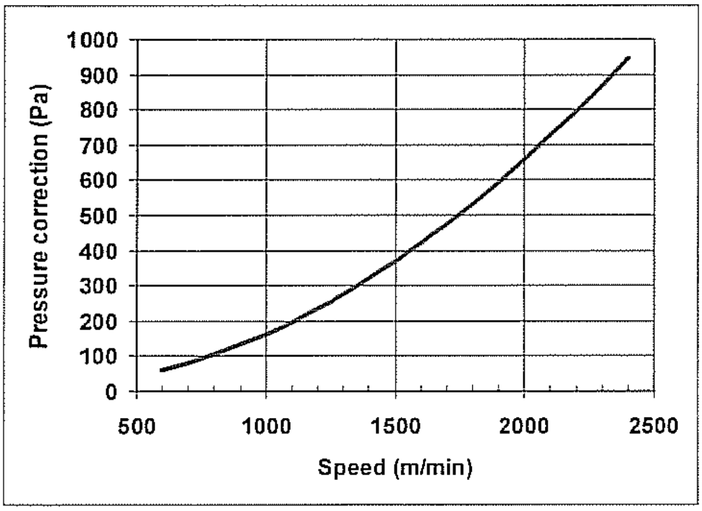


Figure 10 - Pressure signal correction in differential mode measurement when measuring pressures from the surface grooves of a roll with diameter of 600 mm, air temperature is 20 C and relative humidity 30%.

The aerodynamic functioning and efficiency of the prototype roll was tested in a pilot machine. Dryer fabrics with different permeability were used. Figure 11 illustrates the aerodynamic behaviour of the prototype roll. The dryer fabric had an air permeability of 2500 $m^3/m^2/h$. The machine speed was 1600 m/min. Fabric and paper came onto the roll at point A, and they left the roll at point B. When using only fabric, small underpressure on the arc AB covered by fabric was noticed. But the combination of a fabric and a paper web with low permeability lead to an outstanding increase in vacuum in the roll grooves of the covered roll area. Mean vacuum level of about 400 Pa was reached. It is noteworthy that paper web also decreased the harmful overpressure in front of the closing nip (A). The closing nip (A) became underpressurized and into good control even in this example. Further, it is already known that with a new better roll design, the overpressure area can be totally swept away and the web control will improve substantially (Figure 4).

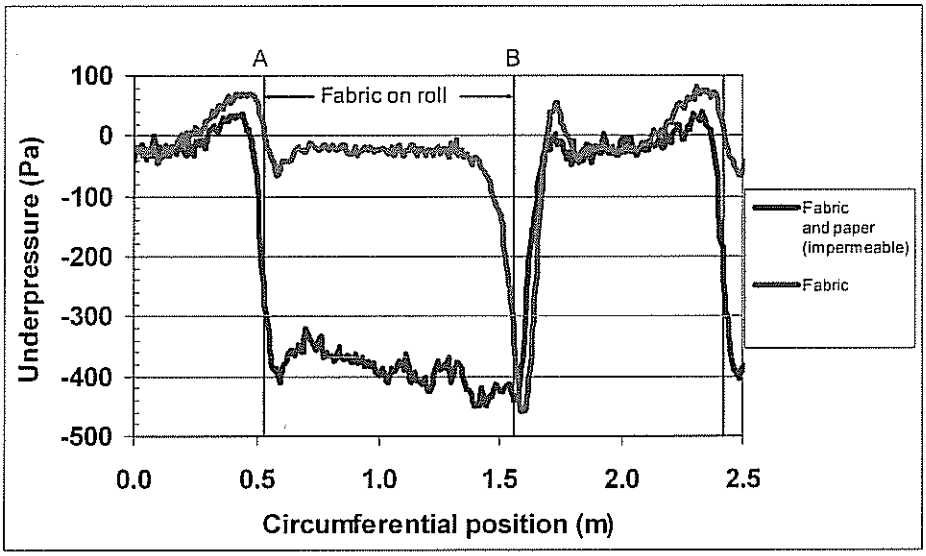


Figure 11 - Aerodynamic behaviour of the prototype roll with and without paper web.

The results presented in Figures 11-12 remain essentially the same if we increase permeability of the dryer fabric. With fabric only, the shape of the pressure curve will change a little bit. With the combination of fabric and paper, the paper of low permeability will dominate and lead nearly to the same results with large quality range of dryer fabrics.

In roll grooves on the arc covered by paper web, underpressure level develops quadratically with machine speed (Figure 12). That is quite a good property. If forces, which disturb web running and its stability, increase in power two or slower with speed, the roll of this new type is an effective means against them. Essentially, gas underpressure on the roll arc covered by paper is approximately of order $\rho v^2/2$ where ρ is the gas density and v is the velocity of groove surface.

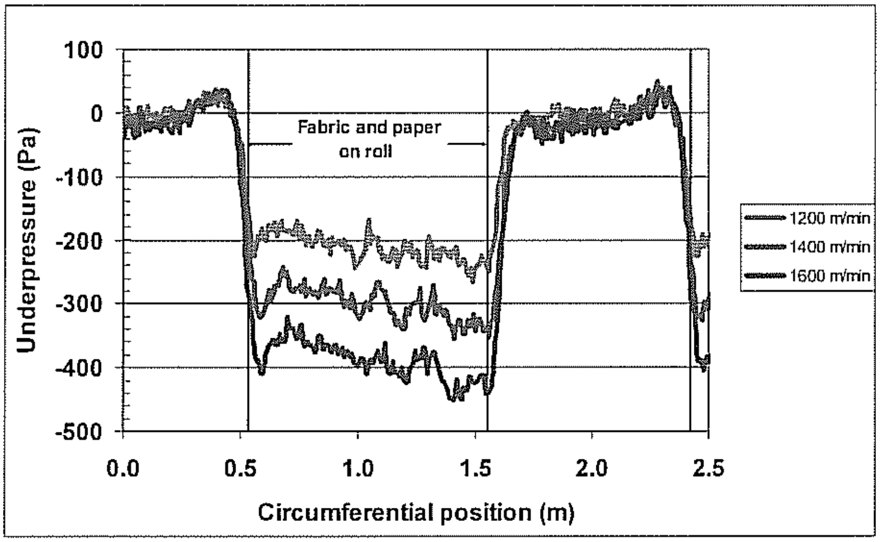


Figure 12 - Effect of machine speed on the aerodynamic behaviour of the prototype roll.

The basic idea and a very rough, non-scientific explanation of why the roll functions can be given with the aid of Figure 13. There we have a web and a roll with surface velocities v. In a large and open room, the velocity of gas is about zero at points 2 and 3, and approximately v in the narrow channel at point 1. Both the web and the roll pump gas.

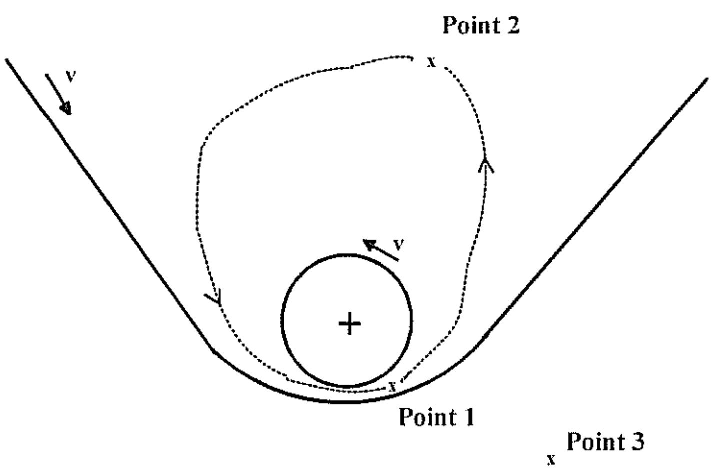


Figure 13 – Simplified scheme of the roll concept for rough energy consideration.

Let's have a simplified and incomplete thermodynamic consideration. We assume that the specific internal energy is the same in all three points. Then the specific system energy at the points 2 and 3 consists only of pressure terms p_2/ρ and p_3/ρ which corresponds to calm atmospheric conditions. The energy loss from the point 1 to point 2 is at most moderate because of viscous effects. Therefore, the system specific energies are essentially the same at all three points. Gas velocity is v at point 1. That means that it must be a pressure difference of order $\rho v^2/2$ between points 1 and 2 or 3. This kind of useful pressure difference exists between web's outer surface and grooves of the roll newly developed [9].

4. DISCUSSION AND CONCLUSIONS

As mentioned earlier, higher web velocities are in central part in increasing paper machine production and efficiency. The significance of web handling will increase, since cost efficiency improvements in paper mills demand also the usage of cheaper raw materials with less adequate strength properties. Nowadays, 65% of average costs of a middle-sized light weight coated (LWC) paper machine are coming from the raw material and energy costs.

From Figure 14 can be observed that the general trend in yearly average production speeds has been rather constantly 45 m/min per year during last decade [1]. From the viewpoint of web handling in high-speed paper making this has two significant consequences: a) high-speed web handling has to be realized with lower quality raw materials, i.e. web materials with lower elasticity and lower strength. On the other hand b) energy consumption will be increasingly important due to environmental contributors [8].

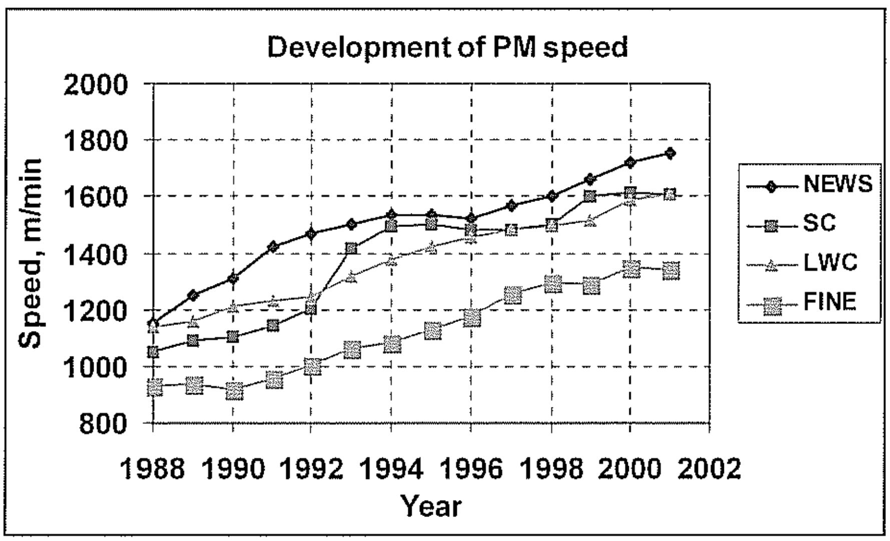


Figure 14 - Speed development of printing paper machines during the 1990's. Each dot marks the average yearly production speed of the best machine.

Presented adaptive web stabilization roll (Figure 15) sets on an important new device development trend where the utilization of harmful physical phenomena is transformed to benefit paper maker. The roll is dependent on the boundary layers developed on the surface of the web or paper making fabric. These boundary layers are the "fuel" creating necessary flow fields building up needed underpressures in roll wrap area. Therefore, roll

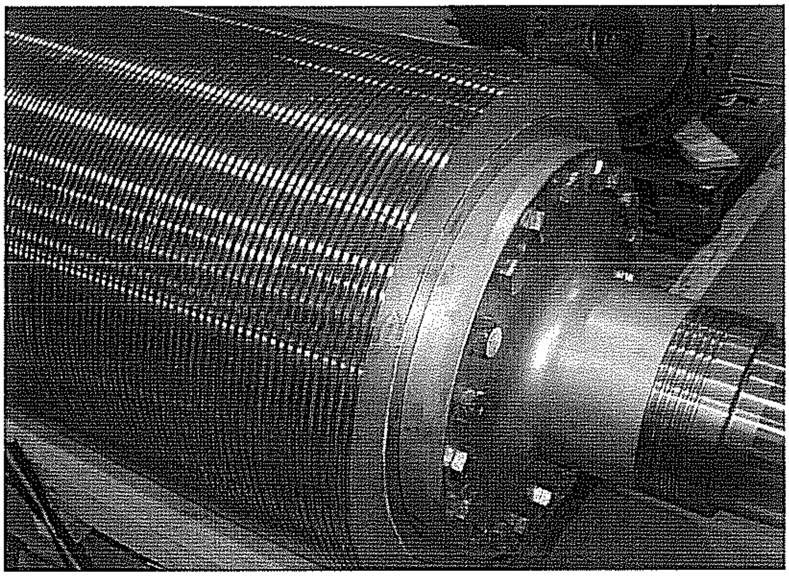


Figure 15 - Manufactured adaptive roll.

performance improves with the speed increase. In the future, this will be of special importance. Present web stabilization techniques are based on air removal from suction roll surface using external suction with piping and fan system. However, the needed suction power increases as a function web velocity and the centrifugal force increasingly hinders the air removal inside the roll. Strictly speaking, in order to keep stabilizing roll underpressures on the same level, fan power has to be increased as second power with web speed.

Adaptive roll design will be interesting also from the viewpoint of pocket behaviour related to the roll and permeable fabric. The excellent aerodynamic functioning of the roll can also put to use with very large web/fabric permeabilities which opens new possibilities from the viewpoint of papermaking process. Typically, the usage of very open dryer fabrics improves evaporation and gives chances for new drying techniques, such as through-fabric drying, where two-sidedness of drying has advantages for paper quality.

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Adaptive, Self-Underpressurizing Suction Roll for Fast Web Handling Concepts

M. Kurki[1] **& P. Martihainen**[2], [1]Metso Paper, Inc, & [2]VTT Processes, FINLAND

Name & Affiliation	**Question**
Young Chung Proctor & Gamble	In your experience, does the web actually come in contact with a grooved roll, surface of the grooved roll, or partially contact?
Name & Affiliation	**Answer**
Matti Kurki Metso Paper, Inc.	It is fully contacting. Yes.
Name & Affiliation	**Question**
Young Chung Proctor & Gamble	So with the groove patterns on your roll does it really help your air layer to escape?
Name & Affiliation	**Answer**
Matti Kurki Metso Paper, Inc.	Yes, depending on the groove structure we can affect how the boundary layer comes in the inner surface of this fabric. You can imagine if the groove affect is very small, 1 mm, it is close up to the normal roll which is creating very high under pressure. But if we're optimizing this closeness we are creating this kind of seal which is now closing this area.
Name & Affiliation	**Question**
Young Chung Proctor & Gamble	So will you look at the layer when you change the groove pattern or space in between grooves?
Name & Affiliation	**Answer**
Matti Kurki Metso Paper, Inc.	Yes, we are looking at that. Yes.