NUMERICAL STUDY ON REFINER FLOWS: DETERMINATION OF REFINING EFFICIENCY AND PULP QUALITY BY MIXING ANALOGY

Juha-Pekka Huhtanen
Tampere University of Technology
P.O. Box 589
FI-33101, Tampere, Finland
E-mail: juha-pekka.huhtanen@tut.fi

ABSTRACT

A refiner is a hydraulic machine, in which complex flow conditions and a heat transfer process are combined with a very delicate wood fiber processing to produce pulp of a required quality. It is therefore extremely important to understand the flow conditions inside the refiner to control the process and to produce the desired type of pulp. A refining process resembles a mixing process, since both aim to produce as homogeneous a suspension or mixture as possible. This is why the mixing theory was adopted for the pulp quality analysis.

In this paper, we have used numerical simulation to analyze refining flows and pulp quality parameters. Simulations clearly showed that mixing theory can be adopted to refining intensity and efficiency analysis. By using the analysis, the refiner’s operating parameters and segment geometry can be connected to produced pulp quality parameters, and the process can be fine-tuned to work as efficiently as possible, thereby, saving considerable energy while still producing standard quality pulp.

INTRODUCTION

The refiner is a hydraulic flow machine in which complex flow conditions and heat transfer are combined with very delicate wood fiber processing to produce pulp of a required quality. It is therefore extremely important to understand the flow conditions inside the refiner to control the process and to produce the required type of pulp. Many different approaches have been tested and several articles written earlier, but only a few of them have provided a complete view of the refiner flows.

One of the best-known basic articles to describe the refining is that by Atack et al [1] in 1984. Even before that, Miles et al [2] wrote a report on the flow conditions inside a refiner. Taking advantage of porous media approximation, they described steam flow through a porous fiber network. Their work continued in a later report, in which they described the flow of a pulp phase inside the refiner [3]. Later on, other reports, e.g., by Allison et al [4], were written on the subject, starting from a new, revised basis, but still not completely describing the real physical phenomenon. Furthermore, some descriptions have appeared in the literature on the effects on the refining process of different operating parameters, such as production rate [5], rotational speed of the refiner [6], chemical addition [7], and variation of operating parameters [8]. Moreover, some attempts have been made to find a connection between the operating parameters and pulp quality [9, 10] and to simulate the mechanism [11]. A numerical program has also been constructed to simulate the flow conditions inside the refiner [12], and several reports have appeared on experiments on the refining process to measure residence time [13], velocities [14] and power distribution [15] inside the refiner. In recent years, some interesting articles [16, 17] and theses [18, 19, 20] have appeared, in which the flow phenomena inside the refiner is explained using measurements and calculations. In addition, attempts to connect the flow conditions to pulp quality parameters through residence time measurements [21] and refining intensity [22] have been published.

In this study, a new approach was adopted, based on the real physical behavior of particle suspensions and flow conditions inside the refiner. The flow situation was divided into two levels of approximation: 1) the main flow in the radial direction of the refiner along the grooves, and 2) a secondary flow inside the refiner grooves and between bars in the angular direction. The main flow characteristics determine the gross features and the functionality of the refiner, while the secondary flow characteristics determine the refiner's pulp quality parameters. The above approach can be applied basically to any refiner, especially to high-consistency chip refiners, but here it was applied only to the small-scale model refiner. Earlier results [20] showed clearly that the bar and segment geometries affected the refining efficiency: bars with larger angle of incident produced flatter radial pressure profile and re-circulation...
decreased. This means that the intensity distribution of refining becomes narrower and the pulp produced is more homogenous. With radial bar geometry, the resultant force acts on fibers by driving them into the bar gap and increasing power consumption, which produces more heat and steam, and radial temperature and pressure profiles become more parabolic. In addition, this process creates an adverse pressure gradient on the stator side and thus more backflow. Pulp quality now varies more, because some fibers that flow along the rotor grooves pass very quickly through the refiner and undergo only a few deformations, while others that flow backward on the stator side remain in the refiner longer and undergo higher net deformation. By analyzing test sheets of paper, and by recording the thermodynamic state inside the refiner and its flow conditions, a relation can be established between the operating parameters of the process and the quality of the pulp.

For a better understanding, following is a brief introduction to the refining process. Usually, thermomechanical pulp (TMP) processing uses very large disc refiners with custom designed segments. Wood chips with certain moisture content are fed by a feeding screw into the rotational center of the refiner and diluted with water. The chips are then fed inside the refiner and between the discs by the pumping section. The center section crushes and fiberizes the chips, while the outer and fine sections refine the fibers and determine the quality of the pulp. The process involves high shearing and deforming of the material and therefore consumes considerable amounts of energy. The high power consumption generates lots of heat, which vaporizes the dilution water and some water from the wood chips, turning the water-chip suspension fed into the refiner into a fiber-steam suspension at the end of the process. This increases the complexity of the problem because the processed material now differs completely from what it was at the inlet into the refiner. Therefore, the problem must be analyzed in a versatile manner, whereby we must exploit various aspects of fluid dynamics: non-Newtonian fluid dynamics, multiphase flow dynamics, heat transfer, and even turbulence theory. In analyzing pulp quality parameters, we can also resort to some statistical analytical methods because of the analogy between the refining and mixing processes.

FLOW-FIELD ANALYSIS AND NUMERICAL SIMULATION

In order to understand the refining process, it is extremely important first to understand the flow phenomena inside a refiner. Secondly, it is important to be able to calculate or compute some basic values of flow field (fluid velocities, mass and volume fractions, residence time, etc.) and thermo-dynamical state (pressure, temperature, latent heat, etc.) of the flow medium. Moreover, it is important to be able to connect these values to refiners’ operating parameters (disc gap vs. power consumption and axial load, dilution water vs. steam production and consistency, etc.) and to have a measure to describe how these values and parameters affect the produced pulp quality (refining intensity or efficiency). For this reason, we have developed a new formula for refining intensity to evaluate the segments’ refining efficiency in different refining conditions.

Main flow-field analysis:
Analysis of the main flow field and the gross features of the refiner flow were based on the reduced set of Navier-Stokes equations combined with continuity and energy equations in cylindrical coordinates. The full set of equations in a steady state situation for incompressible fluid without body forces are as follows [23]

- Continuity equation:

\[
\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{1}{\rho} \frac{\partial \rho}{\partial \theta} = 0
\]

- Navier-Stokes equations:

\[
\begin{align*}
\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + \frac{v_0^2}{r} + v_z \frac{\partial v_z}{\partial z} &= -\frac{\partial p}{\partial r} - \frac{1}{\rho} \left[ \frac{1}{r} \frac{\partial r (r \tau_{rr})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r0}}{\partial \theta} - \tau_{r0} \right] + \frac{\partial \tau_{rz}}{\partial z}, \\
\frac{\partial v_0}{\partial t} + v_r \frac{\partial v_0}{\partial r} + \frac{v_0 v_z}{r} + v_z \frac{\partial v_0}{\partial z} &= -\frac{\partial p}{\partial r} - \frac{1}{\rho} \left[ \frac{1}{r} \frac{\partial (r^2 \tau_{00})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{00}}{\partial \theta} + \frac{\partial \tau_{0z}}{\partial z} \right], \\
\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} &= -\frac{\partial p}{\partial r} - \frac{1}{\rho} \left[ \frac{1}{r} \frac{\partial r (r \tau_{rz})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r0}}{\partial \theta} + \frac{\partial \tau_{zz}}{\partial z} \right].
\end{align*}
\]
- Energy equation:

\[
\rho C_v \left( \frac{\partial T}{\partial t} + \frac{v_r}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right] - \left[ \tau_{rr} \frac{\partial v_r}{\partial r} + \tau_{r\theta} \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + v_r \right] + \tau_{zz} \frac{\partial v_z}{\partial z} \\
+ \left[ \tau_{\theta\theta} \left( \frac{r^2}{\partial \theta^2} + \frac{1}{r} \frac{\partial v_r}{\partial \theta} \right) + \tau_{rz} \left( \frac{\partial v_z}{\partial r} + \frac{\partial v_r}{\partial z} \right) + \tau_{\theta z} \left( \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} \right) \right] + q''' \quad (5)
\]

In the case of a refiner in which the angular velocity component dominates, the gap between the discs is very narrow (\(dg < 1\) mm in the outer section), and the apparent viscosity of the fiber-steam suspension is very high because of a high solid content of fibers (~ 40-50%), the set of equations is reduced to the following simple 1-D set of equations:

- Reduced continuity equation:

\[
m_{\text{in}} = m_{\text{out}} \quad .
\]  

(6)

- Reduced equation of motion in the r-direction:

\[
\rho \omega^2 r = \frac{\partial p}{\partial r} + \frac{\partial \tau_{rr}}{\partial z} \quad .
\]  

(7)

- Reduced energy equation:

\[
\rho C_v v_r \frac{\partial T}{\partial t} = \tau_{\theta z} \frac{\partial v_\theta}{\partial z} + q''' \quad ,
\]  

(8)

where \(q''' = m_g h_{fg} / (A dr)\) is the heat source or sink term owing to the phase change of water, \(h_{fg}\) is the latent heat of vaporization, \(m_g\) is the rate of steam production or condensation, and \(A\) is the local free cross-flow area inside the refiner at radius \(r\).

The final form of the set of equations depends on the material function that is used to determine the shear stress in the flow channel. For example, if we use the simplest non-Newtonian fluid model, the Power-law model, we get the following pressure and temperature profiles in the radial direction [20]:

\[
p(r) = \frac{p_0}{2} \left( r^2 - \eta_1^2 \right) - \frac{(2n + 1) K m_f (l-n) b^{(2n+1)}}{(l-n)(2\pi)^n b^{(2n+1)}} \left[ 1 - \left( \frac{\eta_1}{r} \right)^{(l-n)} \right] ,
\]

(9)

\[
T(r) = \frac{m_g h_{fg}}{\rho C_v U A} - \frac{K m_f (n+z) b^{(n+1)}}{(n+2) \rho C_v U b^{(n+1)}} \left[ 1 - \left( \frac{\eta_1}{r} \right)^{(n+z)} \right] .
\]

(10)

Based on this equation system, an 1-D Fortran-based computer program was constructed to simulate the main flow features inside the refiner in the radial direction. These calculations yield pressure and temperature profiles in the \(r\)-direction. Furthermore, we can define the relation between the volumetric fractions of steam and fibers from the steam generation term. The phase change of water also modifies the material parameters of the suspension, which, therefore, have to be updated all the time during calculation. In fact, the phase change term closes the set of equations, and the whole computation procedure involves numerous iterations between these equations.
Secondary flow-field analysis:
To understand the overall flow situation inside the refiner, we must analyze the secondary flow field inside the refiner grooves and between bars. As the flow field in the refiner is not 1-D, as approximated in the main flow analysis, but a very complex 3-D field, a true 3-D numerical model was constructed. The situation is quite different on the rotor and stator sides: the rotor side shows a centrifugal force component, while on the stator side the component is absent, and the flow field is controlled by pressure and friction forces only. Still, the rotor and stator sides must be simulated together to get the complete view on the refiner flows and information change between rotor and stator sides.

The commercial numerical code POLYFLOW was used for simulation. POLYFLOW is a finite-element-method-based program with a large material function library, and with a capability to handle 3-D flow situations, in which the rotor and stator side models can be constructed separately and combined by Mesh Superposition Technique (MST) to build up the whole model. More about the code and models may be found in the literature [24].

For the refiner flow-field analysis here, we constructed a numerical model of the small-scale refiner. Only a narrow slice of the real segment geometry was simulated, because of computer memory restrictions, and the flow field was assumed periodic to reduce computational requirements. Still, with this small-scale model, the whole refining flow phenomenon can be studied and the full set of governing equations (1-5) can be numerically solved. Moreover, after numerical solution of the flow field, we can use mixing analogy and statistical analysis for pulp quality prediction. More about the numerical model and its results is presented in next section.

Pulp quality prediction:
In many ways, the refining process resembles a mixing process, because both aim to produce as homogeneous a suspension or mixture as possible. During processing, the material is stressed and strained, and the resulting substance is a function of the history of deformation along the flow field. This is why mixing theory was adopted to analyze the quality of the pulp.

One way to measure mixing in a flow situation is to calculate the stretching of the infinitesimal vectors attached to the material points dispersed in the flow domain. As the points move in the flow field, the vectors are stretched. The stretching and the rate of stretching of these vectors are the interesting properties, as they vary from place to place in the flow domain and evolve with time [24].

Figure 1. Schematic view of length stretch of material fiber moving with flow field from domain $\Omega_0$ to domain $\Omega$. 

![Figure 1. Schematic view of length stretch of material fiber moving with flow field from domain $\Omega_0$ to domain $\Omega$.](image)
1. Kinematic parameters of the flow:

If $\Omega_0$ and $\Omega$ denote the domains occupied by a homogeneous fluid at times 0 and $t$, respectively, then the motion of the fluid is described by the relation [24]

$$ x = \chi(X, t), \quad (11) $$

where $X$ denotes the position of a material point $P$ in domain $\Omega_0$ and $x$ in $\Omega$.

If $\lambda S$ denotes the length stretch of a material fiber, it can be shown that [25]

$$ \lambda_S(X, M, t) = \frac{dx}{dX} = \sqrt{M:CM}, \quad (12) $$

where $M$ denotes a unit orientation of a material fiber $dX$ in domain $\Omega_0$, and $C$ is the right Cauchy-Green strain tensor between the two configurations.

Good mixing quality requires high $\lambda S$ values through time and space, and a local mixing efficiency evaluation is given by the ratio [26]

$$ e_\lambda(X, M, t) = \frac{\lambda_S}{D}, \quad (13) $$

where $D = (\text{tr}D)^{1/2}$ is the rate of stretching of a material fiber, $D$ is the rate of deformation tensor, and $e_\lambda$ is a local measure along the path of a material point.

The time-averaged efficiency can be defined as [27]

$$ < e_\lambda > (X, M, t) = \frac{1}{t} \int_0^t e_\lambda(X, M, t')dt'. \quad (14) $$

If we need a global mean efficiency for the flow as a whole, we have to evaluate equation (14) for all the material points dispersed initially in the flow domain [27]

$$ << e_\lambda >> (M, t) = \frac{\int_{\Omega_0} < e_\lambda > d\Omega}{\int_{\Omega_0} d\Omega}. \quad (15) $$

Another definition for a local mean mixing efficiency over time [27] is

$$ < e_\lambda >_2 (X, M, t) = \frac{\int_0^t (\lambda' / \lambda)dt'}{\int_0^t Ddt'} = \frac{\ln(\lambda)}{\int_0^t Ddt'}. \quad (16) $$

Physically, this quantity can be interpreted as follows: for a material point at time $t$, $<e_\lambda>_2$ is the ratio of the final stretching obtained at time $t$ over the total mechanical dissipation until time $t$. 
From the above we obtain a new global mean mixing efficiency [27]

$$<e_{\lambda}>_2 (M, t) = \frac{\int_{\Omega} \ln(\lambda) d\Omega}{\int_{\Omega} (D dt') d\Omega}.$$  (17)

Physically interpreted, $$<e_{\lambda}>_2$$ is the ratio of total stretching of the material until time t over the total mechanical dissipation until time t.

2. Statistical methods:

Mixing can be numerically observed by assigning N material points, with an initial orientation M, to an earlier computed flow field. When the material points are tracked as a function of time, successive values of $$\lambda, S, e_{\lambda}$$ and $$<e_{\lambda}>$$ are being calculated. When the material points are numerous enough, say 1000, they are independent and calculated quantities can be treated statistically.

- Mean and standard deviation:

For any scalar kinematic parameter $$\alpha$$, the time evolution of its mean value ($$\bar{\alpha}(t)$$) and standard deviation ($$\sigma_{\alpha}(t)$$) can be calculated as follows:

$$\bar{\alpha}(t) = \frac{\sum_{i=1}^{N} \alpha_i(t)}{N},$$  (18)

$$\sigma_{\alpha}^2(t) = \frac{\sum_{i=1}^{N} (\alpha_i(t) - \bar{\alpha}(t))^2}{N}.$$  (19)

- Cumulated probability function (or distribution function):

The distribution function $$F_{\alpha}(\beta, t)$$, associated with a scalar field $$\alpha$$, can be defined as [27]

$$F_{\alpha}(\beta, t) = p[\alpha(t) \leq \beta],$$  (20)

where the right side is the probability of field $$\alpha$$ to be smaller than $$\beta$$ at time t.

- Density of probability function:

The density of the probability function $$F_{\alpha}(\beta, t)$$ can be defined as [27]

$$f_{\alpha} = \frac{\partial F_{\alpha}}{\partial \alpha}.$$  (21)

In other words, the function $$f_{\alpha}$$ is the frequency at which the value of $$\alpha$$ can be found in the range ($$\beta - \Delta \alpha ; \beta + \Delta \alpha$$) at time t.
Percentiles:

The evolution of mixing can be studied based on the time dependence of percentiles. For a field \( \alpha \), a value \( \alpha_p(t) \) can be defined such that

\[
F_{\alpha}(\alpha_p, t) = p, \quad \text{(22)}
\]

where \( \alpha_p(t) \) indicates that at time \( t \), \( p\% \) of the material points have a value of \( \alpha \) lower than \( \alpha_p(t) \).

On the basis of this theory, a relation can be established between the deformation history of the fluid and pulp quality parameters such as tear and tensile strength and fiber length. (For more about the mixing theory as a whole, see [28].)

RESULTS

In order to understand the refining process, it is extremely important first to understand the flow phenomena inside a refiner. Secondly, it is important to be able to calculate or compute some basic values of flow field and the thermodynamical state of the flow medium. Moreover, it is important to be able to connect these values to refiners’ operating parameters and to have a measure to describe how these values and parameters are affecting the produced pulp quality. For that reason, we have developed a new formula for refining intensity to evaluate segments’ refining efficiency in different refining conditions.

Results of flow simulations:

The commercial numerical code POLYFLOW was used for simulation. POLYFLOW is a finite-element-method-based program with a large material function library, capable of handling 3-D flow situations, in which the rotor and stator side models can be constructed separately and combined by Mesh Superposition Technique (MST) to build up the whole model. More about the code and models may be found in the literature [24].

A small-scale 3-D model was used in simulations (see Fig. 2a) for computer memory reasons only. The model consists of about 100 000 computational elements, because building-up the whole refiner model would have required several million elements, which was too much for our computational capacity. However, basic phenomena and operating parameters in refining can be studied through this small-scale model: affect of disc gap combined with bar and groove width and height, information change between stator and rotor sides, pressure and shear force variation, and affect of rotational speed.

Figure 2. a) Computational mesh; b) velocity field.
In Figure 2b), the whole model’s velocity field is presented. As the model is rotationally symmetric, we can observe the flow situation inside the grooves even closer by zooming into one representative groove-bar section. Close-up pictures of velocity fields in meeting and separating bar situation are shown in Fig. 3. In rotation, rotor bars are pushing pulp in front of them into stator grooves, when bars are meeting, and when they are separating, rotor bars are sucking pulp back from stator grooves. The variation is clearly seen in the flow field variation pictures, and this information change is a very important mixing effect in refining.

The flow field variation is even more pronounced when we observe z-direction velocity, i.e., velocity in groove direction (see Fig. 4). The area of backflow is greatly dependent on the mutual position of rotor and stator bars. Here again, at pressure side, rotor bars are pushing pulp forward in the grooves while pulp flows backwards at the suction side. In the meeting bars situation, we can see even two separate areas of backflow (Fig. 4a).

Variations in refining conditions can also be seen in pressure fields (see Fig. 5). In the meeting bar situation, an over-pressure peak builds between the bars, but when bars are separating, a sub-pressure peak is located between the bars. The highest peak values occur just when rotor and stator bar edges are meeting each other, and the highest values can be even 100 times higher than the ordinary pressure level in the refining situation. This depends, of course, on the refining conditions and operating parameters (such as disc gap, rotational speed, angle of the bars, pulp material, etc.).

Figure 3. Close-up velocity fields: a) meeting bars, b) separating bars.

Figure 4. Close-up z-velocity fields: a) meeting bars, b) separating bars.
Similar pressure variation has been earlier reported by Eriksen [18], when measuring refiner vibrations. The frequency of vibrations was found to be proportional to the number of bars in the segments. This must be true because every bar edge gives its impulse to the vibrations. Moreover, the amplitude of variations is proportional to refining condition, especially to the disc gap used. The amplitude and frequency of vibrations are important in analyzing segments’ refining intensity and the overall refining efficiency of certain refiners: too high can damage the produced pulp e.g. cutting fibers, but too low intensity produces raw pulp with high shives content and freeness level. Accordingly, the flow situation and refining parameters can be connected to pulp quality parameters.

A close-up picture of velocity vectors when bars are separating is shown in Figure 6. The shear rate field inside the refiner is also seen. The shear rate field is important because it shows us where the refining work is applied to the fibers. A very small amount of work is applied in the rotor or stator grooves. Almost all the work is applied in the disc-gap area. This fact further highlights the meaning of disc-gap. It also shows how important it is to get the fibers off the grooves into the real refining area in between the bars, to get proper treatment on the fibers and to produce good quality pulp. The streamline picture of stator side is shown in Fig. 7a).

In the next section, we are using a mixing analogy to introduce a measure for refining efficiency and to connect the velocity and pressure fields to pulp quality parameters through kinematic variables calculated based on the flow field.
Results of particle simulations and statistical analysis:

In many ways, the refining process resembles a mixing process, because both aim to produce as homogeneous a suspension or mixture as possible. During processing, the material is stressed and strained, and the resulting substance is a function of the history of deformation along the flow field. This is why mixing theory was adopted to analyze the quality of the pulp.

In particle simulations, we are tracking a certain amount of virtual material points as they move along the flow field. It is important to have a big enough number of particles, say 1,000, to make them statistically independent. In Figure 7b) we see an example of a particle-tracking picture, in which orientation distribution of virtual material fibers is presented.

As the material points move with the flow field, they experience deformations and are re-oriented. On them, certain kinematic parameters can be calculated, based on the existing flow field. Using statistical analysis, certain measures, determined earlier in previous section, can be calculated for particles as measures of the efficiency, i.e., how well the work done in the process is transferred into them. In Figure 8, evolution in time for mean values of stretching and dissipation of all particles together is presented.
As we can see, the evolution of stretching, representing the net deformation work on particles, is very fast at the beginning but levels out to a certain value quite fast. Meanwhile, the dissipation, representing the gross work of the process, behaves in a more periodic way. This feature is even more pronounced when we study distributions of stretching and dissipation, respectively, by probability density function (see Fig. 9 and 10). The periodic behavior of both can be clearly seen as a function of time. This behavior shows us how differently work is applied on fibers depending on the mutual position of rotor and stator bars. When bars are in even phase, i.e. they are on top of each other, the deformation work is at highest and the work is applied on particles most effectively, meanwhile, when bars are in odd phase, i.e. bars are on the grooves, the work is at lowest and the efficiency is poor.

Probability density function can also be used to analyze how many particles have experienced a certain amount of deformation work. By using statistical methods, percentage of fibers experiencing inadequate deformation (raw fibers) can be detected. Also, the percentage of fibers experiencing too much deformation (probably leading to cutting of fibers) can be found. Thereby, we can analyze the efficiency of our refining process and calculate a value for refining intensity, when we know our process parameters and the power consumption of our refiner. On the other hand, if we know how much work is needed to make a certain quality pulp, we can tune our process so that it meets the requirements, i.e., it applies enough deformation to the fibers of the total power consumption of a refiner. This way, we can either analyze our existing process or define an operating window in which our process should be standing in. This idea is presented in Fig. 11.
CONCLUSIONS

In the case of opaque material in very harsh conditions, such as a mechanical pulp suspension inside a refiner, it is difficult to make any observation, visual or measured, of the flow field. Therefore, numerical simulation is sometimes the only reasonable way to study the fluid mechanical and thermodynamical phenomena of these materials in complex flow situations. In these cases, material characterization is a key issue for successful modeling.

To understand the overall flow situation inside the refiner, it is necessary to analyze the secondary flow field inside the refiner grooves and between bars. Therefore a 3-D numerical model was constructed. The exact values of velocities, velocity gradients and pressure can be obtained from the computed flow field in every point of the flow domain. Non-Newtonian behavior of pulp suspensions was taken into account by adopting generalized Newtonian fluid models into simulations. Several fluid models were tested, but the results showed no marked difference. Finally, it was decided to take into account only the shear-thinning behavior of pulp suspensions by employing the Power-law model in simulation, because shear-thinning clearly affected the flow field inside the refiner grooves.

The effects of a material’s shear-thinning were best seen in the fluid’s effective area of relative movement on the stator side. With a Newtonian fluid, nearly the entire groove area is moving, whereas with a shear-thinning fluid, the effective area is clearly reduced, and the value of the stream function is much lower than in the former. This is an important phenomenon when we consider mixing inside the groove, for the particles on the bottom of the groove stay there much longer than those on the top and will, therefore, be much less refined than other particles. The intensity distribution in refining is thus wider for a shear-thinning fluid than for a Newtonian fluid. The effects of shear-thinning behavior reflect also on pressure and shear rate values between the bars, because shear-thinning acts on the thrust force, which separates the rotor, and stator discs, and on the deformation sustained by fibers moving through the gap between the bars. The shear stress and pressure in the disc gap are also strong functions of the bar geometry and the disc gap itself. Moreover, the values are not constant but have high peaks at bar edges indicating the variation caused by the rotor bar sliding over the stator bar. In addition, the pressure gradient in the groove direction had a distinct effect on the flow field inside the refiner: with the adverse pressure gradient clear backflow area is visible in the grooves.

As a conclusion, in order to understand the refining process, it is extremely important first to understand the flow phenomena inside a refiner. It is also important to be able to calculate or compute some basic values of flow field and the thermodynamical state of the flow medium. Moreover, it is important to be able to connect these values to refiners’ operating parameters and to have a measure to describe how these values and parameters are affecting the produced pulp quality. All this can be done by numerical simulation combined with particle tracking and statistical analysis. Thereby, a new formula for refining intensity was developed here to evaluate segments’ refining efficiency in different refiners’ operating conditions.
ACKNOWLEDGEMENTS

I would like to thank Metso’s mathematics group for cooperation and providing me valuable feedback on refiner flows and simulations during my work. I would especially like to thank Mats Ullmar and Petteri Vuorio of Metso and Kai Vikman of M-real companies for their enthusiasm and for inspiring me to do this work. I would also like to thank their companies for financial support during the research project.

References


