Application of a pitometer to measure the tangential velocity in a cylindrical through-flow hydrocyclone operated with a fiber suspension

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KEYWORDS: Fiber suspension, Hydrocyclone, Measurement technique, Velocity measurement

SUMMARY: This investigation evaluates a novel fluid velocity measurement method to measure the tangential velocity in a hydrocyclone. The hydrocyclone was operated with an opaque fiber suspension in order to investigate the influence of fiber presence on the tangential velocity distribution. The tangential velocity was measured with a one-hole pitometer, 0.9 mm in diameter, that was equipped with a micro pressure transducer. The pitometer was kept clean with a continuous purge flow. The probe was tested in a cylindrical through-flow hydrocyclone operated with water and 0.4 g/l and 0.8 g/l (0 %, 0.04 % and 0.08 %) addition of a bleached softwood kraft pulp. The velocity profiles measured in pure water agreed qualitatively with velocity distributions that are found in the literature. The outer section had a free vortex-like distribution and the inner section had a solid body rotation. The addition of small amounts of fibers changed the tangential velocity profile significantly. The radius of solid body rotation increased, the maximum tangential velocity decreased and the transition from solid body rotation to free vortex rotation was smoothened.

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Since the 1930s hydrocyclones have been used in the pulp and paper industry in different cleaning applications capable of removing both heavy- and lightweight contaminants from the pulp. In the 1960s the ability of hydrocyclones to fractionate according to fiber wall thickness was discovered. Several patents were approved at the time, among them Pesch (1963), Coppick and Brown (1967) and Malm (1967). The early expectations of economical and beneficial deployment of pulp fiber fractionation on an industrial scale extenuated as the process suffered from low efficiency. Nevertheless, increased energy cost and the demand for higher product quality draw again the attention to fractionation. At the turn of the century, a few new patents for the process were granted (see e.g. Kokkonen 2002, Vinson 1996).

Fractionation has potential e.g. energy-saving applications combined with product improvement (see e.g. Kure, et al. 1997, Sandberg, et al. 1997, Sandberg, et al. 2001, Schlegel 2002) and production of multi-layer products (e.g. Tubek-Lindblom, Salmén 2002). However, the fractionation process still suffers from poor efficiency and inherently low fiber concentration operation levels. A future improvement of fiber fractionation using hydrocyclones requires more knowledge of the governing flow field that in fact controls the fiber fractionation process.

The flow field of conical hydrocyclones has been extensively studied, see e.g. Yoshioka and Hotta (1955), Kelsall (1952), Knowles et al. (1973), Dabir and Petty (1986) and Monredon et al. (1992). A literature review on the previous work was performed by Bergström and Vomhoff (2004). The dominating tangential velocity component has hitherto attracted most of the research attention. Yoshioka and Hotta (1955) used a small pitot tube to measure the tangential velocity. Kelsall (1952) and Knowles (1973) used two different forms of particle tracking velocimetry to record both the tangential and axial velocity components. Dabir and Petty (1986) and Monredon et al. (1992) used laser Doppler anemometry with great success. The typical tangential velocity distribution in standard conical hydrocyclones is a combination of a free vortex-like rotation in the outer region and a solid body rotation in the inner region (*Eq 1*). It has to be noted that *Eq 1* displays some primitivity to be a complete description of the tangential velocity. Studies have revealed flat tangential velocity profiles in the outer region (Thew, et al. 1980) and even tangential velocities increasing with increasing radius (Baranov, et al. 1984).

$$\begin{aligned} v_\theta r^n &= \text{constant} \\ n &= [-1,1] \end{aligned} \qquad [1]$$

were

v_θ = tangential velocity
r = radius

In all the above-mentioned studies pure water or just lightly seeded suspensions were used. The flow field of hydrocyclones operating at a high fiber concentration has never been studied before, simply because the majority of modern flow velocity measurement techniques render useless; probes become plugged and the high opacity of the fluid circumvent optical methods. Flow field measurements in fiber suspensions are necessary in order to increase the knowledge on hydrocyclone fiber fractionation.

In this paper, a novel method to measure the tangential velocity in a hydrocyclone operated with a fiber suspension is presented. A calibration routine was developed to determine the operating characteristics of the probe. An initial velocity measurement test sequence was carried out in an experimental, cylindrical through-flow hydrocyclone operated with water and two different fiber concentration levels. The influence of the fibers on the tangential velocity distribution was investigated.

Materials and Methods

Purge flow-equipped pitometer

For tangential velocity measurements in a hydrocyclone, the so-called pitometer can be used. The operating principle of the pitometer is based on the flow around a cylinder. A standard pitometer consist of a tube with two separate impact holes located on opposite sides of the probe. One hole is facing the stream for the measurement of the stagnation pressure, and one hole is aligned in a downstream direction for static pressure measurements. The pressure difference between the upstream pressure and the downstream pressure is always greater than the dynamic pressure, as the pressure in the wake is lower than the static pressure. Therefore, pitometers always have to be calibrated for the flow situation they are used in.

There are a few commercially available pitometers (see e.g. Furness Controls 2003, United Sensor Corporation 2003), but they all suffer from two major drawbacks making them inadequate for use in hydrocyclones: firstly, commercial pitometers often have too large diameters. They therefore cause considerable disturbance of the flow field. Secondly, commercial pitometers cannot handle measurements in fiber suspensions since the pressure taps will become plugged by the fibers.

For these experiments a single-hole pitometer equipped with a purge flow was developed (*Fig 1*). The purge flow technique used here is similar to that of the Mih and Parker impact probe that was based on the pitot tube principle (Mih, Parker 1967). The dimensions of the pitometer were kept as small as possible to reduce its influence on the flow field. The probe consisted of an off-the-shelf spinal anesthesia Whitacre syringe, 0.90 mm in diameter. A medical pressure transducer from Samba Sensors AB (2001), with a diameter of 0.42 mm was placed inside the probe. The basic measurement idea of this single-hole pitometer is to measure the pressure at the stagnation point and in the wake of the probe by rotating the probe 180° at each measurement point. The difference between the upstream and the downstream pressure can be calculated into a velocity $\mu_{measured}$ as described in *Eq 2*. Since the drag forces on the pitometer were considerable, a supporting pipe from the opposite hydrocyclone wall was therefore used in order to prevent bending of the pitometer (*Fig 2*).

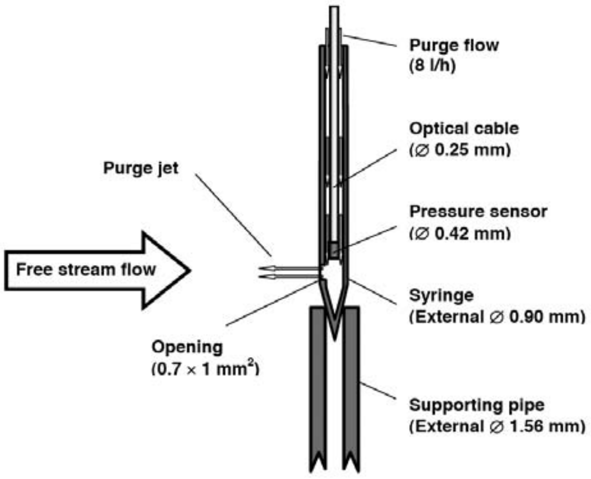

Fig 1. Self-cleaning pitometer.

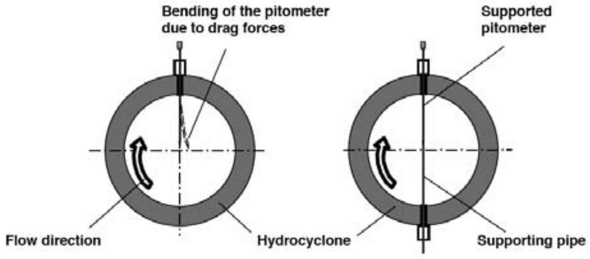

Fig 2. The pitometer inside the hydrocyclone seen from above, with and without the supporting pipe that prevented bending.

$$u_{measured} = \sqrt{\frac{2(p_{upstream} - p_{downstream})}{\rho_{fluid}}} \qquad [2]$$

The pressure opening of the pitometer was kept clean by a purge flow. The purge flow at the same time transmitted the fluid pressure into the tap to the transducer. The cleaning purge flow was manually controlled using a needle valve and a rotameter. A constant purge flow of 8 l/h was used, that resulted in an exiting jet velocity of about 3 m/s.

A near-linear relationship between the estimated velocity ($\mu_{estimated}$) and the real velocity can be expected if choosing the pitometer diameter wisely with respect to the expected operating conditions. The drag force coefficient, C_D, for a cylinder in perpendicular flow is approximately constant for $1000 < Re < 200000$ (e.g. Massey 1989). Given a constant viscosity, this implies that the magnitude of the pressure difference between the stagnation point and the wake changes (smoothly) quadratic as the velocity is changed. In the case of hydrocyclones the tangential velocity is expected to be in the order of 1 m/s to 15 m/s. Using the kinematic viscosity of water at 20°, 10×10^{-6} m^2/s, results in a Reynolds number in the range of $900 < Re < 15000$ for the developed pitometer, which implies that a linear relationship between the estimated velocity and the real velocity can be expected.

Calibration

The pitometer was calibrated in a 2.5 m long plastic pipe with an internal diameter of 53.6 mm. A perforated plate (holes 12 mm in diameter) creating a pressure drop was placed at the upstream end of the pipe to break up swirls and even out the flow. The pitometer was positioned 2 m downstream of the perforated plate, to ensure a fully developed velocity profile. The flow in the calibration pipe was completely turbulent (Re between 10000 and 40000). A simple time-averaging of the 100 Hz pressure signal over ten seconds was used to determine the upstream and downstream pressure.

The calibration pipe was connected to a flow loop that consisted of a 1.1 m^3 chest and a speed-controlled centrifugal pump capable of pumping 3 m^3/min. The flow loop was equipped with a magnetic flow meter (Fischer and Porter 10DS3111) and a pressure transducer (ABB ETP80) on the feed pipe (*Fig 3*).

The pitometer was traversed in the calibration pipe in

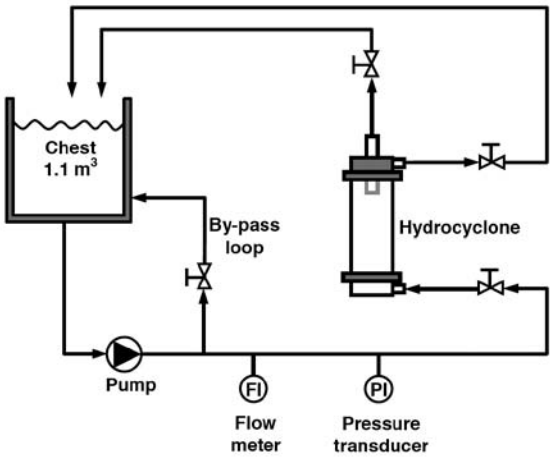

Fig 3. Experimental flow loop.

the radial direction and profiles of the mean axial velocity were acquired. Assuming axi-symmetric velocity profiles, the volumetric flow could be calculated. The ratio between the indicated volume flow, of the magnetic flow meter, $\dot{V}_{flowmeter}$, and the flow estimated with the pitometer represented the calibration factor of the pitometer. The calibration factor was used in *Eq 3* to calculate an improved calibrated velocity estimate $\mu_{calibrated}$ estimate from the estimated velocity, $\mu_{estimated}$.

$$\dot{V}_{flowmeter} = 2\pi\int_0^r u_{calibrated\ estimate}\cdot r\cdot dr = 2\pi\int_0^r c_{calibration}\cdot u_{estimated}\cdot r\cdot dr \qquad [3]$$

Since the basic idea of the pitometer is to function in fiber suspension regardless of fiber concentration, a general calibration factor valid for all (practical) concentrations was sought. Pure water and fiber suspensions with 0.5 g/l and 1 g/l fiber mass concentration (0 %, 0.05 %, 0.1 %) were used in the calibration procedure.

Hydrocyclone experiments

The pitometer was used to measure the tangential velocity in the cylindrical, through-flow hydrocyclone, depicted in *Fig 4*. The feed stream enters an inlet chamber. A symmetrical injection of the fluid into the main cylindrical body is enabled via three 10 mm diameter tangential inlet holes. The reject flow exits tangentially via an outlet that is 30 mm in diameter. The hydrocyclone also features a 30 mm inner diameter vortex finder that can be moved axially during operation. The main body of the hydrocyclone consists of three Plexiglas cylinder modules that can be rearranged or removed to change the geometry of the hydrocyclone. The Plexiglas modules divide the hydrocyclone into four measurement levels. External pressure transducers (Danfoss MBS-32) are connected to the inlet chamber and the upper end of the vortex finder. The hydrocyclone was connected to the flow loop described above.

During the tangential velocity measurements the hydrocyclone was operated at a feed flow of 2 l/s and reject ratio of 50 %. The flow rate was controlled manually. The reject flow was determined using a bucket and stopwatch. The pitometer was placed at a 90° angle (clockwise from above) relative to the reject outlet.

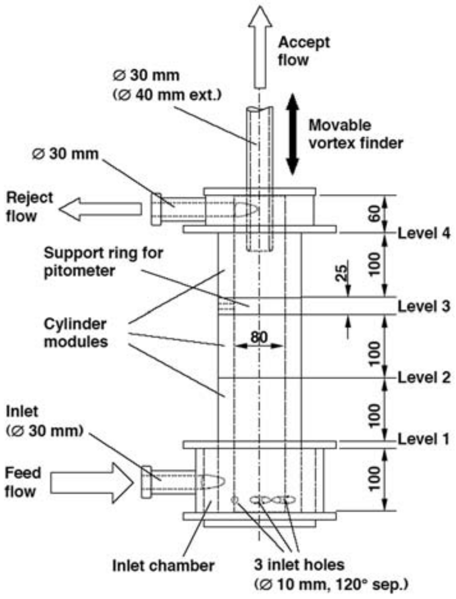

Fig 4. Experimental hydrocyclone.

Results

Calibration

The probe was able to capture the characteristic velocity profiles of turbulent pipe flow, shown in *Fig 5*. It did not however have sufficient spatial resolution to resolve the boundary layer. The probe had a tendency to measure too high velocities close to the wall (< 2 mm), indicating both the integrating behavior the 1 mm large pressure opening and a possible influence of the supporting pipe.

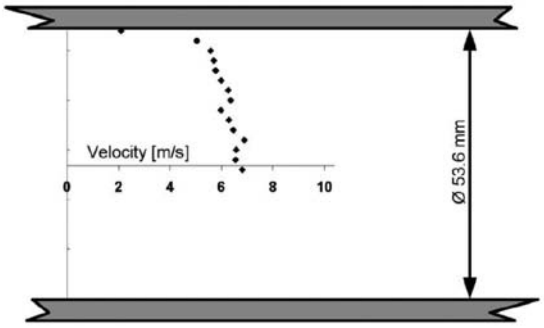

Fig 5. Example of velocity profile measured with the pitometer in the calibration pipe at 0.1 % fiber concentration, Re ≈ 29000.

The expected linear relationship between the measured flow and estimated flow was essentially found (*Fig 6*). Here, the estimated flow is based on the measurement with the pitometer and is compared with the flow measured with the magnetic flow meter. A linear regression over all calibration points yielded a calibration constant $c_{calibration}$ of 0.75.

In the calibration pipe it was observed that the probe was very tolerant to errors in the alignment of the pressure opening towards the free stream. There are two reasons for this behavior: Firstly, the size of the pressure opening integrated the pressure over a large part of the circumference of the pitometer; secondly, the stagnation point in front of a cylindrical probe is typically not restricted into one recognizable point. As the opening of the probe

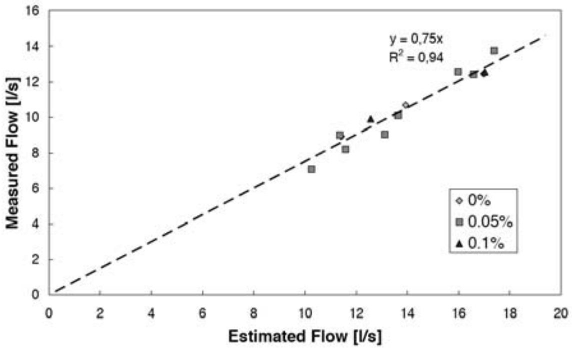

Fig 6. The estimated flow compared with the flow measured by the magnetic flow meter for three different fiber concentrations. The trend line is based on the measurements for all concentrations.

always is aligned in the horizontal direction, any pressure contribution from the axial velocity will be cancelled when the pitometer is rotated 180° around its axis.

The lack of directional sensitivity can be regarded as both positive and negative. It is negative in the respect that the exact angle of attack cannot be found, i.e. the axial component in the hydrocyclone flow cannot be determined accurately given the present geometry of the probe. On the other hand, the tangential velocity can be acquired without paying too much attention to set the correct angle during measurement. The pitometer could be turned approximately 15-20° away from the free stream direction before the pressure changed significantly.

Hydrocyclone experiments

After the calibration, the pitometer probe was used to measure the tangential velocity in the hydrocyclone. Presented in *Figs 7* and *8* are tangential velocity profiles at different fiber concentrations at Level 1 to 4. *Figs 9* and *10* show velocity profiles at Level 1 and Level 4 for different fiber concentrations.

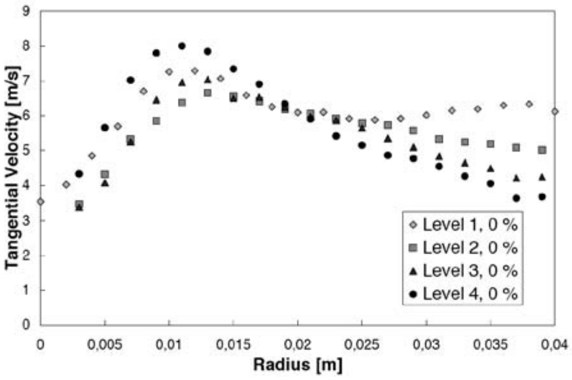

Fig 7. Velocity profiles at all levels, water.

The tangential velocity profiles at all levels and all concentrations have some features in common; a combination of free vortex-like and solid body rotation can be observed. These combined vortices are typical for hydrocyclone swirl flows and are well documented.

The observations can be divided into two parts, one referring to the change of tangential velocity profile as a function of the axial position, and the second, on how the presence of fibers alters the velocity profiles.

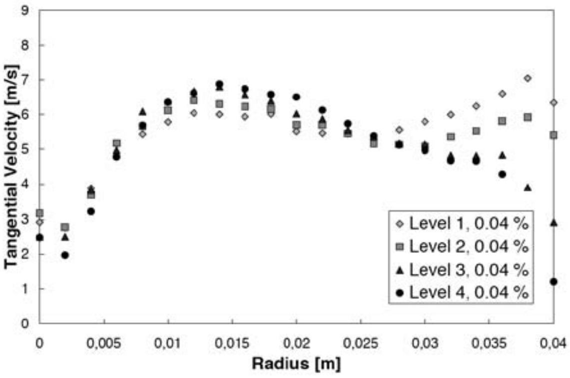

Fig 8. Velocity profiles at all levels, 0.04 % fiber mass concentration.

The tangential velocity profiles changed gradually as the fluid is displaced upwards in the axial direction (*Fig 7*). At the lowest level, close to the inlet, the vortex has two velocity peaks; one close to the hydrocyclone axis and one close to the wall. The velocity peak close to the wall is the tell-tale sign of the nearby tangential feed inlets. The tangential velocity amounts here to about 70 % of the average feed inlet velocity. As the flow moves upwards, the typical combined free vortex/solid body rotation type of velocity distribution evolves. The measurements at Level 4 display the highest top speed of all levels. This indicates a strong inward flow towards the vortex finder opening that in turn increases the tangential velocity due to the principle of conservation of angular momentum.

The coefficient *n* in the vortex equation (*Eq 1*) is approximately 0.45 at Level 4. In the literature, values of *n* for standard conical hydrocyclones can be found in the range of 0.2 (Knowles, et al. 1973, without air-core) to 0.84 (Kelsall 1952, air-core).

The measurements are in good agreement with the findings of Baranov et al. (1984), who performed tangential velocity measurements in a flat-bottomed cylindrical hydrocyclone (non-through-flow). The coefficient *n* (*Eq 1*) for Baranov et al. (1984) varied approximately between 0.35 and 0.55. However, the velocity profiles found here differ from the well-documented flow field of the standard frusto-conical hydrocyclones, where the tangential velocity profiles, below the vortex finder, typically do not vary significantly in the axial direction (e.g. Monredon, et al. 1992). In this study as well as in the study by Baranov et al. (1984) a single coefficient *n* (*Eq 1*) does not provide a full description of the tangential velocity distribution. This is perhaps most obvious at Level 1 or Level 2, where the relative proximity to the inlets made the tangential velocity increase with increa-

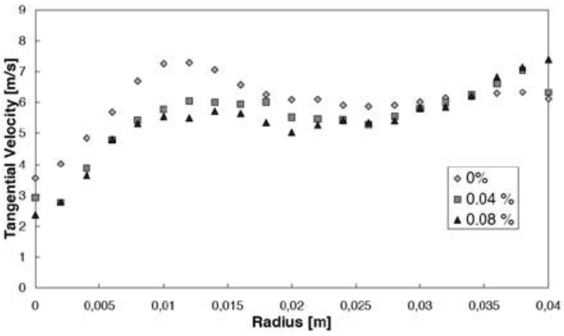

Fig 9. Velocity profiles at Level 1; different fiber mass concentrations.

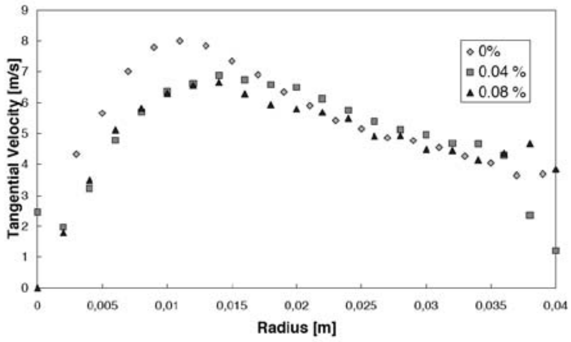

Fig 10. Velocity profiles at Level 4; different fiber mass concentrations.

sing radius in the outer region.

When fibers are added, the tangential velocity profiles are clearly altered – even at low fiber concentrations (*Figs 9 and 10*). Some significant differences can be observed at all levels. Firstly, the peak top speed close to the hydrocyclone axis is lower when fibers are present. Secondly, the radius of solid body rotation in the center increases. Thirdly, the transition between the free vortex-like structure and the solid body rotation is smoother. Furthermore, in *Fig 9*, a structure of solid body rotation can be noticed close to the wall at Level 1. This could indicate that the injected fiber suspension behaves partly like a shear force-resisting entity.

The two measurement points closest to the center spread to some extent. The pressure measurements could have been influenced by the precessing air-core (approximately 5-7 mm in diameter) the hydrocyclone was operated with. The air-core in combination with the support pipe are likely the reasons for the measured non-zero velocities at the hydrocyclone axis, i.e. the probe and support pipe disturbed the flow field. Another reason might be that the rotational center is displaced from the geometrical center. This is displacement of the rotational center would be caused by the hydrocyclone geometry with an asymmetric outlet.

The three points closest to the wall should also be treated with some caution, since the presence of the probe seemed to influence the local flow field, similar to the observations in the calibration experiments along the pipe wall. This effect is probably most pronounced where the tangential velocity is relatively low, i.e. close to the wall. A simple test of the influence of the probe on the rotational flow field was investigated by comparing the hydrocyclone pressure drop at several feed rates. The pressure drop during probe-free operation was compared to the pressure drop when the pitometer was inside the hydrocyclone. No large difference of the two pressure drop curves where found. At the flow rate used for the tangential velocity measurement the pressured drop difference was less than 0.5 %. This indicates that the probe-induced slow-down of the swirl is insignificant.

Certainly there are errors involved in this measurement method. Firstly, there is a spread and an error in the use of a single calibration constant for all fiber concentrations. From the calibration routine, this error in is roughly 6 %. Secondly, there is an error in the pressure measurements. The 10 s averaging of the pressure signals limited the velocity error to a maximum of 1 %. This means that the tangential velocity of a fiber suspension in the hydrocyclone can be estimated with an error of less than 10 %.

All in all, the pitometer method proved to function as anticipated. Interestingly, the velocity curves measured in fiber suspension are similar to those of Dyakowski et al. (1994), who did numerical simulations of non-Newtonian flow in a conical hydrocyclone.

Summary and Conclusions

This paper presented a novel pitometer probe designed to measure the tangential velocity component in a hydrocyclone operated with a fiber suspension. The calibration routine gave a calibration constant that could be used for all fiber concentrations used in the measurements.

The pitometer was used to measure tangential velocity profiles at four different levels in the hydrocyclone. Closest to the vortex finder the highest tangential velocities were recorded. Here, the velocity profiles had the well-known combination of an outer free vortex-like structure and solid body rotation close to the center. The profile closest to the inlet showed traces of the feed flow inlets, as the highest velocity was recorded close to the hydrocyclone wall.

The velocity profiles changed when fibers were added: the maximum velocities were lowered, the transitions from free vortex to solid body rotation were smoother and the radius of solid body rotation increased.

The possibility to measure the tangential velocity of a fiber suspension in a hydrocyclone fills a knowledge void. The customary empirical development of new hydrocyclone geometries is nowadays backed by computational fluid dynamics, CFD. Experimental validation data is a necessary support to the development of plausible and functional hydrocyclone simulation models.

The new method gives opportunities to pinpoint tangential velocity distributions that are favorable to the separation efficiency. It is a well-known fact that the mass reject rate greatly influences the efficiency. However, there is very little knowledge on the tangential velocity distribution at a specific mass reject rate. Similar methodology could also be applied on different hydrocyclone geometries.

The method leaves ample room for improvements and future work. Imminent improvement of the pitometer would be to increase the angular sensitivity, thus enabling detection of the angle of attack of the tangential velocity. This would make the probe even more versatile as the axial component of the flow field in the hydrocyclone also could be determined.

Future work should also explore the fiber concentration limits of the probe. The focus in this study was primarily on the difference between the tangential velocity profiles of pure water and a fiber suspension. An extension of the operable limits would enable measurement on hydrocyclones operated at industrial fiber concentration levels.

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