PREVENTION OF WEB FLOATING AT WRAPPED TRANSPORT AND GUIDE ROLLERS

by

E. G. Welp, A. Kleinert and D. Schüler
Ruhr-University Bocham
GERMANY

ABSTRACT

Increasing productivity of web converting machines requires constructive improvements for the prevention of web floating at transport and guide rollers. Existing solutions which carry off the air like vacuum or grooved rollers as well as rough layers at the roller surfaces are on the one hand complicated and on the other hand limited in their effect.

On this background a novel principle, the so-called "gap throttle effect", which was discovered at the institute of engineering design at the Ruhr-Universität-Bochum (LMK) is presented.

The following analysis contains initial practically orientated investigations of pressure development resp. air entrainment for the conventional system „wrapped roller" and subsequent investigations for the novel system "gap throttle". The aim is to analyse the influence parameters with aid of a developed simulation program based on the finite differences method as well as to verify the results with experimental investigations at a test rig.

To show the influence and the potential of the "gap throttle effect", LWC, SC, Tissue and Newsprint with different material properties especially, air permeability and surface roughness, are analysed by variation of relevant process, gap throttle and machine parameters.

The results prove, that the effect can be used to achieve higher transferable friction forces and therefore higher web speed. Subsequent investigations show, that the effect amount and it's stability can be increased considerably by an additional small pressure on the web surface at the mounting area of the web. The innovation potential and the usefulness of this novel principle for web handling machines should be used for later research work, to increase the range of application, especially for winding and coating.

NOMENCLATURE

A	[m^2]	surface
Ap	[mm/mbar s]	air permeability
b	[m]	length in axial direction
F	[N]	force
h	[m]	gap width
M	[Nm]	torque
p	[bar]	hydrodynamic pressure
p_a	[bar]	ambient pressure
q	[m^2/s]	flow
R	[m]	roller radius
T	[N/cm]	web tension
t	[s]	time
u	[m]	web deflection
U	[m/min]	speed
V	[m^3/s]	volume flow
x	[m]	circumferential coordinate
α	[°]	circumferential angle
η	[mPas]	dynamic Viscosity
ρ	[kg/m^3]	density
Δ		difference
μ		friction coefficient

Indices

a	ambient
äqui	equivalent
G	sliding
GTF	gap throttle foil
max	maximal
min	minimal
R	friction
rdw	roller drives web
w	web
wdr	web drives roller

INTRODUCTION

During web processing it is the task of transport and guide rollers to secure an error free web transport. Existing constructions for the reduction of web floating are complicated, expensive and limited in their effect. The novel principle “gap throttle”, is able to reduce the hydrodynamic pressure between web and roller resp. the unrequested web floating in an inexpensive and efficient way. In the simplest case the effect can be created by a fixed plastic foil placed between web and roller in the mounting area of the gap.

To estimate the range of the „gap throttle effect“ analytical relationships, as well known from the mechanic and fluid mechanic, are unusable. Especially the foil bearing theory [1] and the Eytelwein equation [2] for the analytical description of the relationship between web tension at the mounting and launching area, friction coefficient and web angle only enable the description of ultimate states.

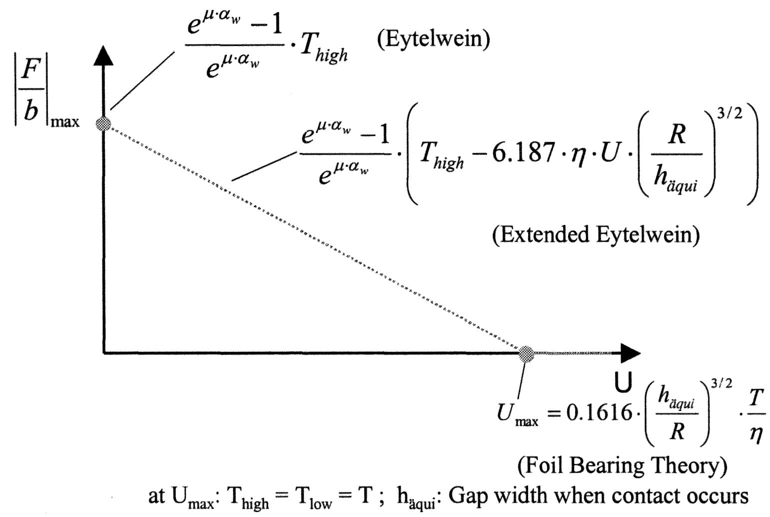

Figure 1 Transferable friction force versus web speed by using the Eytelwein equation and the foil bearing theory

On the one hand, at a web speed of zero, it is possible to calculate the maximum friction force and on the other hand the maximum boundary speed is ascertainable at a friction force of zero. Only a linear decay can be calculated by using the extended Eytelwein equation [3] in the speed range $0 < U < U_{max}$. The hydrodynamic contact pressure between roller and web and in consequence the transferable friction, which characterizes the web floating, is not describable versus the web speed. The calculation of these values is possible with a simulation program, which was developed at the LMK, based on the finite differences method. The utilization of the finite differences method enables the calculation of the local contact pressure resp. the transferable friction force in dependence of web tension, web speed, roller radius, friction coefficient, air permeability of paper and the dynamic viscosity of air. The simulation is based on the following three differential equation, which describe pressure, web deflection and tension.

Fluid pressure p (Reynolds Equation)

$$\frac{d}{dx}\left[p\cdot\left(U\cdot h-\frac{h^3}{12\cdot\eta}\cdot\frac{dp}{dx}\right)\right]=0 \qquad \{1\}$$

Web deflection u

$$\frac{d^2u}{dx^2}=-\frac{p-p_a}{T}\left(+\frac{1}{R}\right) \qquad \{2\}$$

Web tension T

$$\frac{dT}{dx}=\operatorname{sgn}M\cdot\mu\cdot\left(\frac{T}{R}-(p-p_a)\right) \qquad \{3\}$$

The principle of the finite differences method allows an interactive solution of these coupled parameters. A detailed description can be found in the paper published by Schüler [3]. The illustrated relationships were extended by the parameters support pressure and air permeability. The support pressure is considered by a locally defined higher ambient pressure at the wrap.

For the influence of the air permeability *Ap* we get:

$$Ap=\frac{\left(\frac{dV}{dt}\right)}{A\cdot\Delta p} \qquad \{4\}$$

The permeably constant *Ap* is the ratio of volume flow to the surface and the pressure difference. Further on the ambient pressure p_a resp. the pressure difference $\Delta p = p - p_a$ has to be considered. We get for compressible flows and permeable webs:

$$\frac{d(\rho\cdot q_x)}{dx}=\frac{d}{dx}\left[\rho\cdot U\cdot h-\left(\frac{\rho\cdot h^3}{12\cdot\eta}\right)\frac{dp}{dx}\right]=-\rho(p-p_a)\cdot Ap \qquad \{5\}$$

By an isothermal flow we can cancel the proportional constant ρ / p which leads to:

$$\frac{d}{dx}\left[p\cdot U\cdot h-\left(\frac{p\cdot h^3}{12\cdot\eta}\right)\cdot\frac{dp}{dx}\right]=-p(p-p_a)\cdot Ap \qquad \{6\}$$

Besides air permeability and friction coefficient the equivalent gap width $h_{äqui}$ strongly influences the quality of the results [3]. The friction coefficient of the used paper is experimentally ascertainable. The assumed equivalent gap width substitutes the in reality rough surfaces between web and roller with an equivalent distance. With the help of the foil bearing theory and the experimental measurement of the boundary speed, the determination of the equivalent gap width is possible with the following equation.

$$h_{äqui} = 3{,}37 \cdot R \cdot \left(U \cdot \frac{\eta}{T} \right)_{max}^{2/3} \qquad \{7\}$$

This assumption enables the calculation of the hydrodynamic pressure in the wrap and therewith the local contact pressure resp. the transferable friction force.

EXPERIMENTAL SETUP

For the experimental investigations of the gap throttle a test rig at the LMK was used [4]. It consists of three rollers with smooth steel rollers and a continuous web (width 600 mm).

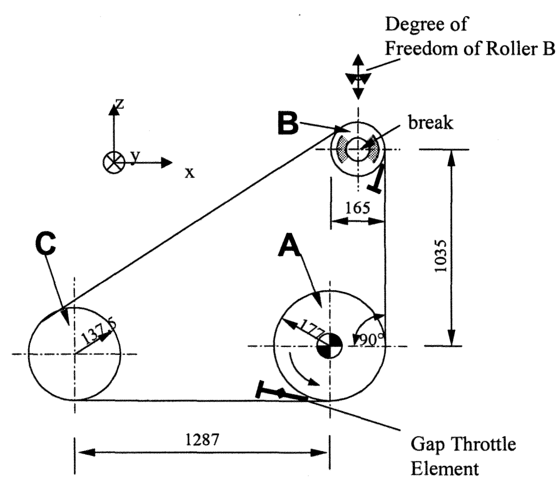

Figure 2 - Web transport test rig

The powered roller A transfers the necessary friction force to the web. Roller B is relocatable in z-direction and enables the web tension control. Furthermore the web guidance regulation is realized by a rotation around the z-axis. The bearing blocks of roller C have beams with strain gages for the measurement of the web tension. All experimental investigations were done with a wrap angle of 90°.

The gap throttle element is located between web and roller A at the mounting area of the gap. An adjustment device is fixing the flexible thin plastic foil and enables a parallel positioning of the gap throttle element for the variation of the immersion depth. An extra gap throttle element at the adjusting roller C ensures a error free web run and the transmission of high break torques. The “supported gap throttle effect“ uses a pneumatic or mechanic pressure, produced by a air nozzle or a support roller fitting to the web (Figure 3).

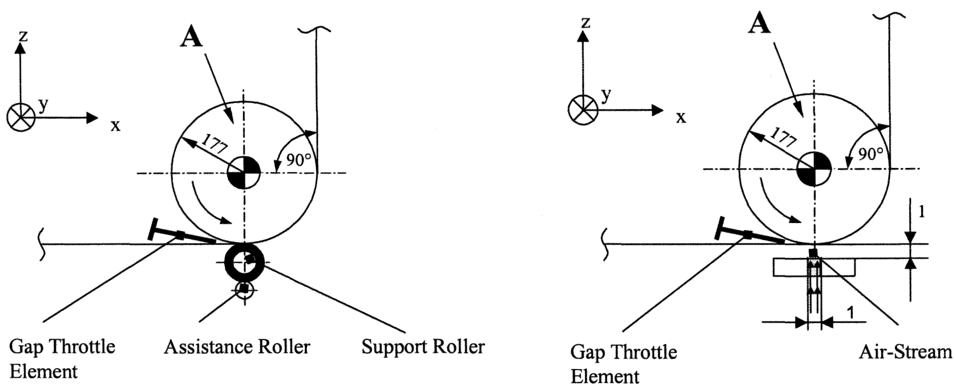

Figure 3 – Support elements for the support pressure

Measurement method

Complete web floating is characterized by the disappearance of solid state friction in the whole wrap angle and by sliding. This process point is easily measurable, because the very small web slip changes into sliding. Incremental encoder at the powered roller A and the web enable the measurement of web and roller speed and in consequence the determination of the process point, which indicates the beginning of complete web floating. Previous investigations of the relationship between transferable friction force, roller speed and measurable electrical motor current create the possibility to acquire the transferable friction force, which is approx. proportional to the effect amount.

The used devices possess a resolution of ±0,5 [m/min] for the speed measurement and a deviation of 1,2 % for the web tension. All the results were done at a slip of 0,7-1 % and a constant web tension (±1,5 %).

Material Properties

The following table (Table 1) shows the relevant material parameters of the tested paper LWC, SC, Tissue and Newsprint.

PAPER		***LWC***	***SC***	***Tissue***	***Newsprint***
Grammage	***[g/m²]***	57	56	80	45
Air Permeability (Bendtsen)	***[ml/min]***	~ 0	~ 0	294	192
Roughness (PPS)	***[µm]***	0,82	1,02	7,99	4,07
Sliding Friction Coefficient Web/Roll μ_G	***[]***	0,34	0,36	0,39	0,38

Table 1 - Relevant material parameters of the tested paper

To guarantee a representative choice of established paper, those with different air permeability and surface roughness were used. Different air permeability (Bendtsen) from 0 to 294 ml/min and surface roughness resp. friction coefficient enable the application area estimation of the gap throttle effect.

INVESTIGATION OF THE CONVENTIONAL SYSTEM "WRAPPED ROLLER"

Complete web floating begins, when solid state friction no longer exists and sliding between web and roller starts. If the gravitation and the centrifugal force is neglected, the hydrodynamic pressure at this point has to be nearly identical with the ambient pressure and the web tension at the wrap.

The following figure shows the calculated pressure difference for the paper SC and Newsprint at different web speed.

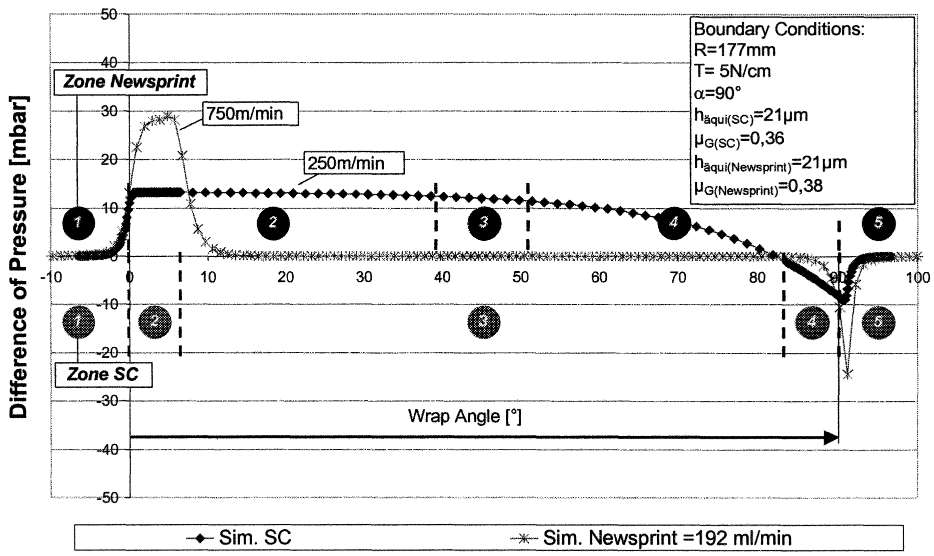

Figure 4 - Pressure difference between gap and ambient area by approx. air tight SC und air permeable Newsprint

The pressure profiles of the conventional systems show a high rising at the gap in the mounting area (Zone 1 and 2) and a following decrease at most parts of the wrap (Zone 3). In the area of the divergent gap (Zone 3 to 5) a higher contact pressure is created by a negative pressure. In particular it is clear, that the hydrodynamic pressure by the air permeable paper Newsprint decreases stronger in comparison to the approx. air tight paper SC and that the contact pressure governed by web tension changes little. Even at high web speed the air permeability of Newsprint enables a comparatively faster pressure equalization.

The contact pressure rises with a decreasing pressure difference, whereupon a maximum is reached in the negative pressure area (Zone 4 and 5). The height of the transferable friction force is proportional to the contact pressure in the wrap.

The friction force profiles in the next figure enable the analysis of the parameter surface roughness and air permeability.

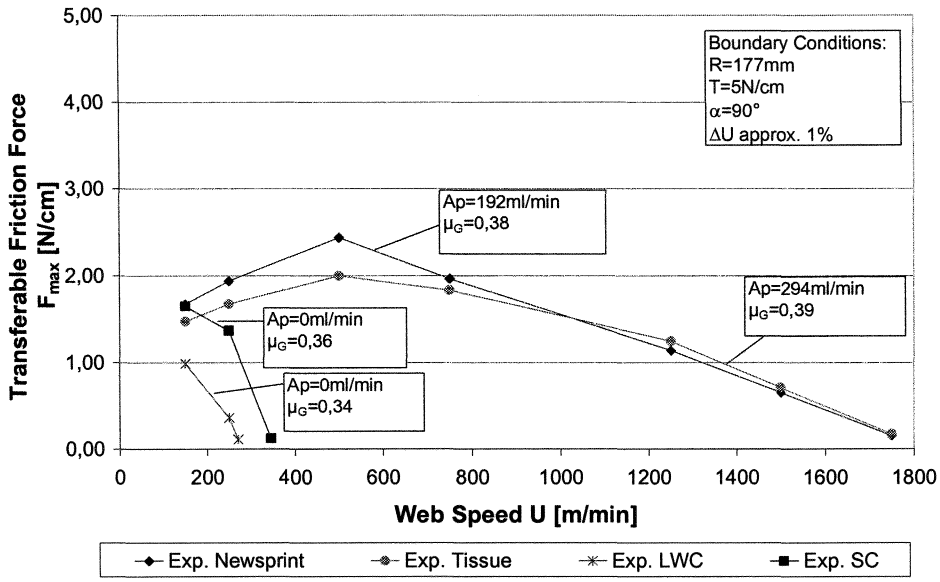

Figure 5 - Transferable friction force versus web speed by variation of surface roughness and air permeability

In the lower speed range the experimental friction force profiles show for air permeable paper Tissue and Newsprint a rise, which cannot clearly be explained. The hydrodynamic conditions in this range are neither explainable with the Eytelwein equation nor with the foil bearing theory. At this point the authors abandon a causal explanation, because in the further investigations only middle and high speed ranges will be of interest and the characteristic only appears for air permeable paper.

As expected the friction force profiles show, that the hydrodynamic pressure inside the wrap increases with rising web speed and only low friction forces are transferable. Further on, a boundary speed exists where web floating starts in dependence to the used web/roller configuration.

Also the relationships in the Eytelwein equation for the approx. air tight paper LWC and SC are approved, especially that with a higher friction coefficient increased friction forces can be transferred. The significant influence of the air permeability becomes clear by comparison of approx. air tight and air permeable paper. For air permeable paper like Tissue and Newsprint the hydrodynamic pressure is lower in the middle and upper speed range and therewith higher transferable friction forces and boundary speeds are possible. So as well known, the danger of web floating is higher for approx. air tight paper with low surface roughness.

INVESTIGATION OF THE NOVEL SYSTEM "GAP THROTTLE"

For the analysis of the "gap throttle" application range the following parameters are investigated.

Process parameter:

- Web tension
- Web speed

- Immersion depth of the gap throttle element
- Support pressure

Parameter of gap throttle element:
- Thickness
- Shape

Machine parameters:
- Pneumatic support pressure for the "gap throttle effect"
- Mechanical support pressure for the "gap throttle effect"
- Drive condition

The hydrodynamic relationships by variation of these parameters are shown in the following figures. Pressure profiles and the transferable friction forces „with“ (GTF) and „without“ a gap throttle element were calculated.

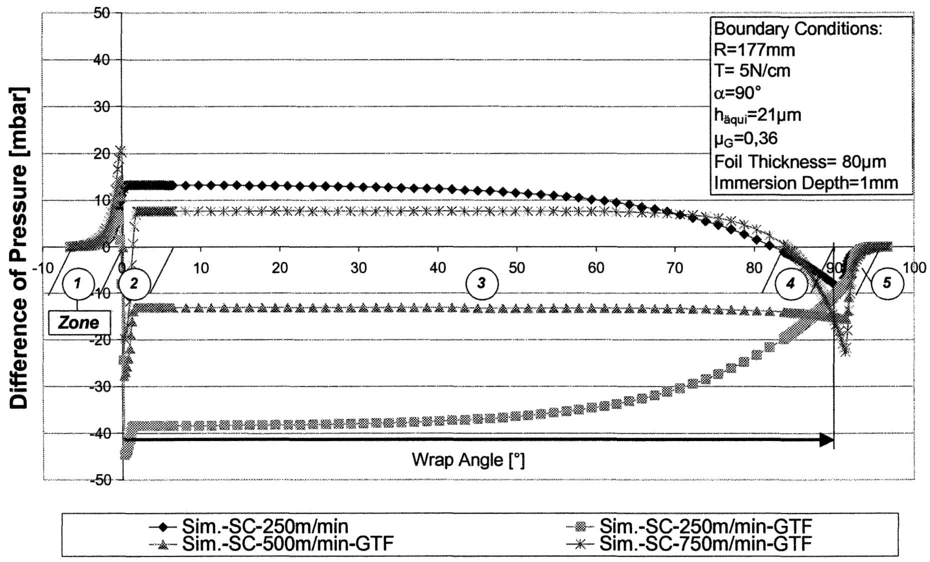

Figure 6 - Pressure difference between gap and ambient area for approximately air tight SC

In the web mounting area a hydrodynamic pressure rise has to be registered (Zone 1). In conformity to the considerations of the so called viscosity pump [3], the simulation results show a pressure decrease at the end of the gap throttle element. In zone 1 and 2 the hydrodynamic pressure is approx. constant for a large area and ends in a negative pressure at the web launching area (Zone 5). The pressure profiles at a web speed of 750 m/min make clear, that a significant higher contact pressure can be achieved by using the gap throttle foil. In the conventional system „wrapped roller“ similar hydrodynamic conditions are reached by a third of the web speed (250 m/min). Both conditions have in common, that the hydrodynamic pressure in the wrap is almost in balance with the present web tension.

As well known, the value of the resulting pressure difference depends on the web speed. With increasing web speed, the hydrodynamic pressure in the wrap increases. Therefore in case of high web tension complete web floating occurs at high boundary speed. In addition to the web tension and speed, the immersion depth of the foil dominates the effect in all parameter variations. A rectangular foil (thickness=80 μm) was used as a gap throttle element.

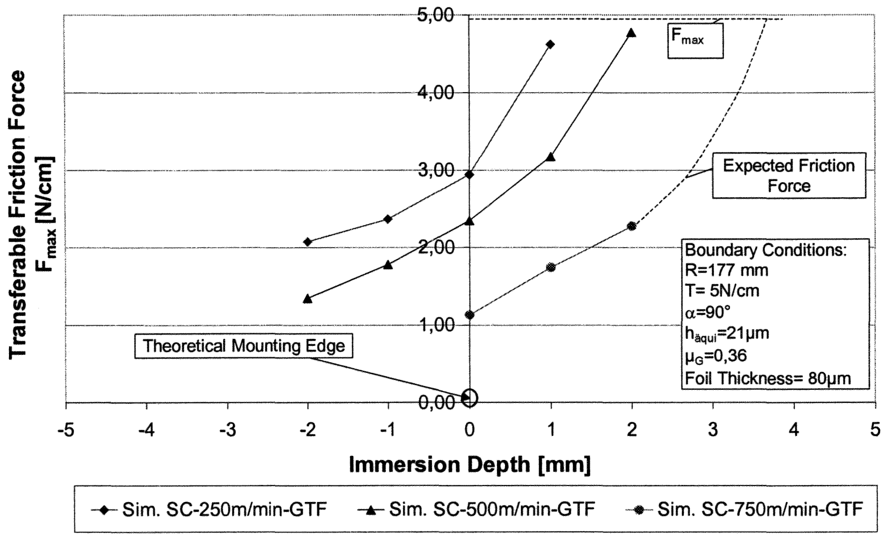

Figure 7 - Transferable friction force versus immersion depth by variation of web speed (SC)

The theoretical web mounting edge of the web is located at the abscissa value zero. The friction force profiles show a high rise, if the gap throttle foil immersion depth is 1 or 2 mm. The theoretical limit of F_{max} is achieved, if the present maximum web tension is transferable. If the transferable friction force is lower, a solid state contact area exists, where friction force transfer isn't possible in the wrap. For the realization of a maximum contact pressure between roller and web by rising web speed, the gap throttle immersion depth has to be increased. The following illustration shows numeric and experimental results for both systems.

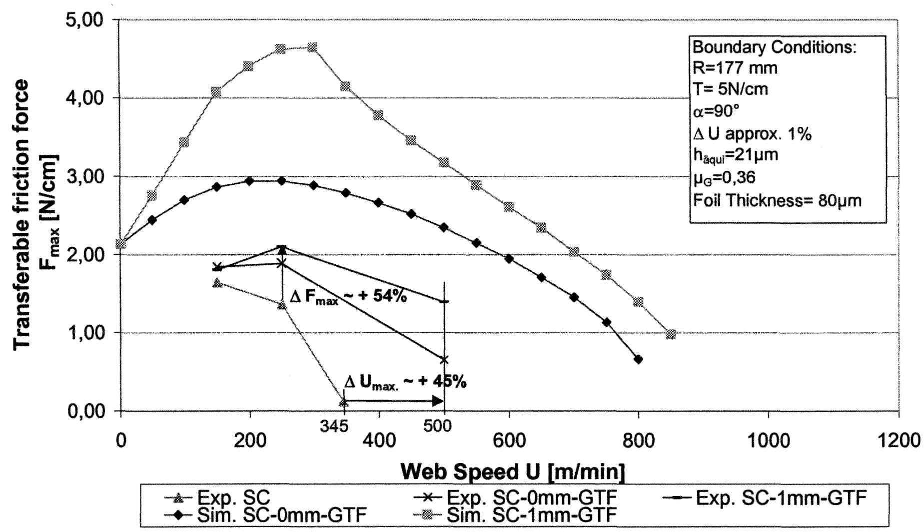

Figure 8 - Transferable friction force versus web speed by variation of immersion depth

By consideration of the friction force profiles it is recognizable, that the effect amount calculated with the simulation program is higher then the experimental results. A further special feature is the rise of the numeric friction force results in the lower velocity range by using the gap throttle foil. After careful consideration, the calculated friction force were found as qualitative correct, because the complex interactions between the vacuum at the end of the gap throttle foil and the hydrodynamic pressure at the wrap angle make these conditions possible in the simulation program.

Both deviations from the experimental investigations result from the assumption, that a vacuum can exists in the wrap (Zone 1 - 5). The negative pressure increases the contact pressure between web and roller and therefore leads to transferable friction forces, which could be higher then the maximum calculated with aid of the Eytelwein equation. In consequence it has to be considered, that in reality a negative pressure in the wrap isn`t achievable. The reason is the "open" wrap. Transverse to the direction of the web transport the web isn`t infinitely long - especially by converting of small web - and therefore side flow resp. pressure equalization occurs. Another point is, that in praxis therefore the maximum transferable friction force can be calculated in the system "gap throttle" with the Eytelwein equation. To improve the theoretical results preconsiderations about simulation program modifications, which pay attention to the described relationships, are under way.

It is interesting that in the system "gap throttle", according to the Eytelwein equation, an approximation to the value 2,2 N/cm (web speed U=0) doesn't occur during the experimental tests. This can result of deviations in the measurement of the electric motor current.

In conclusion it is recognizable that

- the simulation results represent the hydrodynamic influence qualitatively correctly.
- the gap throttle effect allows at a web speed of 250 m/min an approx. 54 % increase of transferable friction forces and the reaching of a boundary speed of 500 m/min (+45 %) for the paper SC.

- to achieve the maximal transferable friction force by high web speed an adjustment of the gap throttle foil immersion depth has to be recommended.
- differing from the theory contact between web and foil resp. foil and roller exists, which should be low by using the suitable immersion depth.
- the area of the optimal immersion depth lies between 0 and 2 mm by SC, because high friction forces are transferable and the gap throttle foil wear is considered.

The gap throttle effect is based on the principle to close the gap in the web mounting area as completely as possible. Therefore the assumption is possible, that by same process conditions a change of the gap throttle thickness or shape leads to a different hydrodynamic state in the wrap.

Numeric simulations with different rectangular gap throttle foils (constant thickness = 20, 40, 80, 100 μm) proved, that on the one hand the influence of foil thickness increase at higher web speed and on the other hand that thin foils increase the effect.

Further on, the geometrical shape of the gap throttle element has a strong influence at the hydrodynamic pressure resp. the contact pressure between web and roller.

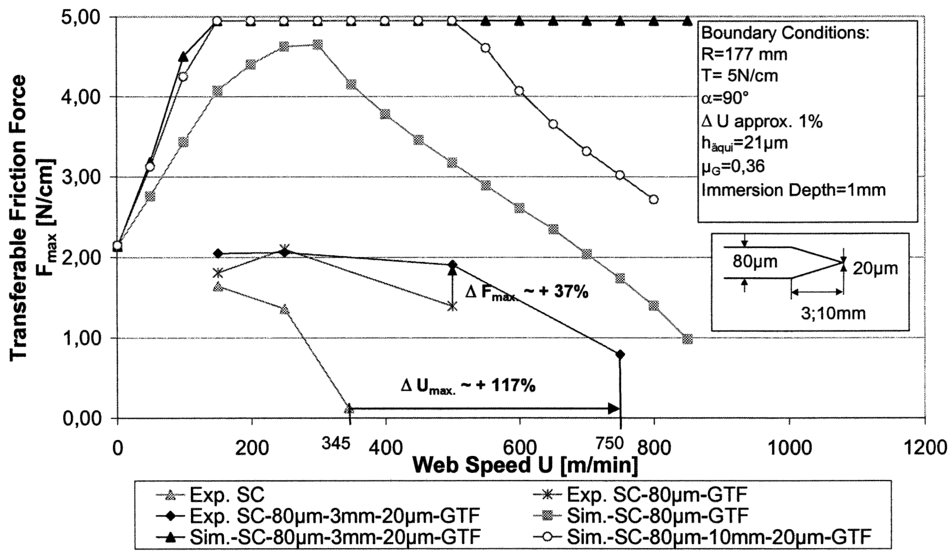

Figure 9 - Transferable friction force versus web speed by variation of gap throttle shape

The calculated friction forces by using a "linear reduced foil" have in common, that compared to the experimental results a raised effect amount is determined. The simulation results by a top length of 3 mm show a constant friction force up to a web speed of 850 m/min. Larger top lengths reduce the effect amount.

The experimental investigations confirm the constance resp. the effect stability in a large speed range. Further on, higher transferable friction forces were realized by using a "linear reduced foil". Compared to the rectangular gap throttle foil an increase of 37 % could be achieved at a web speed of 500 m/min and in comparison to the conventional system "wrapped roller" an error free web transport until double web speed.

The theoretical and experimental results clarify, that with aid of a suitable gap throttle element it is possible to strongly influence the hydrodynamic pressure in the wrap. On the basis of the described principle, further developments finally lead to an optimized gap throttle shape which is shown in the following figure.

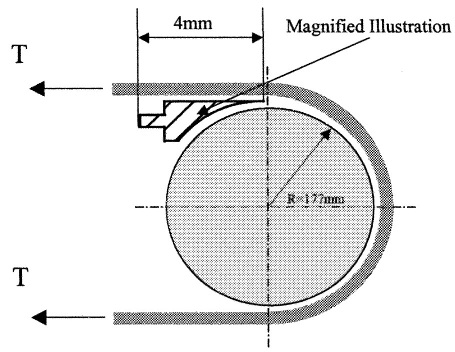

Figure 10 - Principle of an optimized gap throttle element

This gap throttle element fills extensively the gap in the mounting area, decreases the hydrodynamic pressure and should guarantee a high effect amount. At this point it becomes clear, that high production costs and a short life cycle have to be expected. Still the general principle of an optimal solution is deductible. In particular from the previous results and considerations it is clear, that web floating is significantly influenced by the conditions at the mounting area. It can be assumed, that in this area a support pressure at the outside of the web surface has an influence on the hydrodynamic state in the wrap. The support pressure should be located at the mounting area of the web, especially at the mounting edge resp. at the end of the gap throttle foil. This modification was theoretically and experimentally examined.

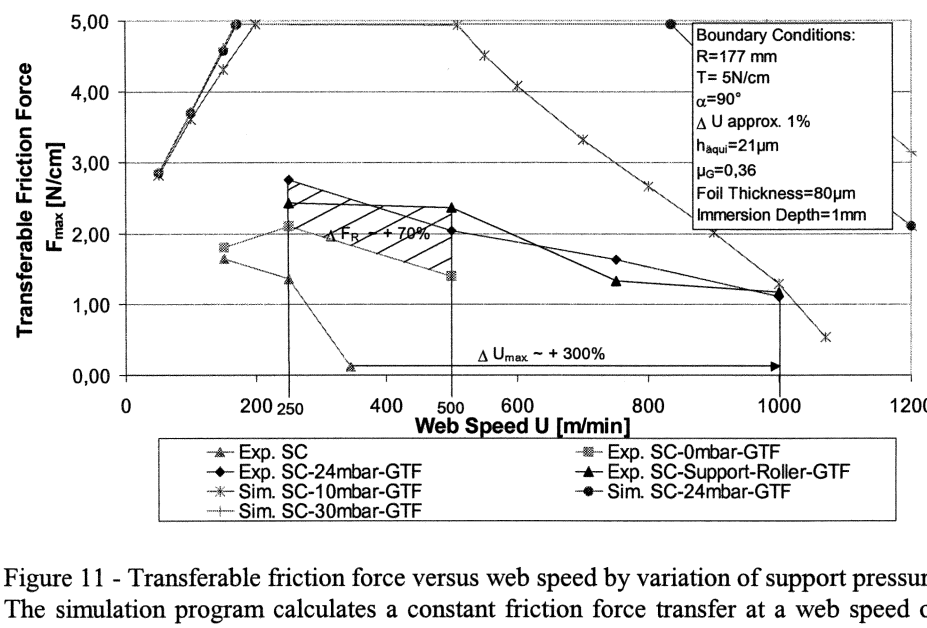

Figure 11 - Transferable friction force versus web speed by variation of support pressure

The simulation program calculates a constant friction force transfer at a web speed of 200 to 500 m/min and a support pressure of 10 to 30 mbar. At higher web speed the transferable friction forces decrease, but significant higher boundary speeds are achieved.

For the realization of the support pressure at the test rig a support roller or a free nozzle jet (24mbar) were used. It is recognizable, that both devices lead to higher transferable friction forces and attainable boundary speed.

Compared to the novel system "gap throttle" enables the “support gap throttle effect” an approx. 70 % increase of the transferable friction forces at a web speed of 500 m/min and an approx. doubling of the boundary speed. The comparative consideration with the conventional system "wrapped roller" shows an approx. duplication of the transferable friction forces at a web speed of 250 m/min and an approx. triplication of the achievable boundary speed.

The investigations show, that the simulation program qualitatively correctly calculates the physical effect of a support pressure. The different shape of the gap in the mounting area reduces the hydrodynamic pressure build up, therefore increase the solid state contact and the Coulomb friction between web and roller in a large speed range. The web fixing at the mounting edge enables the abandonment of the gap throttle foil tracking. Further the height of the attainable transferable friction forces and the achievable boundary speed make clear, that the effect stability is guaranteed in a large speed range and therefore a reliable operating point is realizable in the process.

In the case web drives roller “wdr” the lowest web tension at the wrap angle is, in contrast to the drive condition roller drives web "rdw", located at the mounting area of the web. The maximum web tension has to be registered at the launching area. The hydrodynamic pressure build up strongly depends on the shape of the gap at the mounting area and therefore a different web floating behavior can be assumed for “wdr”. The following illustration shows pressure profiles for different drive conditions and otherwise identical process conditions.

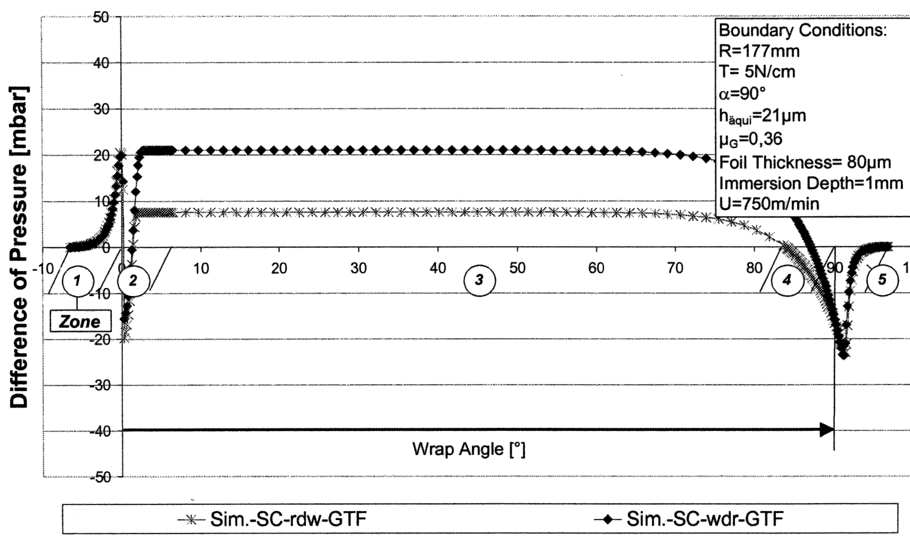

Figure 12 - Pressure difference between gap and ambience by variation of drive condition for the system “gap throttle”

For the case "wdr" the different shape of the gap in the mounting area, which is governed by the local web tension, leads above large areas of zone 2, 3 and 4 to a raised hydrodynamic pressure. The resulting contact pressure enables only the transfer of smaller friction forces. The gap throttle effect amount and the achievable boundary speed is lower in the case of "wdr". Therefore, by otherwise identical process conditions, complete web floating will occur at lower web speed. In analogy, the previous shown relationships for the case "rdw" have to be considered.

CONSTRUCTION PRINCIPLE

In addition to a high innovation and use potential the gap throttle effect is in comparison to present solutions characterized by a simple construction principle and therefore the integration in existing machine equipment is effortless. This bases on the fact, that even simple rectangular gap throttle foils increase the friction force transfer and that the absolute effect amount resp. the effect stability can be raised significantly with a “linear reduced foil” and/or an additional support pressure. The following figure shows a construction principle which considers the wear life-time, low maintenance, a minimum of control units and less space by low web volume and self-weight.

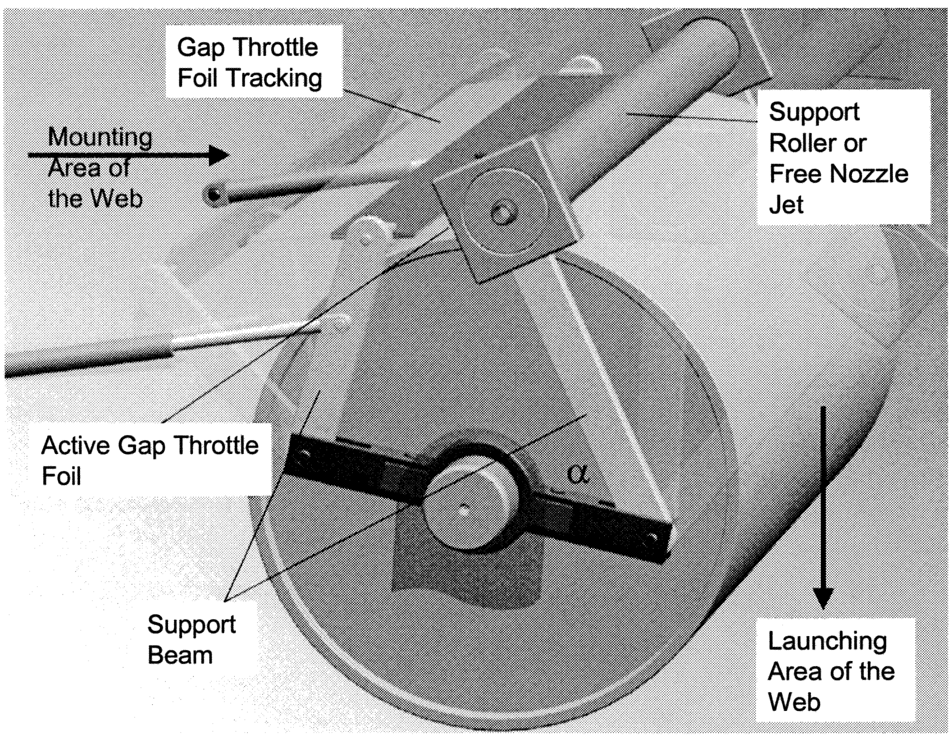

Figure 13 - Construction principle of the gap throttle effect

Two hydraulic cylinders position the active gap throttle foil in direct nearness of the web mounting area. Single foils or a foil storage can be used. The foil material should be high strength, surface strength and flexible. Simultaneously the support pressure, realized by a rotatory move of the two beams and the support element, is applied. During the use of the support roller (Shore-A=0) the height of the support pressure is defined by the angle α.The friction forces transferred from the web to the support roller should proof a rotatory move. If a free nozzle jet provides the support pressure, the value of the support pressure can be controlled by the used pneumatic pressure and the chosen distance of the free nozzle to the web surface. Foil positioning, tracking and changing are on-line possible, so production breaks or downtimes are prevented.

CONCLUSIONS

The investigations confirm, that the novel principle decreases efficiently the hydrodynamic pressure between web and roller and therefor as a consequence the web floating. The construction principle shows, that the realization is on the one hand simple and on the other hand inexpensive.

It is conceivable, that the manipulation of web floating with the gap throttle foil is easier by small webs than for converting of wide webs. In particular the gap throttle effect will help for converting of flexible materials with low air permeability and surface roughness. Especially the

web transport,
cooling and heating,
coating and
winding technology

will improve by using the effect.

Transport and guide rollers, equipped with gap throttle elements, enable the optimization of web transport and guidance. The gap throttle element also supports the heat transfer at temperate roller. The reason is the higher contact pressure between web and roller.

The coating technology reveals another application range. A possible reduction of the adherent boundary layer can increase the error free coating of web.

At this time preconsiderations for the further use in the winding technology are already taking place. Constructively complicated grooved roller or pressure roller can maybe prevented. Whereat by use of a support element the winding can be more gently and consequently a higher winding quality is achievable.

Another point of view is the increased process speed. An improved machine load and therewith a higher productivity can be expected.

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