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Investigation and comparison of fluid dynamics in a hydrocyclone using ultrasonic doppler velocity profiler

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Hydrocyclones are widely used in multiple industries for different separation and pre-concentration tasks. Nevertheless the flow within a hydrocyclone remains complex and depending on the throughput and design several different flow regimes can occur. Understanding and measuring the velocity distribution of the flow regimes, without disturbing it, is key to design the process accordingly. In the presented study, a pilot scale hydrocyclone, in bottom-up flow, was investigated for throughput range of 21.3 to 33.8 L/min of deionised water using the ultrasonic doppler method and air bubbles as tracer particles. The radial average velocity and frequency profiles were analysed, mapped and compared to CFD simulations. Additionally, different angles of the ultrasonic transducers positioned within the hydrocyclone were tested. The results of the average velocity indicated alternating motion of the tracer bubbles away and towards the measurement line and agreed well with the simulation. Investigation of the frequency profile further showed that an inner motion at 1.5 Hz and an outer motion at 2.5 Hz were dominant. Decomposition of the spatiotemporal velocity field of vertical measurements revealed a major steady wave of the hydrocyclone and hydrodynamic instabilities at low Re-Numbers. The ultrasonic doppler method proved to be a valuable tool to investigate and characterize the different flow regimes in a hydrocyclone. These findings allow a more precise design and process control of new generation hydrocyclone processes.

Keywords: Hydrocyclone, flow mapping, air bubbles, spatiotemporal velocity field

1. Introduction

Hydrocyclones are a common method to separate solids by size from a liquid phase. The suspension, particles to be separated in a liquid, are tangentially streamed into a cylindrical or conical body. The resulting particle classification is assumed to be from an opposing centrifugal and drag force balance with radial drag of small particles towards the core, throughout the conical section, and centrifugal drift of large particles towards the wall [1]. Therefore, it is recognized that tangential velocity (v) and fluctuations are necessary to know and can occur due to process parameters and design aspects. With increasing throughput, the suspension is further accelerated and observed tangential velocity increases. Similar behavior was reported with a transition from a cylindrical to a conical hydrocyclone body. Moreover, design aspects, such as height to diameter ratio and symmetrical inlets, have been thoroughly researched [2-4] in order to achieve maximized separation efficiency. The flow behavior within remains complex and advanced knowledge of the hydrodynamics are necessary for process efficiency and stability. Early studies [5] have already estimated the flow pattern, using die injection and the mean tangential and axial velocity using laser doppler anemometry. Another proposed method is ultrasound velocity profiling [6]. This method has already been tested as a valuable tool to estimate the tangential flow within a hydrocyclone [7].

Nevertheless, accessing the complex flow field, without disturbing it, in hydrocyclones remains difficult. In this work, an ultrasonic doppler method is presented to determine the complex flow field within a hydrocyclone using bubbles as tracer particles. In a second stage, the results obtained were then compared to simulations. These findings are key for a new separation process design.

2. Materials and Methods

2.1 Hydrocyclone design

A hydrocyclone (HC) was designed according to the design aspects (see Figure 1) and the dimension stated in Table 1. Throughput $\dot{Q}$ was set at 22.1, 23.5, 33.2 and 33.7 L/min. Additionally, an air inlet with a membrane (max. pore size p= 15 µm, d_m= 20 mm) built into the hydrocyclone at a distance of 5.0 cm from the center and a height of 7.0 cm from the bottom. Airflow was set ranging from 0.07 to 150 mL/min.

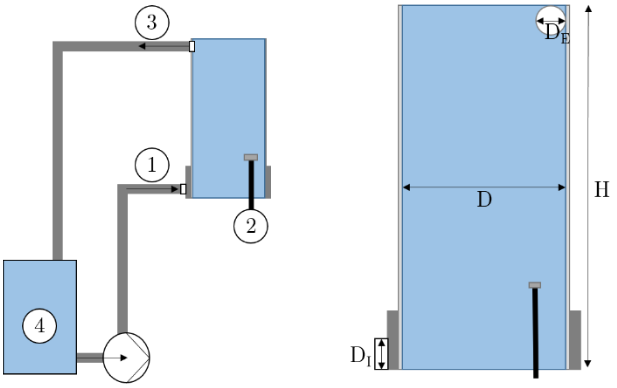

Figure 1: Hydrocyclone design. 1. Inlet, 2. Air inlet, 3. Outlet, and 4. Storage container.

Table 1: Dimensions of hydrocyclone.

D	0.15 m
H	0.895 m
D_I	0.025 m
D_E	0.04 m

2.2 Ultrasonic velocity profiling (UVP) of the hydrocyclone

Ultrasonic velocity profile measurements were carried out with doppler, immersion type 4 MHz, 5 mm active element ultrasonic transducers (TN and TX-line, Imasonic, Bensancon, France) and the UVP-DUO profiler (Met-flow SA, Lausanne, Switzerland). The sound speed was 1480 m/s as the medium was deionized water. For radial measurements, the transducers were positioned every 5 cm starting at 125 mm from the bottom at centerline and 1 cm offset to the centerline of the hydrocyclone (see Fig. 2A). Measurements were performed with a maximal distance of 160 mm and 39 µs. First channel was at 5 mm and a resolution of 0.56 mm/channel. The number of emission/profile was 1024. For angular measurements, the transducer was positioned inside the hydrocyclone at angle α=0°, -30°, -45°and -60°. The sensors were positioned along the x-axis at a height of z=720 mm (Fig. 2B). At last, for vertical measurements, the transducer was positioned inside the center of the hydrocyclone at a height of z=720 mm (Fig. 2C).

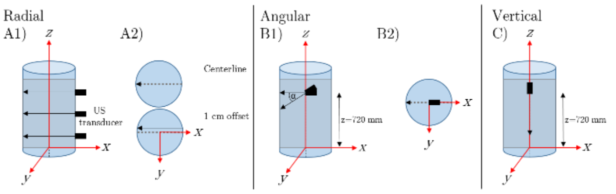

Figure 2: UVP measurement setup for radial, angular, and vertical measurements. A1) side view of HC and attached US transducers. A2) top view centerline and 1 cm offset measurement. B1) side view of HC and US transducer positioned at an angleαand at a height of 720 mm. B2) top view: transducer placed along x-axis. C) side view of vertical placement of sensor at a height of 720 mm.

2.3 Modelling of hydrocyclone

The hydrocyclone was simulated with COMSOL Multiphysics® (Comsol Inc., Burlington MA, USA) simulation software version 5.3. The hydrocyclone was designed according to Table 1. The turbulent flow model with a turbulence intensity of 5% and a turbulence length scale of 1.75 mm were used. A throughput of 33.7 L/min resulting in a normal inlet velocity of 1.14 m/s was set. The walls were treated with a no-slip condition. A maximum mesh size of 0.012 m was applied.

3. Results

3.1 General observations

The hydrocyclone (HC) was operated at different throughput from 22 to 32.7 L/min corresponding to Re-Number from 10^6 to $1.58{\cdot}10^6$ with the inlet diameter D_I as characteristic length. Further, the HC was operated with a bottom-up flow. In contrast to the common hydrocyclone design, where a top down flow is applied and the diameter is decreased, this design purely consists of a cylindrical body. The medium inlet was injected tangentially to the cylindrical body, this led to an upward swirling motion. Figure 3 shows the motion of bubbles within the presented HC at various throughputs.

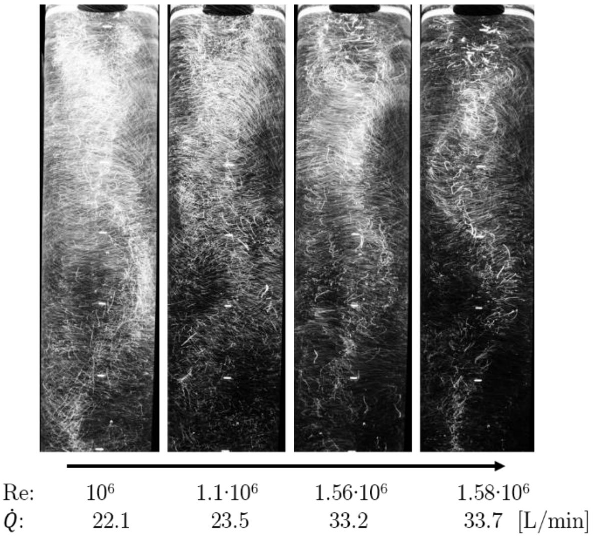

Figure 3: Representative long exposure picture of hydrocyclone operated at different Re-Number/throughput with an air flow set at 150 mL/min.

3.2 Radial velocity distribution

To extract velocity field x-component u, UVP measurements were carried out with the addition of micronized bubbles as tracer particles. The transducers were placed horizontally outside the HC. In Fig.4a), regimes with high velocities $\bar{u}$ (up to 165 mm/s) and low/negative velocities (up to -165 mm/s) showed to be alternating from top to bottom. This suggests that in negative velocity regimes, the bubbles move towards the transducers and to the center. At high velocities the bubbles move away and towards the outer wall. When comparing the UVP data to the simulation, the obtained average velocities $\bar{u}$ from UVP agreed reasonably well with the simulated data (see Fig. 4b)). As the root mean square error was large, further refinement of the data could be carried out in order to achieve a higher degree of validation of the simulation. Further experimental data (not shown here) showed, that the velocity distribution in the x-z plane is independent of the bubble flow for a range of 0.07-150 mL/min of air.

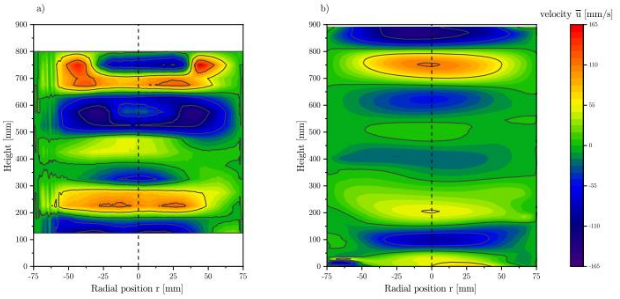

Figure 4: Comparison of average radial velocity a) measured with UVP and b) computed over the height of the hydrocyclone.

3.3 Assessment of the swirling motion

To determine the major swirling motion and frequency, measurements at different angle inclinations from 0° to -

60° were carried out. The obtained frequency spectra were then plotted along the measurement lines in Fig. 5. Two prominent clusters of frequencies could be highlighted. Oscillations at frequencies of 1.5 and 2.5 Hz were clearly visible for all measurement angles. A clear second harmonic oscillation could not be distinguished. When the measurement angles were successively decreased to -60°, oscillations of 1.5 Hz became more prominent, thus this frequency corresponds to an inner rotation. Whereas the higher frequency corresponds to the outer major swirl motion.

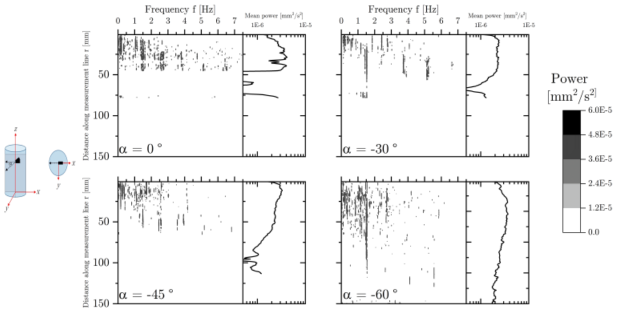

Figure 5: Frequency profiles along the measurement line summarized in a contour plot for angles 0°, -30°, -45° and -60°. Including the measured mean power

3.4 Hydrocyclone core characteristics

To assess the major characteristics of the swirl motion as seen in Figure 3, the spatiotemporal velocity field was obtained vertically for different Re-Numbers. Further, the velocity fields were decomposed into spatial and temporal modes by means of two separate fast Fourier transform (FFT) for space and time. Figure 6 shows the wavenumber over the measurement time of 127 s. High amplitudes at low wavenumbers <0.1 cm^{-1} and wavenumbers larger than 0.6 cm^{-1} were found. Averaging the amplitudes over time (Fig. 6b)) revealed amplitude peaks at 0.072 cm^{-1} and 0.042 cm^{-1} as indicated by the red lines. This indicates periods from 1.38 for small Re and 2.38 for larger Re. These findings correspond to the global motion of the steady wave of the hydrocyclone and are in good agreement with the pictures obtained (Fig. 3).

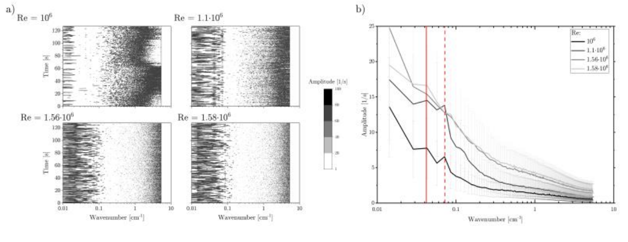

Figure 6: Fast Fourier transformed (FFT(x)) over space for different Re-Numbers. b) Time averaged amplitudes as function of wavenumber. Red lines indicate amplitude peaks at 0.072 cm^{-1} (dashed) and 0.042 cm^{-1} (drawn out).

Similar to the spatial findings, the performed temporal FFT (see Fig. 7) and averaged over the distance revealed that at low Re two peaks at a frequency of 20 and 17 Hz arise. These peaks could be attributed to the lower Re-Numbers and hydrodynamic instabilities [8]. When inlet velocity is further increased these characteristic peaks decreased and a steadier flow was observed. This unsteadiness could also be due to the bubbles used as tracers.

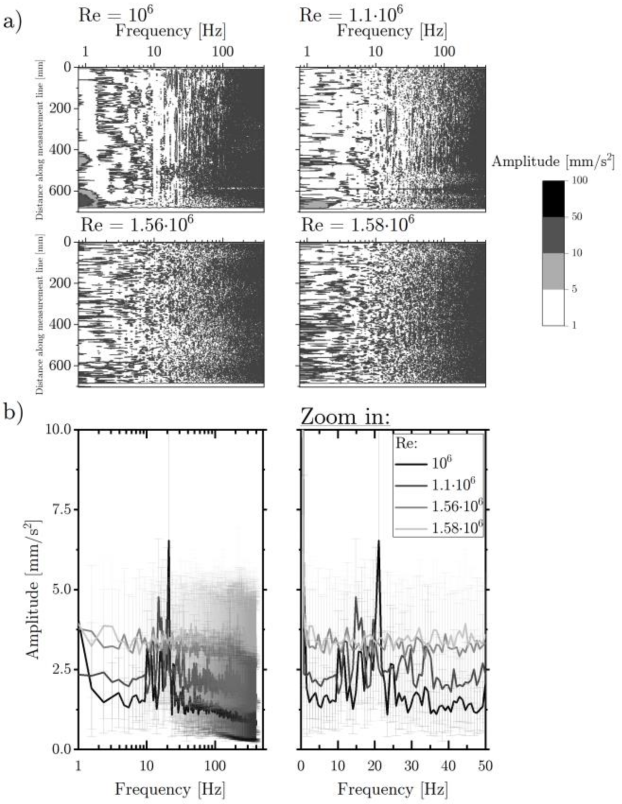

Figure 7: a) Fast Fourier transformed (FFT(t)) over time for different Re-Numbers. b) Distance averaged amplitudes as function of frequency. Zoom in of frequency range from 0 to 50 Hz.

6. Conclusion

The ultrasound doppler method showed to be a valuable tool to access the hydrodynamic characteristics of a hydrocyclone. The presented method used bubbles as tracer particles and used three different transducer positions. The obtained velocity profiles in x-z plane agreed reasonably well with the simulated data showing an alternating movement of the tracer bubbles towards and away from the transducer. When the transducer was placed inside at a range of angles (0 to -60°) an inner and outer motion at 1.5 Hz respectively 2.5 Hz could be distinguished. Further the major vertical steady wave could be accessed with UVP measurements by means of decomposing the spatiotemporal velocity field. Fast Fourier transformation showed to be a valuable tool to find the corresponding global motion and unsteadiness of flow at low Re-Number (Re=10^6).

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