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Flow Field and Fibre Fractionation Studies in Hydrocyclones

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Abstract

Hydrocyclones can be used to fractionate fibres according to their papermaking potential. The obtained fractions typically differ in fibre wall thickness and/or degree of fibre treatment. Despite a multitude of potential application scenarios, the process has so far had little commercial success. This is largely explained by the low fractionation efficiency and unfavourable operating characteristics of the process.

The fractionation efficiency of a hydrocyclone is closely related to its flow field. The influence of pulp concentration on the tangential velocity field was therefore studied, by using a self-cleaning pitometer. It was found that the pulp concentration had a strong influence on the tangential velocity. At a feed pulp concentration above 7.5 g/l, the suspension rotated almost as a solid body. As a consequence, the magnitude of radial acceleration and shear stresses decreased dramatically. It is suggested that this is detrimental to the fractionation efficiency.

The radial velocity field was measured using an Ultrasonic Velocity Profiler. The measurements showed that the rotational centre of the flow field did not correspond with the geometrical centre of the hydrocyclone. This displacement caused the tangential velocity component of the vortex to contribute substantially to the measurement result of the radial velocity component.

Based on the findings in respect to the flow field studies, a novel design for a fibre fractionation hydrocyclone was proposed. The flow field inside this hydrocyclone was compared to that in a conventional hydrocyclone. It was found, that high radial acceleration and shear stresses could be maintained in the novel design even at high fibre concentration. The fractionation efficiency of the novel hydrocyclone was characterised in terms of surface roughness difference between fine and coarse fraction. When operated with refined bleached softwood kraft pulp, the novel hydrocyclone could produce fractions with a substantial surface roughness difference without deteriorating the dewatering characteristics of the fine fraction. A low thickening of the reject is proposed to be the explanation for that. When fractionating TMP, the best efficiency occurred at a concentration of 10 g/l.

Keywords: Fibre suspension, fractionation, hydrocyclone, measurement technique, velocity measurement, shear forces.

List of Publications

This thesis is based on the following publications:

I. *Literature review of experimental hydrocyclone flow field studies*
Bergström, J. and Vomhoff, H. (2006). Accepted for publication in Separation and Purification Technology.

II. *Application of a pitometer to measure the tangential velocity in a cylindrical through-flow hydrocyclone operated with a fiber suspension*
Bergström, J. and Vomhoff, H. (2005), Nordic Pulp and Paper Research Journal, 20(1), 30-35.

III. *Tangential velocity measurements in a conical hydrocyclone operated with a fibre suspension*
Bergström, J., Vomhoff, H. and Söderberg, D. (2006). Accepted for publication in Minerals Engineering.

IV. *Measurement of the radial velocity in a cylindrical through-flow hydrocyclone*
Bergström, J., Poggendorf, S. and Vomhoff, H. (2006). Submitted to Chemical Engineering Science.

V. *Review of practical methods for the quantitative evaluation of fibre fractionation*
Vomhoff, H., Bergström, J., Julien-Saint-Amand, F., Sandberg, C., Schabel, S., Stetter, A., Wittstadt, U. and Kemper, M. (2005), Ecotarget Technical Deliverable D3.1.1.

VI. *Method for fractionating an aqueous paper fibre suspension and hydrocyclone for carrying out said method*
Kemper, M., Norman, B., Sandberg, C. Bergström, J., Ko, J., Vomhoff, H., Mannes, W. and Paul, T. (2006), Patent application WO2006032427.

VII. *Evaluation of a novel fibre fractionation hydrocyclone*
Bergström, J. and Vomhoff, H. (2006).

Other relevant publications not included in this thesis:

1. *Earlywood and latewood fractionation*
   Bergström, J. (2003), In *Ekmandagarna*, Stockholm, Sweden.

2. *Velocity measurements in a cylindrical hydrocyclone operated with an opaque fiber suspension*
   Bergström, J and Vomhoff, H. (2003), In *Hydrocyclones '03*, Cape Town, South Africa.

3. *Velocity measurements in a cylindrical hydrocyclone operated with an opaque fiber suspension*
   Bergström, J. and Vomhoff, H. (2004), Minerals Engineering 17(5), 599-604.

4. *Fiber suspension velocity measurements in a cylindrical through-flow hydrocyclone – Evaluation of pitometer and ultrasonic techniques*
   Bergström, J. (2004), Licentiate thesis, Department of Fibre and Polymer Technology, Division of Paper Technology, Royal Institute of Technology, Stockholm.

5. *Potential benefits by separate bleaching of pulp fractions enriched in earlywood and latewood fibres*
   Brännvall, E., Tormund, D., Bäckström, M., Bergström, J. and Tubek-Lindblom, A. (2005), In *2005 International Pulp Bleaching Conference*, Stockholm, Sweden.

6. *Tangential velocity measurements in a conical hydrocyclone operated with fibre suspension*
   Bergström, J. and Vomhoff, H. (2006), In *Hydrocyclones '06*, Falmouth, UK.

Contents

1 Background

Fractionation is a process in which a mixture is divided into fractions (portions) of different composition or characteristics. In the pulp and paper industry, different types of fractionation procedures are carried out in virtually all steps of the production chain: Already in the forest, the proper trees are chosen to suit the production process as well as the product. Similarly, products manufactured of recycled paper are based on carefully selected waste paper grades.

Fibre fractionation can also be done in a 'wet state' in the pulp mill or stock preparation plant. The large natural variability in fibre morphology of most pulp fibres makes it possible, and sometimes necessary, to fractionate the fibres before passing on the suspension to the paper machine. One way to fractionate fibre suspensions is to use hydrocyclones on which this report focuses on. Their complex internal flow field receives particular attention.

1.1 Hydrocyclones

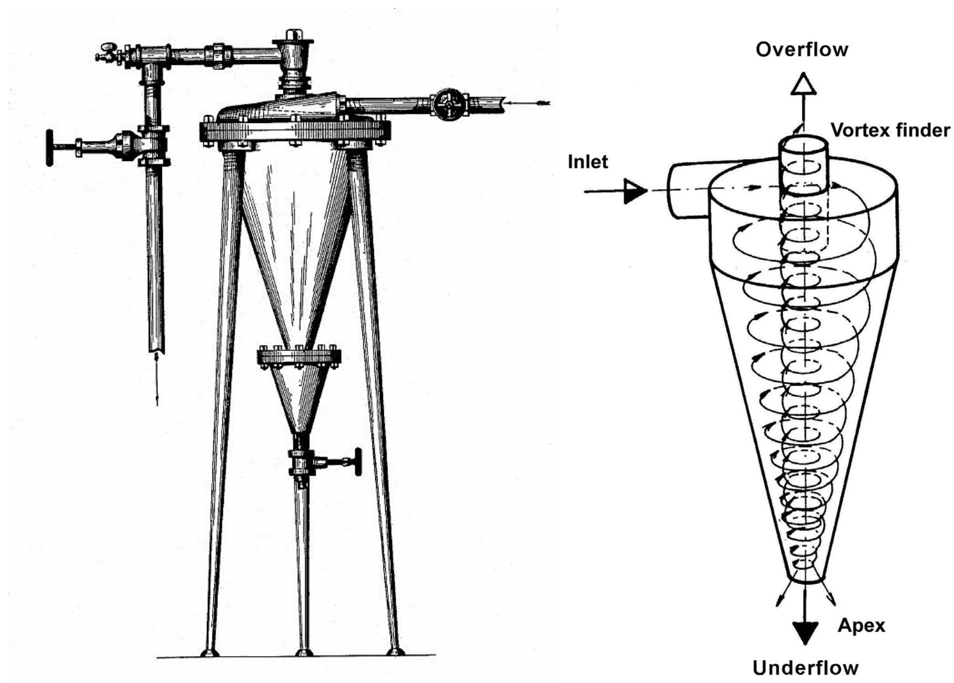

Figure 1. ***(left)*** *Bretney's hydrocyclone (1891).* ***(right)*** *Example of a frusto-conical hydrocyclone with cylindrical top part (Svarovsky, 1984).*

The first patent to be granted on a hydrocyclone was the "Water Purifier" by Bretney (1891) (see *Figure 1 left*). The basic idea was to use the strong gravitational field created by the rotating fluid for removing unwanted heavy contaminants from the water stream. This original concept of using the hydrocyclone as a solid/liquid separator is still widespread, as hydrocyclones are e.g. used for silt removal in water plants, solids recovery in mines, effluent treatment or desanding on oil platforms (Svarovsky, 1984). The astonishing success of hydrocyclones can be credited to their simple design, versatility, high efficiency and low installation and operation costs

Today, the most widely used hydrocyclone design is still the frusto-conical hydrocyclone with a short cylindrical part at the top and the two outlets located at opposite ends of the hydrocyclone (*Figure 1 right*). The two outgoing flows at the top and the bottom are often referred to as overflow and underflow. The overflow is collected in and leaves through the protruding tube called the vortex finder. In the hydrocyclone, the fluid pressure head of the feed stream is converted into rotational motion. A downward moving flow is formed close to the wall and an upward motion close to the hydrocyclone centre axis.

The operation of a hydrocyclone is largely controlled by the feed pressure. The operating state is reflected by the pressure drop from feed to overflow. The feed pressure is in turn linked to the feed flow. The combination of feed flow and geometry of the hydrocyclone ultimately determines the centrifugal effect. Consequently, centrifugal effect, flow rate, pressure drop and hydrocyclone geometry are all interdependent. Albeit versatile, this interdependence exposes the relative inflexibility of a specific hydrocyclone (Bradley, 1965). Some degree of flexibility can however be achieved by throttling the flows with external valves to control the flow split.

The inflexibility of a hydrocyclone implies that its geometry always has to be optimised for a specific separation task. This also explains why there exist countless numbers of purpose-built, specialised designs that feature exotic design elements such as cylindrical main body, multiple outlets, uni-direction axial flow (through-flow), vane-guided rotation, grooved or stepped cone surface, apex in both ends, internal water injection, discontinuous operation dirt hoppers, air-sparged operation, ultrasonic excitation etc.

1.2 Hydrocyclones in the Pulp and Paper Industry

The pulp and paper industry was quick to implement hydrocyclones in their processes. By the end of the 1930's, several industrial installations of pulp cleaning systems were in operation. Early patents witness of a strong development of the hydrocyclone heavy-weight contaminant cleaning technology; one of the earliest patents was Bergès' (1935) hydrocyclone for heavy grit removal from pulp. Baliol Scott (1941) patented an improved vortex type separator with an impurity settling chamber and double underflow streams. Bauer Bros Company (1957) introduced a porous apex for water dilution to minimise fibre loss in the underflow. Tomlinson II (1957) suggested a large diameter hydrocyclone for cleaning purposes.

The early designs were solely intended to remove contaminants of density much higher than the fibres, such as sand and metal. The cleaning ability of hydrocyclones was further refined over time. Later designs had the ability to remove organic material of a density close to the density of the fibres or with a hydrodynamic behaviour close to that of the fibres. The relatively slender hydrocyclone, patented by Samson and Croup (1945), took on the challenging task of removing resinous material, shives and bark specks. Compared to other separation equipment available at the time, the hydrocyclone seemed to be particularly suited for the removal of shives. Tomlinson II and Tuck (1952) showed that the shear stresses in the hydrocyclone flow field were needed to separate shives from fibres.

In the late 1960's, hydrocyclones were developed that could remove light-weight contaminants. By so-called reverse cleaners, waxes, hot-melts, light-rubber, Styrofoam and plastics could now be removed from the pulp. Here, the light-weight contaminants left through the overflow.

High density (HD) cleaners are nowadays installed early in the paper making process to remove abrasive contaminants such as gravel, sand, glass and tramp metal. These sturdy devices are normally operated at a fibre concentration of 20 to 40 g/l. As a comparison, normal cleaners and reverse cleaners usually operate at a mass concentration of the feed of about 10 g/l.

More recent patent activities do not indicate a slow-down of creativity in the field of pulp and paper. The air-sparged hydrocyclone developed by Miller (1981) at Utah university and its refined version by Chamblee and Greenwood (1991), see *Figure 2*, was used in a commercial installation for deinking recycled fibre furnishes. An even more exotic design was patented by Grimes of Beloit Technologies Inc. (1999). His hydrocyclone incorporated a piezoelectric oscillator that introduced ultrasonic waves in the separation chamber in order to improve the heavy-weight particle cleaning efficiency. Its effectiveness remains to be proven.

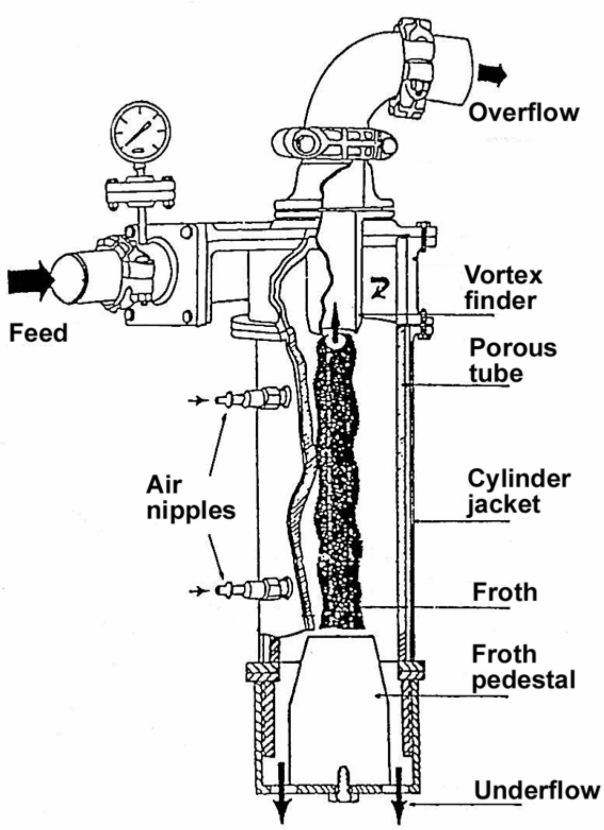

Figure 2. *Air-sparged hydrocyclone used for deinking (Borchardt et al., 1996).*

The pulp and paper industry also use hydrocyclones in processes that are not related to the cleaning of fibre suspensions. Hydrocyclones are e.g. used in deaeration of coating colours, recovery of fillers and effluent treatment. Despite the multi-faceted fields of application of hydrocyclones, they still are often simply referred to as 'cleaners' in the pulp and paper industry. The examples in this chapter illustrate the diversity of hydrocyclone applications and geometries. Despite being a more than 100-year-old invention, innovative hydrocyclone designs continue to be developed to suit new applications.

1.3 Flow Field

The efficiency of a hydrocyclone is closely connected to its flow field. The flow field in a hydrocyclone is commonly represented by three velocity components in a cylindrical coordinate system (*Figure 3*). The coordinate system is usually geometrically centred at the hydrocyclone axis.

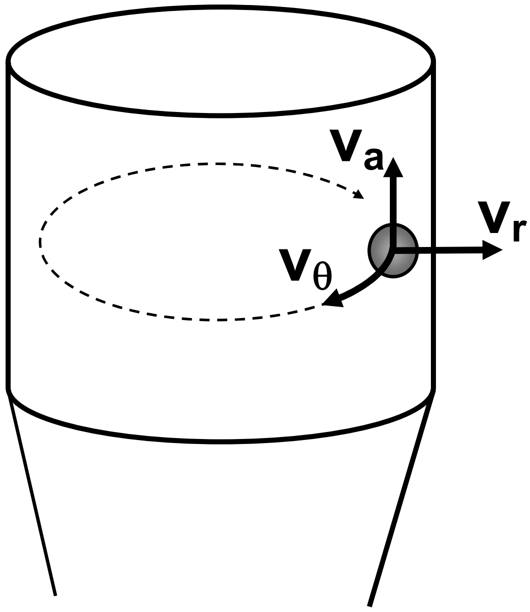

Figure 3. *Depiction of the tangential, axial and radial velocity components.*

In experimental studies of the flow field, the velocity components can either represent the velocity of the fluid phase or the velocity of tracking particles. Under certain conditions and assumptions, these two velocities coincide for one or more velocity components. Typically, it is acknowledged that the separation of particles necessitates a slip velocity in the radial direction, i.e. a velocity difference between the fluid phase and the particle (Albring, 1961).

In order to improve the efficiency of hydrocyclones, there is a constant need of an increased understanding of its complex flow field. The qualitative flow pattern inside conical hydrocyclones has been the objective of several studies (e.g. Bradley, 1965; Svarovsky, 1984; Ohtake *et al.*, 1987). The studies revealed circulatory eddies and a disadvantageous short-circuit flow along the hydrocyclone roof (*Figure 4*). There is very little experimental research made on the flow field of hydrocyclone designs other than the frusto-conical hydrocyclone.

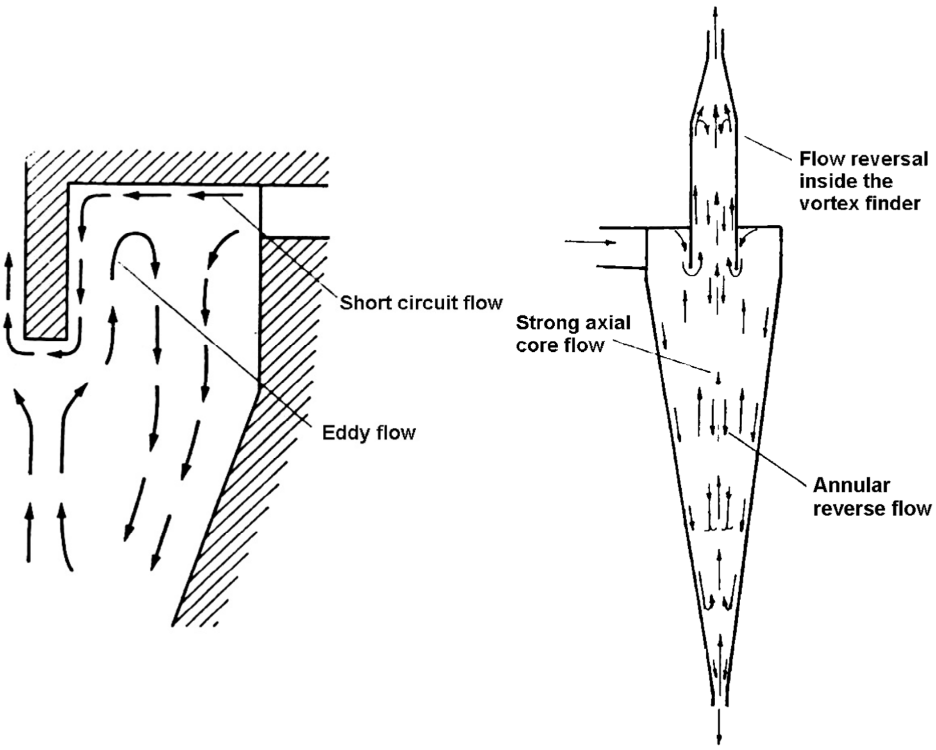

Figure 4. (left) *Short circuit flow and circulatory eddies as described by Bradley (1965).* ***(right)*** *Flow reversal inside the vortex finder and annular reverse flow in the core as observed by Dabir and Petty (1986).*

The velocity field in hydrocyclones is quasi-periodic rather than stationary. These periodical fluctuations are generated by the so-called precession of the vortex core (PVC). The influence of the PVC on the separation efficiency of a hydrocyclone is not clear. Gas cyclone research has indicated that the PVC could be detrimental to the efficiency (Chu *et al.*, 2002). Other non-stationary contributions come from the turbulence present in the flow field. Chiné and Concha (2000) studied turbulence of the fluid flow field, using LDV, and concluded that the turbulence was neither homogenous nor isotropic. The influence of turbulence on particle separation is currently an intensive topic in hydrocyclone research, but lack of suitable experimental measurement methods almost entirely refers the research to computational modelling (see e.g. Cullivan *et al.*, 2004; Nowakowski *et al.*, 2004; Kraipech *et al.*, 2005).

Another striking feature of the qualitative flow field is the presence of an air-core. At the centre axis of the hydrocyclone, the low pressure supports the formation of a rotating air-column – the air-core. The stability and the shape of the air core have been empirically found to have a strong influence on the operational state of the hydrocyclone (e.g. Barrientos *et al.*, 1993; Williams *et al.*, 1995; Schlaberg *et al.*, 2000; Podd *et al.*, 2000; Cullivan *et al.*, 2001; Neesse *et al.*, 2004; Bennett and Williams, 2004).

The tangential velocity is the dominating velocity component in the hydrocyclone. Naturally occurring vortices, e.g. tornadoes, are often a combination of free vortex and solid-body rotation that can be described mathematically by *Equation 2* (see also *Figure 5*). Among the earliest measurement techniques used to quantitatively measure the tangential velocity component were intrusive pitot tubes (Yoshioka and Hotta, 1955; Lilge, 1962). They recorded free vortex-like velocity profiles with increasing tangential velocities towards the centre. Two different types of non-intrusive optical particle tracking measurement techniques were successfully used on hydrocyclones by Kelsall (1952) and Knowles *et al.* (1973). They also found free vortex-like tangential velocities, but the portion closest to the centreline behaved more like a solid-body rotation (*Figure 6*).

$$v_\theta r^n = \text{constant} \qquad (1)$$

Free vortex : $n = 1$

Solid body rotation : $n = -1$

where

v_θ = tangential velocity

r = radius

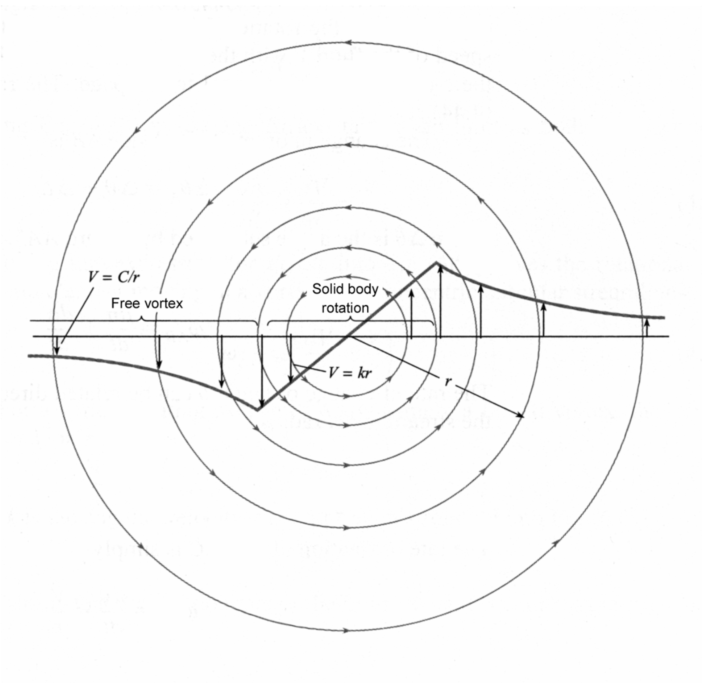

Figure 5. *A combined vortex with the two flow regimes, free vortex and solid-body rotation (Crowe et al., 2001).*

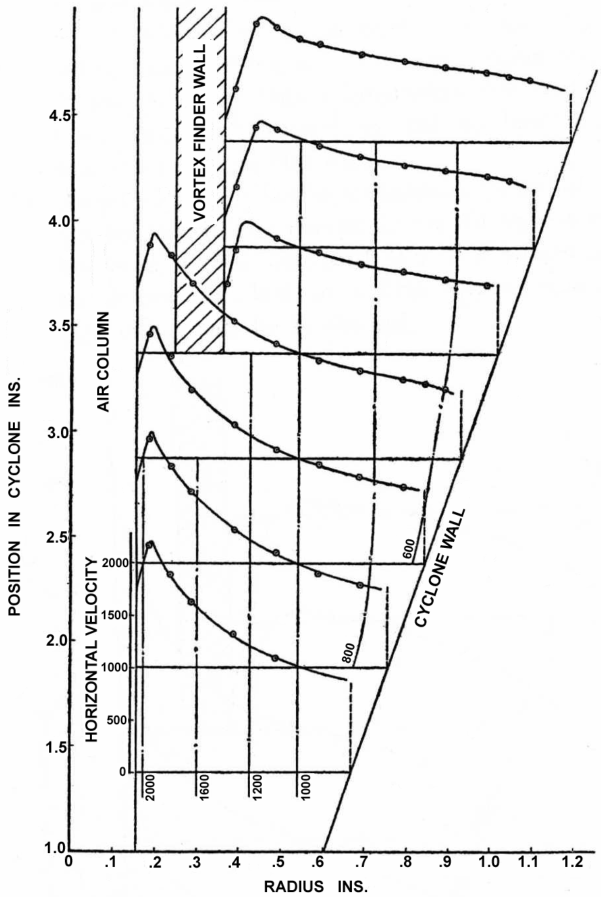

Figure 6. *Tangential velocity profiles measured by Kelsall (1952)*

As Laser Doppler Velocimetry, LDV, became available, research on the hydrocyclone flow field was intensified. Its relatively easy set-up and accuracy made the technique particularly appealing. Both the tangential and axial velocity components were readily measured (e.g. Dabir and Petty, 1986; Hwang *et al.*, 1993), and even the flow fields of new hydrocyclone designs were investigated (Monredon *et al.*, 1992; Chu and Chen, 1993).

The radial velocity component has not received the same attention. This lack of thorough investigations is surprising, as this velocity component is very important in respect to the separation mechanisms. Among the historic reasons for the scarcity of radial velocity investigations is its relatively small magnitude in comparison to the tangential velocity. This makes it difficult to measure it in the strongly swirling field. Kelsall (1952) and Dabir and Petty (1986) used continuity calculations over different vertical levels to estimate the radial velocity. Their results disagree considerably with the results that were later acquired using LDV, e.g. by Luo *et al.* (1989) and Chu *et al.* (1993). Luo *et al.* (1989) found radial velocities that increased towards the centerline below the vortex finder (*Figure 7*). The geometry of the hydrocyclone has a large influence on the radial flow field, as was made clear in a recent study by Fisher and Flack (2002) on a conical through-flow hydrocyclone (the two outlets are located at the same end of the hydrocyclone).

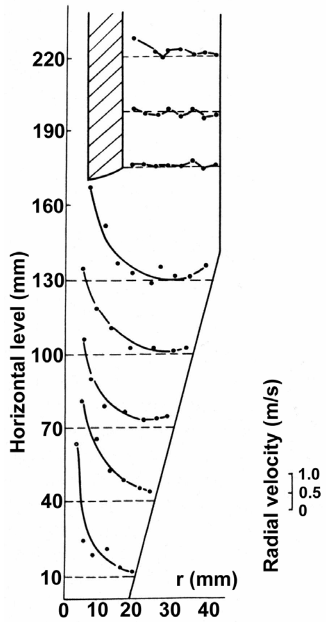

Figure 7. *Radial velocity profiles measured by Luo et al. (1989).*

Unfortunately, the above-mentioned velocity measurements might not reflect the true velocity fields in hydrocyclones when operated with wood fibre suspensions. As all measurements were done in pure or lightly seeded water, two-phase flow effects, such as particle particle-interactions, cannot occur. In the case of wood fibre suspensions, these effects are likely to be particularly severe. The slender appearance and flexible properties of wooden pulp fibres cause them to entangle (Norman, 1989) and build networks above a certain consistency (Kerekes and Schell, 1992; Martinez *et al.*, 2001). Fibre networks are known to be capable of withstanding shear stress (Duffy *et al.*, 1977) and attenuate turbulence (Forgacs *et al.*, 1957; Bennington and Mmbaga, 2001; Norman and Söderberg, 2001; Fällman, 2002). Two-phase effects in the form of fibre interaction should therefore be considered a relevant phenomenon when investigating the flow field in a hydrocyclone.

None of the measurement methods above is capable of measuring local velocities in opaque fibre suspensions; optical methods are rendered useless due to the high opacity of the suspension and probes are prone to become plugged by the fibres. To gain new knowledge on the flow field of hydrocyclones that are operated at normal fibre concentrations, new velocity measurement methods need to be developed.

1.4 Fibre Fractionation

In the pulp and paper industry, fibre fractionation is presently considered to be the process of using screens to fractionate a pulp stream into two fractions. Fibre fractionation using screens is predominantly based on fibre length (Vollmer *et al.*, 2001), but can also develop some differences of cross-sectional fibre dimensions (Wakelin *et al.*, 1999), especially if there is a correlation between fibre length and the cross-sectional fibre dimensions. Screen fractionation has so far earned its biggest commercial and technical success in board mills using recycled brown grades such as old corrugated board (OCC) (e.g. Sloane, 1999; Nazhad and Sodtivarakul, 2004). Screen fractionation is usually followed by thickening and refining of the long fibre fraction to improve strength and print quality of the board (Sloane, 1998; Markala, 2004). Multilayer applications based on these fractions have also been suggested (e.g. Bolton, 1974) and have been later realised, for example in Palm's stock preparation in the beginning of 2000 (Ortner *et al.*, 2006). A very different outcome of the fractionation process can be achieved by using hydrocyclones instead of screens

Hydrocyclones are usually used in the pulp and paper industry to remove detrimental substances from the fibre stream. In the 1960's, the ability of hydrocyclones to fractionate fibres was serendipitously discovered. In the early days, the attention was exclusively directed towards the ability of hydrocyclones to fractionate earlywood and latewood fibres, i.e. to separate thin-walled earlywood fibres from thick-walled latewood fibres (see *Figure 8*) (e.g. Pesch, 1963; Jones *et al.*, 1966; Malm, 1967). Later, it was acknowledged that hydrocyclones could also separate refined pulp according to the degree of fibre treatment (see *Figure 9*) (e.g. Wood and Karnis, 1977; Wood and Karnis, 1979; Wood *et al.*, 1991; Park *et al.*, 2005).

Other fractionation techniques have been suggested: Such as the rotating atomizer (Moller, 1982), pressurized screens (Seifert and Long, 1974), the Johnson fractionator using liquid column flow (Olgård, 1970) or flotation (Muvundamina and Li, 1997; Eckert *et al.*, 1997). These devices do not necessarily fractionate according to the same morphological characteristics as hydrocyclones (Karnis, 1997).

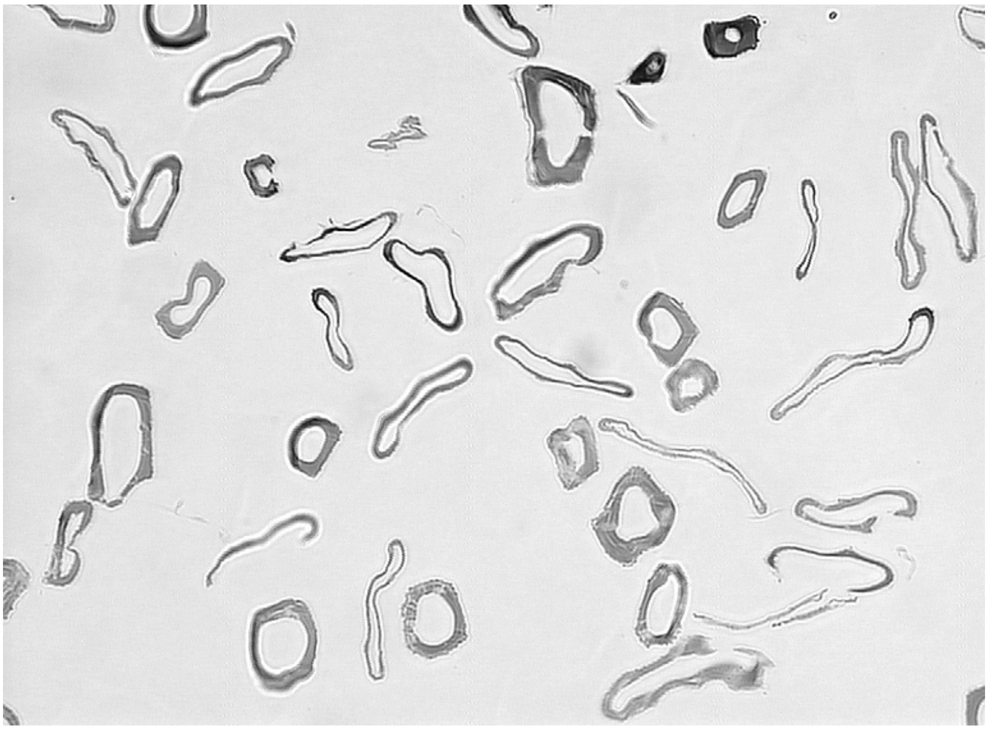

Figure 8. *Cross section image of pulp sample showing thick-walled latewood fibres and thin-walled earlywood fibres of bleached softwood pulp; courtesy of H. Vomhoff, STFI-Packforsk.*

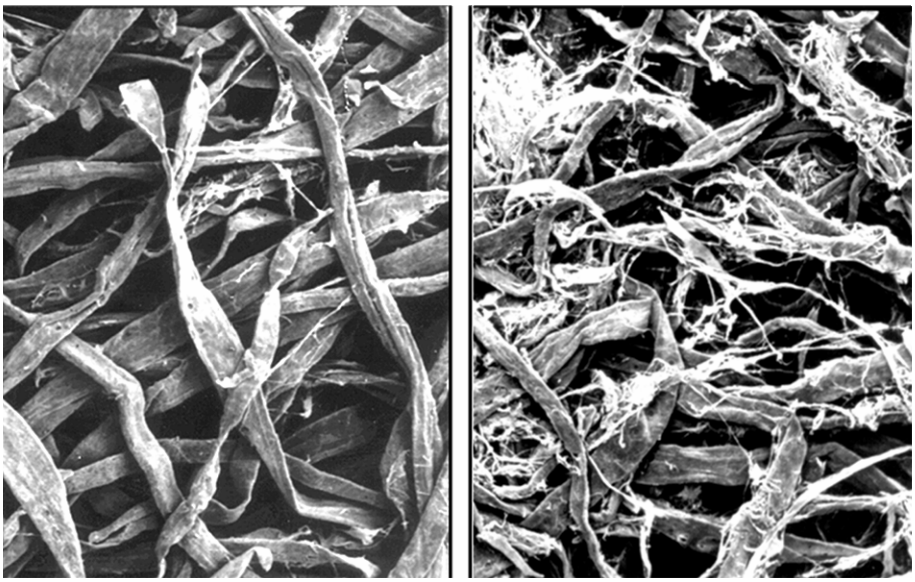

Figure 9. *Electron microscopy images of* ***(left)*** *unrefined and* ***(right)*** *refined softwood fibres; courtesy of U-B Mohlin, STFI-Packforsk.*

Fractionation using hydrocyclones makes it possible to obtain fractions with a large difference in paper properties. Jones *et al.* (1966) found large differences in strength and surface smoothness, when measuring the properties of handsheets made from the fine and the coarse fraction of hydrocyclone fractionated unrefined southern pine pulp. A sheet made of a high content of earlywood is dense and smooth, while a sheet made from latewood fibres is bulky and porous. Several patents were granted on different hydrocyclone fractionation applications (e.g. Pesch, 1963; Coppick and Brown, 1967; Malm, 1967). However, the expected economical gains of fibre fractionation never came to fruition.

Ever-increasing energy and raw material costs, combined with higher product quality demands, have over time made fibre fractionation a more attractive process. At present, the process is successfully used in removing coarse fibres in TMP production for saving energy and improving product quality (e.g. Sandberg *et al.*, 1997; Kure *et al.*, 1997; Wakelin *et al.*, 1999; Sandberg *et al.*, 2001; Hammar and Ottestam, 2001; Schlegel, 2002; Ouellet *et al.*, 2003). A similar approach is also used for TMP-based SC-grade production (Hoydahl and Dahlqvist, 1997; Rodden, 1998). More elaborate fractionation systems have been suggested by Shagaev and Bergström (2005) for improving strength and reducing moisture-induced roughening of SC/LWC. Arguably, the Radiclone AM80-F hydrocyclone developed by Noss AB has earned the most commercial and technical success.

There exists a multitude of proposed future application scenarios for fractionation. Tubek-Lindblom and Salmén (2002) showed that superior newsprint paper can be manufactured by combining multi-layer forming technology with fractionation of TMP. A similar approach was proposed for production of improved multi-ply board (Vollmer and Fredlund, 1999). Moreover, a patent by Vinson (1996) describes how fractionation can be used for the production of tissue paper at a reduced cost, (see also Vinson *et al.*, 2001; Lucas *et al.*, 2004). Kokkonen (2002) suggests fractionation of the stock in the approach flow system in multi-layer board production machines. Demuner (1999) investigated the technical possibilities of eucalypt pulp differentiation by hydrocyclone fractionation. Vomhoff and Grundström (2003) combined fractionation and refining of chemical softwood fibres. The possibility to bleach or to enzymatically treat the fractions separately has also been touched upon (e.g. Panula-Ontto *et al.*, 2002; Brännvall *et al.*, 2005; Tenkanen and Laine, 2005).

Even though the economical circumstances today sometimes motivate hydrocyclone fractionation, its widespread application is still hampered by its poor fractionation efficiency and disadvantageous operating characteristics. In order to reach acceptable efficiency, fractionation hydrocyclones have to be operated both at a low feed concentration and as multi-stage processes. This, in turn, requires auxiliary equipment to handle and redistribute large quantities of water.

1.5 Fibre Properties Influencing the Fractionation Result

Evaluation of hydrocyclone fractionation is a complicated procedure as suitable measurement methods are lacking. Even though the two fibre fractions might have palpable differences that are obvious to the human senses, a quantitative measure of the fractionation efficiency itself is not easily acquired.

To evaluate and optimise the hydrocyclone efficiency, it would be desirable to measure parameters that are linked to the hydrodynamics of the fractionation process inside the hydrocyclone. In the general literature on hydrocyclones, a number of factors are proposed that govern the particle separation in hydrocyclones; e.g. particle size, particle shape, particle density and particle specific surface (Svarovsky, 1984). Not all of these factors translate to pulp fibre fractionation.

Karnis (1997) concluded that fibre fractionation in hydrocyclones is based on the fibre morphological properties that give the largest variation of the hydrodynamic response of the fibres. This means that the controlling fibre morphological factor might be different for different type of pulps.

A number of fibre morphological factors have been investigated. If the shortest fibre fragments are disregarded, studies have shown that hydrocyclones do not fractionate according to fibre length (Fredlund *et al.*, 2001). A quasi-dependence on fibre length can be found in some cases since the fibre length might be correlated to the fibre wall thickness (e.g. Li *et al.*, 1999; Karnis, 1997). Fibre wall thickness alone is a much more significant factor (Paavilainen, 1992). Recently available fibre quality analysis equipment, such as the Metso FiberLab and the Morfi, claim to be capable of measuring the fibre wall thickness. The fibre wall thickness can otherwise be measured with great precision using tedious microscopy techniques. Cross-sectional microscopy images of aligned fibres embedded in epoxy resin is an excellent, albeit costly, way to evaluate earlywood/latewood fractionation (Reme *et al.*, 1999; Vomhoff and Grundström, 2003). The fibre wall thickness data extracted from such images gives a good response. A more refined cross-sectional measure is the Z parameter (or AD-factor) (Reme *et al.*, 1999; Li *et al.*, 1999) defined as

$$Z = \frac{4\pi A_w}{P^2} \cdot 100, \qquad (2)$$

where A_w is the cross-sectional fibre wall area and P the outer fibre perimeter. Vomhoff and Grundström (2003) found that their northern softwood pulp had a bimodal Z parameter distribution before hydrocyclone fractionation, distinguishing clearly between earlywood and latewood. This was not the case for the fibre wall thickness distribution.

The density difference between different water-saturated fibres, e.g. refined and unrefined fibres, can give a fractionation effect, but is not a dominating factor (Park *et al.*, 2005). Fibre coarseness, i.e. the fibre mass per unit length, can give a good response, but not always – for some pulps earlywood and latewood fibres have similar coarseness (Jang *et al.*, 2003). The specific surface area of the fibres has proved to be the most significant factor (Wood and Karnis, 1977; Park *et al.*, 2005). Unfortunately, the specific surface area of fibres is complicated to measure.

Relatively uncomplicated settling experiments have shown that the two fractions differ in settling velocity. This implies that the fibre fractions have a difference in average drag coefficients (Mukoyoshi and Ohsawa, 1986). However, several authors have pointed out that the drag coefficient is an integral concept influenced by a multitude of factors, e.g. Li *et al.* (1999), Green and Wong (2005) and Park *et al.* (2005). It has also been proposed that the fractionation can take place according to fibre flexibility, i.e. the flexibility directly influences the drag coefficient of the fibre and/or its behaviour in the hydrocyclone flow field (Stephens and Pearson, 1967; Marton and Robie, 1969). This would be particularly intriguing from a papermaker's point-of-view since the fibre flexibility is strongly correlated with several very important paper properties, for example the surface characteristics and strength properties of paper (e.g. Mohlin, 1975; Paavilainen, 1993).

1.6 Summary of the Literature

As a result of the literature review, the following conclusions can be drawn:

- There is a multitude of literature available on experimental investigations of the flow field inside a hydrocyclone. The flow field is highly complex. The influence of both stationary and non-stationary flow field contributions on the particle separation and, in particular, the separation mechanisms themselves are not fully understood.
- No experimental investigation can be found in the literature where the velocity field is measured at an elevated particle concentration. Consequently, the influence of the presence of particles on the flow field is unknown.
- It is a well-known fact that hydrocyclones have the ability to fractionate pulp fibre suspensions. Hydrocyclones mainly fractionate according to fibre wall thickness or the specific surface area of the fibres. The fine and the coarse fraction differ significantly in their papermaking potential. However, despite obvious advantages, the commercial implementation of hydrocyclone fractionation is so far

limited as the fractionation process itself has several serious drawbacks. There is no general agreement in the literature on how to evaluate a hydrocyclone fractionation result.

1.7 Objectives of the Present Study

The overall objective of this study is to improve fibre fractionation. As of today, hydrocyclones are considered to be the preferred fibre fractionation equipment. This attempt to improve fibre fractionation using hydrocyclones has its starting point in the current state-of-the-art. The performed literature review identified a number of aspects where knowledge is lacking. The overall objective of this study can be divided into four topics:

- *Determine the influence of fibres on the tangential velocity field in a hydrocyclone.* This aspect requires the development of new measurement techniques in order to succeed. Velocity measurements in a hydrocyclone operated at industrial fibre concentration will give essential information on possible couplings between flow field and fractionation mechanisms.
- *Measure the radial velocity in a hydrocyclone.* This, too, requires new measurement techniques to be deployed, as many of the current techniques give ambiguous results of this important velocity component.
- *Suggest practical measurement methods to evaluate fibre fractionation.* As of today, there is no general agreement on how to evaluate hydrocyclone fractionation. This is partly related to a lack of suitable measurement methods but also to that the goals of hydrocyclone fractionation are varying. The objective here is to identify a method that is simple, practical, sensitive and relevant.
- *Suggest and evaluate improvements to the design of fractionation hydrocyclones.* The knowledge acquired from the flow field measurements serves as incentives of possible improvements to the design of fractionation hydrocyclones. These improvements should be evaluated in fractionation experiments

2 Tangential Velocity Flow Field Measured with a Self-Cleaning Pitometer

The separating effect of hydrocyclones is the result of their flow field. The tangential velocity, which creates the required centrifugal field, has been particularly well-studied. All studies presented in the literature have been performed with pure or lightly seeded water. However, when hydrocyclones are in industrial operation, the particle concentration can reach significant levels. It is therefore not far-fetched to suggest that the presence of the particles should have a significant influence on the velocity field. In the case of pulp fibre suspensions, this influence can be expected to be severe already at low concentrations given the fibres' high aspect ratio L/d (L = fibre length, d = fibre diameter) of approximately 100.

This section summarises the measurement of the tangential velocity in a hydrocyclone operated with a fibre suspension. The influence of the fibre concentration on the flow field receives particular attention.

2.1 Materials and Methods

A self-cleaning pitometer was developed to measure the tangential velocity in a hydrocyclone. This probe is an improved version of the pitometer developed by Bergström and Vomhoff (2004; see also Bergström 2004). The pitometer has the ability to measure the fluid velocity in a fibre suspension. A constant purge water flow keeps the pressure opening of the probe clean from fibres. Principally, the method is based on the flow around a cylinder. By measuring the pressure on the probe's upstream ($p_{upstream}$) and downstream-facing side ($p_{downstream}$), a velocity $u_{measured}$ can be calculated according to

$$u_{measured} = c_{calibration} \cdot \sqrt{\frac{2(p_{upstream} - p_{downstream})}{\rho_{fluid}}}, \qquad (3)$$

where ρ_{fluid} represents the density of the fluid and $c_{calibration}$ a calibration constant.

Figure 10 shows how the pitometer is installed in the hydrocyclone. The probe is traversed in the radial direction in order to obtain radial profiles of the tangential velocity component. The development of the probe and its calibration routine are described in *Paper II*.

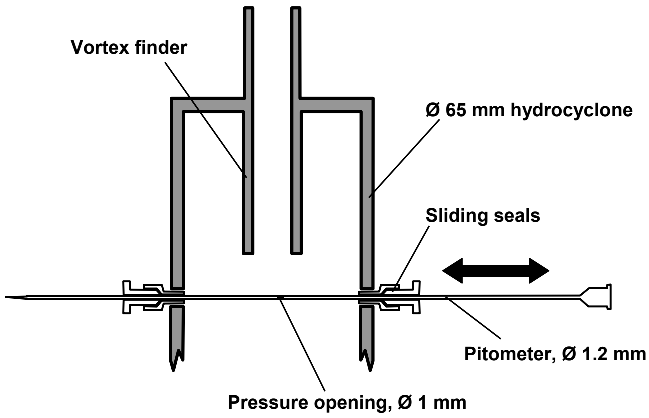

Figure 10. *Mounting of the pitometer in the top part of the hydrocyclone.*

The influence of fibre concentration on the tangential velocity profile was evaluated in a conical hydrocyclone (*Figure 11*). Holes were drilled at five different levels to provide access for the pitometer. The pitometer was placed at 90° relative to the feed inlet. The probe was sealed with sliding conical seals that allowed the pitometer to be easily traversed and rotated.

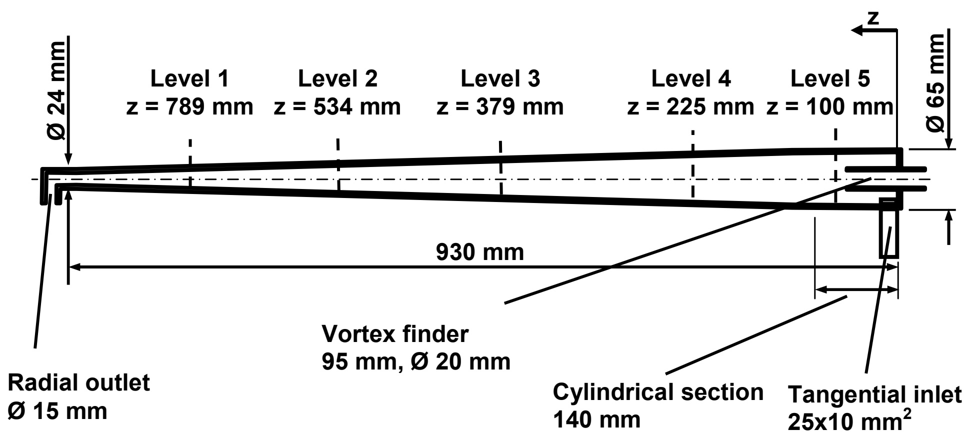

Figure 11. *Conical hydrocyclone with measurement levels.*

The hydrocyclone was connected to a flow loop that provided the hydrocyclone with constant feed flow of 2 l/s. A volumetric reject rate of 40 % was maintained at all trial points.

An unrefined bleached softwood kraft pulp was used. The pulp had a length-weighted mean fibre length of 2.2 mm and a coarseness of 150 µg/m. The mass concentration of the feed flow was varied in four steps: 0 g/l, 1.24 g/l, 7.53 g/l and 10.7 g/l.

2.2 Results and Discussion

Average velocity profiles acquired at Level 2 for different fibre mass concentrations are depicted in *Figure 12*. Since the tangential velocity was not necessarily zero at the centre axis of the hydrocyclone (see e.g. *Paper IV*), the profiles have been shifted along the x-axis to obtain zero tangential velocity at the origin, i.e. the abscissa represents the distance to the rotational centre.

In pure water, it can be seen that the velocity profile assumes the well-known combination of free-vortex-like and solid-body-like rotation. This velocity profile is similar to previous experimental work of e.g. Knowles *et al*. (1973) and Monredon *et al*. (1992).

The tangential flow field changes dramatically as fibres are added: The radius of maximum tangential velocity increases, the transition between the free-vortex-like rotation and the solid-body-like rotation is smoothened and the value of the maximum velocity is reduced. Already at 7.5 g/l, this effect is very dramatic. Virtually, a solid-body-like rotation can be observed throughout the entire flow field at this measurement level, which implies that the suspension rotates almost like a plug. The same results were obtained at the other measurement levels as shown in *Figure 13*.

The behaviour of the fibre suspension in the hydrocyclone is in accordance with the Crowding Number concept of Kerekes and Schell (1992). For the given pulp, a feed concentration of 7.5 g/l represents a Crowding Number of approx 120, i.e. continuous contacts of the fibres. Already at this concentration, the fibres appear to form such a strong network that larger deviations in tangential velocity from the solid-body-like case are not possible.

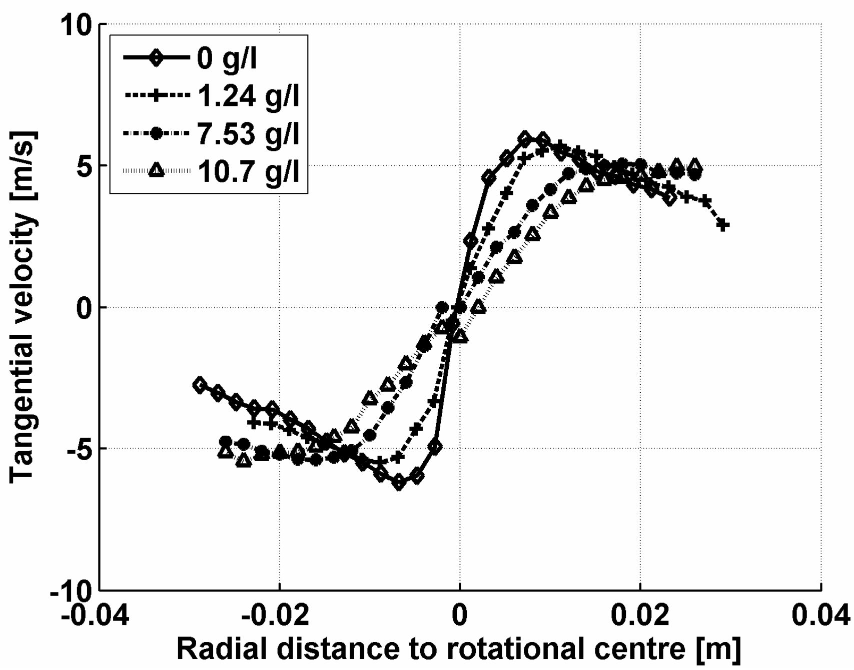

Figure 12. *Tangential velocity profiles at Level 2 measured for fibre suspensions with 0 g/l, 1.24 g/l, 7.53 g/l and 10.7 g/l concentration, respectively.*

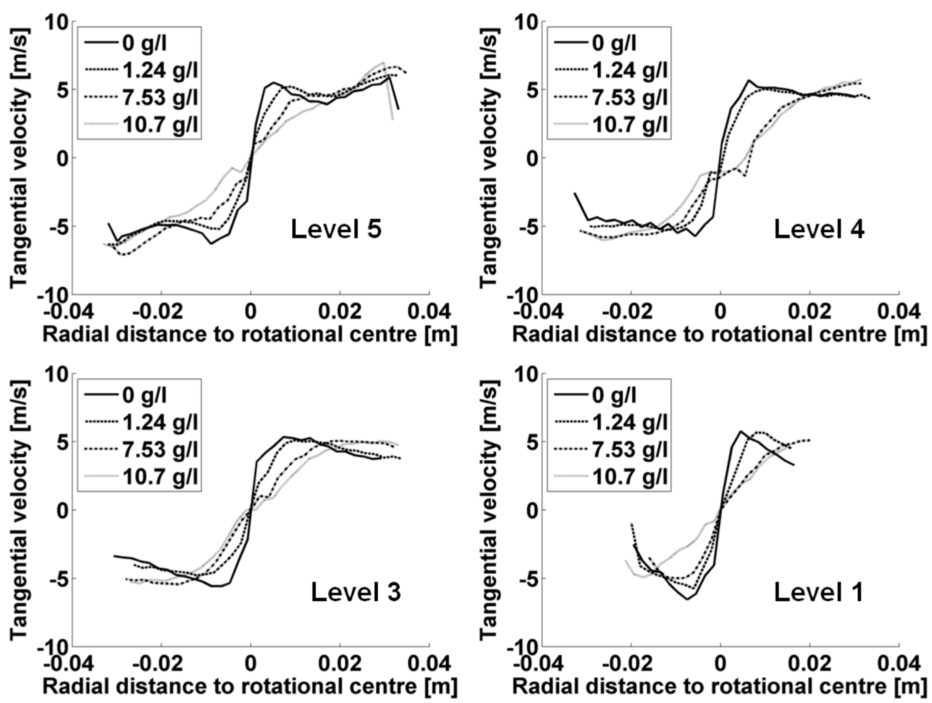

Figure 13. *Tangential velocity profiles at Levels 1, 3, 4 and 5 measured for suspensions with 0 g/l, 1.24 g/l, 7.53 g/l and 10.7 g/l concentration, respectively.*

The radial acceleration is defined as

$$a_r = \frac{v_\theta^2}{r}, \qquad (4)$$

where v_θ is the tangential velocity and r the radius. It is generally regarded as the main driving force of the separation process in hydrocyclones (e.g. Svarovsky, 1984). In *Figure 14*, the radial acceleration is plotted as function of the distance to the rotational centre. Obviously, the influence of the fibres is substantial; the maximum radial acceleration decreased significantly as fibres were added. The example in *Figure 14* is from Level 2, but the trend is similar at all levels. Considering the radial acceleration to be the driving force that controls the separation action in the hydrocyclone, its reduction would negatively influence the separation efficiency.

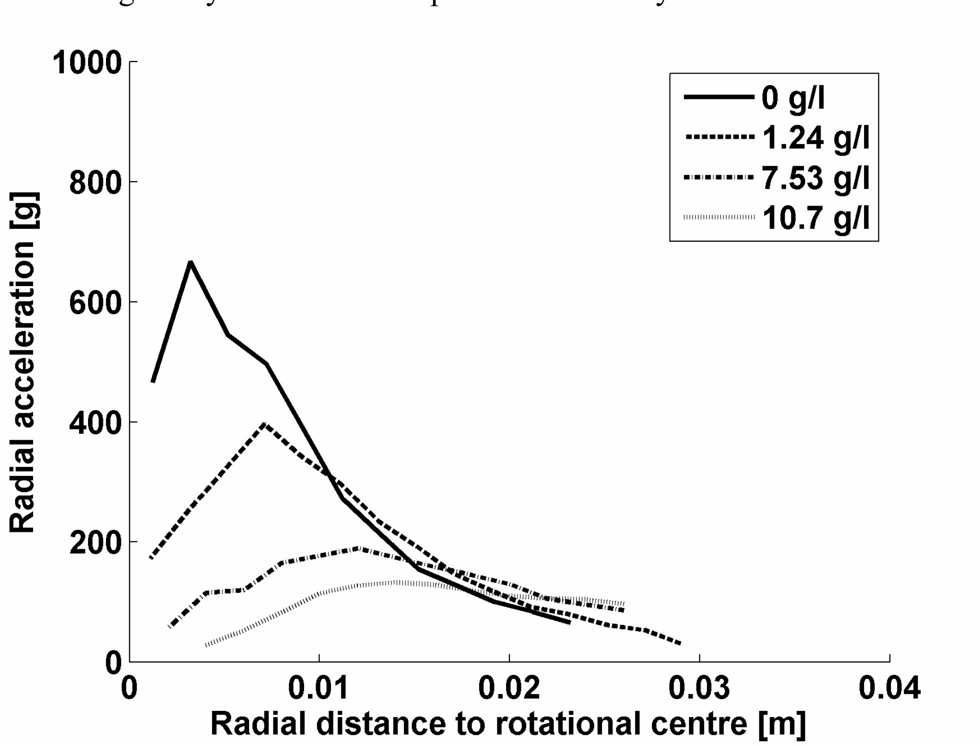

Figure 14. *Radial acceleration at Level 2 as a function of concentration of the suspension.*

The rate of strain in the tangential direction is defined as

$$e_{r\theta} = \frac{1}{2}\left(r\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right) + \frac{1}{r}\frac{\partial v_r}{\partial \theta} \right), \qquad (5)$$

where v_r is the radial velocity and θ the tangential coordinate. It can be approximated from the measured tangential velocity profiles whilst assuming

$$\frac{\partial v_r}{\partial \theta} = 0. \tag{6}$$

The vortex-centred approach supports this assumption. The rate of strain at Level 2 as a function of fibre mass concentration is depicted in *Figure 15*. For water, the highest rate of strain can be found just outside the radius of maximum tangential velocity. In comparison to that the rate of strain decreased by approximately 90% at a fibre concentration of 10.7 g/l. The situation is similar at all levels.

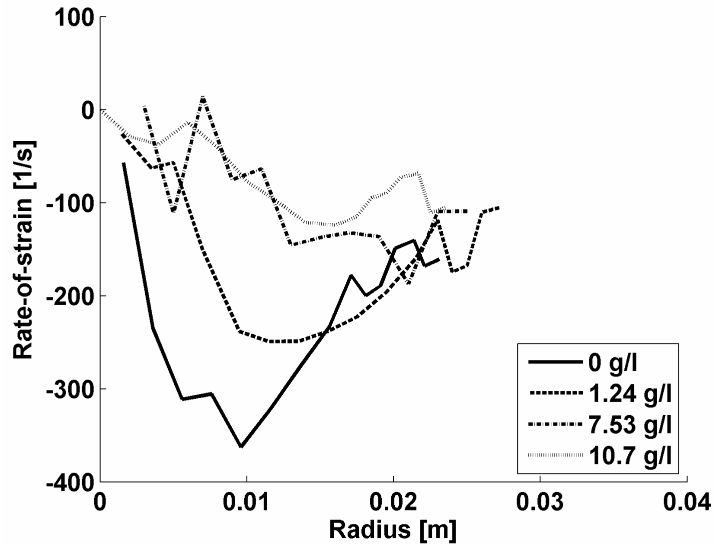

Figure 15. *Rate-of-strain as a function of concentration of the suspension at Level 2.*

The available shear stresses in a hydrocyclone are considered to reflect the ability to break up flocs and networks (e.g. Svarovsky, 1984). In a true solid-body-like rotation, the shear stresses are zero, hence there can exist no relative motion between fibres. This no-shear situation would naturally have an impairing effect on the separation process.

2.3 Conclusions

It was found that the fibres have a strong influence on the tangential flow field, radial acceleration and strain rate. In respect to fractionation, i.e. fibres can move freely relative to each other in order to report to different outlets, there appears to be a favourable combination of high centrifugal acceleration and high strain rate at lower concentrations. Conversely, at higher concentrations, there is an unfortunate combination of both low radial acceleration and shear stresses, which will be detrimental to the separation process. This hypothesis could explain why fibre fractionation using hydrocyclone is relatively efficient at low mass concentrations while the fractionation effect is almost non-existing at higher concentration levels.

3 Radial Velocity Field Measured with an Ultrasonic Velocity Profiler

Since both fibres and fine material are heavier than water they will migrate towards the hydrocyclone wall in the strong centrifugal field. The radial fluid flow, that drags certain fibres more than others towards the vortex finder in the centre of the hydrocyclone, is considered an important feature of the separation mechanism in the hydrocyclone.

Even though the importance of the radial velocity for the separation process is often acknowledged in the literature, the radial velocity has eluded any greater experimental attention. Neither the particle tracking techniques used by Kelsall (1952) and Knowles *et al.* (1973) nor the Laser Doppler Velocimetry (LDV) technique used by Dabir and Petty (1986) could measure the radial velocity directly. Instead, they tried to estimate the radial velocity indirectly, by using radial-axial material balances over different axial velocity profiles. They assumed axially symmetric flow. Unfortunately, the results of the three studies disagree considerably.

Advances in methodology and experimental set-up of the LDV equipment enabled Luo *et al*. (1989) and Chu *et al.* (1993) to directly measure the radial velocity. Both obtained inward radial velocity profiles that increased towards the hydrocyclone centreline. The radial velocity was significantly smaller than the tangential velocity. In a recent study, Fisher and Flack (2002) managed to measure the radial velocity, but the hard-to-interpret and highly oscillating result was excluded from any deeper analysis.

An oscillating nature of the hydrocyclone flow field is repeatedly observed in the literature (e.g. Smith, 1962; Chanaud, 1965; Gupta *et al.*, 1984; Yazdabadi *et al.*, 1994; Hoekstra, 2000; Solero and Coghe, 2001). This phenomenon is known as the Precession of the Vortex Core (PVC), i.e. the movement of the centre of rotation of the vortex. The PVC would emerge as non-stationary values of the radial component. It has been suggested that these non-stationary contributions are an essential part of the separation process (Averous and Fuentes, 1997).

This section describes how an ultrasonic profiler was used to measure the radial particle velocity in a cylindrical hydrocyclone.

3.1 Materials and Methods

A commercial Ultrasonic Velocity Profiler (UVP) from Met-Flow SA (2003) was used to measure the radial particle velocity inside the hydrocyclone. The ultrasonic velocity profiler, a method originally applied in the medical field, has in the 1990s also gained popularity in fluid flow research (Takeda, 1995). On several occasions, this technique has proven its accuracy and capability to measure velocity in fibre suspensions (Ricker and Forster, 1985; Wiklund and Johansson, 2001; Dietemann and Rueff, 2004). The method uses ultrasonic echography to measure velocity profiles in suspensions without any requirement for optical access.

A transceiver sends out short ultrasonic pulses in the fluid to determine the velocity of seeding particles that are travelling in the path of the ultrasonic beam (*Figure 16*). The average velocity v of a particle can be determined according to *Equation 7* using two ultrasonic pulses separated by the pulse repetition time T_{pr} (Signal Processing SA, 2004).

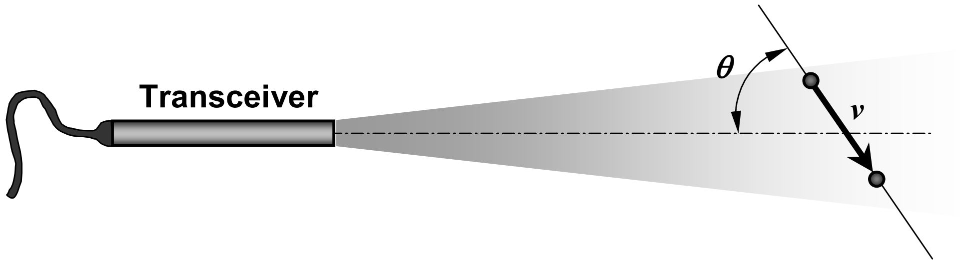

Figure 16. *A particle travelling at average velocity v, at two different positions in time.*

$$v = \frac{c \cdot \delta}{2 \cdot f_0 \cdot \cos\theta \cdot T_{pr}} \qquad (7)$$

where

$c =$ sound velocity in the liquid

$\delta =$ phase shift of the two echoes

$f_0 =$ transducer frequency

$\theta =$ angle of particle path relative to sensor.

The UVP was installed in a cylindrical, laboratory through-flow hydrocyclone (*Figure 17*). The main body of the hydrocyclone consists of three separate Plexiglas modules that divide the hydrocyclone into four measurement levels. The vortex finder can be moved axially during operation. The hydrocyclone was operated at a feed flow of 1 l/s and a volumetric reject ratio of 30 %. To create sufficient echoes, bleached softwood pulp fibres were used as seeding particles. The suspension had a mass concentration of 0.5 g/l. Despite this low concentration, the suspension was opaque.

Velocity profiles were acquired at different distances from the vortex finder opening by moving the vortex finder in the axial direction. Quasi-radial velocity maps in the axial plane were obtained by combining and interpolating several velocity profiles measured at different axial distances to the vortex finder. Similarly, the UVP was rotated around the hydrocyclone axis to create quasi three-dimensional flow maps of the radial velocity.

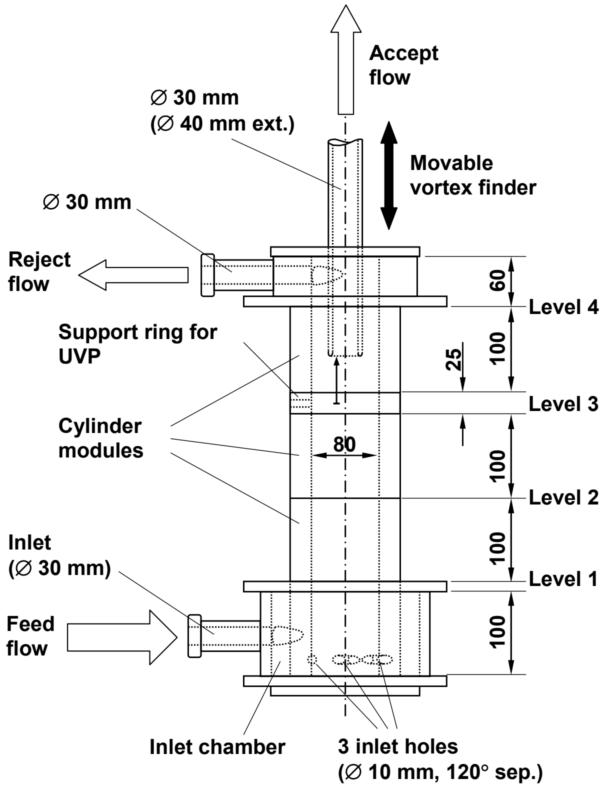

Figure 17. *Laboratory cylindrical through-flow hydrocyclone in the configuration where the transceiver is mounted at measurement Level 3.*

3.2 Results and Discussions

Figure 18 shows 7 velocity profiles acquired at different axial distances from the vortex finder opening. It can be seen that there is an inward radial velocity (negative values) close to the vortex finder, while there is an outward velocity (positive values) further away from the vortex finder.

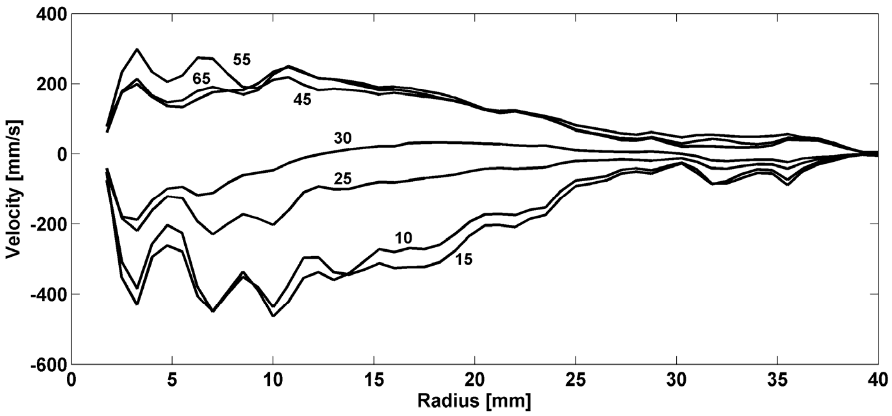

Figure 18. *Radial velocity as a function of distance from the vortex finder opening; the distance is given in the millimetres.*

Figure 19 shows a quasi two-dimensional flow field in the vertical plane of the entire measurement range. This flow field is based on 14 measured velocity profiles. The result suggests that there is a strong inward radial flow in the vicinity of the vortex finder opening. At roughly 30 mm distance from the vortex finder, nearly no radial velocity was measured. Below that distance, the flow field reverses into an outward flow.

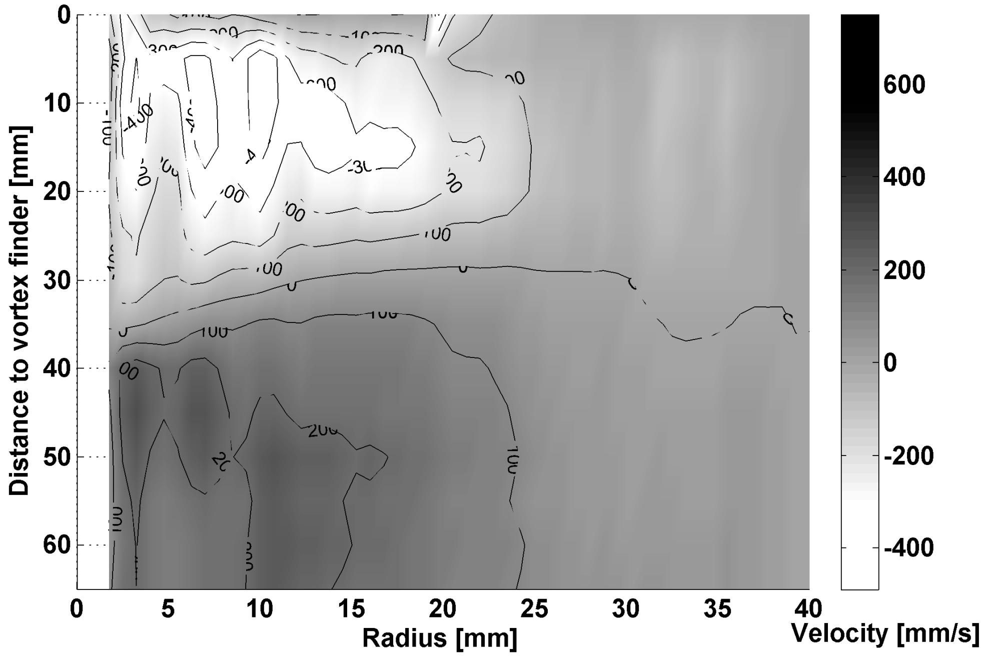

Figure 19. *Two-dimensional radial velocity flow field just below the vortex finder opening (located in the upper left corner); the flow field is based on 14 radial velocity profiles.*

A radial velocity field in the horizontal plane was obtained by rotating the UVP transducer around the hydrocyclone in 20° step-wise rotations. The profiles were recombined, interpolated and greyscale-coded to create a flow map (*Figure 20 left*). Two distinct, diametrically opposing sectors can be identified; one sector has an inward flow (bright area) and the opposite sector has an outward radial flow (dark area). The two sectors are believed to be a result of a radial shift of the centre of rotation of the flow field. If the centre of rotation does not coincide with the geometric centre, the transducer, which is directed towards the geometric centre, will record a velocity that is actually a combination of both tangential and radial velocity component of the swirling flow. An illustration of this phenomenon is shown in *Figure 20 right*.

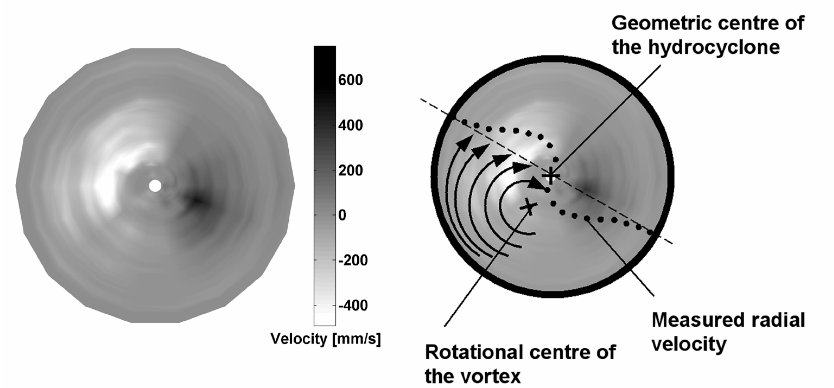

Figure 20. ***(left)*** *Map of the radial flow velocity measured at Level 3 at the axial position of 20 mm below the vortex finder opening.* ***(right)*** *The influence of a displaced vortex centre on the measured radial velocity.*

In *Figure 21*, circular flow maps over the entire measurement domain are depicted. All circular flow maps are measured at 5 mm equidistant axial positions of the vortex finder. A continuous winding motion of the "opposing sectors" described above can be observed. This result indicates that the centre of rotation follows a spiralling path around the hydrocyclone centre axis. Alekseenko *et al*. (1999) showed in swirl tube experiments that the helical shape of the swirl field was largely determined by the geometry. The asymmetry reported in this work could correspondingly be caused by the single outlet design of the hydrocyclone.

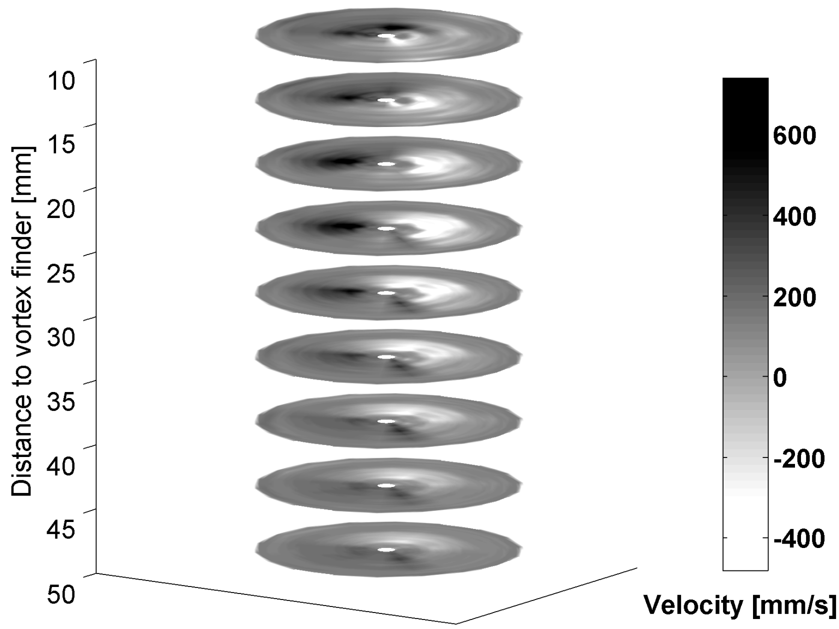

Figure 21. *Three-dimensional flow map of the radial velocity field.*

A frequency analysis of the radial velocity measurements was performed to investigate any non-stationary but periodic contribution to the radial velocity. If the centre of rotation were precessing around the hydrocyclone axis, this would cause periodic fluctuations in both the measured radial velocity and the tangential velocity. *Figure 22* shows power spectra obtained just above and below the vortex finder opening at radius r=23.5 mm.

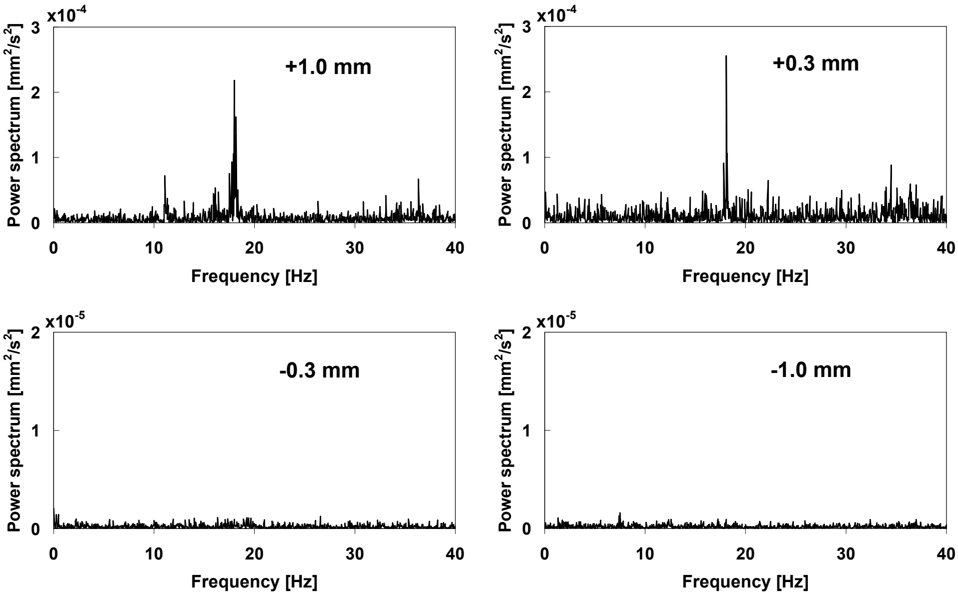

Figure 22. *Power spectra of radial velocity profiles at positions just below (positive coordinate) and above (negative coordinate) the vortex finder opening; the radial measurement position was 23.5 mm.*

Below the vortex finder opening, a clear peak is observable with a frequency of approximately 18 Hz. This implies that the radial velocity fluctuated periodically – a tell-tale sign of vortex core precession, PVC. Velocity measurement results at most radial positions oscillated in a similar manner at this frequency. Only measurements at radii greater than 37 mm, i.e. close to the hydrocyclone wall, showed no apparent periodic oscillations.

The results show that, even though the vortex core constantly precesses, the time-averaged position of the rotational centre of the vortex and the geometric centre of the hydrocyclone are not identical. Indeed, by using laser Doppler velocimetry (LDV) and computational fluid dynamics (CFD) on a gas cyclone case, Gorton-Hülgerth (1998) found that the precessing motion was not centred around the cyclone axis but rather around an axis that spiralled itself around the cyclone axis. This agrees well with the results in the present study.

Above the vortex finder opening, no apparent oscillations can be seen in the power spectrums of *Figure 22*. It seems that the vortex finder stabilises the swirling flow between the hydrocyclone wall and the outer wall of the vortex finder.

3.3 Conclusions

The ultrasonic velocity profiler provided a means for mapping the radial flow field in a hydrocyclone. It proved particularly useful to non-intrusively discover asymmetries of the radial flow field. The precession of the vortex core could be detected in terms of periodic fluctuations of the measure radial velocity.

From the measurement results, it can be concluded that the rotational centre of the flow field did not coincide with the geometrical centre of the hydrocyclone. This displacement caused the tangential velocity component of the vortex to contribute partially, though substantially, to the measurement result of the radial velocity component. Here, it should be emphasised that any measurement technique using the hydrocyclone geometry as a reference for the measurement coordinate system will experience this effect.

4 Evaluation of a Fibre Fractionation Process

The fractionation process in the hydrocyclone exploits the variation of fibre morphology properties in a fibre suspension (Karnis, 1997). As described in *Chapter 1.5*, fibre fractionation in hydrocyclones is based on differences in fibre morphology that gives the largest variation of the fibre settling rate. This means that the controlling fibre morphological parameter of the fractionation process might be different for different pulps.

The goal with this part of the study is to find a practical measurement method to evaluate the result of a hydrocyclone fractionation. The measurement method must be able to evaluate all pulps irrespective of the governing separation parameter. It is nevertheless guaranteed that measurement of a certain fibre morphology characteristic would be the most practical way to evaluate fibre fractionation.

Byrd *et al*. (2002) and Park *et al*. (2003) pointed out that the fractionation process is not only dependent on fibre properties but also on hydrocyclone operating conditions. Of course, this also applies to the influence of geometry and type of the hydrocyclone (Wakelin and Paul, 2001). A fractionation evaluation method has to give a good and relevant response to operating conditions. This means that the evaluation method should be able to be used for optimisation of the fractionation process.

An analysis of the fibre morphology differences (such as fibre wall thickness, fibre density or specific surface area) of the two fractions gives insight into the fractionation mechanism and a natural link to the hydrodynamics of the separation process. Unfortunately, these are often tedious and complex measurement procedures, and their effect on the paper quality is often difficult to predict. This makes the measurement of handsheet properties a more practical way to evaluate hydrocyclone fractionation.

In an overall perspective, hydrocyclone fibre fractionation can be used as a tool to influence the properties of the end-product. Paavilainen (1993) concluded that the collapsibility and flexibility of chemical pulp fibres are “the two most important pulp fibre properties with regard to paper properties such as tensile strength, apparent density, light scattering coefficient, surface smoothness and sheet porosity”. All these paper properties are relevant for hydrocyclone fractionation and consequently potential candidates for a practical evaluation method.

4.1 Round-Robin Test

In order to find a general method for comparing different fractionation devices, a round-robin test has been performed within the EU project Ecotarget. The round-robin comprised methods based on fibre morphology measurements, fibre suspension property measurements and evaluation of handsheet properties. A coarse and a fine bleached chemical pulp (BSK), and a coarse and fine thermo-mechanical pulp (TMP) were chosen. All pulps were evaluated with and without fines. The goal was to identify methods that were easy to use, gave a good response in respect to the characteristics of the fibre fraction.

It is well known that fines have a large influence on paper properties, but the goal of improving fractionation equipment is to improve the selectivity in respect to the fibre fraction. Therefore, the demand of insensitiveness to fines content was posed as an additional requirement as hydrocyclones are known to enrich the fines in the fine fraction. Fractionating pulp suspensions with regards to the fines can relatively easy be realised by using screens equipped with specially designed screen baskets.

Figure 23 and *Figure 24* give an overview on a number of paper properties tested at STFI-Packforsk within the round robin study. The relative differences of the two fractions are plotted, with and without the fines. The only parameter that met the requirements was surface roughness. It showed a large difference between the fine pulp and the coarse pulp, and was at the same time less influenced by the presence of fines. Tensile index gave a good response for TMP but could not distinguish the two BSK.

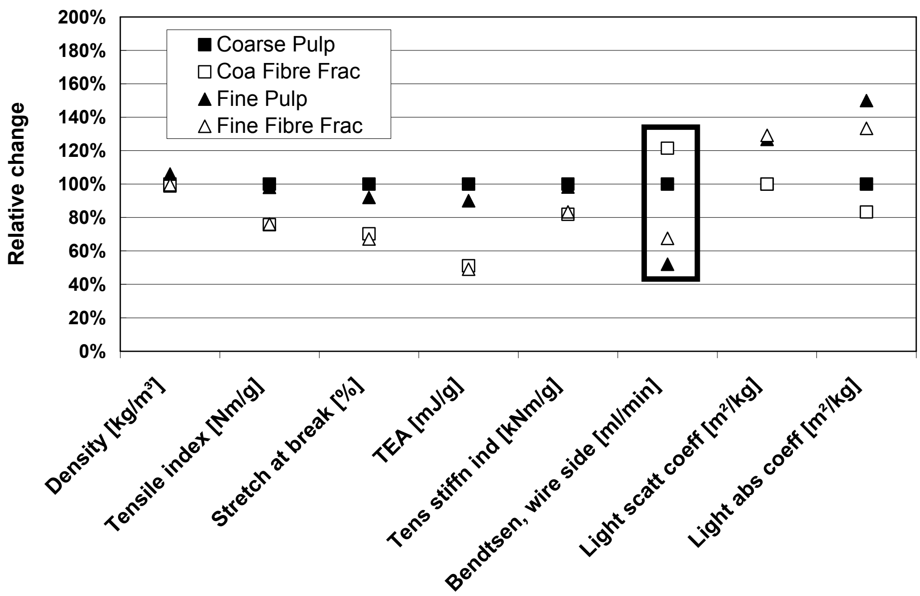

Figure 23. *Relative differences of handsheet properties of the two bleached chemical pulps.*

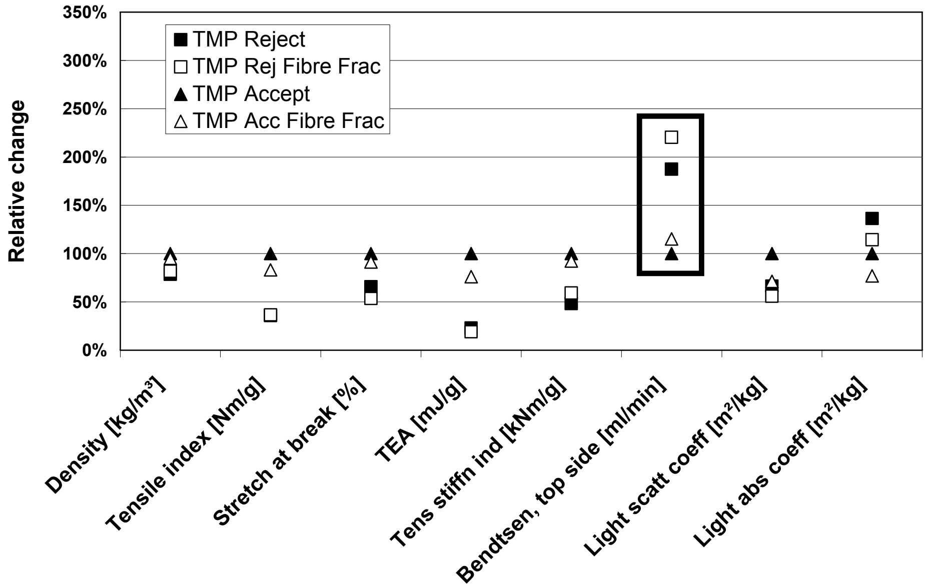

Figure 24. *Relative differences of handsheet properties of the two thermo-mechanical pulps.*

The use of surface roughness as efficiency indicator has other advantages: In the case of earlywood/latewood fractionation of chemical pulps the fractionation will mainly be according to fibre wall thickness. In contrast to that, refined pulps or TMP will be fractionated more according to the degree of fibre treatment, such as fibre flexibility or specific surface area (Jones *et al.*, 1966; Wood and Karnis, 1979; Karnis, 1997; Park *et al.*, 2005). Li *et al.* (1999) fractionated eucalypt pulp on the basis of apparent density differences of the fibres. When using surface roughness as the evaluation criteria, one does not have to distinguish between these fractionation definitions. Instead, the fractionation result is characterised using a very important final product property.

Cell wall thickness/coarseness measurement obtained with the Metso FiberLab and the Morfi gave a good response for the chemical pulps, but not for the TMP. In general, the round-robin study showed that it was difficult to obtain significant differences in fibre morphological properties that can be measured with commercially available fibre quality analysers. *Figure 25* shows an example of the pulp properties measured on the bleached chemical pulps. No parameter seemed to fulfil all requirements.

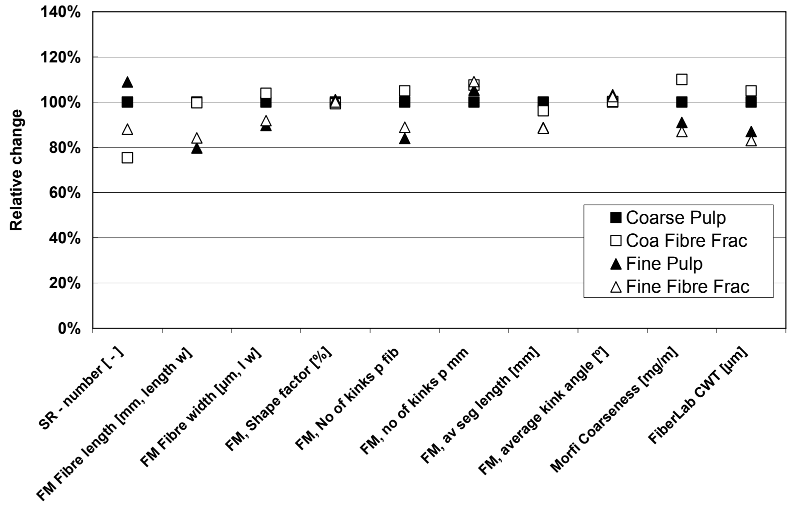

Figure 25. *Relative difference of pulp properties for BSK.*

For TMP, the Canadian standard freeness showed enormous differences between the two fractions. This difference was significantly smaller when the fines were removed. The Schopper-Riegler (SR) value, which is a popular and commonly used indicative measure of the fractionation efficiency, failed to meet the criteria. The SR measurement is simply too sensitive to the fines content. The SR value also failed to make a clear distinction between the two chemical pulps.

4.2 Conclusions

The following criteria were posed on a good parameter for the evaluation of a fractionation process: Sensitivity, practicality and insensitiveness to fines content. Of the methods in the round robin study, the only method that fulfilled these criteria, for both chemical and mechanical pulps, was the surface roughness of handsheets. The criteria of practicality is somewhat compromised since handsheets have to be made. The testing of the surface roughness itself is however both simple and speedy.

Simultaneously, surface roughness is also a very relevant property for virtually all paper and board grades where hydrocyclone fractionation might be considered. For example, when fractionating TMP for newsprint and SC-grades, an improvement in surface roughness is central. The surface roughness is also a highly important aspect when producing other printing paper grades or multiply board (Bliss, 1987).

It should however be remembered, that surface roughness is not the definitive evaluation parameter for fractionation process in industrial applications. System considerations such as a desired mass split between fine and coarse fraction may have a higher priority than the actual difference between the two fractions.

5 Novel Fibre Fractionation Hydrocyclone

The main drawback of conventional hydrocyclones is their inability to operate efficiently at higher fibre concentrations. In industrial applications there is always a trade-off between efficiency and running at practical feed concentration levels. Feed concentrations found in the literature suggest that the practical operating window, as of today, lies in the range of approximately 5-7 g/l (Gavelin and Backman, 1991; Rehmat and Branion, 1995; Demuner, 1999; Wakelin *et al.*, 1999; Shagaev and Bergström, 2005).

The poor efficiency at high fibre concentration is linked to the propensity of fibres to create networks. The interlocking of fibres in the networks prevents the fibres to move freely. The gradual thickening of the coarse fraction towards the underflow outlet in conical hydrocyclones augments this interlocking effect even further. Another issue with standard fibre fractionation hydrocyclones is the inability to run at mass reject rates close to 50 % and still maintain a fractionation effect. A mass split in this range would however be a pre-requirement for the application of a fractionation process in multilayer paper production. Standard hydrocyclones are in a sense self-adjusting where the reject rate is mainly determined by hydrocyclone geometry, feed concentration and the characteristics of the pulp (see e.g. Byrd *et al.*, 2002). For example, an unrefined and unbleached softwood pulp would likely find its mass reject rate at 90 – 95 %. These reject rates are not applicable in any industrial systems. Throttling via valves would not substantially change this reject rate without deteriorating the efficiency.

Therefore, a novel hydrocyclone design was proposed (Kemper *et al.*, 2006). Here, some of the critical issues of standard hydrocyclones were addressed. The geometry of the novel hydrocyclone is very different from ordinary conical fractionation hydrocyclones, see *Figure 26*. The design is basically a through-flow hydrocyclone with both outlets located at the opposite end of the inlet. The single tangential inlet is connected to the feed chamber were the rotation of the suspension is generated. The suspension passes through a narrow gap formed by a double-cone fastened to the ceiling of the hydrocyclone. A dilution water system is connected to the hydrocyclone close to this narrow gap. The dilution water flow, which enters the hydrocyclone main body tangentially, can be controlled independent of the feed flow. The ideas behind the narrow gap and the dilution water were to provide a well-defined and symmetric injection position of the fibre suspension as well as an additional inward radial flow, that would be beneficial for the fractionation process.

Flexibility was brought into the design by a modular design of the novel hydrocyclone. The modules allow the geometry to be easily changed; e.g. the ceiling cones can be varied, the length and geometry of the main body could be changed, a different dilution water chamber can be connected or the inner diameter of the vortex finder can be reduced by inserting bushings.

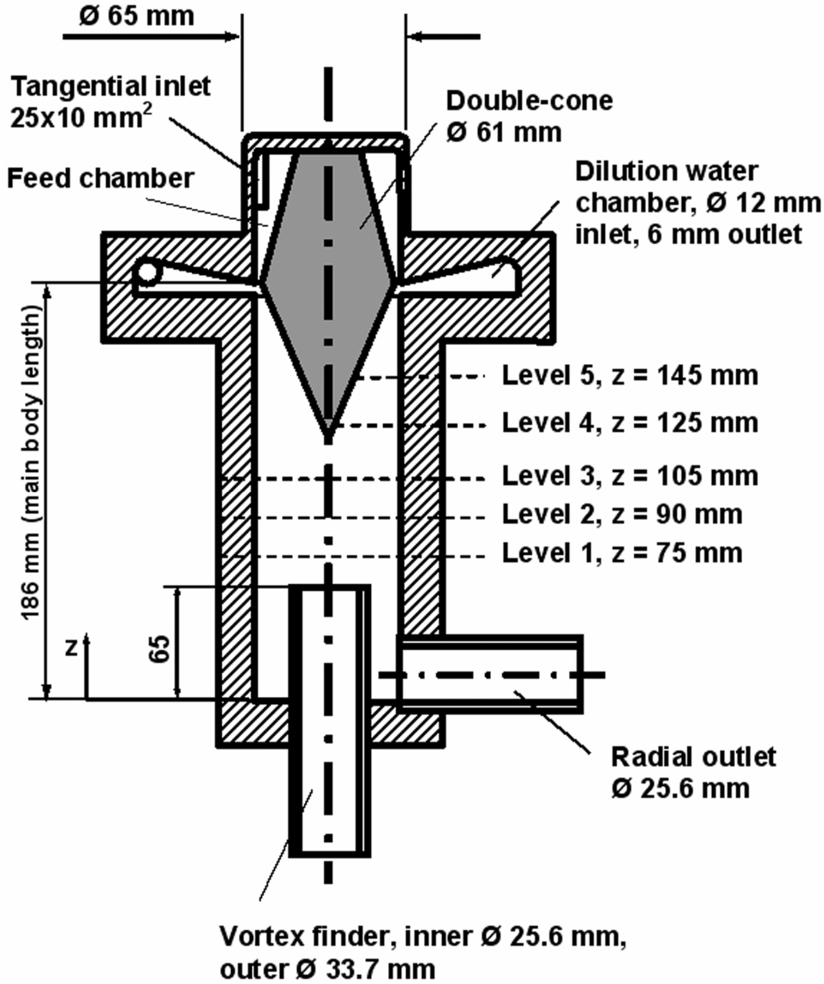

Figure 26. *Novel hydrocyclone and locations of the measurement levels.*

5.1 Tangential Flow Field of the Novel Hydrocyclone

The self-cleaning pitometer described in *Chapter 2.1* was used to measure the tangential velocity field in the novel hydrocyclone. *Figure 27* shows tangential velocity profiles from all levels of the novel hydrocyclone. The hydrocyclone was operated with a feed flow of 2.1 l/s and a dilution water flow of 0.78 l/s (27 %). The velocity profiles in the novel hydrocyclone have the typical combination of free-vortex-like and solid-body-like rotation. These velocity profiles are qualitatively similar to previous experimental work in conical hydrocyclones of e.g. Knowles *et al*. (1973) Monredon *et al*. (1992) and Chiné and Concha (2000). The maximum velocity at each level is located at a radius of approximately 11 mm. Due to accessibility problems of the probe in the vicinity of the cone, the innermost measurement points of Levels 4 and 5 are 3 mm away from the surface of the cone. Level 4 displays the highest tangential velocity of almost 12 m/s. As the fluid moves downwards in the hydrocyclone, the tangential velocity is decreasing. This effect is an excellent illustration of the frictional losses in a cylindrical hydrocyclone.

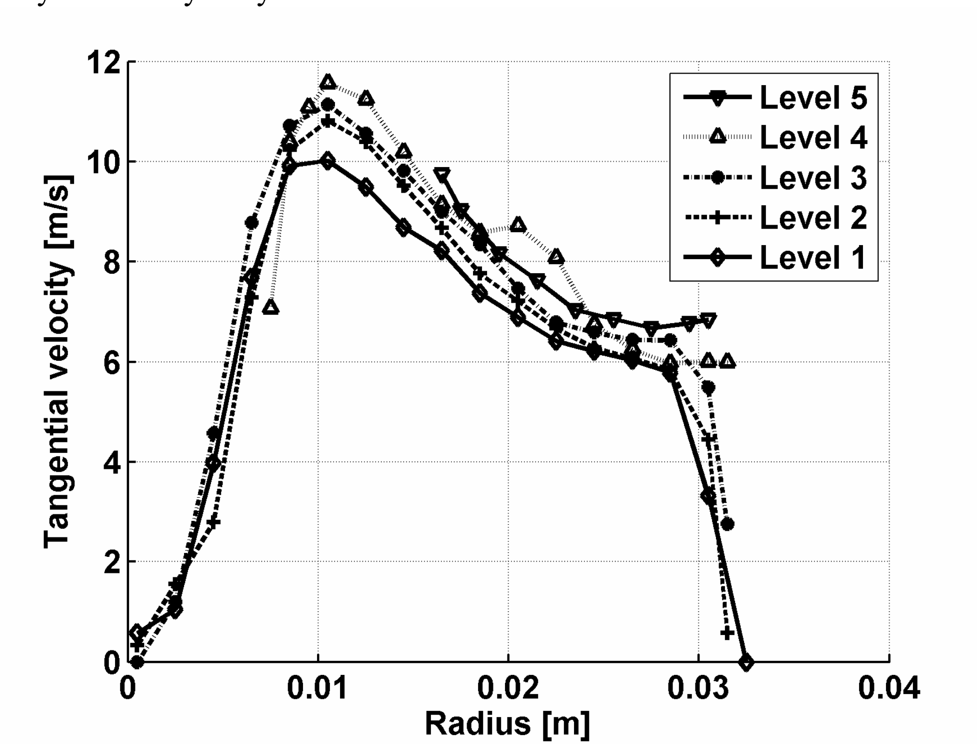

Figure 27. *Tangential velocity profiles at all measurement levels.*

In a set of experiments, the influence of the feed flow rate and the dilution water flow on the tangential velocity was investigated. *Figure 28 (left)* shows the influence of the feed flow rate and *Figure 28 (right)* the influence of dilution water rate. It can be clearly seen that the feed flow has a large impact on the tangential velocity while the dilution water flow has less influence.

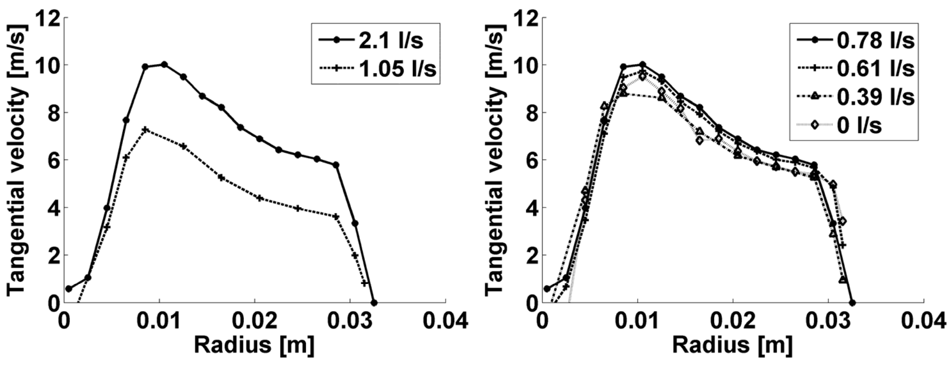

Figure 28. (left) *Tangential velocity at 2.1 l/s and 1.05 l/s feed flow and 0.78 l/s dilution water flow measured at Level 1.* ***(right)*** *Tangential velocity profile as a function of the dilution flow rate. The feed flow rate was kept constant at 2.1 l/s.*

To put the velocity profile of the novel hydrocyclone into perspective, they were compared with measurements from the conical hydrocyclone described in *Chapter2.1*. *Figure 29 (left)* shows the tangential velocity curves at Level 3 for both the novel and the conical hydrocyclone. Although fed with nearly the same feed flow (2.1 l/s vs. 2.0 l/s) and inlet geometry, the tangential velocity is dramatically higher in the novel hydrocyclone. The difference can neither be attributed to the small difference in feed flow, nor the addition of dilution water as the no dilution water-case virtually gave the same velocity profile, see *Figure 28 (right)*.

The qualitative difference between the two designs is even more dramatic when fibres are added. *Figure 29 (right)* shows how the free-vortex-like main rotation is maintained in the novel hydrocyclone, while the conical hydrocyclone almost assumes a complete solid-body-like rotation. The result implies that the fibre suspension in the conical hydrocyclone virtually rotates like a plug.

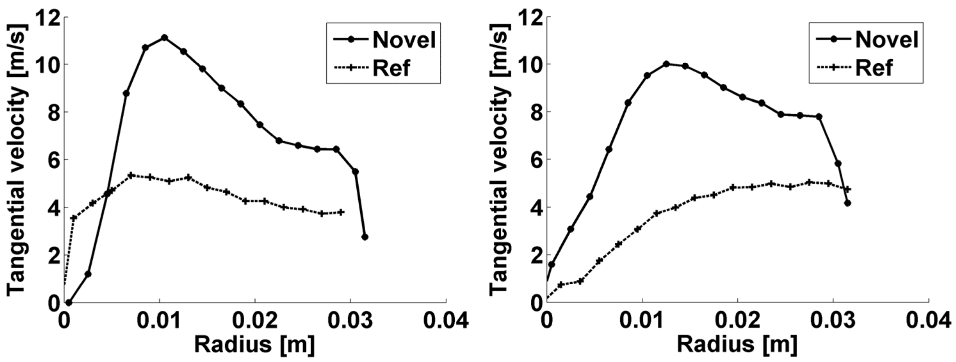

Figure 29. *Tangential velocity profile measured in water* ***(left)*** *and 10 g/l fibre suspension* ***(right)*** *for both reference and novel hydrocyclones; the measurements were performed at level 3.*

The uniqueness of the tangential flow field of the novel design can be further illuminated by determining the radial acceleration and the rate-of-strain profiles, as described in *Chapter 2.2*. *Figure 30* compares the radial acceleration for both hydrocyclones when operated with water and fibre suspension, respectively. When operated with water (*Figure 30 left*) both hydrocyclones have maximum radial accelerations in the order of 1000 g. The reference hydrocyclone has its maximum radial acceleration located at a smaller radius than the novel hydrocyclone; this is most likely a result of the smaller vortex finder diameter. When fibres are added (*Figure 30 right*), the difference between the two designs is remarkable. The novel hydrocyclone looses roughly 35 % of its maximum radial acceleration, whereas the conical reference hydrocyclone drops by 90 %.

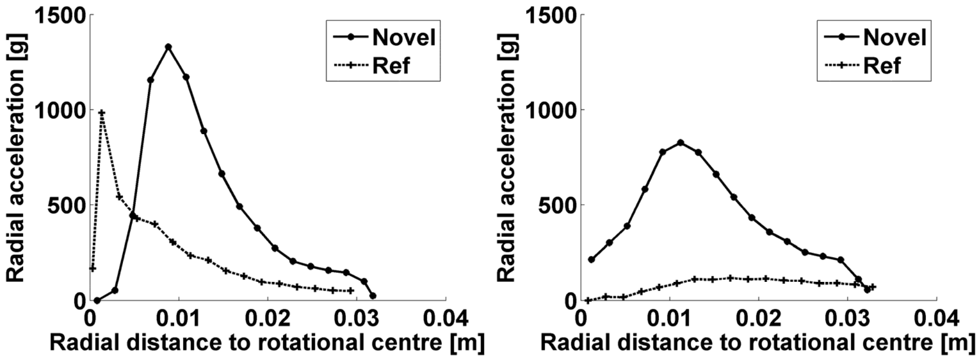

Figure 30. *Comparison of the radial acceleration determined for the tangential velocity measurements with water* ***(left)*** *and a 10 g/l fibre suspension* ***(right)****.*

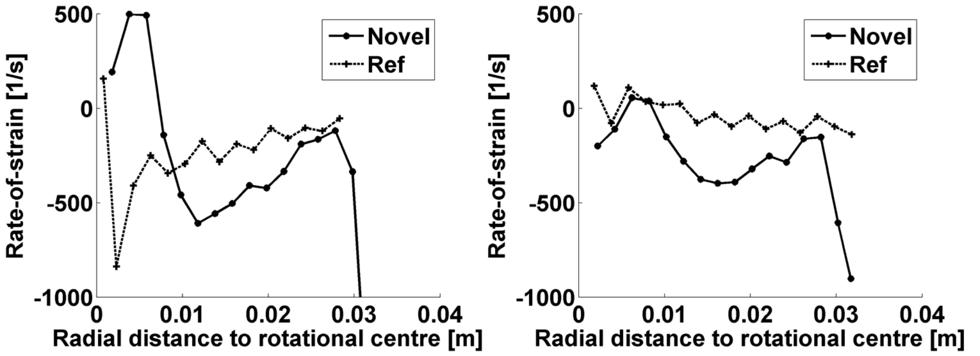

Figure 31. *Comparison of the rate-of-strain determined for the tangential velocity measurement with water* ***(left)*** *and a 10 g/l fibre suspension* ***(right)****.*

Profiles of the calculated rate-of-strain are shown in *Figure 31*. Both hydrocyclones display substantial shear stresses in the main part of the flow field when the hydrocyclone is operated with pure water. At 10 g/l fibre concentration, the solid-body-like rotation in the conical hydrocyclone naturally implies zero shear stresses, as can be seen in *Figure 31 (right)*. In contrast to that, the gradients in the velocity field of the novel hydrocyclone result still in considerable shear stresses.

5.2 Fractionation Experiments with the Novel Hydrocyclone

The fractionation experiments reported here were performed with the novel hydrocyclone having an extended main body with a total length of 289 mm and an inner vortex finder diameter of 20 mm. The conical hydrocyclone described in *Chapter 2.1* was used as reference hydrocyclone. Both hydrocyclones were operated at a feed flow of 2.2 l/s. The novel hydrocyclone had a dilution water flow of 0.55 l/s, i.e. about 20 % of the total flow. The dilution water consisted of standard tap water at a temperature of 45º C. The hydrocyclones were operated at mass reject rates in the range of 50-80 %. The feed concentration was varied between 2.5 g/l and 10 g/l. Two different pulps were fractionated: a refined bleached softwood kraft pulp (BSK) and a thermo-mechanical pulp (TMP). The softwood had an SR-value of 19.2 and a length-weighted mean fibre length of 2.4 mm. The TMP had a CSF of 88 ml and fibre length of 1.6 mm. To investigate the effect of the dilution water, the TMP trials included one test point were no dilution water was used - the dilution water chamber was sealed off - and one test point where a portion of the feed suspension was fed through the dilution water chamber.

Table 1. *Summary of the fractionation data for the novel hydrocyclone with softwood kraft pulp.*

Feed conc. [g/l]	Fract.	Conc. [g/l]	Press. Drop [bar]	Bendts. [ml/min]	Surf. Rgh. Variance [μm^2]	ºSR	Reject rate [%]	Reject Thickn. [%]	BDDJ Fines [%]	Fines conc. [g/l]
-	Feed			455	21.9	19.0	-		7.7	
2.5	Fine	2.0	2.3	274	12.3	19.6	62	116	8.2	0.16
	Coarse	2.8		509	21.6	17.6			6.3	0.18
3.6	Fine	4.1	2.4	386	19.1	21.3	62	164		
	Coarse	6.0		477	20.3	17.4				
6	Fine	5.0	2.7	377	18.9	20.5	47	124		
	Coarse	7.5		484	20.5	17.8				
7.6	Fine	6.4	2.7	378	17.8	20.3	51	116		
	Coarse	8.9		442	18.3	18.0				

Table 2. *Summary of the fractionation data for the reference hydrocyclone with softwood kraft pulp.*

Feed conc. [g/l]	Fract.	Conc. [g/l]	Press. Drop [bar]	Bendts. [ml/min]	Surf. Rgh. Variance [µm^2]	°SR	Reject rate [%]	Reject Thickn. [%]	BDDJ Fines [%]	Fines conc. [g/l]
-	Feed			455	21.9	19.0	-		7.7	
3	Fine	1.5	1.8	205	8.8	31.9	79	171	13.4	0.20
	Coarse	5.1		618	22.6	15.8			5.8	0.29
4.6	Fine	2.9	1.8	219	13.3	33.4	84	193		
	Coarse	8.9		508	23.4	17.2				
7.2	Fine	5.3	1.8	391	18.5	21.3	76	140		
	Coarse	10.5		451	21.8	17.0				
9.5	Fine	5.3	1.6	354	16.4	22.2	70	131		
	Coarse	12.4		475	20.3	17.6				

Table 1 and *Table 2* are summaries of the fractionation results obtained in the softwood fractionation trials. Both hydrocyclones had the same feed concentration, but the values for the novel hydrocyclone are corrected for the addition of dilution water. Generally, both hydrocyclones had similar surface roughness differences between the two fractions, with the reference hydrocyclone being slightly better, however always at a higher reject rate. The difference between the Bendtsen values of the two fractions decreased as the concentration increased, i.e. the fractionation efficiency, evaluated in terms of surface roughness, went down with increasing feed concentration. *Table 1* and *Table 2* also contain surface roughness data measured in a contact-free manner with an optical aberration topography measurement device from Fries Research & Technology. This surface roughness is expressed as the variance in the wavelengths of 15 – 125 µm. These values correlate very well with the Bendtsen values.

A more significant difference between the two hydrocyclone designs was the dewatering characteristics of the two fractions. High SR-values for the fine fraction were obtained in the conical hydrocyclone; this is typical for conical designs. In contrast to that, the novel hydrocyclone had very small differences in dewatering resistance between the two fractions, whilst still having very different surface roughnesses. The fines contents of some of the fractionations were analysed with BDDJ (< 76 µm). Clearly, the fine fraction of the conventional design had much higher fines content than the coarse fraction. In contrast to that, the fines content differences of the two fractions produced by the novel design were remarkably small. By recalculating the BDDJ values to fines concentration, an explanation for this result can be found. The results indicate that there actually was a small up-concentration of fines in the reject of both hydrocyclones. The main feature of the novel hydrocyclone was that the fines content in the fine fraction was substantially lower due to a lower thickening of the coarse fraction. This resulted in considerably lower SR values of the fine fraction, but also higher SR value of the coarse fraction.

In addition to that, the novel hydrocyclone was generally able to run at lower mass reject rates and still produce substantial differences between the two fractions. This is of advantage in e.g. applications for multilayer paper production. In contrast to that, the mass reject rate of the reference hydrocyclone was hard to influence by throttling the valve at the coarse fraction outlet. A closing of the coarse fraction valve, in order to lower the reject rate, was “automatically” compensated for by an increased concentration of the coarse fraction. For a given pulp and feed concentration, the reference hydrocyclone automatically found its preferred mass reject rate.

Table 3. *Summary of the fractionation results for the novel hydrocyclone with TMP.*

Feed conc. [g/l]	Fract.	Conc. [g/l]	Press. Drop [bar]	Surf. Rgh. Variance [μm^2]	CSF [ml]	Reject rate [%]	Reject Thickn. [%]	BDDJ Fines [%]	Fines conc. [g/l]
-	Feed			10.5	88	-	-	29.2	
3.1	Fine Coarse	2.8 3.6	2.0	10.7 13.9	56 101	63	118	31.9 25.9	0.89 0.93
3.1	Fine Coarse	2.8 3.6	1.9	14.0 13.4	60 93	78	116	32.4 27.8	0.91 1.00
5.1	Fine Coarse	4.7 6.1	2.3	15.7 18.5	63 113	53	120	31.7 26.4	1.49 1.61
7.3	Fine Coarse	7.0 8.8	2.3	13.6 18.4	70 113	54	121	30.6 26.1	2.14 2.30
9.8	Fine Coarse	9.2 11.5	2.6	11.9 16.1	78 109	52	118	29.2 25.3	2.69 2.91
3.2 No dilution	Fine Coarse	2.8 3.6	1.6	11.3 15.7	62 98	68	113	30.9 27.4	0.87 0.99
3.2 Feed as dilution	Fine Coarse	2.3 4.0	2.3	7.0 20.0	35 117	74	126	36.8 24.6	0.85 0.98

Table 4. *Summary of the fractionation results for the reference hydro-cyclone with TMP.*

Feed conc. [g/l]	Fract.	Conc. [g/l]	Press. Drop [bar]	Surf. Rgh. Variance [µm^2]	CSF [ml]	Reject rate [%]	Reject Thickn. [%]	BDDJ Fines [%]	Fines conc. [g/l]
-	Feed			10.5	88	-		29.2	
3.2	Fine	2.0	1.9	4.6	23	68	177	39.2	0.78
	Coarse	5.7		24.4	190			22.2	1.27
5.0	Fine	3.2	1.9	5.4	28	66	173	38.7	1.24
	Coarse	8.7		23.2	176			22.2	1.93
7.2	Fine	4.9	2.0	8.7	38	60	159	34.7	1.70
	Coarse	11.5		17.1	167			23.3	2.68
1.01	Fine	7.9	2.0	14.0	55	54	144	31.6	2.50
	Coarse	14.5		18.4	141			24.5	3.55

The results for the experiments with TMP are summarised in *Table 3* and *Table 4*. Due to handsheet forming issues, the surface roughness values were measured with optical aberration topography on the wire side of the Rapid-Köthen sheets. The surface roughness values are presented as the variance (in µm^2) in the wavelengths of 15 – 125 µm. Here, the hydrocyclones were able to operate at comparable reject rates; this was likely due to the higher fines content of the TMP pulp. The reject rate of the novel hydrocyclone could be easily influenced by throttling the reject valve.

In terms of surface roughness change, the reference hydrocyclone generally produced larger differences between the two fractions, but with an efficiency that sharply dropped with increasing fibre concentration. The novel hydrocyclone maintained the difference between the two fractions when the fibre concentration increased. For the standard setting, the novel hydrocyclone had the best fractionation efficiency at the highest feed concentration (10 g/l). Turning off the dilution water, influenced the pressure drop significantly but not the efficiency to any greater extent. The absolute highest efficiency for the novel hydrocyclone was achieved when the feed fibre suspension was partially fed through the dilution water chamber. A possible explanation for this might be related to the fact that the two feed flows were physically connected to each other via a T-coupling at the main feed line of the flow loop. This means that the tangential velocities of the two streams are always self-adjusting to match perfectly at the mixing point in the hydrocyclone.

The reason for why the efficiency improved with increasing fibre concentration can only be speculated. One explanation could be that the radial acceleration was too high at lower fibre concentration to separate the fines and well-treated fibres from the coarse fraction. As the fibre concentration increased, there might be a point where the influence of the fibres on the flow field created a more beneficial combination of radial acceleration and shear stresses. This aspect should be investigated further in future research.

5.3 Conclusions

The velocity field of the novel hydrocyclone had unique characteristics. The flow field was found to be able to maintain high radial accelerations and shear stresses even at high mass concentration. This is considered to be very important for hydrocyclone fractionation.

The novel hydrocyclone showed very different operation characteristics when compared to a standard conical hydrocyclone. It could be operated at lower reject rates and still produce substantial differences between the fine and coarse fractions. In relation to this, the novel hydrocyclone could also avoid the customary deterioration of the dewatering characteristics of the fine fraction due to a reduced thickening of the coarse fraction.

In the case of fractionating TMP, the novel hydrocyclone had its best efficiency at a fibre concentration of 10 g/l. It was speculated that the water-like behaviour of the TMP suspension at low fibre concentration allowed for too high radial accelerations to be generated leading to an undifferentiated settling of the fibre suspension rather than a fractionation. A more beneficial combination of radial acceleration and shear stresses appeared to be present at higher fibre concentrations.

6 Summary and Conclusions

The potential of hydrocyclones to fractionate fibres according to fibre wall thickness and fibre flexibility was revealed already in the early 1960's. Despite a multitude of papers on laboratory studies, there are virtually no experimental studies emanating from the pulp and paper research community on the flow field of hydrocyclones. Understanding the flow field is however considered to be the key to improve fibre fractionation hydrocyclones. Therefore, the hydrocyclone flow field was investigated in the present study. New velocity measurement methods were developed and applied. The goal was to identify potential weak spots of the flow field in order to suggest improvements to the design of fibre fractionation hydrocyclones.

A self-cleaning pitometer was developed and proved useful for measuring the flow field in different hydrocyclone designs operated with a fibre suspension. It was found that the fibres had a surprisingly large impact on the tangential velocity field. In a conventional conical hydrocyclone, the suspension rotated like a solid body when the hydrocyclone was operated above a certain fibre concentration. This is proposed to be the reason for the poor fractionation efficiency of this types of hydrocyclones at higher fibre concentration.

The radial velocity in a cylindrical through-flow hydrocyclone was measured with an ultrasonic velocity profiler (UVP). It was found that the centre of the rotational flow field did not coincide with the geometrical centre axis of the hydrocyclone. At certain locations in the hydrocyclone, this caused the tangential velocity component to contribute substantially to the measurement of the radial velocity component. It was acknowledged that this effect would enter the measurement of the radial component irrespective of velocity measurement technique.

Based on the experience of the flow field of a conventional conical hydrocyclone, a novel hydrocyclone design was proposed. The novel hydrocyclone was a through-flow design in which the feed suspension was first accelerated and passed through a narrow gap where dilution water was injected. The tangential flow field of the novel hydrocyclone looked very different when compared to the conical hydrocyclone, especially at higher fibre concentration. Here, the novel hydrocyclone maintained its high tangential velocity and free vortex-like velocity distribution. This means that the important radial acceleration and shear stresses are maintained even in fibre suspension. This was proposed to be a requirement for improved efficiency at a higher fibre concentration.

The fractionation efficiency of the novel hydrocyclone was evaluated with a slightly refined bleached softwood kraft pulp and a TMP. The surface roughness of handsheets was used as the main evaluation parameter. For the softwood, the novel hydrocyclone could be run at lower reject rates while still maintaining a substantial fractionation effect. Furthermore, the novel hydrocyclone could fractionate the pulp without impaired dewatering characteristics of the fine fractions. This was mainly due to that the thickening of the reject was avoided considerably. Both the lowering of the reject rate and good dewatering characteristics of the fine fractions are beneficial in e.g. multilayer and multiply paper applications. For TMP, the best efficiency occurred at a concentration of 10 g/l. It was speculated that the flow field had an advantageous combination of radial acceleration and shear stresses at this particular concentration for the given hydrocyclone design.

7 Recommendations for Future Work

In a bid to improve the fibre fractionation efficiency of hydrocyclones, the novel hydrocyclone design was developed. Although the novel design displayed positive fractionation and operation characteristics, it would without doubt benefit from further optimisation. For example, the length of the main body was found to influence the separation efficiency greatly, but the length chosen is by no means optimised. This goes as well for the shape of the central cone. The shape of the cone can possibly improve the separation of fibres by controlling the inward radial velocity. The symmetry of the flow can likely be improved by a different geometry of the inlet chamber. The vortex finder opening could be used to control the right level of radial acceleration and shear stresses. This type of basic flow field optimisation is well-suited to be performed in conjunction with computational fluid dynamics.

Both through visual observations and measurements it became clear that the conventional hydrocyclone and the reference hydrocyclone were operated with an air-core. Air-core stability and shape has, as acknowledged in e.g. oil-water separation and mineral classifier applications, a strong link to the separation performance. The influence of the air-core on the fibre fractionation efficiency is however completely unclear, and hence requires further studies.

The influence of fibre morphology on the separation process is only partially studied. Fibre flexibility has only been speculated to be a governing factor in hydrocyclone fractionation. With carefully selected model fibres, the possible link between the flexibility of a fibre and its drag resistance could be investigated in e.g. the settling device described by Green and Wong (2005). This could be extended to model fibre fractionation experiments similar to the ones made by Ho *et al.* (2000). The concept of drag resistance differences of fibres should be expanded to cover settling of fibres in networks, i.e. hindered settling. A relevant issue that needs to be resolved is the possible movement of individual fibres in networks. Can for example flexible fibres "slip through" fibre networks under the influence of a difference in gravitational or drag force?

The strong dependence of separation efficiency on fibre concentration is also a well-known effect in hydrocyclone sand separation. Ricker and House (1984) suggested that this effect was the probable results from the effect of the fibres on the internal flow field. They were not able to confirm this hypothesis due to lack of suitable measurement methods. In a recent study, Yli-Viitala *et al.* (2005) stretched this reasoning to the Crowding Number but did not couple this to the hydrocyclone flow field. With the measurement methods introduced in this study, hydrocyclones used for cleaning could be further studied and possibly improved. Indeed, the novel hydrocyclone design has unique flow field features that should even be explored for cleaning purposes.

Different process schemes and applications for hydrocyclones fractionation have been proposed in the literature. All applications have the conventional fractionation hydrocyclone in common. This does not mean that the requirements on the involved hydrocyclone are exactly the same for all applications. The commercially most successful fibre fractionation application is fractionation of TMP and subsequent refining of the coarse fraction in newsprint and SC mills. For maximum energy efficiency, this fractionation idea requires that the coarse fraction contains as little fines as possible. Typically 2-stage cascaded systems with dilution between the stages are used. This system effectively washes the fines towards the fine fraction while the coarse fraction is heavily thickened and separated at a suitable total reject rate (~15-30 %). This actually renders the arrangement a very ‘cleaner-like’ fractionation system. In contrast to that, very different requirements are imposed on fractionation systems for multilayer and multiply applications. Here, a suitable mass split has to go hand-in-hand with an efficient fractionation of the fibre fractions. In order to avoid dewatering problems with the fine fraction as well as z-strength issues of the coarse fraction layer, the fines must not be accumulated in the fine fraction.

For future research, application-specific requirements on hydrocyclone fractionation systems have to be specified. The two above mentioned examples illustrate how very different these requirements might be. An acknowledgement of the variability of fractionation system requirements would allow for more specialised hydrocyclones geometries to be developed in the future.

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Jonas Bergström

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