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Optimisation of screen plate design for the removal of stickies from deinking pulps

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Abstract

A study about stickies screening in deinking lines was launched in the frame of the European project ScreenClean. The screening program in this project, led by CTP, was focused on PSA stickies and included lab screening tests, numerical simulation at LEGI and pilot tests in cooperation with AFT.

Basic research work was performed to understand the extrusion of stickies through slots and improve screening efficiency. A single-slot screening device was used to visualise the extrusion of cylindrical PSA particles. Water-based acrylic adhesives were revealed to be much weaker than hot-melt rubber adhesives, especially at high temperature after alkaline soaking, and required lower pressure and less time to be extruded through slots. Gentle screening conditions with a low maximum pressure during the positive pressure pulse as well as reduced temperature and pH should thus minimise stickies extrusion, as expected. Both experimental and numerical simulation results led to the same conclusions about the effects of key screening parameters. Particles 2 to 3 times larger than slot width were extruded at the typical pressures measured in screens, but the time required to pass the slot was considerably higher than the duration of typical positive pressure pulses, which suggested that particle extrusion should take place step-by- step over several rotor revolutions.

The laboratory screening tests showed less stickies extrusion with milled screen plates that had two sharp slot inlet edges compared to wedge wire screen plates with a convergent slot inlet. Pilot screening tests with various screen plates (0.15 mm slots, 0.6 to 1.2 mm contour height with different angles) confirmed this trend as milled slots showed higher stickies removal efficiency - though fibre passage was increased with wedge wire slots. Contour design was found however to have more effect on screening efficiency than the slot inlet design. The best results were obtained with the lowest contours, while reducing contour angle showed only a positive effect at a higher contour height. The pilot tests also confirmed that screening should be performed at lowest possible temperature to optimise the removal of PSA stickies.

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1 Introduction

Despite progress in recycling technology and the efforts engaged to develop environmentally benign adhesive products, stickies problems are far from being solved. PSA stickies from pressure sensitive adhesives (labels, tapes, envelopes, etc.) are the main concern in the field of deinking while hot-melt glues (container sealing, book bindings, etc.) contribute strongly to the paper machine deposit problems in the field of packaging papers. The research presented in this paper was performed in the framework of a European project named “ScreenClean” [1], which aims at improving the removal of primary PSA stickies at the different deinking process steps, with a special focus on pressure screening.

Screening is clearly the most effective technology to remove primary stickies (solid particles introduced with the raw material and showing an adhesive effect under standard test conditions) especially the “macro-stickies” fraction. Indeed, macro-stickies do not refer to particles in the visible size range, but to the particles retained by laboratory screening with typically 0.10 mm slots for deinked pulps, according to widely accepted standard test methods [2-4]. By contrast, “micro-stickies”, which are defined as the fraction of primary stickies passing the lab screen, are much more difficult to remove by screening. Large micro-stickies particles produce visible dots in the paper sheet as they are generally covered with ink, while micro-stickies are mainly responsible for paper machine deposits [5-6].

Screening is currently performed in deinked pulp mills with slots down to 0.10 or 0.12 mm for respectively wood-free (MOW) and wood-containing (ONP/OMG) deinked pulp [7-9]. Fine screening systems in European DIP lines are typically operated with 0.15 mm wedge wire slots in the low consistency range [10]. The particular behaviour of stickies in screens is characterized by their ability to be extruded through the slots by the pressure generated by the rotor and the pulp flow, which is a consequence of the visco-elastic properties of the adhesive material. Soft, deformable stickies which can be extruded though slots should be considered as “probability” contaminants (normally particles with at least one dimension smaller than the slot width) rather than “barrier” contaminants (normally particles with all dimensions larger than the slot width). The behaviour of such particles in pressure screens can be characterised, on average, by a particle passage ratio, which is defined by the ratio of the downstream to the upstream particle concentration in a screen cylinder section, according to the probability screening theory [11-16]. Particle passage ratios should be determined for particles of different size and shape classes to correctly predict the performance of industrial screening systems.

Basic studies were carried out over the last decade at several research institutes, as reviewed in [16], to develop an understanding of the screening process at the scales of both pulp macro-flow conditions around the rotor, and unsteady micro-flow conditions and particle separation phenomena at the surface of the screen plate and through the slots. Studies at CTP in this field were first performed with relevant probability contaminants, i.e. flat-shaped particles (0.5 mm^2 films) and long-shaped particles (shives) with a smaller thickness than the slot width. A major conclusion about these studies [16-17] was that all the parameters which improved the passage of the fibres through the slots, i.e. increasing the slot width and effective normalised slot velocity, also increased the passage of the probability contaminants. Increasing the passing velocity (as calculated from the accept flow rate), reducing the slot friction factor with wedge wire design and increasing the intensity and duration of the positive pressure pulse created by the rotor were assumed to increase the effective slot velocity during the screening phase and thus to increase the probability for particles to be captured in the fluid exit layer and then to pass the slot. The effective normalised slot velocity was an extended definition of the normalised slot velocity [18], i.e. the ratio of the effective slot velocity to the tangential velocity at surface of the screen cylinder. Increasing the thickness of the exit fluid layer taken from the flow above the contour and turning into the slot (cf. figure 11)

was assumed to enhance the ability to drive particles towards the slot inlet. CFD simulation showed that this fluid layer thickness was roughly proportional to the normalised slot velocity and to the slot width [19]. The effects observed when changing rotor velocity were attributed to changes induced by the tangential fluid velocity in the exit layer thickness [16-17]. From a practical viewpoint, probability screening efficiency, i.e. the selectivity of separation between fibres and thin contaminants, was shown to be very difficult to improve by changing slot velocity and design, or rotor velocity and design, for a given contour design. Clear improvement of the screening efficiency was only achieved by reducing the height of the contours, from 1.2 to 0.6 mm, which was attributed to the thought that particle contacts with the inclined contour walls more efficiently rejected large and stiff contaminants compared to flexible fibres [17].

Indeed, the hydrodynamic screening mechanisms revealed through the investigations with thin flat and long-shaped particles should also apply to stickies - at least until the particle has reached the slot inlet. The extrusion process should then become decisive. Recent research reported on experimental studies of the passage of acrylic PSA particles through a fine slot in a single slot laboratory device using vacuum to extrude the particle through the slot [20-21]. The particle passage probability was shown to increase as temperature and pressure drop increased and as the particle width, thickness or area decreased. Particle size and shape were controlled by changing the pulping conditions, which produced mainly string-like particles. Slight changes in particle size and shape were observed after the extrusion of the particles through the slot.

The work reported in this paper deals with two major aspects of stickies screening: The first part is about fundamental studies on the extrusion of stickies through slots [22], and it includes both experimental results obtained at CTP and numerical simulation results obtained at LEGI. The second part, aiming at optimising the design parameters of the screen plate, is devoted to pilot screening tests performed at CTP in cooperation with AFT.

2 Extrusion of Stickies Through Slots

2.1 Experimental Studies

The objective of this study was to develop a better understanding of the stickies extrusion process through visualisation, in connexion with the numerical simulation work engaged at LEGI in the framework of the ScreenClean project.

2.1.1 Experimental Set up

The single slot channel screen shown in figure 1 was designed to simulate the flow conditions at the surface of the screen plate and through the slots during the positive pressure pulse and to change and easily control the width and design of the slot. The channel height was 10 mm and the width 15 mm. The device was equipped with a syringe, intended (but not used) to introduce stickies at the right level to drive the particle toward the slot inlet according to the channel velocity (controlled by feed and reject valves) and to the slot velocity (controlled by the accept valve). A high-speed CCD camera (Sony XC-HR300) was used at 100 or 200 images per second to visualise the particles in transmitted light, with a continuous light source located behind the transparent channel. The resolution was 2 or 8 µm depending on the magnification of the optics (x1 or x4).

The visualisation test was limited to the extrusion of stickies through the slot, as a consequence of the shape of the PSA particles and procedure used for the tests.

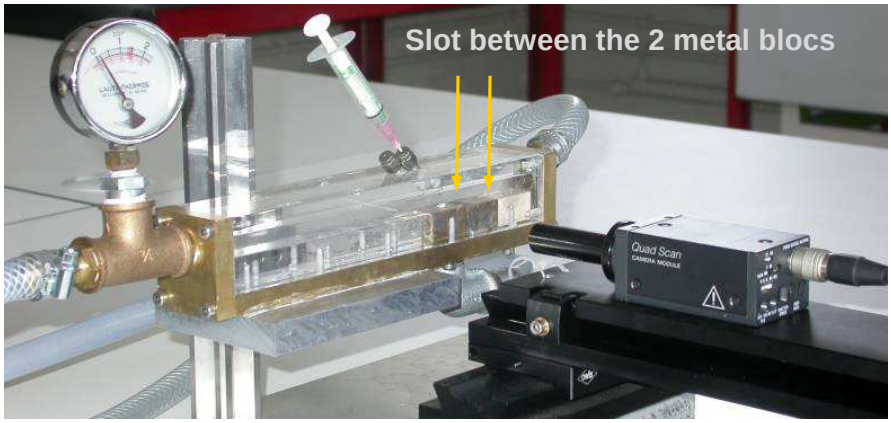

Figure 1: *Single slot channel screen with camera*

2.1.2 Adhesive particles and test procedure

PSA stickies particles observed in mills have various sizes and shapes, depending on the type of adhesive and pulping conditions. Previous adhesive label re-pulping tests [4] showed that acrylic labels gave more flat-shaped particles than the SBR labels, which was attributed to the higher trend of the less hydrophilic rubber-based adhesive film to stick onto itself and form thick rolled up particles in the pulper. Subsequent lab screening tests with 0.08 mm slots showed a low screening efficiency of about 50% with the acrylic adhesive (the total area of micro-stickies passing the slots and measured in the visible size range on hand-sheets for specks > 0.01 mm^2 was about half of the stickies area in the feed pulp) compared to 90% efficiency obtained with the thicker and larger SBR adhesive particles.

Long-shaped particles were considered to be most relevant to a study of the extrusion of mill PSA stickies. Indeed, flat-shaped stickies with lower thickness than the slot width (down to 20 or 30 µm, the thickness of wet adhesive films) are not relevant to investigate extrusion while spherical particles are typically found after dispersing, especially kneading, i.e. in the second deinking loop after fine screening.

It was thus decided to use the cylinder as the model particle shape in the extrusion studies. Special rolls of adhesive films between two silicone release papers were used to manufacture cylindrical adhesive particles of different diameters (figure 2). Two commercial adhesives from Avery Dennison Jackstädt were tested:

- a water-based acrylic adhesive (ref E115)
- a hot-melt based rubber adhesive (ref D170)

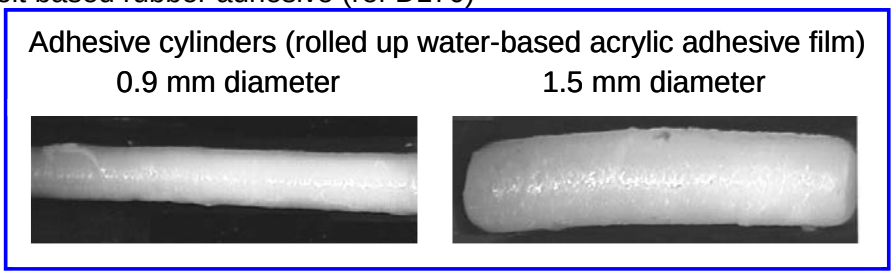

Figure 2: *Adhesive particles manufactured for the tests*

These products were taken as reference adhesives in the ScreenClean project [4] as they represent respectively the most common type of adhesive used for label application in Europe, and a growing market share among the other types of adhesives. The adhesive cylinders were measured and tested after soaking about one hour, which is particularly important with the acrylic adhesive which showed to absorb about 50% water.

The cylindrical shape of the adhesive particles did not allow them to be introduced in the channel flow through the syringe (figures 1). The following procedure shown in figure 3 was adopted:

- the adhesive cylinder was introduced in the device through the valve V2 while a very low flow rate was maintained in the channel until the cylinder reached the slot inlet and was properly aligned with the slot,
- the valves V2 and V4 were closed, the flow rate in the channel was increased with the pump after opening V3 and the pressure was set to the desired value with a sufficient flow rate through the channel,
- the valve V4 was then opened rapidly (less than 0.5 s) to set the pressure on the adhesive particle.

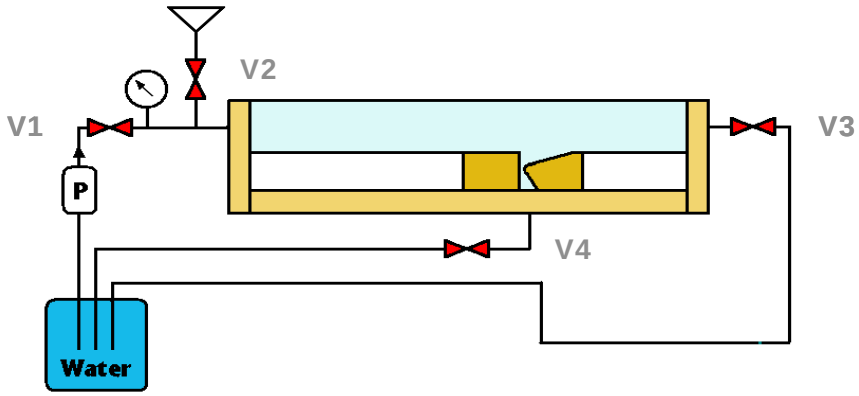

Figure 3: *Adhesive extrusion test procedure*

This procedure was established in order to control, as far as possible, the pressure during the extrusion process, since the flow rate through V3 was much larger than through the open slot area, about half of the slot being covered by the adhesive cylinder. Most of the tests were performed only to determine the pressure required to extrude the particle as a function of adhesive and slot characteristics. Images were recorded under certain conditions to analyse deformation of the particles and to determine the extrusion time. Some tests were also performed at extrusion pressures far above the usual range of positive pressure pulses observed in screens, i.e. typically 20 to 100 kPa.

2.1.3 Effect of adhesive material parameters

A first test series was performed with 0.5 mm slots with “wedge wire like design” to study the adhesive material parameters. New slots with a more accurate design were used later to study the effects of slot design parameters. Figure 4 shows the pressure required to extrude the adhesive particle versus the normalised particle size defined as the ratio (d/w) of the cylinder diameter to the slot width, for the two reference adhesives at room temperature (22℃) and at a typical temperature in deinking circuits (50℃). The extrusion pressure was significantly lower with the acrylic adhesive (E115) than with the hot-melt rubber adhesive (D170) at both temperatures. This suggests that the acrylic adhesive material is softer and that acrylic stickies should be more difficult to screen as larger particles are extruded through the slots for a given pressure. Increasing the temperature reduced the extrusion pressure, especially with the acrylic adhesive, which suggests a higher softening of the adhesive material. It is interesting to note that the extrusion pressure is roughly proportional to the particle “oversize” (d-w) though the extrusion phenomenon is probably strongly non-linear. The results in figure 4 indicate that acrylic adhesive particles with diameters 2 to 3 times larger than the slot width were extruded through the slots in the temperature and extrusion pressure range of mill screening systems.

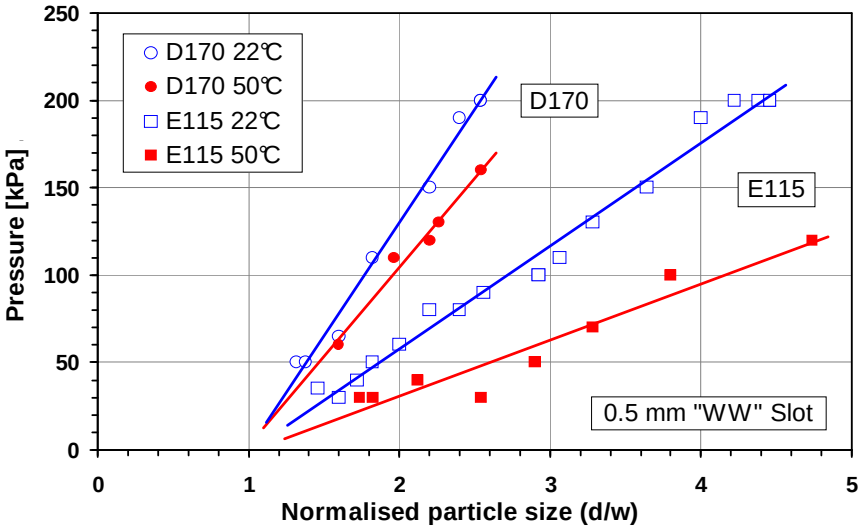

Figure 4: *Effects of adhesive material and temperature*

Extrusion tests were performed after soaking the adhesive particles in cold or hot water at pH 10 to investigate the effect of caustic soda added to the pulper in deinking mills. The results in figure 5 show a large decrease of the extrusion pressure when acrylic adhesive particles were soaked at room temperature with caustic soda. At high temperature, the decrease of the extrusion pressure was lower as soaking pH was increased. These results suggest that the penetration of water and/or the dissolution of adhesive components (assumed to be responsible for softening the adhesive particle) required higher pH at low temperature.

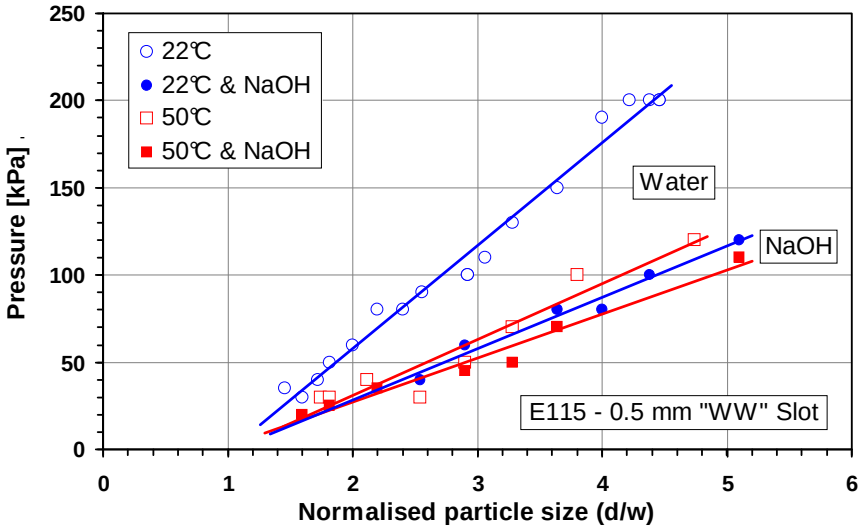

Figure 5: *Effect of alkaline soaking of acrylic adhesive*

Soaking caustic soda produced the opposite effect with the hot-melt rubber adhesive, as a significant increase of the extrusion pressure, by about 50%, was observed as soaking pH was increased (pH 10) at both temperatures (22 and 50℃).

2.1.4 Effect of slot design parameters

Milled and wedge wire slots were compared to investigate the effect of slot inlet design which was supposed to significantly influence the extrusion process. Metal blocs shown in figure 6 were manufactured at scale 1 and at scale 5 to improve the accuracy of the slot inlet radius. The dimensions in figure 6 were defined on the basis of 0.10 mm slots and chosen to cover the variations observed with commercial screen plates [22].

Slot type	Slot scale	W (mm)	R (mm)	B (mm)	L (mm)	H (mm)
MS	1	0.10	0.05	0.10	0.8	1
WW	1	0.10	0.20	-	-	1
MS	5	0.50	0.25	0.50	4.0	5
WW	5	0.50	1.00	-	-	5

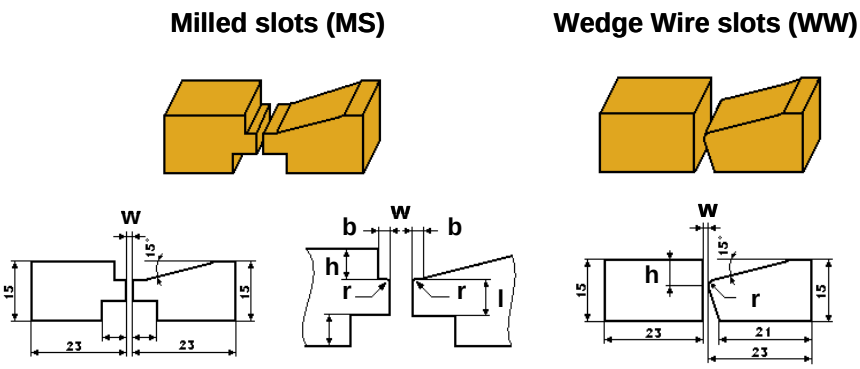

Figure 6: *Design and dimensions of the tested slots*

The extrusion tests were first performed with the slots at scale 5 in order to improve the accuracy of the size and shape of the adhesive cylinders. The results in figure 7, which were obtained at 47℃ after soaking the adhesives in tap water, confirmed the higher extrusion ability of the acrylic adhesive. The extrusion of both types of adhesive particles clearly increased with the wedge wire slot compared to the milled slot, as expected when looking at the shape of the slot inlet section. In short, the particle is submitted to lower stresses when extruded through one round edge with slightly converging contour walls (165° angle with the wedge wire contour in figure 6) than through two sharp edges (4 times lower radius with the milled compared to the wedge wire slot) with slot inlet location on a flat contour bottom.

The time needed for the adhesive particles to pass completely through the slot was recorded under the same conditions as in figure 7, except for the pressure, which was 50 kPa for all the tests. The results in figure 8 showed a much higher extrusion time with the milled slot compared to the wedge wire slot, but only with the acrylic adhesive. The higher trend of the hot-melt rubber adhesive to stick at the slot walls was responsible for the very high extrusion time measured with wedge wire design. In fact, the extrusion time was over-estimated as it was recorded when the whole adhesive cylinder had passed the slot, after detachment of all the parts stuck on the slot outlet wall (fig. 10). The sharp inlet edges and the higher length of the milled slot are thought to be responsible for the longer extrusion time observed with the acrylic adhesive.

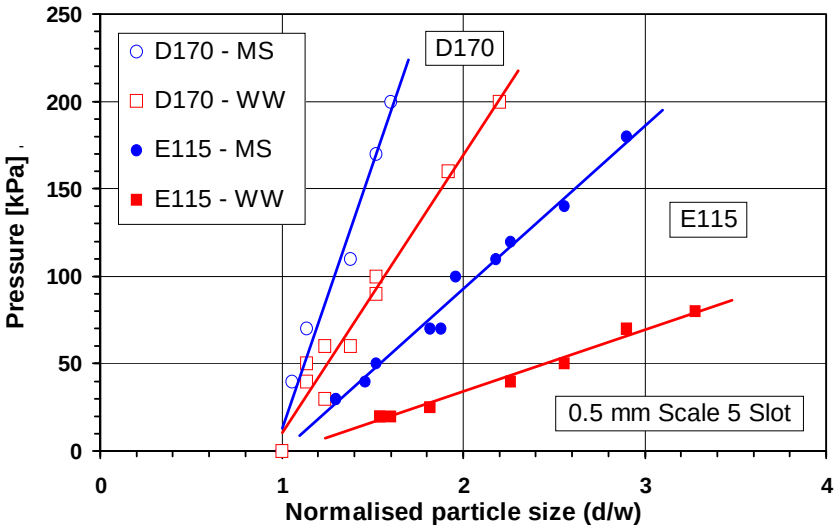

Figure 7: *Effect of slot design on extrusion pressure*

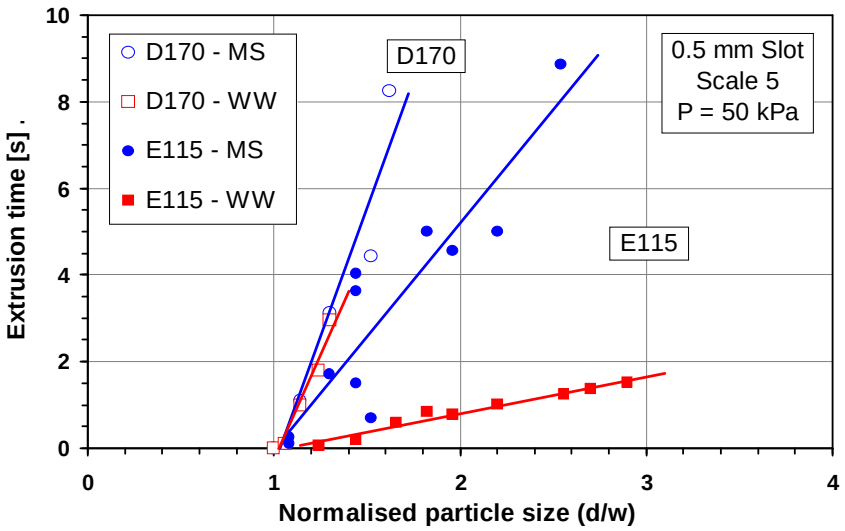

Figure 8: *Effect of slot design on extrusion time (at P = 50 kPa)*

The most important conclusion from the results in figure 8 is that the extrusion time is about two orders of magnitude higher than the duration of the screening phase, i.e. a few seconds compared to typically 20 ms, which gives new insight in stickies extrusion mechanisms. This means that adhesive particles with significantly larger thicknesses than the slot width cannot pass the slot during one positive pressure pulse and that the passage of such particles through the slots most probably takes place over several rotor revolutions in a multi-step extrusion process. One should, however, keep in mind that the experimental procedure does not take the inertia of the particle approaching the slot into account, which means that extrusion times in figure 8 are over-estimated compared to the real situation, especially for low extrusion times.

Concerning scale effects, some tests were performed with the slots at scale 1 to evaluate the extrusion pressure at mill relevant conditions, i.e. at 47℃ and with acrylic adhesives after neutral and alkaline soaking. The results were less accurate, as expected, but gave similar pressure values and led to the same conclusions regarding the influence of slot design and alkaline soaking of the adhesive, though the effects were lower [22].

The pictures in figures 9 and 10 illustrate the extrusion of acrylic adhesive cylinders through the milled and wedge wire slots at scale 5. The ends of the cylinders passed the slot first,

especially with the small cylinders. One can observe with the wedge wire slots that parts of the adhesive particle still stick at the wall, generally at the right side, when the particle has passed the slot.

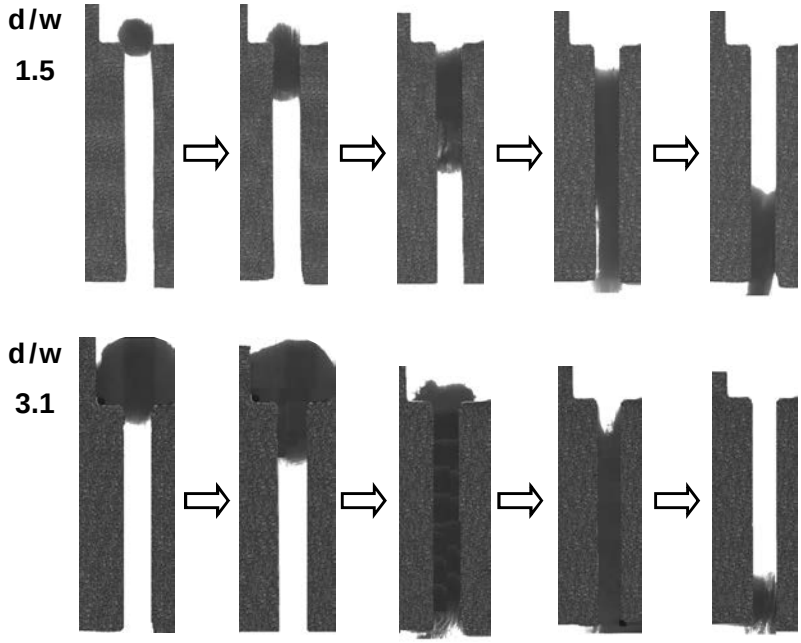

Figure 9: *Stickies extrusion through milled slots*

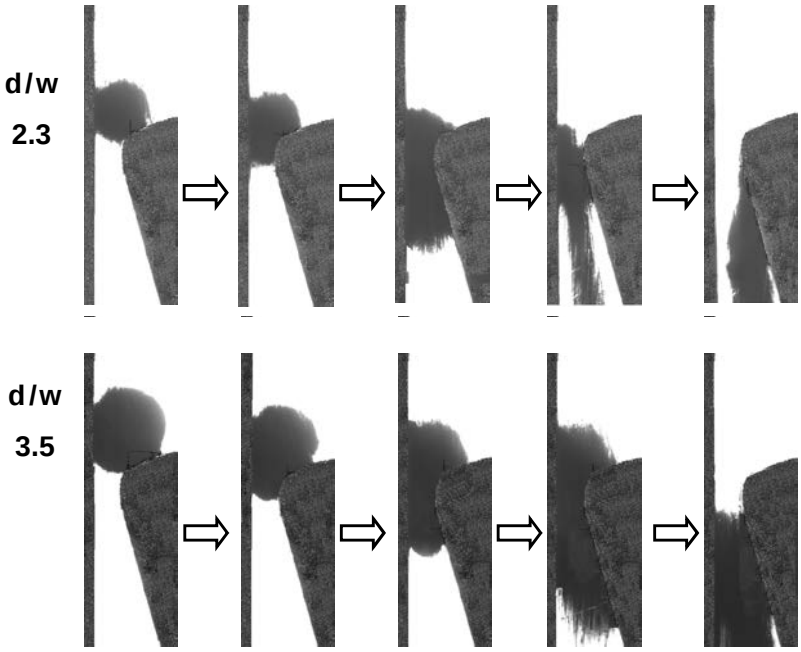

Figure 10: *Stickies extrusion through wedge wire slots*

2.2 Numerical Studies

Application of CFD simulation to screening started at LEGI in the framework of a thesis prepared in cooperation with CTP and Kadant Lamort [19,23-25] and was continued in the framework of the ScreenClean project [22].

2.2.1 Screen plate flow simulation

The numerical simulation of the extrusion of stickies through slots first requires the simulation of the flow conditions at the screen plate in order to establish the pressure exerted on a particle at the slot inlet. The velocity at which the particle approaches the slot is also an important parameter when taking particle inertia into account. Figure 11 shows a 2D CFD simulation of a typical flow pattern at a milled screen plate during the screening phase, where the exit layer was coloured in dark [19,23].

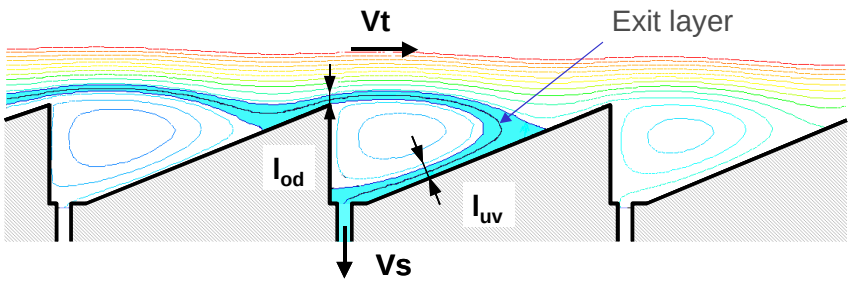

Figure 11: *CFD simulation of screen plate flow [23]*

Further 2D CFD simulations were performed with the commercial code FLUENT (version 5.4) to characterise the micro-flow at the slot inlet in a large range of tangential velocities (Vt = 5 to 20 m/s) and slot velocities (Vs = 1 to 10 m/s) and to determine the thickness of the exit layer over the detachment point at the top of the contour (l_{od}) and under the vortex (l_{uv}) as a function of the normalised slot velocity (Vs/Vt) for 0.10 mm slots [22]. Particles were then introduced at the slot inlet in the simulations, which were performed in 3D with both spherical and cylindrical particles. Figure 12 shows the flow pattern in the central section of a cylinder placed at the inlet of a milled slot.

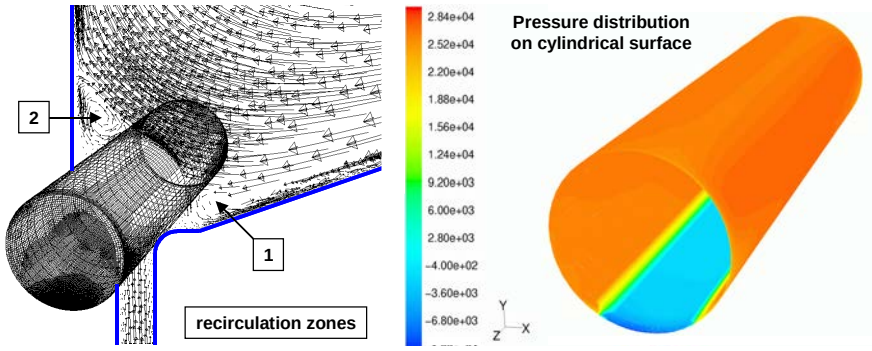

Figure 12: *CFD simulation of the flow pattern and of the pressure exerted on a cylinder at the slot inlet*

The pressure distribution at the surface of the cylinder revealed two zones with roughly constant pressure, a high pressure area at the feed side and a low pressure area at the accept side of the slot (figure 12 right). The “extrusion pressure” can then be approximated, in such a case, as the pressure difference between these two areas.

2.2.2 Simulation of particle extrusion

The results in figure 12 led to a strong simplification of the simulation of the extrusion of cylindrical particles, as the simulation could be treated in 2 dimensions, though it is believed

that three-dimensional effects will occur during the deformation of soft particles. The rheological properties of the adhesive material as well as the friction factor between the particle and the slot walls are required as input data for the simulation.

The simulations of the particle deformation were done with the commercial code ANSYS (version 5.7) and with the use of a viscoelastic constitutive model where the material properties are represented by the elementary Maxwell model:

$$\sigma / \eta + (\partial\sigma/\partial t) / G = \partial\varepsilon/\partial t \qquad \text{or} \qquad \sigma / \lambda + \partial\sigma/\partial t = G\,(\partial\varepsilon/\partial t)$$

where σ is the stress, ε the strain, G the shear (elastic) modulus, η the viscosity and $\lambda = \eta/G$ the relaxation time (the ability of the material to relax stresses).

The deformation of a cylindrical viscoelastic particle placed at the inlet of milled and wedge wire slots is shown in figure 13 at the initial time (deformation caused by elasticity only) and after 20s under a pressure of 10 kPa. The extrusion is slower with the milled slot because of the concentration of deformation and stress in the particle at the contact edges compared to the wedge wire slot where particle deformation is more uniform.

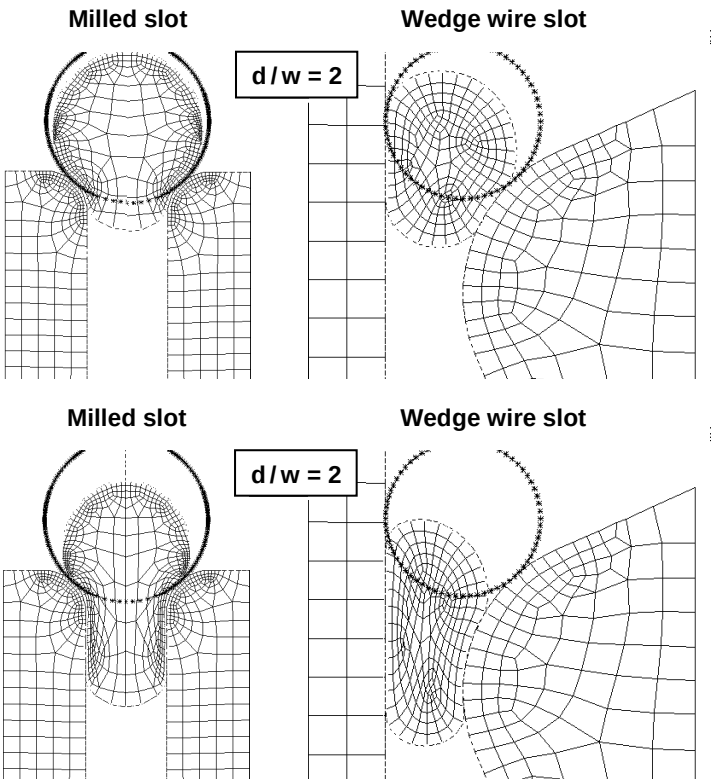

Figure 13: *Particle extrusion under p = 10 kPa, at t = 0 and t = 20s*

The simulation results were consistent with experimental results and allowed the determination of the effects of the screening parameters. Both visualisation (fig. 10) and numerical simulation (fig. 13) indicated elastic expansion in the divergent outlet section of the wedge wire slot. The following parameters turned out to increase particle extrusion:

- high screening pressure,
- particle “softness” (small elastic/shear moduli),
- short shear relaxation (more viscous behaviour),
- wedge wire compared to milled slots,
- slot inlet edge roundness (higher radius),

- reduced friction, smooth contour surfaces.

It should also be mentioned that the simulations gave approximately linear relations between the particle oversize (d-w) and the extrusion pressure or time, as observed experimentally.

2.3 Work under Progress

The analysis of possible single step extrusion of adhesives through slots shows that both the strain and strain rate would be very high with particles much larger than the slots, if the particle effectively passes the slot during the screening phase. For example, the strain rate ($\partial\varepsilon/\partial t$) would be of the order of 10^2 s^{-1} for a particle squeezed by a factor 3 in 10 ms. Results for the dynamic moduli, G' and G", of adhesive products have been reported but the measurements were performed in a dry state at a much lower strain rate [26].

2.3.1 Dynamic behaviour of adhesive material

The analysis of the dynamic behaviour of adhesives was subcontracted, in the framework of the ScreenClean project and to provide input for the numerical simulation, to LEMTA where expertise was available in this field as well as for the analysis of friction factors with soft materials [27]. The test equipment and methods used at LEMTA had, however, to be adapted to the very soft adhesive materials to be tested. The principle was to drop a weight from different heights on a cylindrical adhesive sample and to record at the same time the compression stress and strain curves, which were obtained at a sharply decreasing strain rate [22]. A theoretical model under development [28-30] is then used to determine the stress, strain, strain rate relations and the relaxation times in the generalised Maxwell model.

Preliminary low-speed adhesive elongation tests were done at CTP before the high-speed compression tests under progress in order to provide a starting point for the simulations [22].

2.3.2 Discussion

Both the numerical simulation and lab screening tests were limited to the screening phase with the adhesive particle initially at rest at the slot inlet. The reverse flow phase and particle inertia should also be taken into account to further investigate stickies extrusion in screens.

The average slot or passing velocity Vp in screens is controlled by the accept flow rate, while the effective slot velocity during the screening phase depends on the pressure pulse. CFD simulations revealed high slot velocity fluctuations (for example +5 to -20 m/s with a foil rotor and wedge wire slots) since the effect of fluid inertia on the time lag and slot velocity fluctuation was limited [23,24]. The average effective slot velocity during the screening phase $Vs^{(+)}$ can also be evaluated by simple flow rate balance ($t^{(+)}\ Vs^{(+)} - t^{(-)}\ Vs^{(-)} = t\ Vp$) assuming constant slot velocity over the duration of both positive and negative pressure pulses $t^{(+)}$ and $t^{(-)}$. Increasing, for example, the duration of the negative pressure pulse from 10 to 20 % of the whole pulse duration (t) would then give $Vs^{(+)}$ = 2.8 to 5 m/s for $Vs^{(-)}$ = 15 m/s and a typical passing velocity Vp = 1 m/s. The flow velocity in the exit layer under the vortex would then be roughly equal to $Vs^{(+)}$ according to [22] for a tangential flow velocity Vt = 10 to 15 m/s.

Under these conditions the inertia of the particle approaching the slot inlet at the same velocity as the fluid in the exit layer cannot be neglected. Particle inertia should reduce or delay particle extrusion in the case of milled slots located in the middle of flat bottom contours (with large b value in figure 6) as the particle might pass along the slot inlet. By contrast the inclined wall of the convergent inlet of wedge wire slots should increase particle extrusion as a result of the inertia of the particle turning smoothly into the slot, as illustrated in figure 14. Assuming a constant deceleration of the particle over a distance equal to particle radius, which gives $\gamma = V^2 / d$, and inertial forces applied on a section equal to the particle diameter, the "equivalent pressure" is given by $P = (\pi/4)\ \rho\ V^2$, for a cylindrical particle. Such additional

“inertial extrusion pressure” (e.g. 20 kPa for $Vs^{(+)}$ = 5 m/s) should have a similar effect as the hydraulic extrusion pressure, which is generally higher (typically 50 kPa) but with the resulting pressure limited to the particle section between the contact lines with the slot inlet (fig. 13).

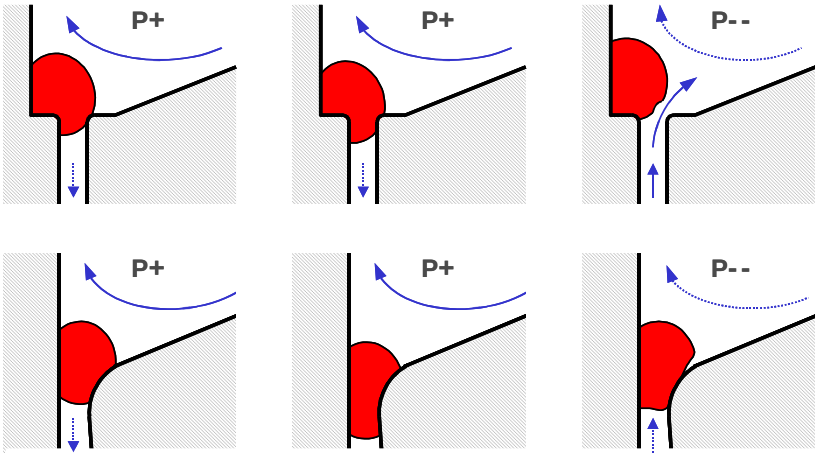

Figure 14: *Possible particle extrusion mechanisms*

The behaviour of partly extruded adhesive particles during the reverse pulse should also play an important role in a multi-step stickies extrusion process, since the duration of the reverse pulse is extremely short, down to 2 ms with foil rotors. This means that the detachment of the adhesive particle from the slot wall could strongly retain the particle as long as water has not penetrated in the surface between the adhesive and the slot wall, assuming that time and pressure were sufficient to expel the water from the contact surface during the positive pressure pulse. The viscous component of the adhesive material might help to detach the particle during the reverse pulse if relaxation time is much longer than the reverse pulse. Figure 14 illustrates possible “reverse extrusion” mechanisms of cylindrical adhesive particles. With the milled slot, the particle should be extracted very quickly from the slot inlet assuming low penetration, but difficult to detach from the corner along the contour wall. By contrast, the extraction of the adhesive particle from the wedge wire slot should take more time, especially if the particle having passed the narrowest slot section is submitted to “reverse extrusion”. Low friction factor and high relaxation time should promote reverse extrusion. The particle should then, after detachment, be ejected very quickly back to the main flow since particle inertia can be neglected and the velocity of the reverse jet out of wedge wire slots is very high [23,24]. Unfortunately the possible extrusion mechanisms described in figure 14 do not allow one to easily conclude what the most effective slot design is regarding the efficiency of the reverse pulse in rejecting stickies retained at the screen plate.

3 Optimisation of Screen Plate Design

The objective in this study was to investigate the effects of screen plate design parameters in order to optimise the removal of stickies under fine screening conditions typically observed in deinking mills. The programme was therefore focused on screening with 0.15 mm slots.

Pilot screening trials were performed with re-pulped adhesive labels in order to work with "real stickies", and also because it is not possible to prepare calibrated adhesive particles in large quantities. On the other hand, using such PSA stickies does not allow one to correctly determine real particle size and shape distributions. These are the most decisive parameters which determine the stickies screening ability, since valuable direct stickies size and shape control methods have not yet been developed.

3.1 Raw Materials, Equipment and Methods

The stickies-containing pulps used for the screening tests were prepared as follows:

- Acrylic or hot-melt rubber adhesive labels (20 g/m2 adhesive film) were stuck onto fresh newspaper to produce dark particles, as ink is absorbed on the adhesive film [4].
- The adhesives (newspaper / adhesive / back paper complex) were added at a ratio of 2% adhesive material, to a mixture of 50% newspapers / 50% magazines and re-pulped in a LC pulper for 30 minutes at 55℃, with standar d INGEDE deinking chemistry.
- The adhesive-containing pulp was then mixed with a mixture of bleached chemical pulps (50% hardwood, 50% softwood) to enhance the contrast between the adhesive particles and the handsheets, which led to about 0.1 % adhesives in the final mix.

The pilot screening tests were performed with the experimental screen designed to simulate a slice of industrial screens (figure 15). This slice screen design facilitates the investigations of the influence of some of the most relevant screening parameters, since flow conditions, pulp consistency and composition are roughly constant over the width of the screen slice, and the reject flow rate is kept large. In the case of full size screen baskets, the pulp consistency and long fibre content increase from the inlet to the reject section, and the flow conditions are not constant. The screen cylinder diameter of the experimental screen is 500 mm. The pressure in the screen is maintained above 150 kPa to avoid cavitation and the reject flow rate is normally 50 % to improve the precision of the determination of the particle passage ratios.

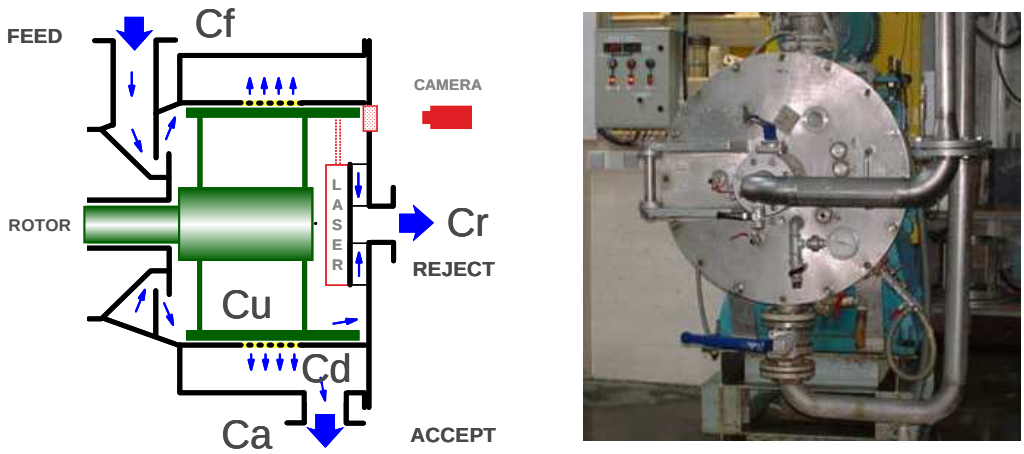

Figure 15: *Experimental "slice screen" – 500 mm screen cylinder diameter*

The ability of a particle to pass the screen plate under given screening conditions can be characterised by its passage ratio, P = Cd/Cu, which is calculated from the consistencies measured upstream Cu and downstream Cd the screen plate. According to this approach [11-16] the characteristics of a full size screen can be assessed using the mixed-flow model (case of perfect mixing in both radial and axial direction, which is close to the flow observed in short screen cylinders with an open rotor) or the plug-flow model (case of no axial mixing, close to the flow observed with long screen cylinders with a closed rotor). The mixed-flow model applies to the slice screen design equipped with foil rotor, which allows the fibre and contaminant passage ratios to be determined in order to provide input for the simulation and optimisation of screening systems [26]. The performances of screens can be predicted according to these flow models assuming no interactions between the particles and constant particle passage ratios P_x over the screen plate, where the subscript x identifies the type of particle [11-16]. Standard nomenclature is used in the equation below, where *Rv* and *Rw* are the reject rates by volume and by weight and *Si*, *Sa* and *Sr* are the shives or contaminant contents in the inlet, accept and rejects. The equations giving the reject thickening factor ($T = Cr/Ci$) are only valid for homogeneous particles:

$T = 1/(P - Rv\,P + Rv)$ for the mixed-flow model

$T = Rv^{(P-1)}$ for the plug-flow model

In the hypothesis of homogeneous fibres with a passage ratio P_F and contaminants with a passage ratio P_K, the ratio $\beta = P_K / P_F$ is simply related to the standard efficiency definitions and to the Nelson screening quotient *Q*, which is in widespread use in pulp screening:

$E_R = Rw\,Sr / Si$ Reject (removal) efficiency

$E_C = 1 - Sa / Si$ Cleanliness efficiency

$E_R = Rw / (Rw + \beta - \beta\,Rw)$ for the mixed-flow model

$E_R = Rw^{\beta}$ for the plug-flow model

In real situation, the passage ratio distributions of the contaminants and pulp components have to be included in the calculations to establish the models of screening systems.

The method used to control the stickies in the pulp samples were:

- the INGEDE method n°4 for the analysis of some sc reening conditions,
- image analysis on handsheets for all the tests conditions, as the method is more accurate (since more particles were counted) and less time consuming.

3.2 First Test Series: Influence of Screening Temperature and Extrusion Pressure

The objective in this first test series was to determine the influence of the screen operating parameters assumed to have an effect on the extrusion of stickies, namely the passing velocity which influences the average extrusion pressure, the rotor velocity which influences the maximum extrusion pressure during the positive pressure pulse (roughly proportional to the square of the rotor velocity), the screening temperature which influences the rheological properties of the adhesive material, and the slot inlet design as shown in the previous section. The following screening conditions were tested (16 trials):

- Type of stickies Hot-melt rubber adhesive D170
- Screen plate 0.15 mm slots, wedge wire, 1.2 mm contour height
- Rotor 4 foils, 15 and 23 m/s
- Passing velocity 1 and 3 m/s
- Consistency 1.3 %
- Temperature 23, 36, 51 and 69 °C

The hot-melt rubber adhesive was chosen instead of the more common acrylic adhesive because it was suspected that temperature would have more influence on the rheological properties of such a “hot-melt” adhesive material (the results in figure 4, which were obtained later, suggest higher softening of the soaked acrylic adhesive as temperature is increased). The wedge wire screen plate design with high contours has been chosen as it was supposed to be more sensitive to stickies extrusion compared to low contours and milled slots.

The effects of temperature and slot passing velocity on the pulp passage ratio are shown in figure 16. A large increase of the pulp passage ratio with the passing velocity, as well as a low influence of the rotor velocity were observed which is usual under similar screening conditions [16-17]. The slight decrease of the pulp passage ratio observed as the temperature is increased is attributed to the reduction of the fibre to liquid friction (less fibre entrainment in the exit layer) and to the increase of the fibre to slot wall friction (more solid to solid contacts) caused by the viscosity decrease (by about 60% between 20 and 70°C). This observation is consistent with recently reported results showing a clear increase of the fibre passage ratio as CMC was added to increase strongly the fluid viscosity [27].

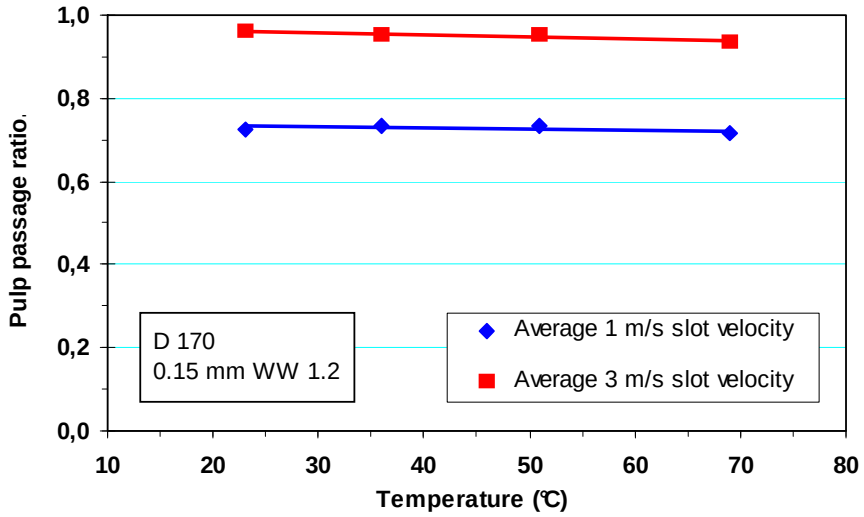

Figure 16: *Effect of temperature and slot velocity on fibre passage*

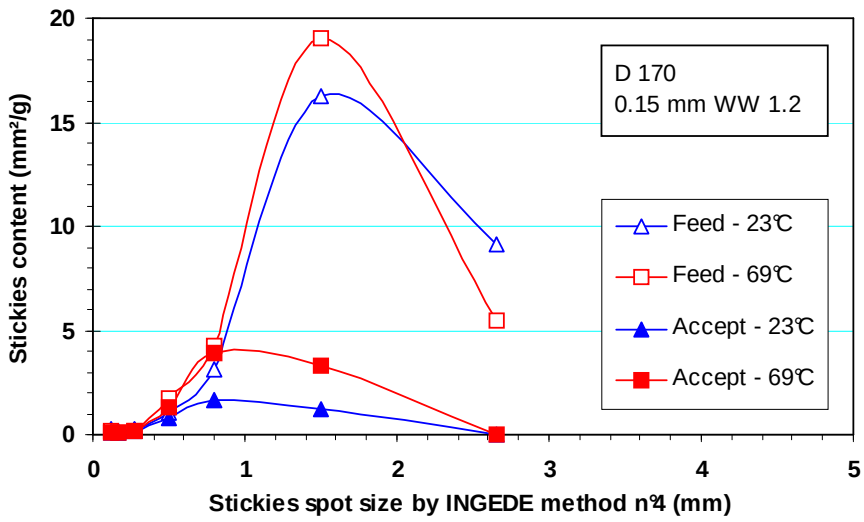

Figure 17: *Effect of temperature on stickies removal efficiency*

The influence of temperature on the stickies removal efficiency (figure 17) is much higher, with the stickies content in the accepts being much lower for the large stickies (spots > 0.5 mm) at low temperature, which suggests that stickies extrusion is much higher at high tempera-

ture. The results in figure 16 also indicate a certain fragmentation of the stickies particles during the screening tests, which were performed in recirculation on the feed chest. In particular, less large stickies were counted at the inlet at the beginning of the test series (tests at 23℃) than at the end of the test series (tests at 69℃).

The cleanliness efficiency based on the INGEDE method n°4 decreases from 87% to 72% for the stickies producing spots larger than 0.02 mm^2 and from 93% to 83% for the stickies producing spots between 1 mm^2 and 5 mm^2, as the screening temperature was increased from 23℃ to 69℃. These efficiency drops are exagg erated since they correspond to relatively large spot size classes, because of the fragmentation of the large stickies, the average stickies particle size in the feed pulp is lower for the tests at high temperature.

The cleanliness efficiencies in the figures 18 and 19 were determined according to feed and accept pulp handsheet image analyses. The size classes do not correspond to those in figure 17 as the stickies spread out more with the INGEDE method n°4 (heating at 105℃ after vacuum drying) than in handsheets (dried at 94℃ un der vacuum). In addition, only the macro-stickies retained on 0.10 mm lab slots are controlled with the INGEDE method n°4, which means that thin stickies (which spread out less than thick ones) are only taken into account with the handsheet image analysis method. The drawback with this method is that small thin stickies are difficult to count or may be counted as several very small particles if they are embedded in the thickness of the handsheet. Consequently the efficiencies obtained in the small size classes were not relevant and were removed from the figures. It should also be kept in mind that the screening tests were performed with the slice screen at 50% reject flow rate (to provide input for further screening system simulation studies), which means that the accept pulp is only 40 to 50% of the feed pulp (cf. figure 16). The stickies removal efficiency becomes much lower as the final reject rate is decreased down to about 1% fibre losses, especially at low efficiency level. Consequently the low cleanliness efficiencies obtained with the stickies in the small size classes (< 0.15 mm^2) are not only wrong but also not relevant since such stickies would practically not be removed in multi-stage screening systems.

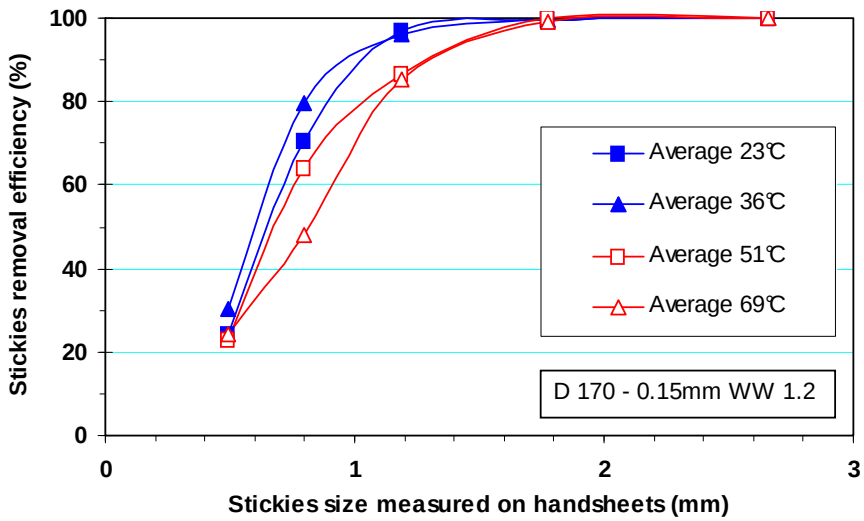

Figure 18: *Effect of temperature on stickies removal efficiency*

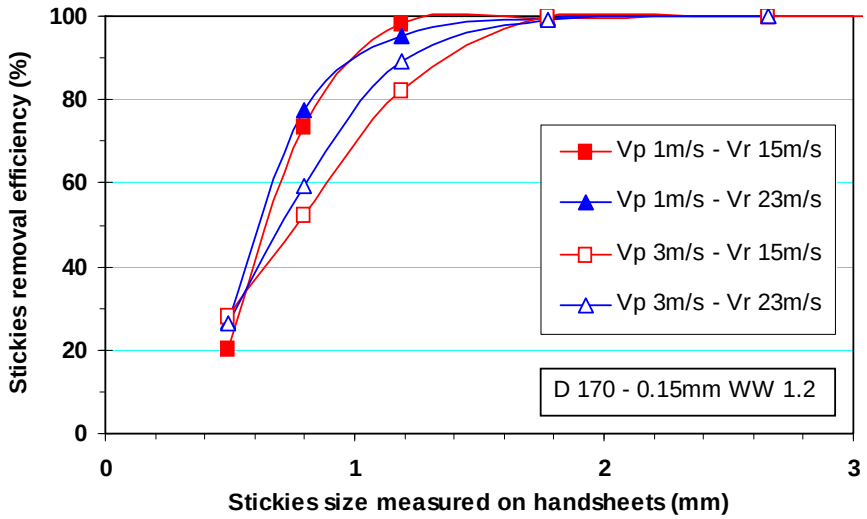

Figure 19: *Effect of rotor velocity on stickies removal efficiency*

Figure 19 shows the effect of the velocity of the rotor (Vr) on the stickies removal efficiency, at different passing velocities (Vp). No large influence is observed at low passing velocity, while an increase of the efficiency is observed as the rotor velocity is increased at high passing velocity. The results in figure 19 are quite surprising since rotors with low positive pressure pulses are generally recommended to reduce the extrusion pressure applied on the stickies and thus to improve their removal efficiency. Indeed, the positive pressure pulse is relatively low with the tested foil rotor even at a high rotor velocity, i.e. about 7 to 15 kPa between 15 and 23 m/s [24]. At a high passing velocity, the variation of the extrusion pressure (i.e. the positive pressure pulse plus the average pressure drop caused by the passing velocity) explains that the reduction of the rotor velocity is more positive (no negative effect) at low passing velocity. On the other hand, the increase of the velocity of the rotor increases, roughly proportionally, with the velocity of the pulp at the surface of the screen plate, if the equilibrium tangential velocity is reached. This is the case with the slice screen where only the central part of the contoured screen cylinder in slotted, but generally not the case in the feed section of industrial screens where the pulp is fed at much lower tangential velocity. This means that dynamic phenomena such as particle slip and particle contacts with the inclined contour wall could have more impact on the efficiency than stickies extrusion phenomena, as shown in the next section.

3.3 Second Test Series: Influence of Screen Plate and Slot Design

The objective in this second test series was to determine the influence of the screen plate parameters and of the parameters interacting with screen plate design, i.e. slot inlet design, contour height, passing velocity and rotor velocity. The tests were limited to the most usual situation regarding the type of stickies and the screening temperature, which corresponds to soft adhesive material and should consequently include stickies extrusion phenomena. The following screening conditions were tested (12 trials):

- Type of stickies Water-based acrylic adhesive E115
- Screen plate 0.15 mm slots with 3 different contour / slot designs (figure 20)
- Rotor 4 foils, 15 and 23 m/s
- Passing velocity 1 and 3 m/s
- Consistency 1.3 %
- Temperature 42 ℃

The three screen plates compared in this test series are illustrated in figure 20. The pitch was about the same for the 3 screen plates (3.2 mm), which gave about equal contour angle for the two high-contour screen plates.

- The wedge wire screen plate with high contours (1.2 mm) was a conventional wedge wire screen cylinder with welded wires.
- The milled screen plate with high contours (1.2 mm) was made up of U-shaped rings with milled contours and laser cut slots.
- The wedge wire screen plate with low contours (0.6 mm) was a constructed screen plate, with a more accurate slot width compared to the conventional wedge wire screen plate.

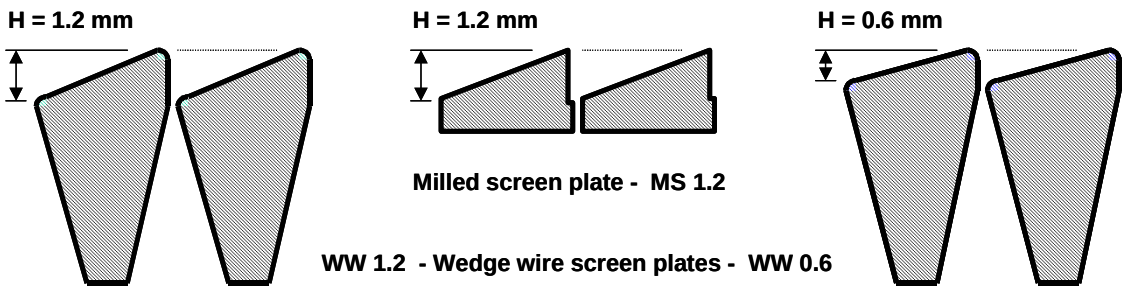

Figure 20: *References and design of the screen plates tested in the second test series*

The results in figure 21 confirmed the trends already observed, i.e. a relatively low effect of rotor velocity on the pulp passage ratio and improved fibre passage as passing velocity is increased and as well as with wedge wire screen plates, which was attributed to the higher effective slot velocity and to the favourable slot inlet design [16-17]. A reduction of the contours reduced the pulp passage ratio, which was attributed to a higher probability for the fibres to be rejected through contacts with the low-angle contour walls [17], especially at low passing velocity as the vortex generated between the contours is elongated in the main flow direction [19] with the exit layer turning sharper back to the slot inlet.

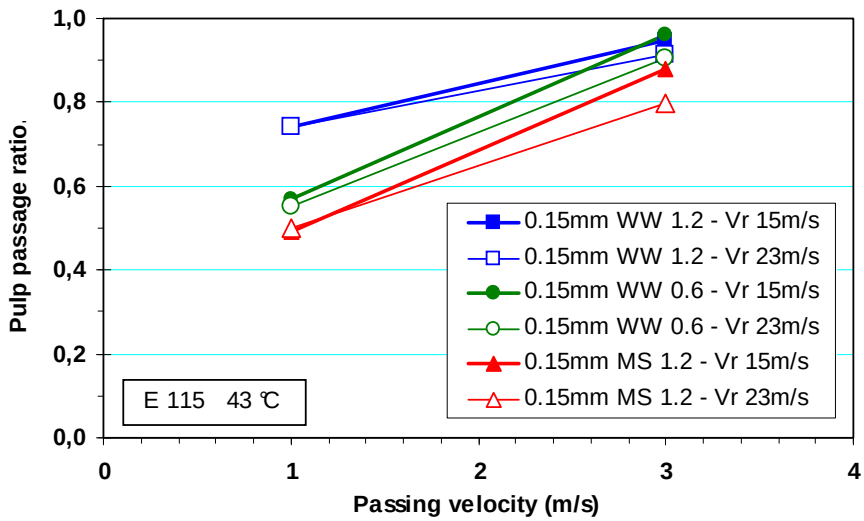

Figure 21: *Effect of screen plate and rotor velocity on fibre passage*

The efficiency of the screen plates in removing stickies is shown in figure 22, where the cleanliness efficiency is plotted against the stickies spot size according to INGEDE method analyses, which were performed for the screening trials at low passing velocity only.

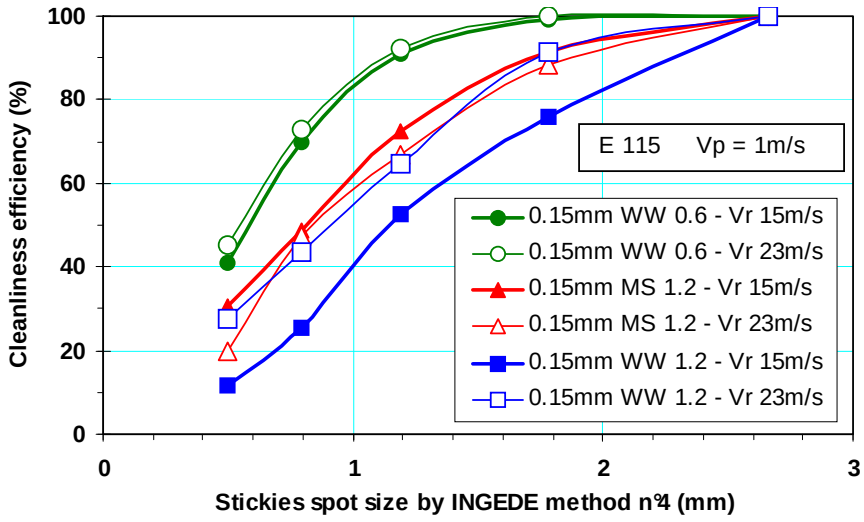

Figure 22: *Effect of screen plate and rotor velocity on efficiency*

The curves in figure 23 correspond to the average values, at 15 and 23 m/s rotor velocity, of the efficiencies given in figure 22. They represent the distributions of the stickies passage ratio Pk, which were calculated directly from the average efficiencies (mixed-flow model), and of the stickies to pulp passage ratio β = Pk/Pf. As indicated in section 3.1, this β ratio represents the selectivity of the separation of the contaminants with respect to the fibres, and would allow one to calculate screening system efficiencies in the case of homogeneous stickies and fibres in different size or length classes.

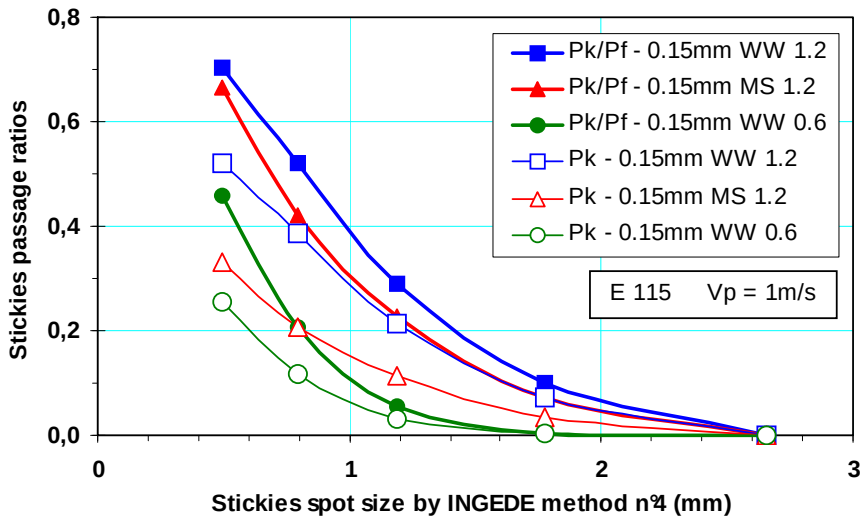

Figure 23: *Effect of screen plate on stickies passage ratios*

The results in figure 22 and the Pk values in figure 23 indicate a higher cleanliness efficiency of the milled slots at given contour height or angle. The β ratios indicate that a slightly higher screening selectivity is finally obtained with the milled slots despite lower fibre passage ratio.

The stickies to pulp passage ratios (β = Pk/Pf) in figure 24 were calculated from the average cleanliness efficiencies determined by handsheet image analysis for the tests at 1 and 3 m/s passing velocity. The best results, i.e. the lowest β ratios, were always obtained with the low-contour wedge wire screen plate. The comparison of the two high-contour screen plates showed higher efficiency with the milled than with the wedge wire screen plate, at least at low passing velocity as in figure 23, the results being rather unclear at high passing velocity.

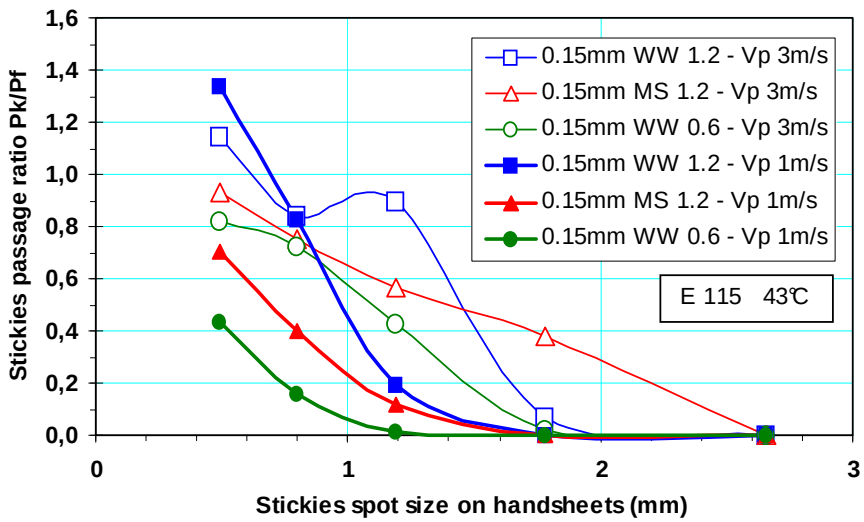

Figure 24: *Effect of screen plate on stickies removal at Vp = 3m/s*

Indeed, the experimental points in figure 24 with the high-contour wedge wire screen plate are average values of the results obtained at the 2 rotor velocities, where the test at 23 m/s rotor velocity has been the last one of the test series. At this step, there were very few stickies left in the size classes above 2 mm^2, so that the high efficiencies (low β ratios) found for these stickies are not accurate. This means that the better results reported in figure 24 for the large stickies with the high-contour wedge wire screen plate compared to the milled screen plate could be wrong. If not, i.e. if the wedge wire screen plate was effectively better than the milled one, one explanation could be that the reverse pulse was less effective in removing stickies located at the slot inlet as illustrated in figure 14, especially at high passing velocity, which reduces the efficiency of the reverse pulse.

The best results in terms of separation selectivity between stickies and fibres were clearly obtained with the low-contour screen plate compared to the high-contour screen plates, where slightly higher efficiency was achieved with the milled screen plate, most probably because of less stickies extrusion than with the wedge wire design.

A main conclusion of this second pilot test series is that the extrusion of PSA stickies particles is not the only phenomena to consider in the optimisation of stickies screening conditions, as it is suggested that hydrodynamic phenomena, which should occur at the surface of the screen plate before stickies even reach the slot inlet, should be considered first.

The higher efficiency of low-contour screen plates, which was already observed with small model films and shives [17], has been attributed to the higher effectiveness of low-angle contours in rejecting contaminant as they approach the screen plate and hit and slip over the inclined contour walls. The relatively lower influence of stickies extrusion phenomena on the screening efficiency under the tested conditions was confirmed by the low influence of the velocity of the rotor (a foil rotor with quite low positive pressure pulse) on the efficiency.

3.4 Third Test Series: Optimisation of Screen Plate Contour Design

The results obtained in the previous test series suggested that further research should focus on the optimisation of the design of the contours of the screen plate, i.e. contour height, angle and related pitch. The previous stickies screening trials also showed that the test procedure should be improved and the number of tests increased in order to improve the precision of the results since slight differences between different screen plates will probably have to be determined for the optimisation of contour design.

The stickies preparation procedure in this third test series was the same as previously, except that a new batch of bleached kraft pulp (50 % softwood, 50% hard wood) was prepared for each screen plate, by mixing each time the same amount of stickies-contaminated pulp taken from a large quantity prepared for the whole test series. The stickies were prepared as previously by re-pulping adhesive labels with deinking raw material and chemistry in a small low consistency pilot pulper (5% consistency, 100 l capacity), but the size and shape of the stickies appeared to be different when looking at the handsheets:

- the E115 acrylic adhesive labels used for the second test series were about 8 month old, and showed an average particle thickness (calculated from the total stickies weight and the total stickies area measured in hansdheets) of 38 µm.
- the E115 adhesive labels used for the third test series was a mixture of 75 % fresh labels produced 2 week before and 25 % of the previous labels which were 14 month old. The average stickies thickness in handsheets was 51 µm.

Additional analyses performed on the fresh and old adhesive labels re-pulped separately, confirmed the significantly lower average stickies thickness when re-pulping of the labels was performed with aged adhesive material compared to fresh adhesive.

The following screening conditions were tested (6 trials with each of the 5 screen plates):

- Type of stickies Water-based acrylic adhesive E115
- Screen plate 0.15 mm slots with 5 different contour height and/or angle (table 1)
- Rotor 4 foils, 15 and 23 m/s
- Passing velocity 1, 2 and 3 m/s
- Consistency 1.2 %
- Temperature about 42 to 45 °C

Screen plate references	Slot width (mm)	Contour height (mm)	Pitch (mm)	Contour angle (°)
2nd test series (September 2003)				
06 32 13°WW	0.149	0.6	3.35	13.2
12 29 23° MS	0.153	1.2	3.20	23
12 29 25°WW	0.154	1.2	3.05	25
3rd test series (February 2004)				
06 32 13°WW	0.149	0.6	3.35	13.2
06 26 17°WW	0.153	0.6	2.75	17.3
09 32 20°WW	0.150	0.9	3.35	19.6
09 26 25°WW	0.153	0.9	2.75	24.8
12 29 25°WW	0.154	1.2	3.05	25

Table 1: *References and characteristics of the tested screen plates.*

The five screen plates are compared in figure 25 in terms of pulp passage ratio achieved on average at 15 and 23 m/s rotor velocity. Figure 26 confirms the trends observed during the previous tests series: A slightly higher pulp passage ratio was achieved with all the screen plates as rotor velocity was reduced. The comparison of the screen plates in figure 25 revealed an increase of the fibre passage as the wire width was reduced down to 2.6 mm compared to 3.2 mm, at 0.6 and 0.9 mm contour height. The relatively high pulp passage ratio of the wedge wire screen plate with 1.2 mm contours could be due to both the intermediate wire width (2.9 mm) and the higher contours, which were shown to improve slightly the

fibre passage ratio in the frame of previous studies [17]. The broader slot width distribution of the 12 29 25° WW screen plate (with welded wires) compared to all the other screen plates (constructed) could also contribute to explain this higher pulp passage ratio.

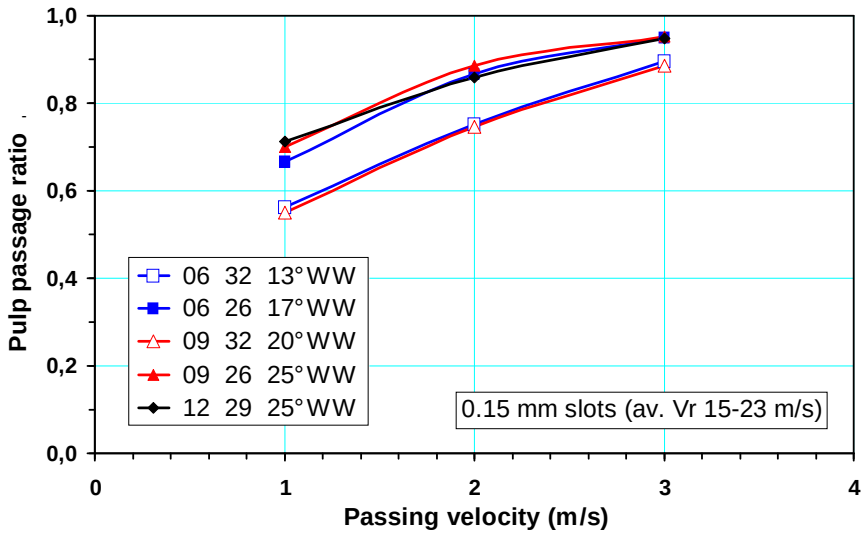

Figure 25: *Effect of contour design and slot velocity on fibre passage*

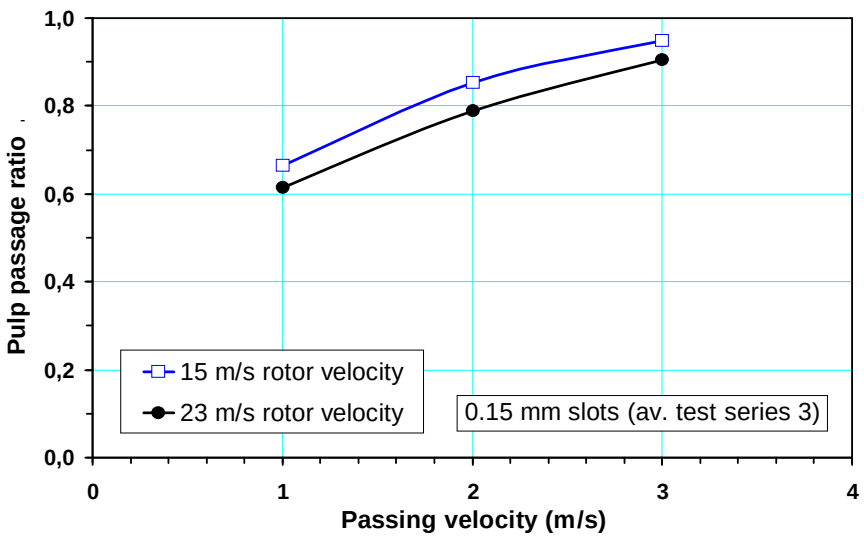

Figure 26: *Average effect of rotor velocity on fibre passage*

The positive effect of the reduction of the pitch on the fibre passage is assumed to be due to the increase of the pulp flow passing the screen plate per unit area, which increases the quantity of fibres accumulated during the screening phase for a given instantaneous fibre passage ratio and consequently the consistency of the pulp at the feed side of the screen plate at the end of the screening phase. As the instantaneous fibre passage ratio is defined as the instantaneous (or local) feed to accept pulp consistency ratio, this hypothesis would explain the higher average pulp passage ratio observed with the 2.6 mm wires.

One should however note that these experimental results about the influence of wire width and their analysis correspond to low/medium consistency pulp (1.2 % fibre consistency with 50 % softwood, which should be equivalent to 1.5 to 2 % consistency with deinking pulp). At high screening consistency, the faster increase of the consistency assumed to take place

during the screening phase as pitch is reduced, might lead to a too high consistency increase and thus to fibre flocculation, which might reduce the average pulp passage ratio, instead of increasing it, or even plug the screen, especially at low rotor velocity.

The cleanliness efficiencies observed in the accept pulp (less than 50 % of the feed pulp) with the different screen plates are compared in figure 27, showing the results obtained with the stickies in the most sensitive size classes, i.e. 0.3 to 1.0 mm^2 measured on handsheets. A decrease of the height and of the angle of the contours improved the cleanliness efficiency, which confirmed the high efficiency increase already observed in previous studies with flat-shaped model contaminants [17] as the height of the contours was reduced when comparing the 06 32 13°WW screen plate to the 12 2 9 25°WW screen plate.

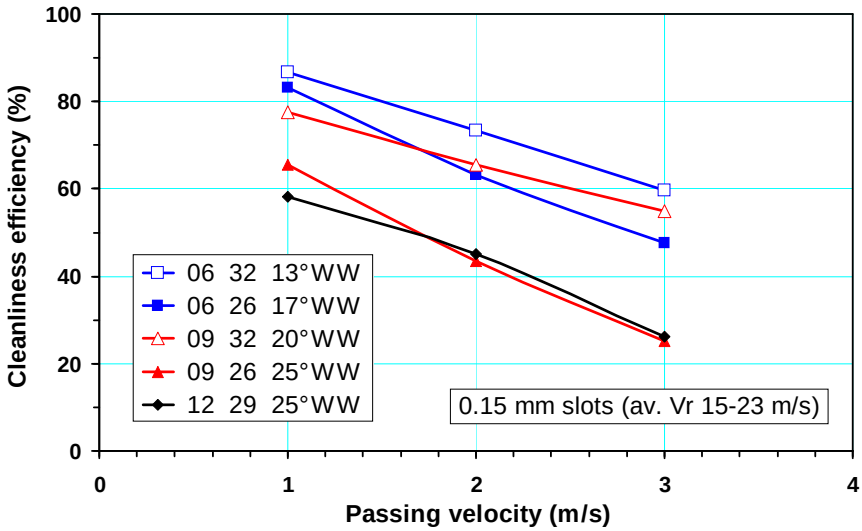

Figure 27: *Cleanliness efficiencies of the different screen plates*

The cleanliness efficiencies achieved with the different screen plates are shown in figure 28 as a function of the pulp passage ratio in order to compare the results at equal reject rate. The two screen plates with the lowest contours (0.6 mm) gave the best results. A reduction of the contour angle down to 13° reduced the stickies passage ratio (improved their retention) which was attribute to the higher probability of the particles to be rejected through contacts with the inclined contour walls as the angle was reduced [17]. The reduction of the contour angle also reduced the passage of the fibres in about the same proportions, which was attributed to a slower fibre concentration during the screening phase rather than to the effects of fibre contacts with the contour walls, as fibres are flexible and contacts should occur with only one end of the fibre [17]. These phenomena could explain the similar screening selectivity observed with the two low-contour screen plates. The results in figure 28 indicate that, with the low-contour (0.6 mm) screen plates, a further reduction of the contour angle from 17 to 13° does not improve the screening selectivity. By contrast, with the medium-contour (0.9 mm) screen plates the reduction of contour angle, from 25 to 20° improved the screening selectivity, suggesting that the reduction of the angle had more effect on rejecting stickies through contacts with the inclined contour walls, compared to the effect of pitch increase on the fibre passage ratio reduction. Finally the screen plate with the highest contours (1.2 mm) showed slightly lower screening selectivity than the screen plate with lower slightly lower contour height (0.9 mm) and equal angle (25°).

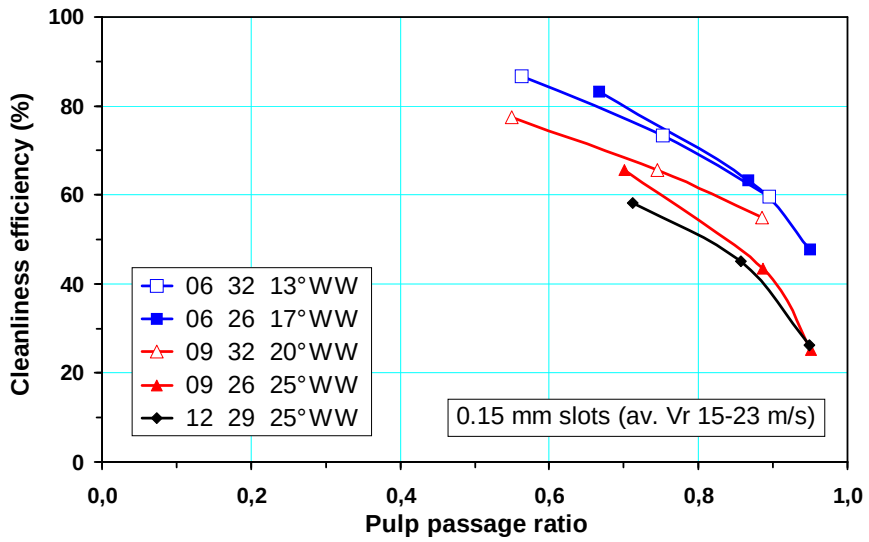

Figure 28: *Selectivity curves of the different screen plates*

The velocity of the rotor showed no large influence of the screening selectivity as observed in the frame of previous studies with model flat shaped contaminants [17] and illustrated in figure 29 showing the average selectivity curves obtained with the five screen plates at 15 and 23 m/s rotor velocity. The lower rotor velocity gave, on average, slightly better results but only at low passing velocity.

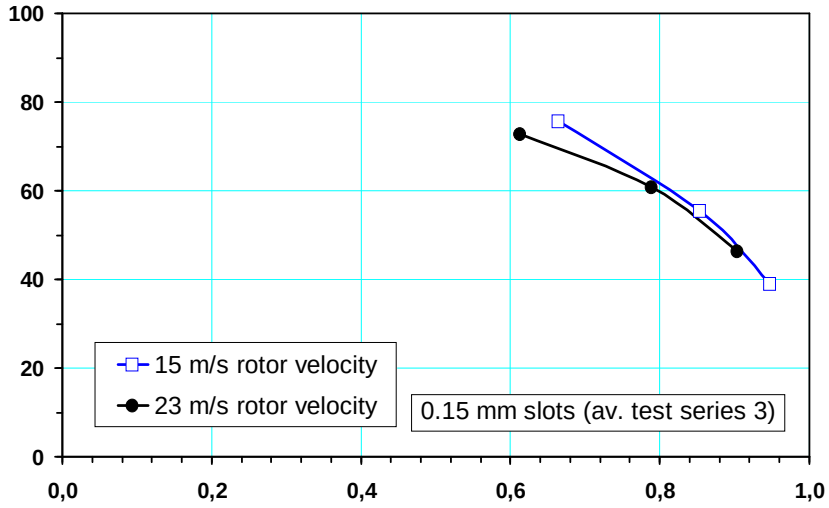

Figure 29: *Average effect of rotor velocity on cleanliness efficiency*

The results in figure 28 show that the two low-contour screen plates achieved about the same efficiency at given pulp passage ratio, i.e. at given reject thickening factor, corresponding to lower passing velocity with the 06 26 17° compared to the 06 32 13° screen plate. However, since the 06 26 17° screen plate offers about 20 % higher open area, both screen plates should have similar screening capacities at given stickies removal efficiency.

Indeed, the comparison of the different screen plates should be further analysed with the help of the simulation model developed to predict screening system efficiencies [26]. The model however requires the passage ratio distributions of the stickies (figure 23) assuming constant stickies shape in a given size class, as well as the fibre passage ratio distributions,

i.e. the fractionation effect to predict the concentration of the long fibres in the rejects. Such investigations are under progress in the framework of the ScreenClean project [1].

Simplified calculations can be established to compare the efficiency of multistage screening systems equipped with the different screen plates. The results in figure 30 were obtained on the basis of the experimental results in figure 28, by using the plug-flow model (representing quite well screening systems with several stages and all the accepts fed forward) and for a final reject rate of 1 %. The calculations in this figure are only valid for the stickies in the size range considered in figure 26, i.e. stickies forming specks between 0.3 and 1 mm^2 area, and assuming that all these stickies have the same shape and rheological properties. It is also assumed that all the fibres have the same passage ratio as the average pulp passage ratio. Clearly these hypotheses are not realistic, but the fact that both the thick stickies and the long fibres concentrate in the rejects more or less compensates the wrong assumptions.

Under these simplifying hypotheses, the curves in figure 30 look similar to those in figure 28 and lead to the same conclusions when comparing the different screen plates. The main difference is the lower efficiency level, which was logically obtained as the final reject of the screening system was reduced down to 1 % fibre losses. Only the screen plates with low contours (0.6 mm) and/or low angle (< 20°) should be able to achieve stickies removal efficiencies above 50 %, if operated at low passing velocity, under the hypothesis in figure 31.

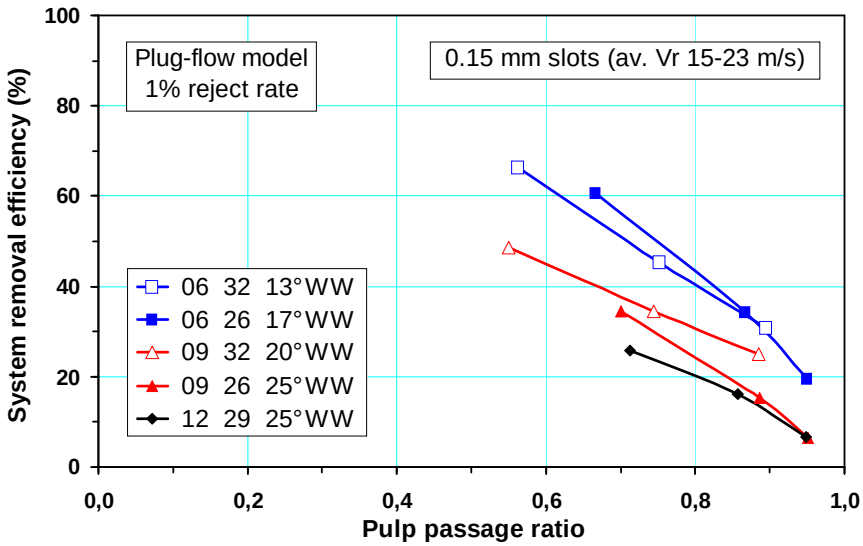

Figure 30: *Simulation of the efficiency of screening systems*

Finally, it should be keep in mind that the shape of the stickies influences strongly the screening efficiency, as illustrated in table 2 where the cleanliness efficiencies measured on accept pulp handsheets for the stickies in the 0.4 to 1.0 mm^2 size class are compared at the same screening conditions between the different tests series. Table 2 also gives the average thickness of the adhesive spots measured in the handsheets.

Screen plate	12 29 25°WW			06 32 13°WW	
Test series - Adhesive Av. spot thickness	1 - D170 $_{Old}$ 52 µm	2 - E115 $_{Old}$ 38 µm	3 - E115 $_{Fresh}$ 51 µm	2 - E115 $_{Old}$ 38 µm	3 - E115 $_{Fresh}$ 51 µm
Efficiency - Vp 1 m/s	76 %	20 %	60 %	78 %	92 %
Efficiency - Vp 3 m/s	56 %	10 %	37 %	20 %	68 %

Table 2: *Cleanliness efficiency measured on accepts handsheets for the 0.4 - 1mm^2 stickies*

The best efficiencies were obtained with the hot-melt rubber adhesive D170 and the lowest with the acrylic adhesive E115 produced from old labels. The higher efficiency obtained with the acrylic adhesive in the third test series with fresh re-pulped adhesive labels is attributed to the higher thickness of the stickies with the fresh adhesives, compared to the old labels which produced more flat-shaped particles.

The fact that the efficiencies obtained with the hot-melt rubber adhesive (1st test series) were higher than those obtained with the fresh acrylic adhesive (3rd test series) could be due to the lower extrusion ability of the hot-melt adhesive D170 compared to the acrylic adhesive E115 (see figure 4), since both adhesive particles gave the same average spot thickness in the handsheets. However, the higher trend of the hot-melt rubber adhesive to spread out during handsheet drying suggests that the average stickies thickness calculated from the total stickies spot area is more underestimated with the hot-melt rubber adhesive compared to the acrylic one. Previous studies have effectively shown that the hot-melt rubber adhesive films showed higher trend to stick onto itself during re-pulping and to form thicker particles compared to the acrylic adhesive. Consequently, it is not possible to conclude definitely that the higher screening ability observed with the hot-melt rubber adhesive particles during the pilot screening tests is due to the lower particle extrusion ability which was observed at lab scale compared to the acrylic adhesive particles.

4 Conclusion

The basic studies performed experimentally at lab scale as well as numerically to understand the mechanisms of the extrusion of adhesive particles through slots allowed to quantify the effects the main parameters governing the extrusion process: relative particle size, adhesive material and soaking conditions, temperature, extrusion pressure and slot inlet design. Stickies up to 3 times larger than slot width were effectively extruded at typical extrusion pressures observed in screens, as reported earlier, but the most important finding was that the time required to pass the slot was considerably higher than the duration of the positive pressure pulses, which suggested that particle extrusion should take place step by step over several rotor revolutions. This led to the conclusion that, reverse extrusion and rejection of the stickies particles during the reverse pulse should further be investigated to develop the knowledge about the effects of key screening parameters such as slot design on the stickies removal efficiency, in relation to the rheological properties of the adhesive material.

The pilot screening tests performed later to optimise stickies screening conditions confirmed the effects of the main parameters tested, e.g. higher efficiency at reduced temperature and with the hot-melt rubber adhesive compared the softer soaked acrylic adhesive material. Concerning the optimisation of screen plate design, better results where effectively obtained with a milled screen plate compared to a wedge wire screen plate with similar contour design, which was attributed to less stickies extrusion. However, the main conclusion of the comparative tests with other wedge wire screen plates with different contours was that a reduction of the height or angle of the contours led to much higher efficiency gains than using milled screen plates. This means that particle contacts and slip phenomena over the inclined contour walls have more impact than particle extrusion through slots, as these phenomena contribute to remove the stickies before they even reach the slot inlet. Practically, when comparing only 0.15 mm slotted screen plates, the best results were obtained with the lowest contours, i.e. 0.6 mm height and 13 to 17° angle, while a reduction of the contour angle from 25° to 20° improved the efficiency with the medium contour height of 0.9 mm. Future

work should include the optimisation of slot width and screening system design with the help of simulation tools developed on the basis of the probability screening theory.

Finally, it should be kept in mind that the screening tests were performed at relatively low consistency, using a conventional low-consistency foil rotor. Conclusions might be different about coarse screening in the high-consistency range (a key screening step as soft stickies should be removed as early as possible in the recycling line to minimise their fragmentation) since rotors producing higher pressure pulse are normally used at this step and because concentrated fibres and flocs probably transfer particle separation phenomena to the slot inlet and should contribute to increase the extrusion of stickies.

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