Flow conditions in the grooves of a Low-Consistency refiner

Lisa Pahl Wittberg, Magnus Björkman, Gohar Khokhar, Ulla-Britt Mohlin and Anders Dahlkild

KEYWORDS: Disc refiner, Chemical pulps, Fiber suspension, Flow, Softwood pulps, Hardwood pulps, High-speed imaging, Computational Fluid Dynamics

SUMMARY: The flow pattern in the grooves plays a major role for the homogeneity of refining as well as for the transfer and loading of fiber flocs in refining position on the bar edges. However, it is an area where very little information is available. In the present study, flow conditions in the grooves in a Low-Consistency (LC) - disc refiner were studied both experimentally and numerically. The experimental study involved high-speed imaging through a 3 cm peephole into a commercial refiner. The Computational Fluid Dynamics (CFD) simulation focused on the flow condition in a radial groove, considering both Newtonian and non-Newtonian flows. Flow conditions for stator and rotor grooves were modeled along the groove at different angular speeds and pressure differences over the refiner. Both the experimental and the modeling results show a dual flow pattern in the grooves; a rotational/spiral movement at the top of the groove and a flow in the direction of the groove at the bottom, which to the authors knowledge has not been reported in literature. The strong vertical motion at the top of the grooves observed both for the rotor and the stator are believed to be important for placing the fibers onto the bar edges and to induce shear forces in such a way that the fibers get treated. Moreover, a large sensitivity to suspension properties in terms of the development of flow pattern was detected.

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In papermaking, refining is used to control the paper quality. Refining is carried out in disc or conical refiners at 3-5% consistency. The flow conditions in the refiner are important for the refining action.

One of the most cited work concerning the flow in a refiner was carried out in the beginning of the 1980's by Fox et al. (1981, 1982), using high speed imaging for flow measurements in a 12" (305 mm) Plexiglas disc refiner. However, the consistency of the pulp was fairly low, 0.1% and the refiner was run with a wide gap clearance. Lumiainen (1994) used Laser Doppler Anemometry (LDA) to study the flow in the stator grooves using water. A recent study was performed by Kondora and Asendrych (2009) using CFD to numerically simulate the flow in a LC-refiner.

Fox et al. (1981) reported that the flow in a refiner is directed inwards (towards the center) in the stator grooves and outwards in the rotor grooves. A feature also observed by Herbert and Marsh (1968). Moreover, Fox et al. (1982) found a circular/spiral fluid motion within the grooves due to the velocity difference between the stator and rotor. Similar results were presented by Lumiainen (1994) for water flow in a conical refiner. Another flow feature was observed by Lumiainen (1994) and Halme (1962) where a stagnation point was found to occur in the stator groove in a conical refiner.

Regarding the rheology of a fiber suspension related to papermaking, review articles addressing this matter have been published during the past year (Derakhshandeh et al. 2011; Lundell et al. 2011; Hämäläinen et al. 2011). Another often cited review article on fiber suspension is that of Petrie (1999). Detailed studies of the fiber interaction, with both neighboring fibers as well as with the flow is another vivid research area (Krochak et al. 2009; Tornberg Shelly 2004; Carlsson et al. 2011). In terms of increasing the understanding of the underlying physical properties governing these flows, this is an important field.

Fiber suspensions are commonly classified as a non-Newtonian fluid, i.e. the shear stress and shear rate exhibit a non-linear behavior leading to that the viscosity of the suspension cannot be characterized by a constant viscosity (Hemström et al. 1976; Lee Duffy 1976). However, in a recent study by Chaussy et al. (2011), investigating the rheological properties of a 4% bleach softwood fiber suspension during refining conditions, it was found that for values below a critical shear rate, the pulp displayed Newtonian behavior.

In literature, great focus has been directed towards Thermomechanical pulping (TMP), an area to which the studies by Huhtanen (2004) and Lindstedt et al. (2009) are connected to. Although literature displays a lot of research concerning the refining process (Hietanen, Ebeling 1990; Roux 2001; Sjöström 1993, Heymer et al. 2011, Muhie et al. 2011), many questions still remain to be answered concerning LC-refining. There are issues concerning the effect the retention time in the refiner has on the refining results that need to be resolved in order to understand LC-refining. Ryti and Arjas (1968) carried out experiments regarding retention time and its effect on pulp quality. Moreover, the flow pattern in the groove can be expected to play a major role for the homogeneity of refining and for the transfer of fiber flocs into refining positions on the bar edges. Thus, motivating the present study in which both visual observations through high-speed camera recordings and numerical simulations using CFD have been applied in order to further increase the knowledge of the flow features occurring in the stator and rotor grooves of a LC-refiner. The purpose of the numerical simulations was to aid the interpretation of the
Fig 1. The experimental set-up including the gap sensor hole used to capturing the flow.

experimental results as well as extend the description of the flow beyond what could be observed.

Materials and Methods

In this study, both experiments and numerical simulations have been carried out. Details regarding the set-ups are given in the following section.

Experimental set-up

In the experiments, a 24" (600 mm) Double Disc (DD)-refiner (Beloit Jones) was used. Two fillings were applied, a coarser softwood filling of type 24901/24902BJ and a finer softwood/mixed furnish filling, type 24101/24102BJ (National Refiner Plate). Bar geometries for the coarser filling were; bar width 4.0 mm, groove width 4.7 mm and groove depth 7.1 mm and, for the finer filling the dimensions were 3.2 mm, 3.2 mm and 7.1 mm respectively. The trials were performed at three occasions. In Trial 1 and 2, the coarser filling was used whereas in Trial 3 the finer filling was considered. An overview of the refining conditions is given in Table 1.

The furnish used in Trial 3 were bleached softwood kraft pulp, evaluating three different consistencies (2, 3, 4%) and mixtures (100/0, 50/50, 75/25, 90/10 and 0/100) of unbleached softwood and bleached eucalyptus pulp at 4% consistency.

High-speed imaging

The high-speed imaging set-up is displayed in Fig 1. In order to study the flow conditions in the bottom of the stator grooves, Particle Image Velocimetry (PIV) was applied, using a Phantom V5.1 high-speed camera. Optical access was obtained through a Plexiglas dummy mounted in a 33 mm wide hole, originally made for a gap clearance sensor. The Plexiglas dummy was tailored to fit the pattern of the bars and grooves in the filling. Figs 2 – 3 display the Plexiglas dummy used in Trial 1 as well as the position of the Plexiglas dummy in the stator disc (indicated by the arrow). As shown in Fig 1, illumination was obtained from a ring of 9 halogen lamps positioned by the Plexiglas dummy. The illumination was in the order of 2000 lumen. In Trial 1, a mirror was inserted in one of the bars in the Plexiglas dummy to allow studying the flow conditions around the bar edge and at about 2.5 mm down into the groove. Fine grinded coffee particles were used as tracer particles. By recording the movement of the tracer particles, the velocities were computed and related to the fiber flow.

<table>
<thead>
<tr>
<th>Table 1. Overview of the refining conditions.</th>
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<tr>
<td><strong>Filling</strong></td>
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<td>Pulp</td>
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<tr>
<td>Pulp consistency</td>
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<td>Refiner speed</td>
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<td>Net flow rates</td>
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<td>Power applied</td>
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<td>Exposure time</td>
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<td>Frame rate</td>
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Fig 2. The Plexiglas dummy used in the experiments, with a diameter of 33 mm. The width of the grooves and bars visible in picture is 4.7 mm.
Fig 3. The stator disc in a 24" (610 mm) DD-refiner (Beloit Jones) with mounted fillings. The hole in which the Plexiglas dummy is mounted is marked by the arrow.

Table 2. The parameters included in the Herschel-Bulkley model that were tested.

<table>
<thead>
<tr>
<th>Consistency factor</th>
<th>$K$ [Pas$^n$]</th>
<th>0.01, 0.1, 1 and 10</th>
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<tr>
<td>Yield stress</td>
<td>$\tau_y$ [Pa]</td>
<td>50, 100, 200 and 300</td>
</tr>
<tr>
<td>Shear index</td>
<td>$n$ [-]</td>
<td>0.1, 0.5 and 0.9</td>
</tr>
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**Numerical modeling and Geometry**

For the CFD simulations, *Ansys Academic Research, release 12.1* FLUENT solver was used. The RNG $k - \varepsilon$ turbulence model was applied (Yakhot et al. 1992), using the SIMPLE scheme for the pressure-velocity coupling with second and first order discretization in space and time, respectively.

The fiber suspension was modeled as a single-phase (individual fibers were not modeled) and incompressible fluid, considering both Newtonian and non-Newtonian formulations.

In the Newtonian simulations, the fluid density was set to 998 kg/m$^3$ whereas four different fluid viscosities ($\mu$) were investigated, 0.001, 0.01, 0.1 and 1 Pas ($\mu_{\text{water}} = 0.001$ Pas), in order to simulate more viscous fluids.

In the non-Newtonian simulations, a Herschel-Bulkley model was applied, accounting for both the yield stress and shear-thinning properties of a suspension to compute the apparent viscosity ($\mu_{\text{app}}$) of the suspension. The model parameters that need to be assigned are the consistency factor ($K$), the yield stress ($\tau_y$) and the shear index ($n$). However, the numerical values that are to be appointed to these parameters are not fully resolved (Hemström et al. 1976; Wikström 2002; Hammarström 2004). Therefore, a sensitivity study was carried out. The values tested are displayed in Table 2.

Instead of considering the flow in the whole refiner, the geometry studied in the numerical simulations was represented by a single groove. In a disc refiner the stator and rotor grooves are facing one another. However, in the numerical simulations, the geometry was further simplified by modeling a groove and a flat plate at different rotational speeds, Fig 4. The dimensions were the same as in the experimental set-up; the groove width and depth were 4.7 and 7.1 mm, respectively. The length of the groove was 125 mm. The origin was located 175 mm from the center of rotation. The gap clearance between the groove and the flat plate was 0.2 mm.

The computational mesh was created in *Ansys Academic Research, release 12.1* ICEM. Three different grid resolutions were tested; consisting of 284 031, 562 518 and 806 157 nodes. The grid sensitivity showed that a grid of 284 031 was sufficient in order to properly resolve the flow field.

**Boundary Conditions and Case set-up**

Depending on the boundary conditions applied, the flow in the groove model represents either the flow in a stator or in a rotor, with the assumption that the top wall is a flat plate with a different rotational speed instead of another groove model. Moreover, the groove was aligned in the radial direction, i.e. without an angle as in the actual refiner. No-slip conditions were applied at the walls and periodic boundary condition was applied as showed in Fig 5.

In order to simulate the flow in the stator, back pressure differences ($\Delta P_{\text{back}}$) of similar magnitudes as found in the experiments were applied over the inlet and outlet boundaries to impose an inward flow. The flat plate in Case 1, see Fig 4, was given a constant velocity of 18.6 m/s, corresponding to 750 rpm at the center of the groove, over the whole length of the groove. For Case 1, the effect of different dynamic viscosities was studied, considering a Newtonian fluid behavior. Also, a non-Newtonian fluid flow case was investigated. The different viscosities investigated in the Newtonian simulations were 0.001, 0.01, 0.1 and 1 Pas. Moreover, for these
simulations, the pressure differences studied were 100, 150 and 200 kPa. In the non-Newtonian flow case, the pressure difference was set to 150 kPa, defining the consistency factor, the yield stress and the shear index as shown in Table 2.

In Case 2, the flow pattern along the groove in both stator and rotor was investigated by applying a rotational velocity to the flat plate. Here, solely a Newtonian fluid was considered. The viscosity was set to 0.1 Pas with the groove positioned 175 mm away from the center of rotation in order to consider the offset in radial position of the grooves occurring in the refiner used in the experiments. The rotational velocities (Ω) studied were 600, 750 and 900 rpm. The pressure differences applied over the groove were 50, 75, 100 and 125 kPa. The reason for lower pressure differences as compared to Case 1 is due to matching the flow in the rotor and the stator (the flow magnitude in the rotor is smaller than in the stator).

To simulate the flow in the rotor, a rotational framework was used to model the rotation of the groove, i.e. the flat plate was given a relative angular velocity. Therefore, in the figures showing the simulation results of the rotor, the direction of the rotational motion of the flat plate will be indicated.

**Results**

In this section, the experimental results will first be discussed, followed by the results from the numerical simulations. The main purpose with the numerical simulations was to aid the interpretation of the experimental results and to obtain information regarding the flow features appearing in regions in which results could not be obtained by the experimental studies, i.e. along the groove and in the rotor grooves.

**Flow behaviour as revealed by the experiments**

The experimental results revealed a complex flow in the stator grooves. The difference in speed between the rotor and the stator induce a rotational motion of the fiber suspension. This rotation was in turn mixed with a transport of the suspension moving towards the center of the refiner. Depending on the suspension properties and the running conditions of the refiner (speed and throughput), several different flow situations occurred.

In Trial 1, using a bleached softwood kraft pulp, BSK, a rotational movement, as reported by Fox et al. (1982), was dominant for a refiner speed of 600 rpm. The rotation was observed both at the bottom of the groove and at the topside of the groove, with the speeds being somewhat higher at the top of the groove as compared to the bottom. The rotation was at an angle to the direction of the groove. For 750 rpm the flow pattern at the bottom of the groove was a mix between rotation and a flow in the direction of the groove towards the center of the refiner.

Trial 2 was carried out at a slightly higher consistency and included more combinations of refiner speed and throughput. In this case, the flow in the bottom of the groove was mainly in the direction of the groove for all trials using softwood pulp, Fig 6(top). Fig 6 shows the fibers as observed through the mirror placed in the bottom of the groove. The shaded area visible in the background is passing rotor bars and grooves. The flow speed changed with the refiner speed and throughput. The rotation pattern found in Trial 1 was not possible to observe although it has to appear at the top of the groove. The difference in flow pattern between the Trial 1 and 2 for the softwood pulps was unexpected, as a non-spiraling flow in the direction of the groove has not been previously reported in the literature. The only difference between the trials was the slightly lower consistency used in Trial 1.

Moreover, Trial 2 also included two experiments using a hardwood pulp of 4% consistency. The fillings were much too coarse to be used together with hardwood pulps. However, the results are still of interest as the flow pattern in the grooves was completely different from what was observed for the softwood pulp. In this case, the rotational flow extended all the way down to the bottom of the groove; see Fig 6(bottom). The reason for the different flow pattern for the hardwood pulp was hypothesized to be an effect of the difference in floc size in relation to the dimensions of the grooves.

Trial 3 was run with finer fillings, 3.2 mm wide grooves instead of 4.7 mm as in Trial 1 and 2, and included experiments with a bleached softwood pulp at three consistencies, 2, 3 and 4%. The 4% consistency showed an unexpected low speed that was believed to be due to clogging of the groove. For 2% and 3% consistency, the flow in the direction of the groove was dominating. However, at a consistency of 2%, a greater element of rotation was observed. Thus, this trial indicates that the consistency may have an effect on the flow pattern in the grooves favoring rotation extending all the way to the bottom of the groove at lower consistency.

From the results obtained in Trial 2, it was also hypothesized that floc size in relation to groove width has an impact on the level of rotational movement that can be observed at the bottom of the groove. With the finer
filling, a series of experiments was performed with mixtures of unbleached softwood pulp and bleached eucalyptus of 4% consistency. Also for these mixtures, the flow in the direction of the groove was the dominant flow. However, the element of rotational movement that could be observed at the bottom of the groove increased with increasing eucalypt content in the mix. This is in line with the hypothesis that the floc size in relation to the groove size has an impact on how far down into the groove the rotational movement will extend.

The different flow patterns observed for the softwood and the hardwood pulp with the coarse filling are believed to be due to difference in fiber length/floc size. The flow pattern observed for hardwood pulp is similar to that earlier reported by Fox et al. (1981) and Lumiainen (1994). In these studies, 0.1% fiber suspension and water was used for the flow measurements, respectively. The low viscosity seems to favor the flow pattern where the rotation extends the whole depth of the groove.

The flow in the direction along the groove, as found in this study for the softwood pulp and also for all the furnishes investigated using the finer filling, has not been reported in the literature. In this case, the fibers are assumed to form fiber flocs of similar size as the groove width. Therefore, the suspension will move as a single body filling the entire width of the groove, but not the entire groove depth.

The average transport flow speed was found to be within the range of 2–8 m/s, although locally as high as 15 m/s. A strong positive correlation was detected between the pressure increase over the refiner and the average return flow speed in the bottom of the stator grooves, Fig 7. Similar speeds were observed for the two fillings at a given pressure increase of the refiner. The transport flow speed increased with increased refiner speed and was reduced with increasing net flow.

As a result of these experiments, the flow pattern in the grooves gave rise new questions as well as increased interest, since it is easy to picture several impacts on the operation of the refiner connected to changes in flow conditions in the grooves. The main factors are the retention time for fibers in the refiner affecting the homogeneity of fiber treatment, and the trapping of fibers to the bar edges. The results from the experimental work contained some unexpected flow patterns. Modeling was applied to assist in increasing the understanding how these complex dual flows were obtained.

**Numerical modelling; Newtonian vs. non-Newtonian**

In these simulations, the flow in a stator groove was modeled (Case 1). The rotational motion of the flat plate was neglected; instead the plate was given a constant velocity over the whole length of the plate corresponding to 750 rpm at a radius of 237.5 mm. Both Newtonian and non-Newtonian fluids were considered.

The pressure difference over the groove was found to only influence the velocity of the fluid and not the flow pattern (in the Newtonian flow case). Thus, only $\Delta p_{\text{back}} = 150$ kPa is presented in this paragraph.

Fig 7. The velocity versus pressure difference in the stator for different net flow (lit/min) and refiner speeds (rpm) for all experimental sessions investigated. The results indicate a linear trend between the speeds in the direction of the groove versus the pressure increase, included in the figure as a black line.

**The Newtonian flow case**

Similar to what was observed in the experiments, the numerical simulations of the Newtonian fluid flow in the stator groove indicated that the fluid properties have a clear effect on the flow in the bottom of the stator groove. Figs 8–9 display the motion in the cross-section located in the middle of the stator groove for different viscosities for $\Delta p = 150$ kPa and $\Omega = 750$ rpm, represented by streamlines and the velocity magnitude, respectively. The simulations showed that with a viscosity of 0.001 – 0.01 Pas, a rotational motion was found in the entire groove, corresponding to what was observed by Fox et al. (1982) and Lumiainen (1994). For a viscosity of 0.1 Pas, two different zones appeared in the groove, a strong rotational motion in the top of the groove and a weak rotation in the bottom of the groove, Fig 8. The flow in the bottom zone was mainly in the direction of the groove. This corresponds well with the experimental results for the softwood.

The velocities found in the simulation using a viscosity of 0.1 Pas corresponded well with the velocities of approximately 6 m/s detected in the bottom of the groove in the experiments for 150 kPa, a net flow rate of 500 lit/min and a rotor speed of 750 rpm, see Fig 7. Moreover, the viscosity of 0.1 Pas is of the same order of magnitude as 0.37 Pas, reported by Radoslavova et al. (1996) to correspond to a 4% fiber consistency. Furthermore, Chaussy et al. (2011) pointed out that the apparent viscosity of the fiber suspension in the gap clearance in a refiner is approximately 100 times than that of suspensions of individualized fibers.
Fig 8. The surface streamlines in the cross-section located in the middle of the stator groove for different viscosities at $\Delta P_{\text{back}} = 150$ kPa and $\Omega = 750$ rpm. Starting from the left, the viscosities are as follows: 0.001, 0.01, 0.1 and 1 Pas.

Fig 9. The velocity magnitude in the cross-section located in the middle of the stator groove for different viscosities at $\Delta P_{\text{back}} = 150$ kPa and $\Omega = 750$ rpm. Starting from the left, the viscosities are as follows: 0.001, 0.01, 0.1 and 1 Pas.

Fig 10. The surface streamlines in the cross-section located in the middle of the groove applying a non-Newtonian model (the Herschel-Bulkley model) for different consistency factors at $\Delta P_{\text{back}} = 150$ kPa and $\Omega = 750$ rpm. Starting from the left, the consistency factors are as follows: 0.01, 0.1, 1 and 10 Pas, $n = 0.5$ and $\gamma_0 = 100$ Pa.

**The Non-Newtonian Flow Case**

As described in the Methods section, a Herschel-Bulkley model was applied to include the non-Newtonian behavior of a fiber suspension into the numerical simulations. However, it was ambiguous what numerical values to use for the shear index, consistency factor and yield stress in order to best model the flow. Therefore, simulations were carried out to evaluate these parameters, Table 2.

Table 2.

The simulations showed that the shear index and the consistency factor influenced the flow the most. Considering the overall flow velocities, a shear index of 0.9 and a consistency factor of 0.1 Pas resulted in a flow corresponding reasonably well with that measured in the experiments.

In general, the non-Newtonian simulations overestimated the flow velocity as compared to the experiments. Moreover, as displayed in Fig 10, the non-Newtonian flow cases investigated failed to capture the feature of the motion along the bottom of the groove observed for softwood pulp, obtained in the simulations using a constant viscosity of 0.1 Pas.

In the refiner there exists a complex interaction between the fibers and the fluid. If performing a detailed numerical simulation of a fiber flow properly, the individual fibers need to be correctly represented along with the consideration of fiber-fiber and fiber-flow for detailed simulations of these flows, such as the Lattice-Boltzmann method combined with an external forcing or the Immerged Boundary method combined with a flow solver (Wu and Aidun 2010; Peskin 2002). However, simulating fiber flows are far from trivial, and problems are encountered when increasing flow rates, fiber volume fractions and modeling flexible fibers. Commonly, simulations are limited to simple geometries. The study by Wu and Aidun (2010) is one of few studies available focusing on the flow of flexible fibers of volume fractions of 1.7 - 12.4%, considering pipe flow. In the present study, a more complex set-up is considered including moving boundaries.

According to the above sections, the results obtained by the Newtonian model provided good agreement with the experimental results. Furthermore, insight into the behavior of the suspension can also be obtained from the power and gap clearance relationships. Chaussy et al. (2011) suggested that the refiner has many similarities with a parallel plate rheometer. In the study by Chaussy et al. (2011), a linear relationship between power and the inverse of gap clearance was interpreted as an indicator of a Newtonian behavior of the fiber suspension and a nonlinear declining power versus 1/gap relationship was interpreted as a shear thinning behavior. Thus, for low shear rates, as considered in the present study, the fiber suspension was suggested to display a Newtonian behavior. In the experiments performed in the present
study it was not possible to measure gap clearance as the sensor position was used for filming. However, in other similar experiments using the coarse fillings and bleached softwood kraft pulp, a linear relationship was observed for 3.6% and 800 l/min in the power range 70 – 240 kW. For 400 l/min, a nonlinear behavior was observed above 160 kW, Fig 11. For the finer fillings linear relationships were observed within the whole power range 70 – 240 kW (4%, 500 and 1000 l/min).

All of the above, combined with the uncertainty followed by the use of non-Newtonian models in terms of how to best tune the model, the simulations for Case 2 considering the flow in both the rotor and the stator was carried out for a Newtonian fluid. In the following sections, solely $\mu = 0.1$ Pas is considered, a choice supported by the study by Radoslavova et al. (1996).

Case 2: The flow in the stator and the rotor applying a viscosity of 0.1 Pas

In the above section we found good agreement between experiments and numerical modeling for the stator. However, in the experiments it was not possible to study the flow inside the rotor. Hence, numerical simulations were used to evaluate and compare the flow in the stator and the rotor, including the effect of varying radial speeds.

Fig 12 displays the mass flow rate through both stator and rotor. It is clear that the flow in the stator is independent of the angular speed, but increases with pressure difference. However, the flow in the rotor decreases with pressure difference and increases with angular speed. In reality, a valve on the outlet from the refiner is used to set a target net flow rate and this controls the $\Delta P_{\text{back}}$. The net flow rate is the difference between the flow in the rotor and the stator, implying that only conditions above the red line in Fig 12 are relevant for the operation of the refiner.

The simulations showed that the flow pattern (velocity distribution) inside the groove was fairly independent of flow speed.

In the following sections, the simulations will show that the flow pattern inside the stator and rotor grooves display similar features. The applied backpressure difference over the groove and the refiner speed were set to 50 kPa and 750 rpm, respectively.

The Stator

Fig 13 shows the flow in the stator following a tracer particle. Driven by the pressure difference, the flow in the stator grooves are directed towards the center of the refiner (negative $y$-direction), as found in the experiments. Moreover, in the top groove a vortical motion is detected. A section of rotational motion is also found in the bottom of the groove, although exhibiting much less rotation as compared to the top of the groove.

The flow development within the stator groove at different cross-sections along the length of the groove is depicted in Fig 14, showing the $y$-velocity component of the velocity vector in color with the arrows representing the $xz$-components. As the flow enters the stator, the vortical motion has not had time to develop and is therefore less significant. However, due to the rotation of the flat plate, the velocities near the plate are greater as compared to further down in the groove. Moving further downstream in the groove, the vortical motion is strengthened and at 90 mm, a second recirculation zone appears in the bottom of the groove. This secondary recirculation zone develops and becomes larger with decreasing distance to the center of the refiner. Considering the top vortical motion, the rotational flow in this area is not changing as much as the lower recirculation zone. The center of the top recirculation zone is shifted towards the left, corresponding to the direction of the motion of the flat plate. Fig 14 indicates that the rotational motion in the top of the groove acts in order to transport the fibers towards the bar edge.

The Rotor

The flow in the rotor is affected by two forces acting in opposite directions; the pressure difference over the groove acting in order to move the flow towards the center of the refiner and the centrifugal forces acting in order to move the flow outwards. The resulting flow direction is towards the periphery (positive $y$-direction) as showed in Fig 15. Compared to Fig 13, the flow in the rotor appears to experience a lower spiraling frequency.

Fig 16 shows the variation in the $y$-component of the velocity vector and the rotation in terms of the $xz$-components by color and arrows, respectively. The top
with increasing pressure difference in the rotor, and increases with increasing pressure difference in the stator. Furthermore, studying the streamlines for the rotor and the stator groove a difference is observed. In the rotor, three different recirculation zones are detected for 0.1 Pas, 750 rpm and 50 kPa as compared to the two zones found for the stator, Fig 18. One explanation may be due to the presence of the Coriolis force in the rotor, leading to the appearance of a counter-rotating vortex. Fig 18 also shows that the rotational component in the bottom of the groove is less significant compared to the rotational motion at the top.

Concluding Discussion
The flow in a LC-disc refiner has been investigated through experiments and numerical simulations. In the numerical simulations, the flow pattern at a viscosity of 0.1 Pas was found to correspond well with the experiments. The viscosity of 0.1 Pas is also of the same magnitude as what is reported in the literature for a pulp fiber suspension at 4% consistency (Radoslavova et al. 1996). The modeling replicated the dual flow observed experimentally; a strong rotation/spiral movement at the top of the groove and a flow in the direction of the groove with very little rotation at the bottom. The overall movement between the spiraling and the radial movement was in the same direction; inwards in the stator grooves and outwards in the rotor grooves. In previous work by Fox et al. (1981) and Lumiainen (1994) only the rotational/spiral movement was observed. Their results better reflect what was modeled at lower viscosities of 0.001 Pas (water (Lumiainen 1994)) and 0.01 Pas (~ 0.1% consistency (Fox et al. 1981)). The only other study reporting the dual flow pattern in the grooves is the numerical study by Kondora and Asendrych (2009). However, they reported that the flow in the bottom (outwards) and the top (inwards) of the stator grooves had different directions, which in turn is dissimilar to our experimental and numerical results. This difference in results is probably connected to the choice of boundary conditions. In the present study, the flow was only controlled by the pressure difference between the inlet and the outlet, allowing back flow to occur in both ends of the stator grooves. Kondora and Asendrych (2009) used a constant inlet flow rate boundary condition that may control the flow direction.

The balance between the flow speed in the stator and the rotor grooves determines the retention time for the fiber suspension in the refiner and thus the probability of the fibers getting mechanically treated. The rotor flow speed was found to be reduced by an increase in pressure difference and a reduction in angular velocity. The flow rate in the stator grooves was only affected by the pressure difference, not by the angular speed. As changes in the net flow rate are usually activated by changing the pressure difference, a change in the flow rate implies a change in the level of recirculation inside the refiner and the probability for fiber treatment.
Fig 16. Variation of the y - component of the velocity at different locations within the rotor groove. The xz - velocity vectors are represented by arrows. $\Delta p_{\text{back}} = 50$ kPa, $\mu = 0.1$ Pas and $\Omega = 750$ rpm. The motion of the rotation of the flat plate is directed to the left. The negative sign of the velocity indicates the direction that is towards the centre of the groove.

Fig 17. Variation of the y - component of the velocity for different pressure ratios; $\Delta p_{\text{back}} = 50$, 75 and 100 kPa for the rotor (top) and the stator (bottom). The xz - velocity vectors are represented by arrows. $\mu = 0.1$ Pas and $\Omega = 900$ rpm. The cross-sections are located the middle of the groove (62.5 mm). The motion of the rotation of the flat plate is directed to the left.
Moreover, the flow conditions at the top of the grooves is believed to also play a major role in bringing the fibers into position to get treated and for the mechanical loading of the fibers (Mohlin 2010). The high speed films indicated that the fibers are brought to the bar edge by the rotational movement and when collected on the bar edge, the fibers get strained by two shear fields: one along the bar surface originating from the speed difference between the rotor and stator, and another directed downwards into the groove originating from the rotational movement of the fluid. The shear field along the bar surface is controlled by the gap clearance and the shear field along the groove side is defined by the development of the rotating/spiraling movement.

This numerical study showed that the flow pattern in the groove varies along the length of the groove. As shown in Figs 14 and 16, the spiraling movement is not fully developed until about 30 mm into the groove. The positioning of fibers on the bar edge as well as the fiber loading is probably not achieved until some distance into the groove. Also, the magnitude of the fiber loading will increase along the radius of the refiner due to the increase in actual speed of the rotor. This is in turn is transferred to an increased speed in the rotation/spiraling movement at the top of the refiner.

The experimental study revealed very different results for the softwood and the hardwood pulps in coarse fillings although using the same consistency. The hardwood pulp behaved like a low viscosity pulp suspension; the rotation was clearly observed also in the bottom of the groove. The difference between the two pulps is the floc size. This can be interpreted as that in order to develop the dual flow pattern it is important that the size of the fiber flocs fit the groove and that there is not room for more than one floc. Hardwood pulps are usually refined in finer fillings with a typical groove width of 2 - 3 mm.

This study, combining experimental studies with numerical simulations has put a focus on the flow conditions inside the refiner. It has shown the large sensitivity to suspension properties in terms of the development of the flow pattern. The pressure difference over the refiner is often used as a criterion of how well the refiner is operating. This study provides insight into interpreting the pressure difference and the differences developed when changing refining parameters.

**Conclusions**

The results obtained in this study through experimental and numerical studies can be summarized as follows:
- An unexpected flow pattern was observed for softwood pulp of 4% consistency. The experiments revealed a dual flow pattern consisting of a strong rotating/spiraling motion at the top of the groove and a flow with little rotation in the bottom of the groove.
- The dual flow pattern was found to move inwards towards the center of the refiner, in the stator grooves.
- The numerical simulations using a constant fluid viscosity of 0.1 Pas reproduced the experimenta findings.
- In the simulations, the dual flow pattern was found to move outwards in the rotor grooves.
- The experiments and the numerical simulation indicated that the consistency may affect the flow pattern observed in the grooves, favoring a rotations motion that is extended to the bottom of the groove with decreasing consistency.
- Decreasing the floc size in relation to groove width had a similar effect as reducing the viscosity.
- The pressure increase and the average return speed at the bottom of the stator groove were found to strongly correlate.
- In the simulations, the flow in the stator was found to only depend on the backpressure applied over the groove, whereas the flow in the rotor groove showed dependency on both the backpressure and the angular velocity assigned to the flat plate.
- Comparing the flow pattern in the rotor and stator grooves, the numerical simulations displayed the occurrence of three different recirculation zones appearing in the rotor grooves as compared to the two zones found in the grooves of the stator.

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