Aspects to running economy of cylinder dryer opening nip runnability systems

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Introduction

Runnability as a word has often been connected to high-speed paper machines. Fast and wide machines are challenging. They are usually equipped with single felted cylinder dryers and the runnability problems are usually concentrated to the drying cylinder opening nip. The wet web is meant to follow the fabric but it often tends to follow the cylinder surface instead causing a web break. The opening nip runnability depends on the equilibrium of the affecting forces at the web detachment line on the cylinder surface. The forces maintaining the web contact to the cylinder surface are adhesion between the web and the cylinder, under-pressure induced by the opening nip. On the other hand the web tension is in an important role in releasing the web from the cylinder surface.

There are three separate and independent phenomena inducing forces affecting to the web. The equilibrium of these forces determines the position of the detachment line on the cylinder surface and the position of the reattachment line on the fabric surface. With low running speeds the opening nip under-pressure can often be neglected and the equilibrium is the combination of the adhesion and the web tension. Low dry solid content and low quality mass are simultaneously increasing the adhesion and decreasing the web elastic modulus and further on reducing the web tension. Combination of high adhesion and low web tension moves the web detachment line on the cylinder surface away from the fabric nip. The position of the detachment line is not stable and this causes a sharp bend to the weak web. In theory the web always follows the cylinder surface at least a short way. In some cases this distance may be infinitely short but the small bend exists. An unfavorable combination of the nip forces will cause strong increase in the distance leading finally to a web break.

The equilibrium of the forces is often manipulated by causing artificial under-pressure against the fabric on the opposite side of the fabric. The fabric permeability is much higher than the permeability of the wet web. The under-pressure affects trough the fabric to the web. Because of the permeability this under-pressure has no direct effect on the fabric but the pressure difference across the web causes a force pushing the web against the web. This is changing the equilibrium of the forces. There are a lot of commercial technical solutions available for producing this mentioned under-pressure. The dimensioning of the systems is usually done intuitively and based only to practical experiences in same kind of conditions. When the need for the runnability systems became obvious, the needed level of underpressure was low. Typically some tens of Pascals. Still a lot of machines are running without problems using these low pressure level systems. In the beginning large areas of drying fabric at the opening nip area or even the whole pocket was underpressurized. With the rising running speed the drying pocket was divided to two or more pressure zones. Near the opening nip there is usually a high vacuum zone to move the web from the cylinder surface together with the fabric towards the suction roll. A lot of constructions creating and maintaining pressure differences between the zones have been developed. They all are based on two main principles. The first system launched for this purpose was based on blowing technology. The underpressure was created with a thin air jet used as ejector. The other possibility is to use a combination of suction and mechanical seals.

The market in paper and board production has strongly changed since most of the systems were delivered. Usually they were optimized to maximize the production. Now the systems are commonly modified to minimize the production cost with a lot of weight on fan energy. A lot of these modifications are done by small local actors without the knowhow of the original manufacturer. This has lead to situations where the planned cost reductions have not been achieved and the old problems have been replaced with new ones. The major machine manufacturers have all strongly cut their research and development resources and the amount of product launches and published articles in this area have dropped drastically.

In this paper the systems are compared theoretically and with experimental models (Leimu, 2012) from the energy point of view with a brief view to practical running conditions.

Runnability systems based on blowing

Underpressure to the vacuum zone is created by blowing an air jet out from the zone which induces a secondary flow causing a pressure decrease. The jet momentum spreads to the whole volume flow. The function is exactly the same which is used in jet pumps and ejectors in various industrial applications. Usually jet pumps and ejectors are constructed so that a round jet is placed in a rotation symmetrical chamber where the jet meets the secondary flow (see figure 1).

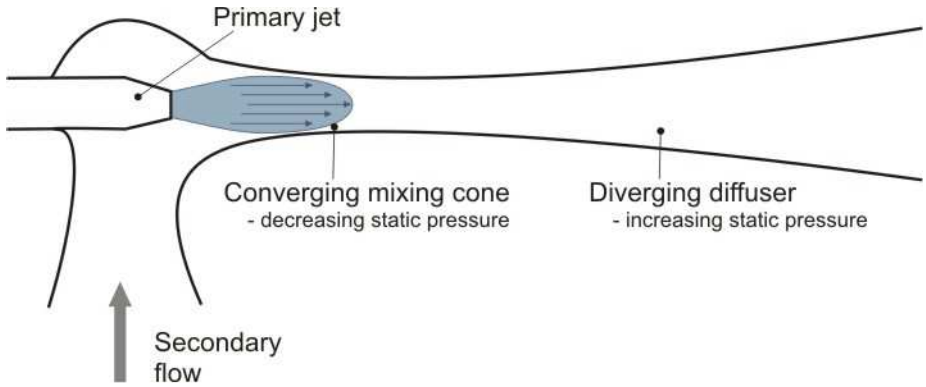

Figure 1. Fluid flows in an ejector

The combined mass flow is led to a converging mixing section where the whole jet momentum is spread to the whole flow area. The mixing section ends to the ejector throat which is the narrowest place in the channel. The flow has high kinetic energy which is recovered to static pressure in the diverging diffuser section. Cherkassky (1980) has derived the governing equations for both compressible and incompressible cases.

Ejectors and jet pumps have been studied a lot because they are commonly used in several industrial applications. Ejector losses have been studied by Arbel A. et al. (2003) by working with the process irreversibility. Ejectors with multiple hole nozzles and short wide angle diffusers have been studied by Cornelius and Lucius (1994). They show that dividing the jet mass flow to several nozzle holes gives some benefit and explain this with changed turbulence conditions in the mixing section. Neve (1993) made a CFD study of gas powered jet pumps and found out that with small volume flows the diffuser is not very useful. He also mentions that according to his analysis gas jets around 100 m/s can safely be studied as incompressible.

In runnability applications the ejector throat is a machine width cross machine slot which separates the vacuum zone from the atmospheric pressure (see figures 2 and 3).

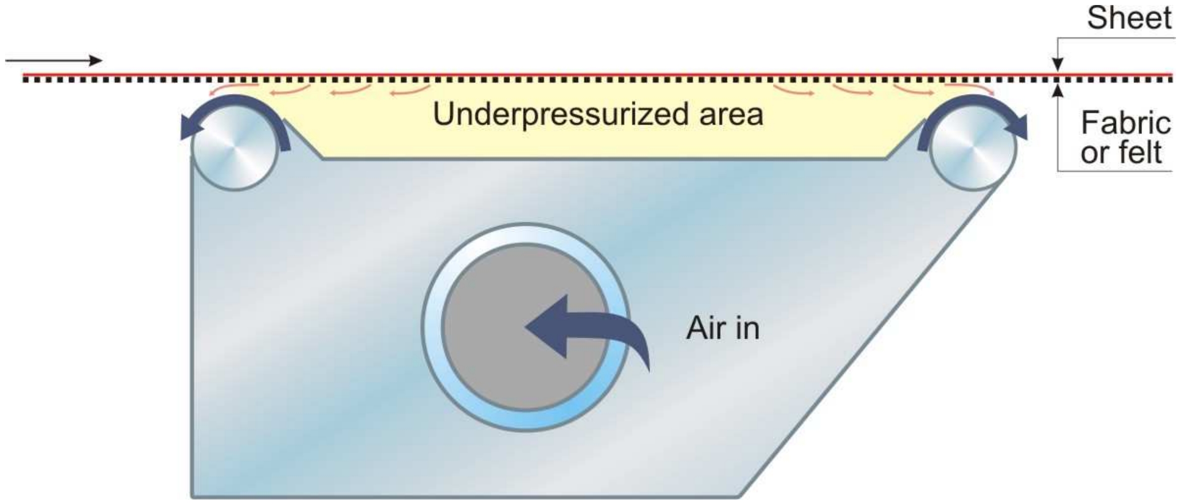

Figure 2. An example of a runnability creating underpressure against the drying fabric

One side of the ejector throat is a rounded construction cross the machine while the opposite side is the moving drying fabric. The fabric moves in machine direction but often also movement perpendicular to the fabric surface is possible. This together with the risk of tightly packed waste paper may get through the throat in case of web breaks means that the nozzle can not be placed too near the fabric. In commercial applications the jet nozzle is usually placed deep into the vacuum zone against the round surface. The jet is blown along the surface and it follows attached the rounded surface turning out from the vacuum zone. The jet tendency to follow a turned out surface is called as Coanda phenomenon according to Henri Coanda who patented this feature in the beginning of 20th century. The rounded surface in the construction will later on be called as Coanda surface.

The mentioned ejector studies assume that the mixing takes place fully supported by the construction in a controlled volume. The jet pumps and ejectors are a good base for comparisons but the one sided curved geometry of the runnability system makes it impossible to use them for estimating the runnability system performance.

Neuendorf et al. (1999) have studied attached jet behaviour on a round surface using a nozzle and geometry very much like the one used in runnability systems. They show that the jet stays attached on the round surface in this kind of conditions without problems 180-270 degrees. They also show that with high wrap angle a jet on a round surface is spreading clearly faster compared to plane wall jets. In runnability applications the wrap angle is always less than 100 degrees. This means low values x/R and then the difference to a plane wall jet is small. Coanda surface radius of curvature is R and x is the distance from the nozzle along the surface.

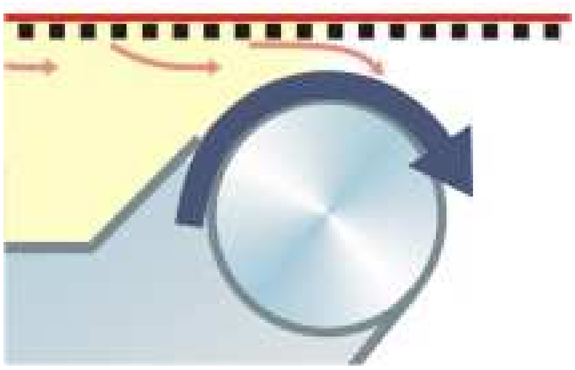

Figure 3. Suction by blowing a jet along a curved surface.

According to the wind tunnel experiments (Eriksson 1999) the drying fabric velocity boundary layer velocity profile thickness is in most studied cases thinner than 40 mm. In old systems the distance between the fabric and the construction is usually approximately 20 mm and in the systems built after year 2000 it is often between 10 and 15 mm. A typical running speed in elder systems is in the order of magnitude 15 m/s and in the latter group close to 30 m/s. With 30 m/s fabric speed the fabric velocity boundary layer is transporting air towards the underpressure zone and the air velocity at 10 mm distance from the fabric varies in different cases (Eriksson 1999) between 10 and 17 m/s. Part of this air flow is penetrating in to the vacuum zone meeting the jet boundary layer which is coming out on the opposite side of the opening. The jet from the nozzle is blown towards the opening along the curved Coanda surface. The curved jet is spreading and its purpose is to fill the opening, giving all of its momentum stopping and blocking the opening. To achieve zero net flow in the opening some of the jet has to get out from the zone to compensate the in leaking part of the fabric velocity boundary layer.

The fabric is moving in the studied case towards the vacuum zone and there is a velocity boundary layer moving on the fabric surface. On the opposite side of the throat there is the attached jet velocity boundary layer going out from the zone. There interaction between the meeting velocity boundary layers and the stronger one wins. There is always at least a thin layer of air flowing in to the vacuum zone. Finding optimal performance would mean exact fitting of the meeting velocity boundary layer together in the ejector throat.

In early eighties an acceptable level of runnability was achieved with vacuum zone underpressure less than 100 Pa. With raising paper machine running speed the used level of underpressure in most new fast machines is between 1 and 4 kPa. The highest underpressure levels created only by using jets are between 1 and 2 kPa and most commonly the jet technology is used to create 100-400 Pa underpressure.

Cherkassky (1984) mentions that in optimal conditions a jet pump can create with zero volume flow a pressure difference which is 74% of pressure difference over the nozzle. In the runnability systems the jet flow conditions are far from optimal but the order of magnitude for the jet feeding pressure is some kilo Pascals. This can be produced with cheap standard fans with high efficiency. It makes also possible to use standard ventilation ductwork components. The system can also be studied fully incompressible.

Earlier when the vacuum zone underpressure was low high distances up to 25 mm were used. The fabric transported an air volume flow into the vacuum zone and the jet came out from the zone so that the net flow was close to zero. The system efficiency was not of high interest because the needed fan power was so low. Higher running speed led to higher system underpressure and further to higher fan power. Then also more exact dimensioning of the distance, nozzle size and blowing velocity was needed.

The used underpressure together with the wanted distance between the Coanda surface and the fabric sets the limits for the needed jet momentum which can be achieved with several combinations of nozzle slot and blowing velocity.

Momentum of the jet

A situation where the opening between the construction and the fabric is blocked by the jet and the jet is totally stopped can be used as a reference case for the real systems. Then the momentum and kinetic energy of the jet are fully used. The force created by a jet is the jet mass flow at the nozzle $\dot{m}$ multiplied with the velocity change. The mass flow can be expressed with the jet velocity at the nozzle v_1 and the nozzle slot size d_1, which gives the jet thickness after the nozzle.

$F = \dot{m}\Delta v$ where $\dot{m} = v_1 d_1 l \rho$.

In this case the jet end velocity is assumed zero and the change in the jet velocity Δv equals the original jet velocity v_1. Area in the opening where the distance between the fabric and the construction is in the minimum distance d_2 multiplied with zone length l. Multiplying the opening area with the pressure difference over the opening gives the force which is needed to maintain the vacuum zone underpressure. Atmospheric pressure outside the vacuum zone is p_0 and p_1 is the vacuum zone pressure.

$$F = (p_0 - p_1) d_2 l \qquad \text{Eq.(1)}$$

After substituting the momentum to the pressure equation gives equation 2 which is the underpressure if 100 % of the jet momentum could be used.

$$(p_0 - p_1) = \frac{d_1}{d_2} \rho v_1^{2} \qquad \text{Eq.(2)}$$

The vacuum zone underpressure p_C which is computed with the experimental model can be divided with momentum equation underpressure can be seen as momentum efficiency. This is written as equation 3.

$$\eta = \frac{p_c}{\frac{d_1}{d_2} \rho v^2} \qquad \text{Eq.(3)}$$

This efficiency depends strongly on ratio d_1/d_2 and also on the blowing velocity. The computed system underpressure can be written as equation 4.

$$p_C = \eta_m \rho v^2 \frac{d_1}{d_2} \quad \text{where} \quad \eta_m = \eta_d \eta_v \qquad \text{Eq.(4)}$$

Efficiency η_m consists of two components. η_v from the velocity dependence and η_d from the dependence to ratio d_1/d_2. η_d can be written as an exponent function of d_1/d_2. Equation 5 describes the dependence compared to the experiments with R^2 0.998.

$$\eta_d = 1.882 \left(\frac{d_1}{d_2} \right)^{0.4356} \qquad \text{Eq.(5)}$$

Here the efficiency η_v is written as a function of jet velocity. Equation 6 shows this dependence with R^2 0.999.

$$\eta_v = 1.3944 v^{-0.077} \qquad \text{Eq.(6)}$$

Equations 5 and 6 are substituted to equation 4 which gives equation 7.

$$p_v = 0.2624 \rho v^{1.923} \left(\frac{d_1}{d_2} \right)^{0.5644} \qquad \text{Eq.(7)}$$

Equation 7 is an estimate for a well sealed vacuum zone underpressure p_v. A larger regression model has been used for modifying the parameters of the theoretical momentum equation to make the computed results to fit the experimental results. Increasing the fabric speed from 1500 m/min to 2000 m/min increased the difference between the pressure estimates to 1.35 percent. Equation 7 can well be used for approximating the vacuum zone underpressure in commercial applications.

Suction method with static sealing

In the suction method the underpressure is created by removing the suction airflow from the vacuum zone with a fan. The seals of the runnability device are placed against the fabric and the suction airflow flows between the seal tip and the fabric, causing a pressure difference over the seal. If there is atmospheric pressure outside the vacuum zone, the seal pressure loss equals the vacuum zone underpressure value. The seal can consist of one or several fins. The factors affecting the need for fan energy and the size of the air systems with different levels of underpressure and distances between the fabric and the seal tip will be studied next. There is very little material published on sealing in the paper machine environment, but the same kinds of problems have been an object for active research in turbo machines. Like in the runnability applications, contact between the sensitive counter surfaces should be avoided in turbo machines. The research on turbo machines is briefly reviewed and after that the situation is studied with CFD analysis. The computed results are first compared to the experimental results from a static test arrangement and, finally, to the experimental results from pilot machine experiments where the seal was placed against a moving fabric. The purpose of a seal is to reduce the leaking airflow. A factor describing the seal performance in this task is the coefficient of fluid resistance (Daugherty et al., 1985). Figure

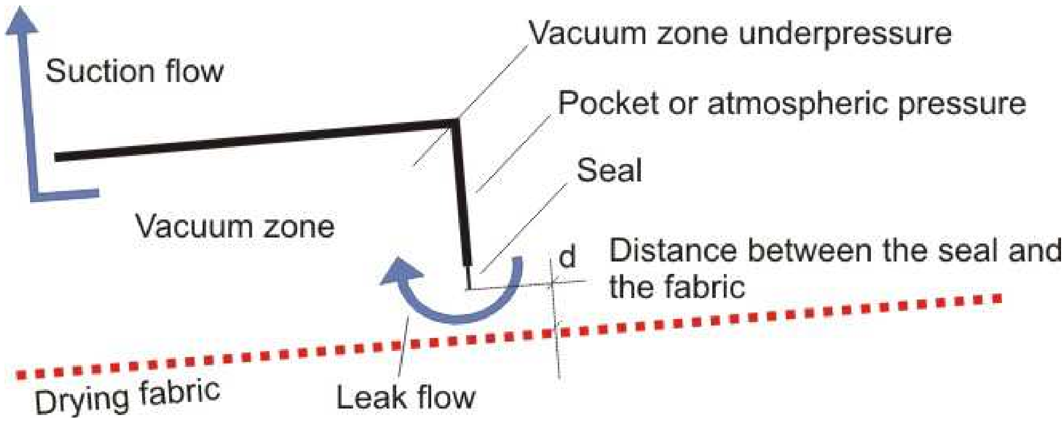

Figure 4. Sealing arrangement in a system of mechanical sealing and suction. The seal in the figure often consist of several sealing elements.

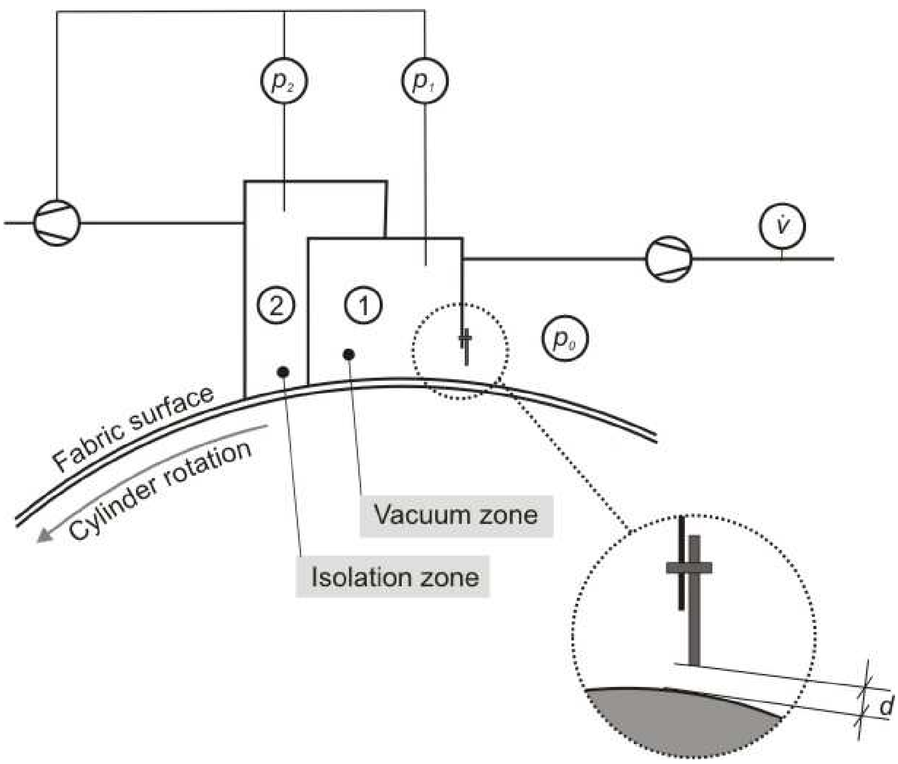

Figure 5. Measuring arrangements in the sealing performance testing.

The used model is based on a larger investigation (Leimu, 2012), where the experiments, results and analysis are all shown.

According to Buckingham's Pi theorem, the variables are arranged in dimensionless groups:

$$\Pi_1 = \frac{\dot{V}\rho}{d\mu}$$ Dimensionless volume flow

$$\Pi_2 = \frac{\rho d^2 \Delta p}{\mu^2}$$ Dimensionless pressure difference

$$\Pi_3 = n$$ Number of fins in the seal

$$\Pi_4 = \frac{\rho d w}{\mu}$$ Dimensionless running speed

The dimensionless leakage volume flow is shown as a function of the rest of the dimensionless groups. Equation 8 is the chosen function type, where the parameters are fitted with the statistical software. There were two separate series of experiments, one for the fabric entering the vacuum zone and one for the fabric leaving the vacuum zone. The parameters were separately fitted to the same basic function to get individual models for both cases. The model gives a good correlation between the measured and computed values. The *R* squared of the model for the fabric entering the vacuum zone is 0.921 and 0.913 for the fabric leaving the vacuum zone, meaning that the model estimates the leakage flow with good accuracy.

$$\Pi_1 = a_0 \Pi_2^{a_2} \Pi_3^{a_3} \Pi_4^{a_4} \qquad \text{Eq.(8)}$$

Parameter values when the fabric is entering to the vacuum zone are.

$a_0 = 4.974$
$a_2 = 0.419$
$a_3 = -0.131$
$a_4 = -0.000178$

Parameters for the fabric leaving the vacuum zone are

$a_0 = 427.287$
$a_2 = 0.234$
$a_3 = 0.0343$
$a_4 = 0.0152$

The results are applied to compute the needed air flows for runnability systems with blowing and suction technologies with different levels of underpressure. Energy consumptions are computed with estimated system pressures and the suitability of the systems in different running conditions are discussed.

Distance between the construction and the fabric

The runnability system size and energy economy are very sensitive for the distance between the construction and the moving fabric. Producing underpressure against the fabric needs always some kind of construction close to the fabric surface. If the underpressure is created with suction there has to be a mechanical seal placed against the fabric maintaining the pressure difference. The seal is fastened to a construction like a beam or box. This cross machine construction is supported to both sides of the machine. The straightness tolerance of the construction at delivery is usually 1 mm with high quality products but 2-3 mm tolerances are sometimes seen. Part of this can be compensated with skillfull mounting. During the production high underpressure is also bending the construction. If the seal is placed against the fabric at free draw, the fabric is bending. The fabric bending depends on the machine geometry and the fabric tension and can often be several millimeters (Leimu, 2016).

The fabric tension is not constant cross the machine but varies so that the tension may be double in the machine centerline compared the tension at the edges leading to uneven cross machine bending profile. Combining all the worst scenarios of these factors would lead to lead to impossible use of energy. In practice an acceptable level in fabric and seal damages can be achieved with distances on 4 – 8 mm of a still standing machine. A combination of low fabric tension, high underpressure and too small distance lead to a situation which is familiar to all who have tried to vacuum clean curtains. The suction captures the fabric to continuous contact leading to seal or / and fabric damages.

In blowing technology based solutions the jet momentum is used to create the underpressure. The jet is spreading after leaving the nozzle slot. If the distance between the coanda surface and the fabric is reduced, it will throttle the jet flow first reducing the ejector efficiency and finally turnin part of the jet flow back to the underpressure zone. The system is some self balancing so that too small distance causes a reduction in the underpressure preventing the contact between the fabric and the construction. In most systems based on blowing technology, the nearest part to the fabric is a smooth and rounded metal surface, which doesn't cause any ham in occasional contacts.

Computed results

The developed models are applied to estimate the needed air system volume flows to create and maintain the wanted levels of underpressure.

Sealing

In the systems using mechanical sealing and suction the leakage flow between the fabric and the seal is computed as a function of the distance between them with underpressures of 500, 1000 and 1500 Pa. The leakage is computed separately for the seals where the fabric enters the vacuum zone and where it is leaving the vacuum zone. Comparing figures 6 and 7 shows that with low underpressure and small distance the fabric velocity boundary layer is of great importance. The difference between the seals is smaller when the distance and the underpressure are increasing.

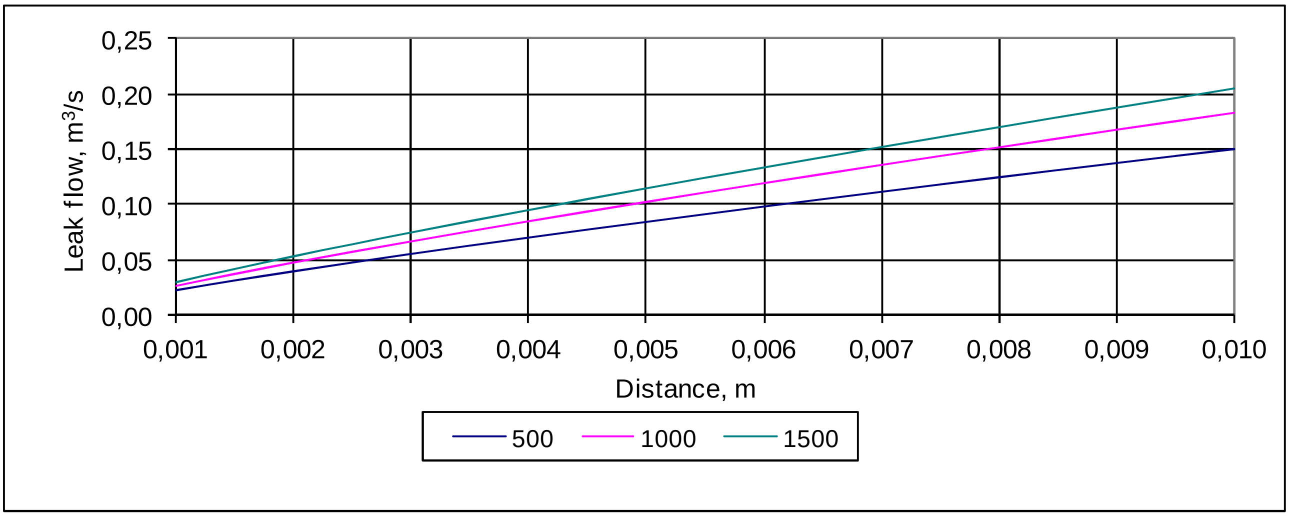

Figure 6. Leak flow / machine width between the seal and the drying fabric as a function of distance at the seal where the fabric is leaving the vacuum zone. The results are shown with underpressures 500, 1000 and 1500 Pa.

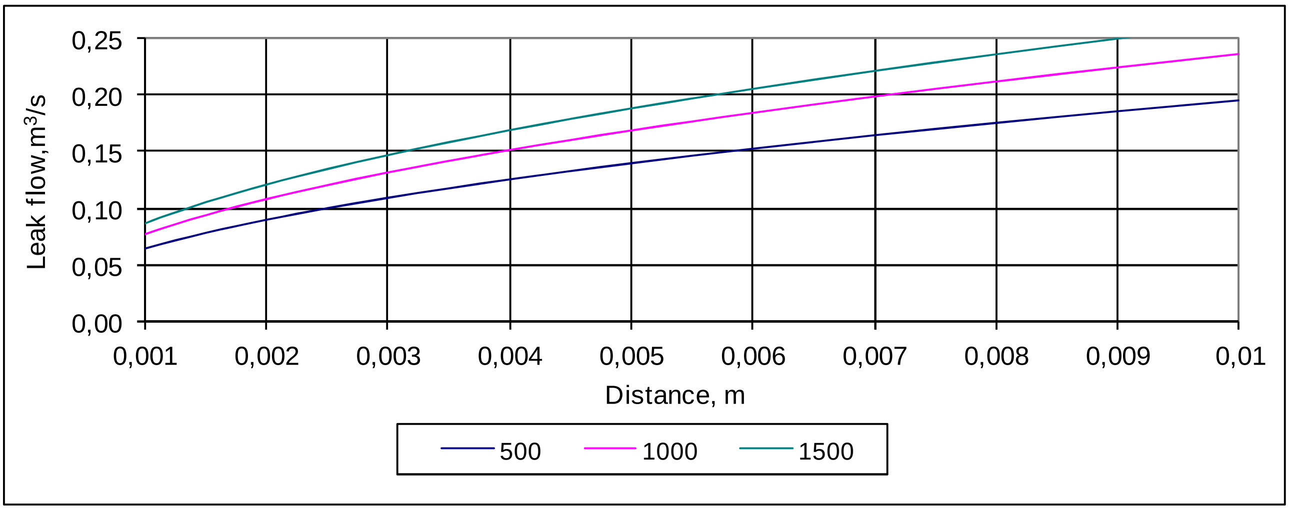

Figure 7. Leak flow/ machine width between the seal and the drying fabric as a function of distance at the seal where the fabric is entering the vacuum zone. The results are shown with underpressures 500, 1000 and 1500 Pa.

Blowing

The blowing based systems are computed so that the created underpressure is shown as a function of the jet blowing velocity. In this example case the nozzle slot is chosen to be 2 mm. Same effect could be achieved with smaller airflow and higher pressure by using 1 mm nozzle slot. The tolerances in production and small damages during the mounting and running the machine cause easily remarkable deviations to the cross machine pressure distribution. The underpressure is computed with three distances 5, 8 and 10 mm. In jet systems the jet eliminates the fabric velocity boundary layer so effectively that the difference caused by the velocity direction is here neglected.

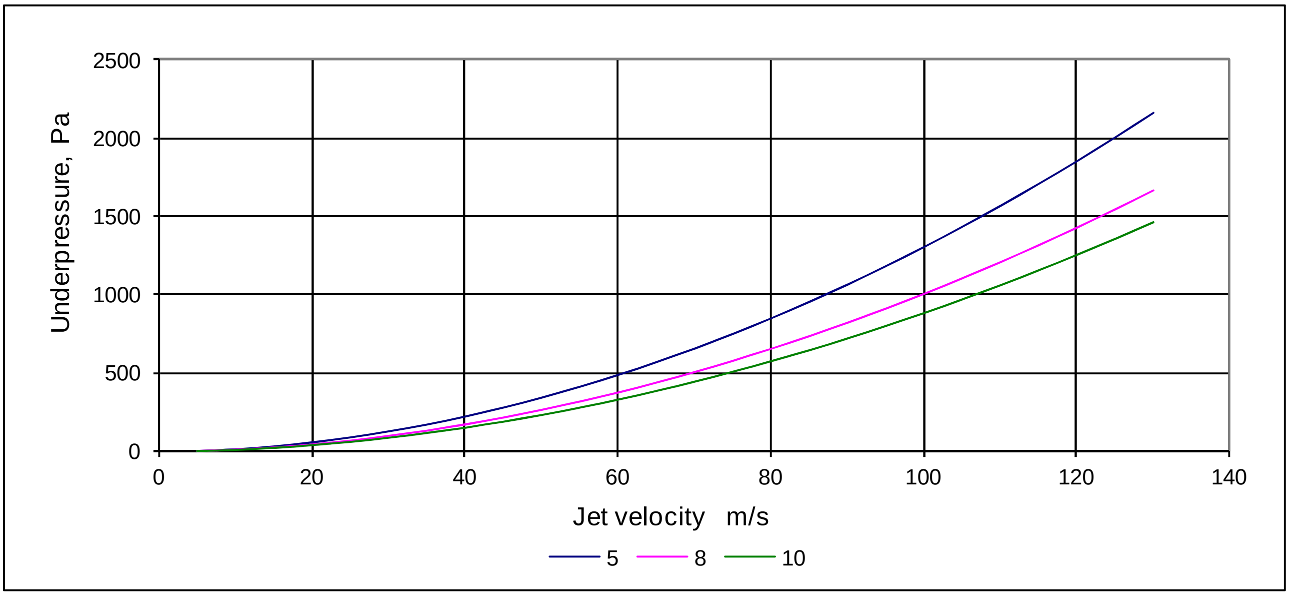

Figure 8. The created underpressure as a function of jet velocity with distances of 5, 8 and 10 millimetres between the drying fabric and the construction.

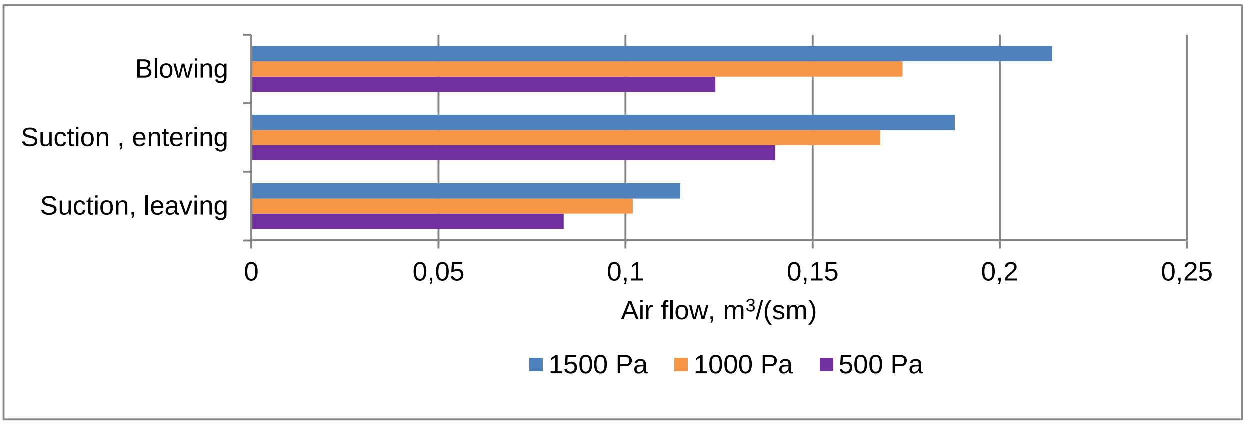

Figure 9. Comparison of the air system volume flows of three different vacuum zone limiting arrangements with distance of 5 mm between the drying fabric and the construction. Figure 1. Fluid flows in an ejector

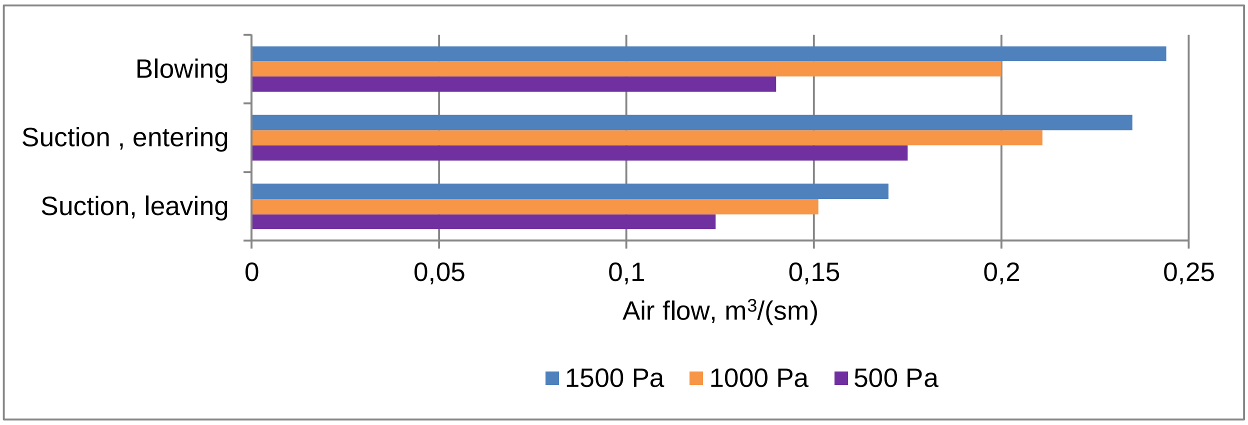

Figure 10. Comparison of the air system volume flows of three different vacuum zone limiting arrangements with distance of 8 mm between the drying fabric and the construction. Figure 1. Fluid flows in an ejector

Energy consumption

The runnability system fan power is the product of the volume flow and the pressure drop of the device. This study concentrates to the runnability components between the machine frames neglecting the ductwork and all system losses outside the machine as well as the fan efficiency. In the blowing based systems the jet velocity is created with static pressure.

The experimental regression fitted model includes all the losses in the nozzle and the runnability device. So the volume flow together with the jet dynamic pressure can be used to compute the fan power.

In the suction based systems distribution of the suction is a problem. The dimension of the dryer pocket set limits for the flow areas in the runnability devices. Small cross section leads to high cross machine air velocities and further on to high dynamic pressures If nothing is done most of the suction air is removed from one side of the machine. Inclined suction profile destroys the runnability. This is why the suction devices often are equipped with an extra internal pressure loss to ensure even pressure distribution cross the machine. This pressure loss is typically at the level of 1 kPa and this pressure loss is handled as a system loss of the suction device.

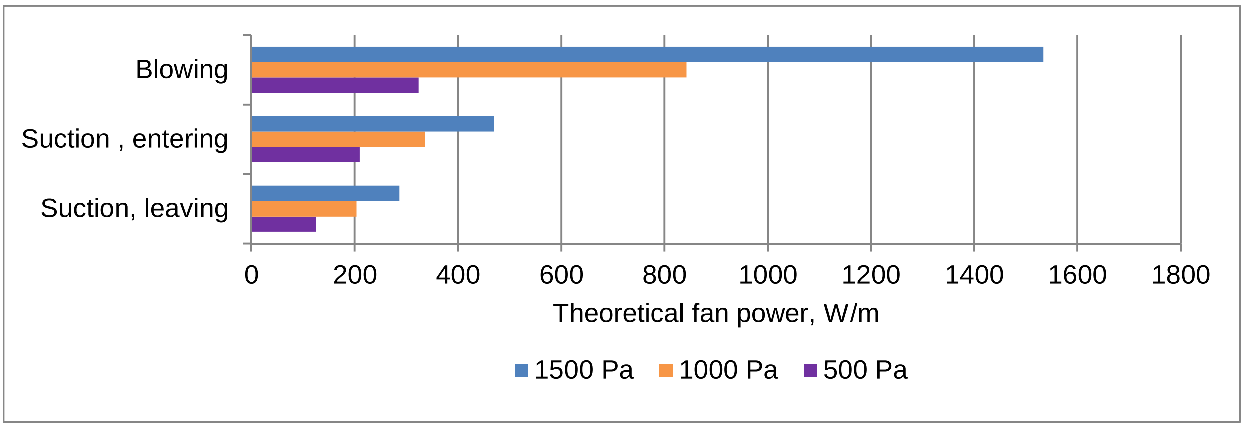

Figure 11. Comparison of the theoretical fan powers of three different vacuum zone limiting arrangements with distance of 5 mm between the drying fabric and the construction. Figure 1. Fluid flows in an ejector

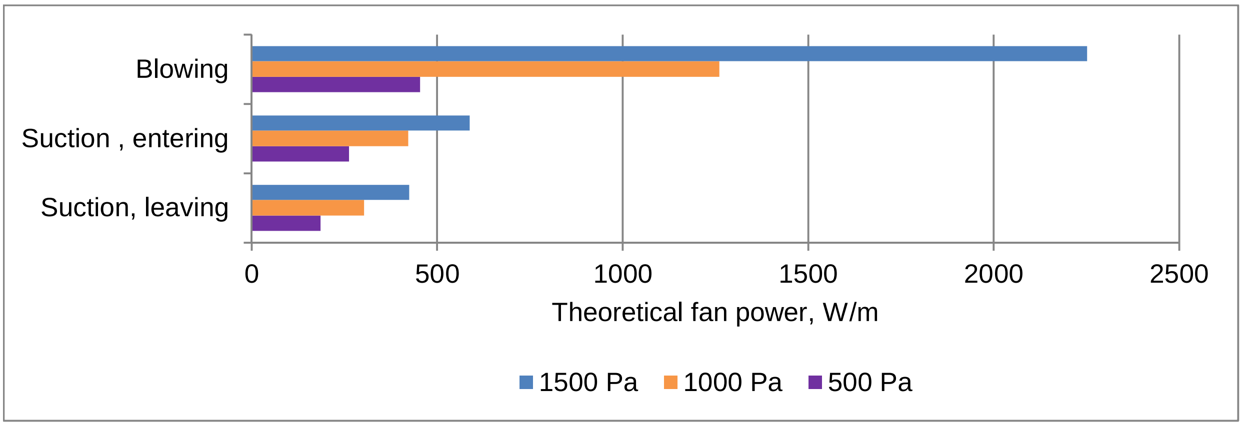

Figure 12. Comparison of the theoretical fan powers of three different vacuum zone limiting arrangements with distance of 8 mm between the drying fabric and the construction. Figure 1. Fluid flows in an ejector

Conclusions

In new machines the manufacturers are able to optimize the runnability systems according to the product, materials and the customer’s wishes. In present situation the problems are concentrated to machines which are optimized in different time, with different cost structure, different product and materials. These machines are now modified to fit the new circumstances. Because of small budgets the rebuilds are splitted to small slices which are sub optimized and implemented by separate companies.

Adhesion and web tensile strength depend on the mass quality and the web dryness. The running speed affects the aerodynamic forces. All these factors together lead to the need of runnability system underpressure. There are different methods to produce the runnability system underpressure. The fabric tension and especially the cross machine distribution affect the fabric bending. Combining the optimal system is very complicated. The results of this study can be a part in the analysis of the runnability system changes.

The volume flow of the air systems correlates with the cost and space need of the air systems. In the existing machine air system allows the use of seals or blowing equipment freely if the needed underpressure is lower than 500 Pa.

With the earlier mentioned pressure differences and the computed airflows were used to get the fan energy consumptions. The systems are compared with the air systems volume flows and fan power.

Energy consumption is computed for suction systems both with the fabric entering and leaving the vacuum zone. In blowing systems the difference between the entering and leaving fabrics is so small that only one value is computed. The studied underpressures are 500, 1000 and 1500 Pa. Distances between the fabric and the construction are 5 and 8 mm.

In systems where the underpressure is under 200 Pa, the fan energy usually is not an important cost issue. Air system volume flow or the energy consumption seldom gives grounds for investing to system changes. With 500 Pa underpressure the lowest needed fan power with suction systems is approximately half of energy consumption of the blowing system. The absolute level is between 150 and 300 W/m. With 1000 Pa underpressure the blowing systems fan power is three times the suction systems fan power. Also the absolute level is high. 1500 or higher underpressure with blowing technology can be used only in special occasions like very dirty machines and sticky masses, where suction systems don't survive.

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