

Erosion by turbulence: Discovering the counter-wise vortex events and their effect on wear

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ABSTRACT

Understanding the wear process has been critical for developing and maintaining engineered systems handling particle-laden flows, such as pipelines, valves, pumps, and mixers. This work explores the use of ultrasound velocimetry for determining the velocity and impact angle of particles projected from a turbulent slurry flow onto a moving target surface. The flow is generated in a slurry pot configuration at four levels of rotational frequency: 1900, 2200, 2500 and 3300 rpm. Acoustic images acquired in the B-mode are processed by Ultrasound Particle Tracking Velocimetry (U-PTV) and Ultrasound Particle Image Velocimetry (U-PIV) to determine the impact velocities and impact angles of individual particles in the radial plane. Particle impacts at velocities higher than the tangential velocity of the rotating axis are observed and named counter-wise impact due to their association with counter-wise vortices impacting in the direction contrary to the translation of the moving surface. The applicability of U-PTV and U-PIV for the study of particle-laden turbulent flow is discussed and a statistical analysis of particle impacts energy is conducted. The counter-wise impacts are found relevant to erosive wear because of their relatively high velocity (upper quartile) and because most of the impact energy is conveyed through the tangential component.

1. Introduction

Turbulence is an intrinsic feature of multiphase flows observed in practical applications. In engineering, turbulence determines the efficiency of various processing systems and hydro-transport of solids such as mixers, slurry pumps and slurry piping. Particle-laden turbulent flow is a key factor in the erosive damage of materials used in these systems, motivating research to improve their structural integrity, to reduce the risks associated with failure or leakage, and to improve productivity in favour of sustainability [1].

The degradation of engineering materials by erosion under turbulent flow is typically extended in time and, thus, selection of materials requires accelerated testing such as the direct impact test or the slurry pot [2]. Although such exposure rigs provide data of mass loss in time, they are not suitable for a mechanistic study of the involved degradation processes, the understanding of which requires measuring how the individual particles, carried by the medium, do impact the target surface and how these impacts sum up to a measurable wear loss [3,4]. In this

context, gathering information on the geometry of particles' impact, in particular the direction of impact with respect to the nominal (average) flow direction and the angle at which the impacts take place, are of interest. This work focuses on rotary machines in which the nominal flow direction corresponds to the tangential direction of the rotating element, simulated at the laboratory scale in a slurry pot.

In the slurry pot configuration with a target surface located at the inner rotating axis (Fig. 1(a)), the impact velocity and the impact angle of individual particles are not controlled, but they can be inversely determined by inspecting the morphology of wear scars. Molina et al. [5, 6] have presented this approach for a range of particle sizes, with flow induced by a shaft rotating at 4.456 rpm. This rotational frequency corresponds to a nominal flow velocity, i.e., tangential velocity of the target surface ($\vec{V}_{\text{surf}}$), of 10 m/s. Yet, the statistics of impact velocities reported by Molina et al. [5,6] have shown outliers exceeding the system's input velocity of 10 m/s (Fig. 2(a)), which could be considered an apparent contradiction. The number of such outliers diminished with increasing particles size, which has been observed but not elaborated in

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the original paper. An explanation has been suggested by Espinoza-Jara et al. [7] based on the orientation of particle velocity ($\vec{V}_p$) with respect to $\vec{V}_{surf}$. Presence of particle impacts from a direction opposite to the surface rotation would produce effective impact velocities ($\vec{V}_{imp}$) of magnitude higher than that of $\vec{V}_{surf}$. Such a configuration of velocity vectors is physically possible when particles are projected from a vortex rotating contrary to $\vec{V}_{surf}$, as represented schematically in Fig. 1 (b and c). Impact from such vortices, hereafter referred to as counter-wise impacts, could indeed have taken place in the experiment of Molina et al., as suggested by the presence of wear scars with deformation lips located opposite to the direction of tangential flow. Fig. 2(b) shows an example of wear scars produced by the indicated flow direction. Example of wear scar profiles consistent with normal and counter-wise impacts are shown in Fig. 2(c). Yet, numerical simulations of the experiment by LES-WALE [7], consistent with DNS simulation of Taylor-Couette flow [8], have not provided the explanation. Corroborating the premises, the presence of local and occasional counter-wise vortices would provide an explanation to outliers of both impact velocity statistics and wear scar morphology. However, such vortices have not been studied experimentally and also have not been given special attention in simulation by the current models of particle-laden flows. Since the effective velocity of particle impact is the main factor controlling rate of erosive wear [9], in this work, we hypothesize that particles can be projected from counter-wise vortices and, what more, that the occurrence of this phenomenon might be relevant for the wear rate produced in systems with rotatory walls.

In order to verify the existence of counter-wise vortices and counter-wise particle impacts, we adopt a method for the direct observation of particle impacts based on ultrasound imaging, which has been shown applicable for particle-laden flows as summarised by Poelma [10]. In particular, we process ultrasound images by Particle Tracking Velocimetry (PTV, based on a Lagrangian approach) and Particle Image Velocimetry (PIV, based on a Eulerian approach) to determine the fluid velocity field specific to particles interacting with the rotating target surface. This focus on the near-wall zone is a novelty because the current uses of ultrasound PIV (U-PIV) and ultrasound PTV (U-PTV) have only considered the particle-laden flow in the bulk region. Little or no attention has been given to the interaction of the particles with the walls, especially in rotary geometries, as most of the reported work was conducted on pipe loops. Although other ultrasound techniques were applied to the rotating cylinder configuration, specifically the use of radio frequency data to determine particle concentration and flow velocity fields [11], also in this case no analysis was reported on the interaction between the particle-flow and either of the system's walls.

2. Material and experimental procedure

2.1. Slurry pot test and exposure to turbulent flow

The exposure to turbulent slurry was implemented in a slurry pot set-up, with inner and outer cylinder radii of 7.5 mm and 35 mm, respectively. The flow was induced by the inner rotating axle on which the sample (target) was mounted as shown in Fig. 3. The flow medium was distilled water (liquid phase) with glass bead particles (solid phase). The glass beads had a density of 2.5 g/cm³ and a Vickers hardness of 6.2 ± 0.2 GPa as specified by the supplier (Lorenzini, Chile). The particles were sieved through 50–60 mesh to select the mean size of 276 μ m and then added to the liquid phase in the concentration of 1 wt%. Flow velocity was controlled by the rotational frequency of the inner axle, testing four levels: 1900, 2200, 2500 and 3300 rpm, corresponding to the nominal tangential velocity of the target surface $\vec{V}_{surf}$ of 1.46 m/s, 1.73 m/s, 1.96 m/s and 2.59 m/s, respectively.

2.2. Ultrasound system and image acquisition

The ultrasound system applied in this experiment was Teledyne ultrasound, model ArtUs EXT-1H Rev.C1S with digital beamformer, equipped with a linear array transducer, model L12-5N40-A4 (length of 40 mm, frequency range of 5.0 – 12.0 MHz). The transducer was mounted at the exterior of the slurry pot aligning the linear array with the radial plane of the target (Fig. 3).

To produce optimal image near the target surface, the probe was operated at the frequency of 5.0 MHz in parallel beamforming, i.e., generating planar wave [12], using 50% of the elements that captured 20 mm of space in the image width. The image depth was set at 30 mm, corresponding to the position of surface target with respect to the transducer. The frame rate acquisition was 360 fps using the standard high scanning speed mode for standard lines density. The images were acquired using EchoWave II (X64) 4.1.0 by Teledyne, recording the brightness corresponding to acoustic impedance, i.e., the B-image [10, 12]. For each condition of exposure, a sequence of 1077 frames was recorded, corresponding to approximately 3 s of physical time. This time was estimated to be sufficient for producing statistically representative number of impacts by comparing with the turnover time [7].

2.3. Ultrasound Particle Tracking Velocimetry (U-PTV)

The particle tracking algorithm used in this work was adopted from Brevis et al. [13] and applied to the ultrasound B-images. The images were first filtered by a grayscale threshold of 75–255 to produce their binary (black and white) versions. Then, the centroids of the particles were identified using a local maximum and a gaussian filter. For tracking, a hybrid method involving cross-correlation and a relaxation algorithm was used. In particular, candidate detection was conducted in

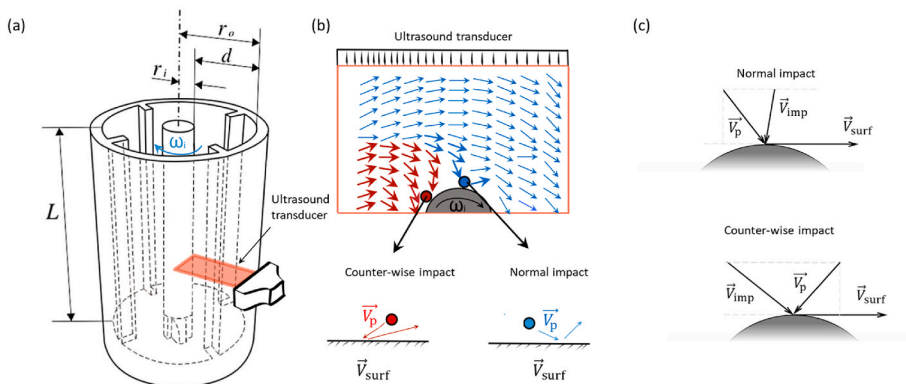


Fig. 1. Schematic representation of a slurry pot rig and definition of normal and counter-wise vortex observed in a radial plane illuminated by an ultrasound transducer. (a) Location of ultrasound plane in the slurry pot. (b) Geometry of flow field. Particles are projected with velocity $\vec{V}_p$ onto the surface rotating at linear velocity $\vec{V}_{surf}$. Projection from a vortex rotating in the direction of $\vec{V}_{surf}$ is marked in blue, from a counter-wise vortex is marked in red. (c) Geometrical relations between velocity vectors.

the radius of 28 pixels estimated from the maximum velocity that a particle could achieve. The candidates were then verified by cross-correlation in five consecutive frames using a vector filter of 0.74 with minimum allowed correlation of 0.65. Finally, the relaxation algorithm was employed to assure coherence of the detected tracks, using a parameter of 0.58 pixels with 30% minimum probability by the detection criterion of 0.001. These parameters were selected to allow a minimum quantity of outliers in each instantaneous frame.

2.4. Ultrasound Particle Image Velocimetry (U-PIV)

The particle image velocimetry U-PIV algorithm [14] was applied to ultrasound B-images using the software PIVLab v2.57, which is based on Matlab version 2.56 [15]. The particles are interpreted as flow tracers in a Eulerian framework to obtain the particle velocity field. Direct Fourier transform correlation with multiple passes and deforming windows was used for cross-correlation. The interrogation area was 232×232 pixels with overlay of 50%, including 4 consecutive sub-steps of 116, 58 and 29 pixels, all executed with overlay of 50%, repeating the last pass of a multipass analysis until the average difference to the previous pass is less than 0.01 as quality slope. These settings were selected using the software suggestion for the image particle density and displacement to achieve higher correlation index (> 0.5).

In order to extract the velocity of physical particles from the velocity field data, the algorithm for the velocity vectors associated to individual particles was implemented. The velocity field was filtered by reducing the area of interest to a square of minimum size to which the physical size of particle dimension would fit and the filtered velocity field was processed to assign the mean velocity vector to the particle's centroid. Details of the procedure are described in Section 3.2.

2.5. Data postprocessing

The U-PTV tracks and U-PIV velocity fields were post-processed with the R-language and the Tidyverse library ([16,17]). Post-processing was based on ultrasound velocimetry correction (applicable to PTV and PIV algorithms), velocity field unwrapping, counter-wise identification, and impact energy determination based on impact velocity and angles, described with detail in Section 3.

3. Theory and data processing

3.1. Ultrasound velocimetry correction

The generation of an image of a moving particle consists of three stages: sound wave transmitting (Tx), echo wave receiving (Rx), and signal filtering and processing to produce the B-images. Fig. 4 shows the three stages for a transducer consisting of a series of elements activated in the sweep direction to produce a plane front wave of maximum intensity at the distance of focus. During the Rx stage, each element reads

the signal sequentially in one direction, forming a sequenced parallel beam. Once the Rx stage has finalised, the data is transferred to the signal postprocessing stage, where the echo waves are filtered and transformed (through the Hilbert transform) to display the B-mode frame, while the Tx stage of the next frame is acting.

The Rx stage is relevant for the U-PTV and U-PIV analysis because each line of the frame is acquired in a slightly different time lapse. Effects of scattering and apparent deformation may emerge depending on the sweep direction with respect to particle displacement, especially when the displacement between consecutive frames is similar to the length of the pulse. Owing to these errors, the velocity determined from raw data may bear an error of up to 20% [10]. The velocity vectors determined from U-PTV and U-PIV analysis were therefore corrected for the sweep, as follows:

$$V_x = \frac{U_{\text{sweep}} U_x}{U_{\text{sweep}} + U_x}, V_y = \frac{U_{\text{sweep}} U_y}{U_{\text{sweep}} + U_y}, \quad (1)$$

where V_x and V_y are the corrected velocity components in the x and y directions, respectively; U_{sweep} is the magnitude of sweep velocity (having only x -component because the transducer is aligned with the x -coordinate), U_x and U_y are the uncorrected velocity components in the x and y directions, respectively.

3.2. Estimation of particle concentration in ultrasound volume of interest (U-VOI)

The particle concentration is relevant to the efficiency of the PTV and PIV algorithms. Whereas, for conventional data processing speeds, PTV performs best with relatively low particle concentration (such that images of individual particles do not overlap), PIV does so with higher particle concentration (such that at least 0.05 particle appears per square pixel) [18]. The concentration of physical particles that determines the actual limits depends on the type of the particles (chemical composition) and their shape and size. Thus, the possible variation of particle concentration should be considered to evaluate its effect on the applicability and the possible limitations of both algorithms. For this purpose, both optical and acoustic methods were used.

Given the physics of the particle-laden flow in the slurry pot, both inertial motion and settling of particles are possible. The number of particles that remain in suspension depends on the rotation frequency. At relatively low rotational frequency, particles tend to settle resulting in a concentration gradient along the vertical (axial) direction, whereas increasing the rotational frequency homogenizes the particle distribution. The effective particle concentration was estimated at the axial position corresponding to the plane illuminated by the transducer, i.e., the height of the target surface, as follows. An optical plane was generated by an expanded laser beam (3 mW, $\lambda = 650\text{--}670$ nm) and projected on the slurry pot to visualize an axial plane in front of the rotational axis. The images were captured in original colour (RGB coded) with a cell phone camera (Samsung s22, lens: 50 MPx Dual Pixels

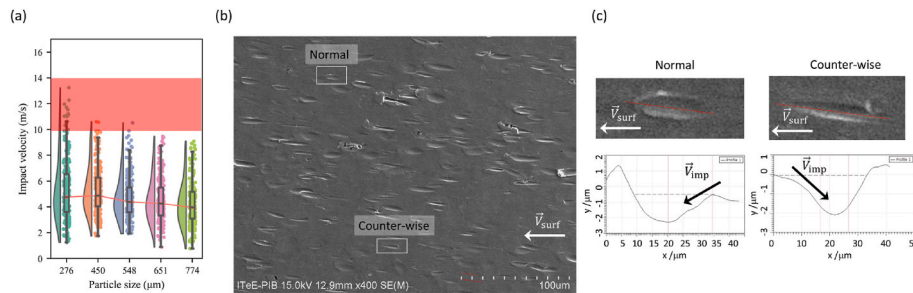


Fig. 2. Experimental premises: (a) Impact velocities exceeding system's input velocity of 10 m/s (marked by the semi-transparent red rectangle) (Adapted from Molina et al. [5]); (b) Example of normal- and counter-wise impacts as suggested by the location of deformation lips with respect to nominal flow direction shown in (c).

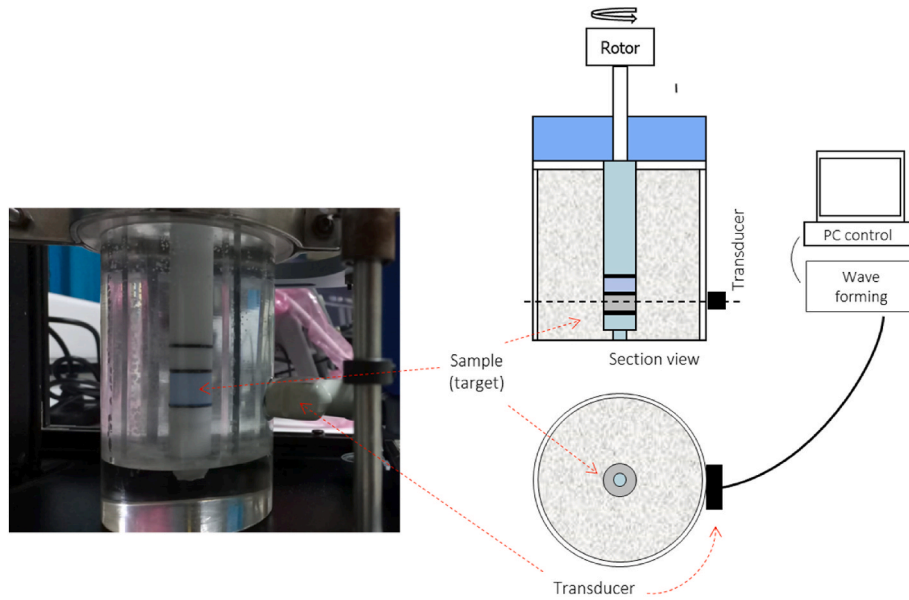


Fig. 3. Experimental set-up of slurry pot equipped with ultrasound image acquisition. The target surface (copper cylinder) is located at the rotating axis. The transducer generates a wave in the radial plane of the cylinder sample.

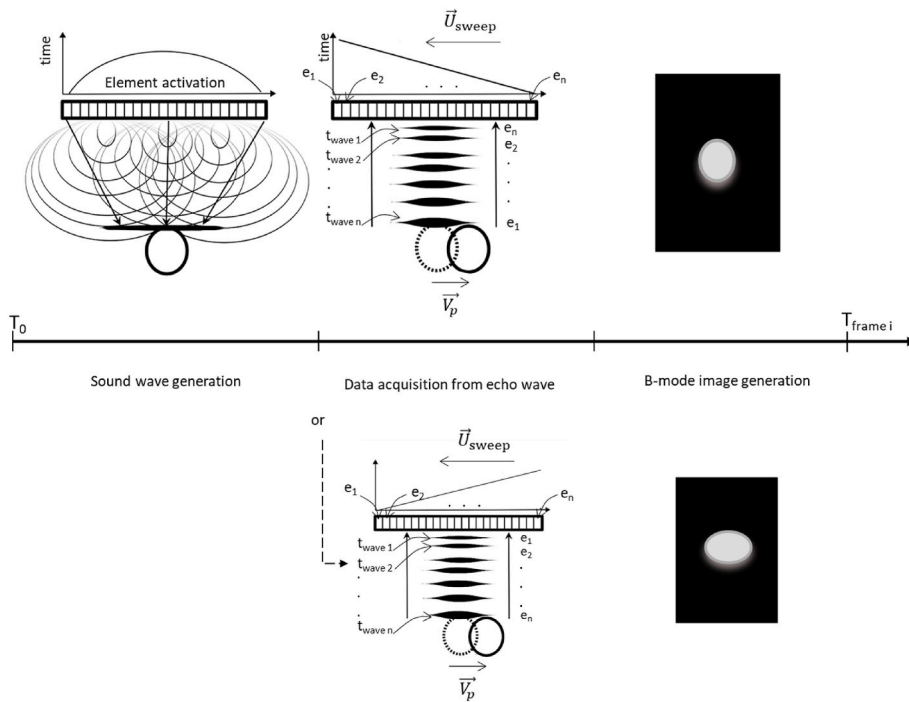


Fig. 4. Schematic representation of the relevance of particle motion direction relative to sweep direction of image generation. Top: Particle moves contrary to sweep direction. Bottom: Particle moves in the sweep direction.

AF f/1.8) and processed by OpenCV library on Python language to analyse the pixel density in the red channel of the RGB-images. The visual effect of rotational frequency on solid concentration and the red-channel equivalent are shown in Fig. 5. Although the quantitative relation between the intensity value in the red-channel to the effective particle concentration is unknown, it can be assumed to be proportional due to optical scattering of the red light on the particles. In particular, it is assumed that a given pixel intensity corresponds to the same particle concentration in the different images, thus the concentration observed in the plane illuminated by the transducer changes with rotational frequency as indicated by the pixel value corresponding to the height of the

target surface in Fig. 5.

Particle concentration was determined by counting the particles in the acoustic B-images [19–21]. In each frame of a sequence, the particles were identified by the U-PTV algorithm (see section 2.3), then counted and normalised by the Volume Of Interest (VOI) considered for analysis. The VOI of ultrasound B-image, the U-VOI, does not represent a physical infinitesimal plane because ultrasound wave forming system generates a plane with a certain thickness, referred to as elevation pitch or elevation [10], which is determined by the physical height of the probe. It is worth noting that the appearance of a particle in the B-image depends on the particle's position relative to the elevation pitch (Fig. 6). A particle

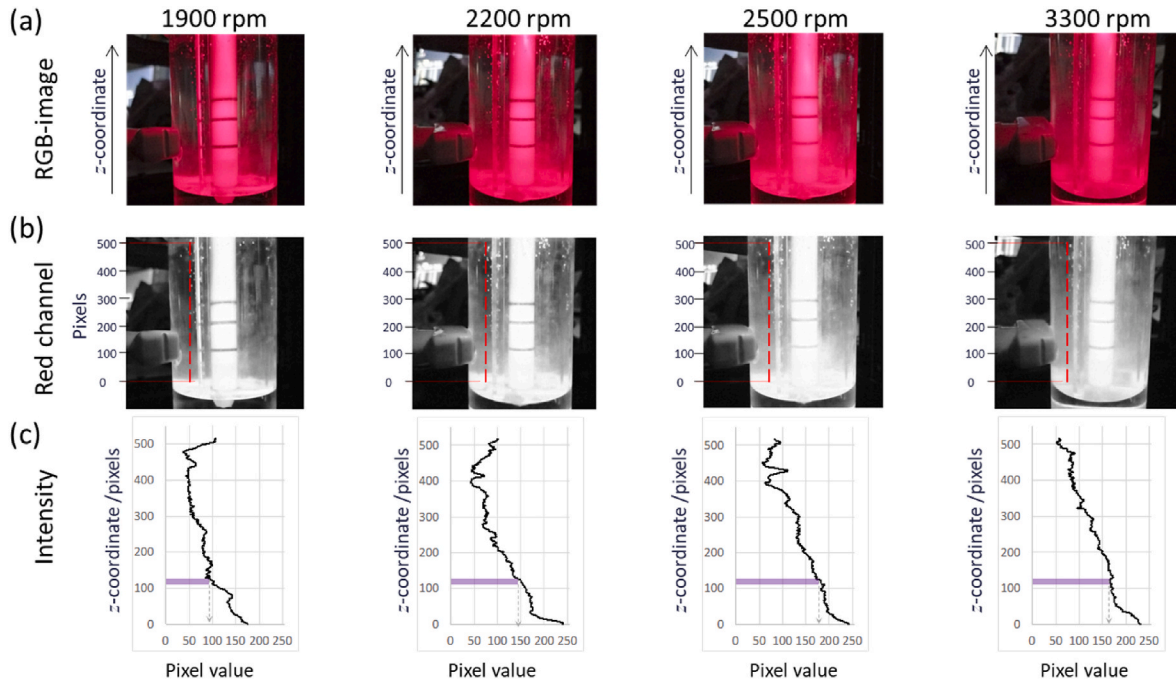


Fig. 5. Estimation of particle density in slurry pot by analysis of RGB-images. (a) Original RGB-images observed at the different rotational frequencies when illuminated by laser plane (red light). (b) Images of the red-channel only. (c) Pixel value of the red channel along the axial direction located inside the pot (red dashed line in (b)). The grey dashed arrows indicate pixel value for the position of the transducer (purple line).

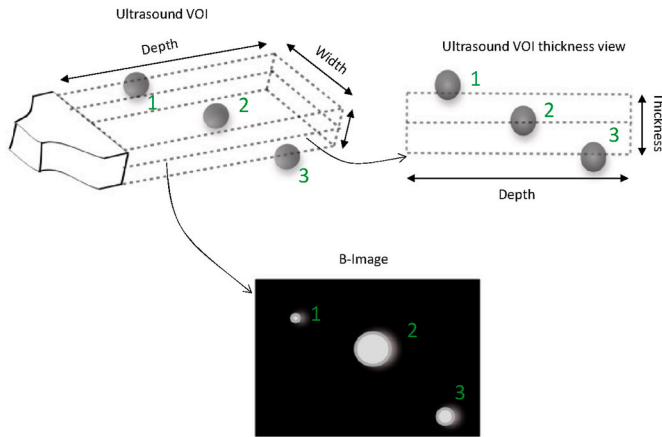


Fig. 6. Effect of particles position with respect to ultrasound volume of interest (U-VOI) and its relevance to particle representation on the B-mode image. Particle located in position 2 appears larger than when located in position 1 and 3.

smaller than thickness of the elevation pitch and located inside the U-VOI (position 2) scatters more and thus it appears larger than the same particle located only partially in the U-VOI (positions 1 and 3).

The effective particle volumetric concentration Φ_p was then calculated as:

$$\Phi_p = \frac{n\pi d_p^3}{6V_{U-VOI}}, \quad (2)$$

where n is the number of particles in the frame, d_p is particle diameter, V_{U-VOI} is the volume delimited by the width and depth of the frame, i.e., the U-VOI, and the elevation expressed in [m]. A sequence of 1077 frames was processed using the suitable libraries (Scikit-Image, SciPy, OpenCV and Matplotlib of Python 3.0) to obtain a value of solid volume fraction statistically representative for the time of exposure.

The particle concentration is also relevant for the determination of velocities specific to the physical particles. In fact, whereas the particles are identified directly in the U-PTV algorithm, the U-PIV algorithm requires further processing to filter the relevant velocity vectors. From the complete flow field determined by the U-PIV algorithm only a subset of vectors corresponding to solid particles was selected for further analysis. These vectors are identified by coinciding with bright area of the B-image as shown by the example in Fig. 7.

3.3. Velocity field unwrapping and counter-wise identification

In order to determine the impact velocities and the impact angles of the individual particles, the velocity fields produced by U-PIV and U-PTV algorithms were transformed from the directly measured Cartesian coordinate system to a cylindrical coordinate system, which appears the most straightforward choice for the curved target surface under consideration. The tangential (V_θ) and radial (V_r) components of the particle velocity were determined by unwrapping the velocity field:

$$V_{p,\theta} = -V_{p,x} \sin(\theta) + V_{p,y} \cos(\theta), \quad (3)$$

$$V_{p,r} = V_{p,x} \cos(\theta) + V_{p,y} \sin(\theta). \quad (4)$$

The origin of the cylindrical coordinate system was located at the centre of the rotation axis, identified using a graphical tool to fit a circle over the bright arc visible in each B-mode image, e.g., Fig. 7(a), corresponding to the target surface.

Since particles effectively impacting onto the target surface are of interest, only the near-wall area was taken into account. This area was defined as the radial distance by which a particle moving at the highest speed is displaced between two frames. The counter-wise impacts were then identified in the near-wall area as velocities contrary to rotation direction, i.e., those characterised by negative values of V_θ . The frames containing such vectors were then processed for visualization purposes.

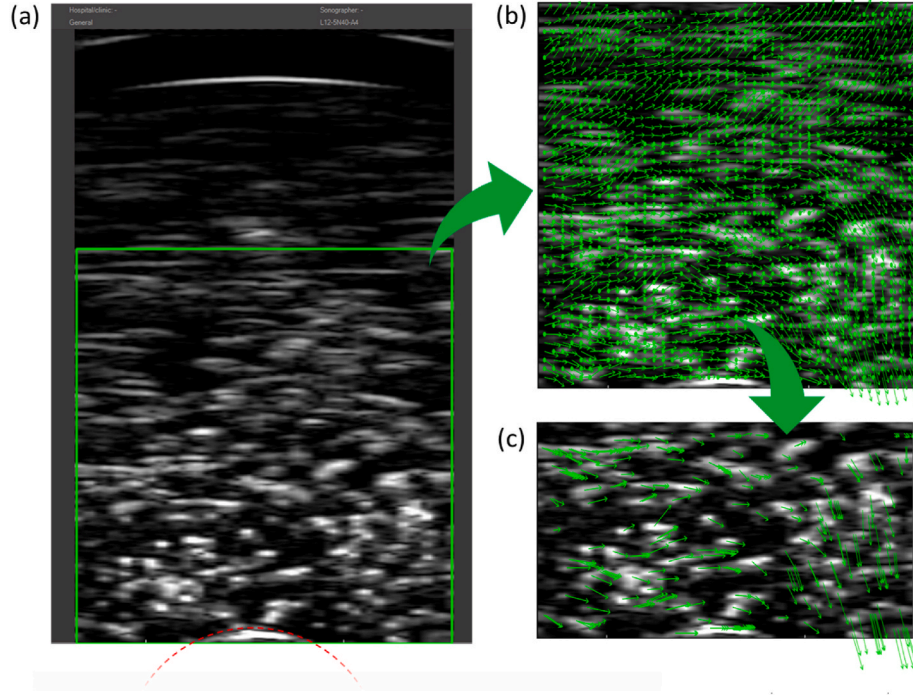


Fig. 7. Example selection of velocity vectors from velocity field that are specific to particles: (a) Selection of region of interest in a B-image frame near the target surface (red arc). (b) Complete flow field determined by the U-PIV algorithm. (c) Velocity vectors associated with physical particles near the target surface.

3.4. Determination of the particle impact velocity and the particle impact angle

The effective impact velocity, $\vec{V}_{\text{imp}}$, of a particle projected from the fluid corresponds to the relative velocity between particle velocity, $\vec{V}_p$, and the velocity of the target surface due to rotation, $\vec{V}_{\text{surf}}$, and it was determined as:

$$\vec{V}_{\text{imp}} = \vec{V}_p - \vec{V}_{\text{surf}}. \quad (5)$$

The particle velocity $\vec{V}_p$ was evaluated from its components in the cylindrical coordinate system (Eq. (4)) and, since $\vec{V}_{\text{surf}}$ is tangential to the target surface, Eq. (5) simplifies to:

$$\vec{V}_{\text{imp}} = \left(\vec{V}_\theta - \vec{V}_{\text{surf}} \right) + \vec{V}_r. \quad (6)$$

The effective impact velocity is decomposed into its normal ($V_\perp$) and tangential ($V_\parallel$) components to the physical surface:

$$\vec{V}_{\text{imp}} = (V_\perp, V_\parallel) \quad (7)$$

$$V_\perp = \left| \vec{V}_r \right|, V_\parallel = \left| \vec{V}_\theta - \vec{V}_{\text{surf}} \right|$$

which were further used for evaluating the impact energies (Section 3.5). It should be noted that, unlike $V_{p,\theta}$ used for identification of counter-wise impacts, the value of $V_\parallel$ is always positive.

The particle impact angles (α) were determined as:

$$\alpha = \arctan\left(\frac{V_\perp}{V_\parallel}\right). \quad (8)$$

3.5. Determination of the impact energy

The energy associated to the individual particle impacts was quantified using the kinetic energy framework, adopting the derivation of

Bitter [22] and Clark [23]:

$$E_T = E_c + E_D, \quad (9)$$

where E_T , E_c and E_D are the total energy, the energy associated with cutting and the energy associated with the deformation of the target, respectively. The components are expressed through the effective kinetic energy:

$$E_T = \frac{1}{2} \frac{m_p V_\parallel^2}{\varepsilon} + \frac{1}{2} \frac{m_p V_\perp^2}{\varphi}, \quad (10)$$

where m_p , ε and φ are the mass of the particle and materials specific parameters, respectively. The parameters ε and φ are relevant for relating the kinetic energy with the effective wear loss. However, they are considered 1.0, representing the entire kinetic energy that can potentially be transferred to the material, because only the instances prior to impact are considered, which are independent of how much the energy would be later converted in cutting and deformation.

4. Results

4.1. Effective volume concentration from U-VOI

Fig. 8 summarizes particles concentrations determined from U-VOI for all the rotational frequencies. At the two lower frequencies (1900 and 2200 rpm), a quite low effective concentration, $\Phi_p < 0.5\%$, is observed. Increasing the rotation frequency to 2500 rpm increases the average concentration, which then decreases for the highest rotation frequency (3300 rpm). This observation is consistent with the visual appearance of the slurry with respect to the axial position of the transducer as already seen in Fig. 5(b). At the two lower rotational frequencies (1900 and 2200 rpm) the particles tend to remain at the bottom so that only a fraction is effectively suspended, explaining the similar concentrations observed at the height of transducer position. At 2500 rpm, most of the particles are in suspension but not spread in the entire height of the pot, so that the effective concentration at the plane of interest (observed by the transducer) is slightly higher than nominal.

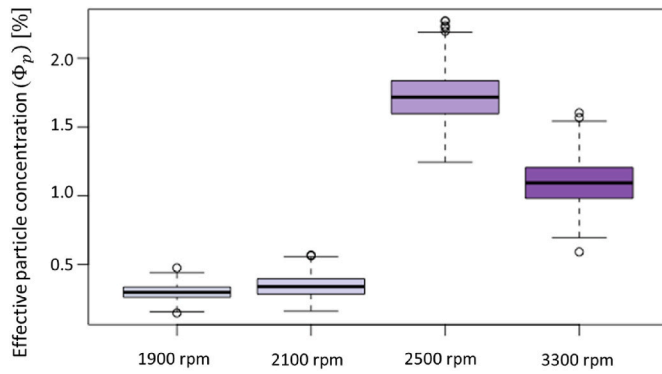


Fig. 8. Statistics of effective volume concentration determined from U-VOI for the different flow velocities.

Finally, at 3300 rpm, all of the particles are suspended and near-homogeneously distributed in the fluid volume consistent with the apparent drop of concentration. These results are consistent with the estimation derived from optical images (Fig. 5(c)).

4.2. Counter-wise impacts

Given the effect of rotational frequency on the particle concentration (Fig. 8), the U-PTV and U-PIV algorithms did not perform with the same efficiency for analysing particle velocities when applied to the same number of frames recorded for the different velocity levels. The U-PTV algorithm produced coherent particle trajectories for the 1900 and 2200 rpm levels, but it failed at the higher levels because less particles could be successfully identified due to the apparent overlapping (ultrasound images of two or more particles overlap although they are not necessarily in physical contact). Conversely, at the 2500 and 3300 rpm levels, the higher particle concentration allowed for an acceptable correlation index for the U-PIV algorithm. However, this was no longer the case at the lower rpm levels because the too low number of particles in the interrogation window diminishes the appropriate correlation for window translation and/or deformation, resulting in a greater number of interpolated results rather than of correlated results. In other words, although it is the effective concentration Φ_p that limits the applicability

of U-PTV and U-PIV algorithms, for a constant number of particles in the pot, it will also limit the rotational frequency that can be analysed by the two methods. Further, because of the difference in how the counter-wise impacts are detected and visualised by the U-PTV and U-PIV algorithms, the results obtained by the two methods are presented separately.

4.2.1. Counter-wise impacts determined from U-PTV data

Fig. 9 shows selected frames in which both normal and counter-wise particle impacts are visualised for the rotational frequency of 1900 and 2200 rpm. The trajectories of the particles prior to impact are visualised on a single frame as dots of brightness increasing with lapsing time, i.e., the brightest position is the latest in time, connected by lines that follow particle tracks prior to impact. To appreciate the full sequence, the reader is advised to see the videos of particle movement provided in the Supplementary Material. It should be noted that normal and counter-wise impacts may but not necessarily occur in the same sequence. The frames in Fig. 9 were selected for concise visualization of the counter-wise impacts along with the normal impacts. Independent of the type of impact, the particles continue the main flow direction after impacting the target surface.

Table 1 summarizes the statistics of impact velocities identified using the U-PTV algorithm. The total number of impacts found in the same number of frames, i.e., in the same time lapse, is higher for the higher velocity amounting to 60 and 286 for 1900 and 2200 rpm, respectively. However, the fraction of counter-wise impacts is approximately the same for the two rotational speeds (21% and 22%). The impact velocity increases slightly at the higher rpm level, which can be observed by the increased value of both normal and tangential components. These components are presented separately to observe that at both rpm levels the tangential velocity component ($V_{||}$) is considerably higher than the normal component ($V_{\perp}$). Accuracy of the velocity data is discussed in Section 5.

4.2.2. Counter-wise impacts determined from U-PIV data

Fig. 10 shows examples of normal and counter-wise vortices detected by the U-PIV algorithm for rotational frequencies of 2500 and 3300 rpm. Because the single frames in Fig. 10 are not suitable for proper visualization of particle impacts, the reader is advised to review the videos provided as Supplementary Material, focusing on the location of the rotation axis (centre bottom) at the moment of vortex approaching the

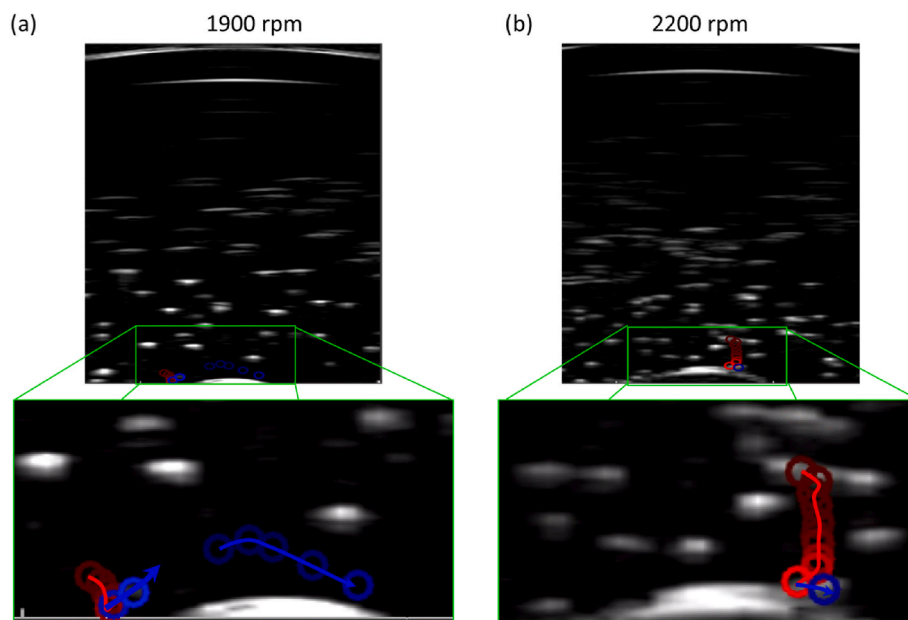


Fig. 9. Example of normal (blue dot track) and counter-wise (red dot tracks) particles impacts identified by particle tracking for two flow conditions: (a) 1900 rpm, and (b) 2200 rpm. The direction of time lapse corresponds with the increasing brightness of the dot colour. See Supplementary Material for the full video.

Table 1

Statistics of particles impacts determined by U-PTV. Mean values are highlighted as bold. The normal and tangential components are in the radial plane of the slurry pot.

Velocity level	1900 rpm				2200 rpm			
Impact velocity component	%Counter-wise impacts (observed/total)	Tangential [m/s] $V_{\parallel}$	Normal [m/s] $V_{\perp}$	Impact angle ($^{\circ}$) α	%Counter-wise impacts (observed/total)	Tangential [m/s] $V_{\parallel}$	Normal [m/s] $V_{\perp}$	Impact angle ($^{\circ}$) α
Min.	22% (13/60)	1.101	0.051	2.652	21% (59/286)	1.123	0.070	3.567
1st. Q		1.199	0.091	4.340		1.239	0.092	4.247
Median		1.279	0.113	5.049		1.334	0.161	6.882
Mean		1.324	0.140	6.036		1.355	0.174	7.317
3rd. Q		1.422	0.202	8.085		1.463	0.254	9.849
Max		1.635	0.348	12.016		1.640	0.363	12.481

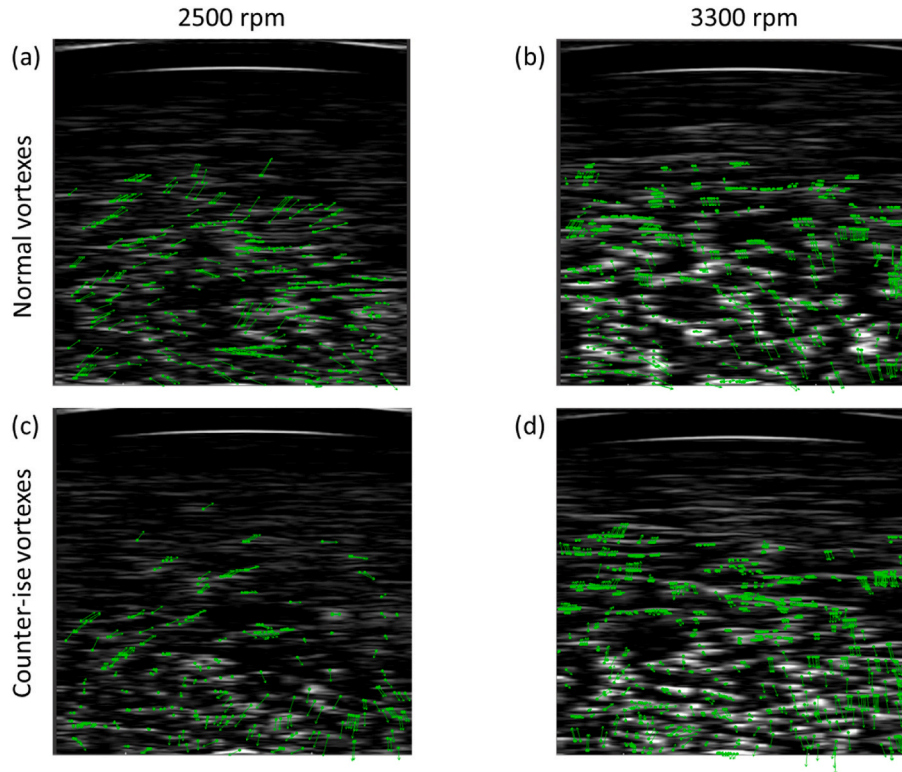


Fig. 10. Example of normal and counter-wise particles impacts identified by U-PIV in different frames of the indicated flow conditions. See Supplementary Material for the full video.

target surface. The full sequence of vortex evolution, from formation to dissipation, can be appreciated in the video. Unlike the U-PTV, the U-PIV does not produce directly the particle trajectories. The velocity components of particles impacts are obtained from the velocity field, averaging velocity vectors around the particle on 2 consecutive frames on which the last corresponds the very particle impact. The counter-wise

impacts can be identified qualitatively as those associated with counter-wise vortices and quantitatively as those producing $\vec{V}_{\parallel}$ vectors contrary to the direction of target rotation.

Table 2 summarizes the statistics of particle impacts identified using the U-PIV algorithm. The results showed similarities and differences compared with the two low rpm cases analysed using the U-PTV

Table 2

Average impact velocities determined by UPIV. Mean values are highlighted as bold. The normal and tangential components correspond to radial plane of the cylinder sample.

Velocity level	2500 rpm				3300 rpm			
Impact velocity component	%Counter-wise impacts (observed/total)	Tangential [m/s] $V_{\parallel}$	Normal [m/s] $V_{\perp}$	Impact angle ($^{\circ}$) α	%Counter-wise impacts (observed/total)	Tangential [m/s] $V_{\parallel}$	Normal [m/s] $V_{\perp}$	Impact angle ($^{\circ}$) α
Min.	6% (117/1869)	1.571	0.000	0.000	7% (347/5220)	2.108	0.000	0.000
1st. Q		1.772	0.022	0.711		2.373	0.029	0.700
Median		1.833	0.049	1.531		2.451	0.071	1.659
Mean		1.832	0.064	2.001		2.442	0.055	1.290
3rd. Q		1.891	0.089	2.695		2.517	0.096	2.184
Max		2.112	0.353	9.489		2.723	0.382	7.986

algorithm. Also in the two high rpm cases, in fact, the total number of impacts in the same time lapse was found to be higher for the higher rotational speed of the shaft, with almost the same percentage of counter-wise impacts. However, if we look at the percentage from a quantitative basis, an important difference becomes immediately evident. In fact, the fraction of counter-wise impacts was about 6% at the 2500 and 3300 rpm levels, whereas it was around 21% at the 2500 and 3300 rpm levels (Table 1). The magnitude of impact velocity increases considerably between the 2500 and 3300 rpm levels, and this increase is mostly attributed to increase of the normal component of impact velocity. Accuracy of the velocity data is discussed in Section 5.

4.3. Impact energy

Fig. 11 summarizes the statistics of energy impacts evaluated after Eq. (10) and represented as rainclouds, boxplots and envelopes of energy distribution. In the rainclouds, each detected impact is represented as a colour-coded dot to discriminate between normal impacts (blue dots) and counter-wise impacts (red dots). The distribution envelopes and boxplots correspond to all the impacts. In general, the mean impact energy increases with increasing rotational frequency and in all the rainclouds the counter-wise impacts are observed with higher energies (approximately 3rd quartile of the distribution).

Table 3 summarizes the cumulative energy of particle impacts integrated from all the impacts detected during the lapse of 3 s. The contribution of normal and counter-wise impacts is expressed as absolute value and relative to the total cumulative energy. The total energy conveyed by the impacting particles increases with the increasing rotation frequency, which is consistent with the increasing number of observed impacts at given rpm level (Tables 1 and 2). On the other hand, the relative contribution of counter-wise impacts diminishes from about 30% observed for the 1900 and 2200 rpm levels to about 7% observed at the 2500 and 3300 rpm levels, although the average energy conveyed by the counter-wise fraction is higher (Fig. 11). It should be noted that the fraction of energy conveyed by counter-wise impacts does coincide with the fraction of impact numbers (Tables 1 and 2) because the distributions of velocities specific to normal and counter-wise impacts overlap slightly (see Supplementary Material).

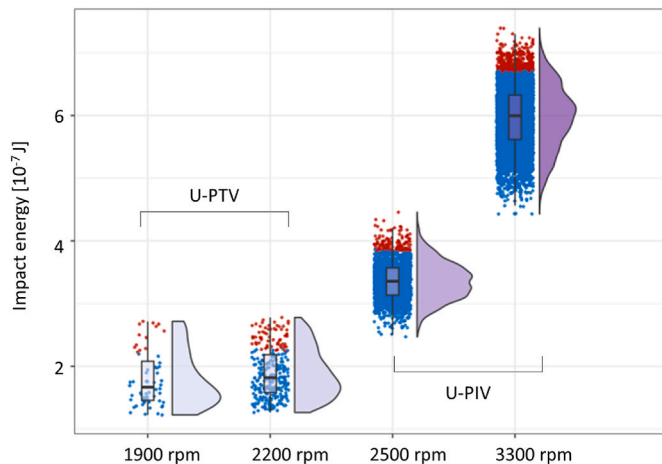


Fig. 11. Energy of particle impacts evaluated for the four levels rotation frequency. Individual dots represent individual impacts distinguishing between normal (blue) and counter-wise (red). Envelopes of the distributions correspond to all impacts.

See Fig. 11(S) in Supplementary Material for the energy distributions plotted separately for the normal and counter-wise components.

5. Discussion

5.1. Applicability of ultrasound velocimetry

The observation of slurry flow using ultrasound B-mode images at sufficiently high rate of acquisition allows visualising the flow of potentially abrasive particles in the turbulent slurry flow. Further application of image analysis based on particle tracking or particles image velocimetry in the region of a target surface allows extracting information on the impact conditions of the individual particles. Considering the depth at which the acquisition of B-images is set, in our case 35 mm corresponding to the distance between the target surface and the transducer, provides an opportunity of extending the proposed method to slurries in which conventional optical methods are not applicable due to opacity of the medium caused by light scattering.

Observation of individual particles allows determining the statistics of impact conditions, in particular those of impact velocity, and identify the turbulent structures from which the impacts are projected. The existence of vortices producing particle impacts in directions opposite to rotation velocity, i.e., counter-wise impacts, was demonstrated in this work. However, this proof of concept is not readily applicable for general analysis of arbitrary particle-laden flow as several aspects must be considered.

First, the accurate evaluation of impact velocity and impact angles requires proper validation of the measurements. This is not presented here because qualitative consistency assessment was found sufficient to report the hypothesised existence of counter-wise impacts and evaluate their relevance to wear (discussed in Section 5.2). These two aspects are independent of the measurement's precision as long as no coarse errors are committed. In this context, the order of magnitude of the velocity values are consistent with the velocity magnitudes obtained from the simulation of the inner cylinder of a relevant Taylor-Couette turbulence [7,8] and also with the experimental values derived from analysis of wear scars by Molina et al. [5]. In order to determine accurately the uncertainty of the velocity measurements by U-PTV and U-PIV, a multi-technique calibration supported by DNS modelling would be necessary. Furthermore, sufficiently rapid image sequences are needed for the application of the U-PTV and U-PIV algorithms, and this imposes a requirement on the minimum acquisition rate necessary for measuring the maximum particle velocity. By considering the requirements of correlation between consecutive frames, which is particularly relevant for the characterization of turbulent flows, it was estimated that the transducer used in this work allowed measuring particle velocities up to 2.7 m/s. This is just an approximated value, estimated by the maximum displacement that could be quantified for a particle present in at least three consecutive frames. The exact limit of measurable velocity depends on particle concentration and it would have to be determined experimentally. Notwithstanding, the method was shown suitable for characterising large scale turbulence structures defined by the relation between the integral scale time and the frame rate acquisition. In particular, aliasing was avoided by using the bandlimit of integral scale time higher than 0.0014 cycles/s [24].

Second, the application of PTV and PIV algorithms for the analysis of optical images is knowingly sensitive to particle, or speckle, density in the images [18]. Thus, in addition to the temporal limitation by the rate of frame acquisition, there are restrictions to particle concentration that can be analysed due to limited capacity of the algorithms to correlate images. Our results indicate that the U-PTV algorithm applies well to the maximum value of effective particle concentration on U-VOI, Φ_p , of approximately 0.5%. The exact value depends on image quality, in particular on the location of the focus plane in relation to the physical location of the particle, which is not constant, thus affecting the capacity of the algorithm to distinguish individual particles. On the other hand, the application of U-PIV is limited by speckle identification. In our case the algorithm was shown applicable for $\Phi_p > 0.5\%$ as assessed by the correlation factor. Since Φ_p depends on the rotational frequency, the

Table 3

Summary of total energy and the relative contribution of normal and counter-wise impacts.

	1900 rpm		2200 rpm		2500 rpm		3300 rpm	
Impact	Cumulative energy (J)	Fraction (%)	Cumulative energy (J)	Fraction (%)	Cumulative energy (J)	Fraction (%)	Cumulative energy (J)	Fraction (%)
Counter-wise	$3.23 \cdot 10^{-6}$	30.02%	$1.46 \cdot 10^{-5}$	27.13%	$4.65 \cdot 10^{-5}$	6.97%	$2.38 \cdot 10^{-4}$	7.64%
Normal	$7.54 \cdot 10^{-6}$	69.84%	$3.93 \cdot 10^{-5}$	72.87%	$6.62 \cdot 10^{-4}$	93.03%	$2.88 \cdot 10^{-3}$	92.36%
Total	$1.08 \cdot 10^{-5}$	100%	$5.40 \cdot 10^{-5}$	100%	$6.68 \cdot 10^{-4}$	100%	$3.12 \cdot 10^{-3}$	100%

exact limitations of both algorithms of measurable velocity range for a given particle concentration would require a dedicated study. Notwithstanding, the results presented here are not affected by these limitations as the parameters of ultrasound acquisition and algorithms of image analysis were selected to be efficient. In particular, we present no intermediate case of rotational frequency level to be analysed by both U-PTV and U-PIV because both algorithms would then provide inaccurate results for wrongly rejecting or including data.

Finally, the demonstration of counter-wise impacts and their relevant contribution to erosive wear, discussed in the next Section, highlights the importance of turbulent structures that are not accounted for in multifactorial models of erosive wear. On the other hand, the experimental tool of inspecting individual particles impacts projected from complex flow structures would allow for direct validation of models based on Computational Fluid Dynamics (CFD) coupled with Discrete Phase Modelling (DPM), which are capable of tracking particles in particle-laden flow. The currently used models of this kind generally make use of Reynolds-Averaged Navier-Stokes (RANS) approach for the simulation of fluid flow coupled with Discrete Random Walk (DRW) models for particle turbulent dispersion. However, the capacity of such models to simulate the counter-wise impacts remains to be confirmed. In this context, the ultrasound velocimetry could be used for validating the RANS-DRW simulations, which being less computationally demanding compared to the Large Eddy Simulations (LES) and Direct Numerical Simulation (DNS), are of practical interest for studying complex flow geometries of practical engineering interest.

5.2. Relevance for erosion wear

Conventional methods for determining the rate of erosive wear experimentally rely on exposure to slurry flow and measurement of the overall loss of weight or dimension in time. The empirical models are then global-scale in that integral-scale parameters are considered, i.e., integrating the effect individual particles' impacts over time and surface area. In this paper, we argue that in order to develop a reliable model of erosive wear loss, applicable to arbitrary geometries of slurry flow, it is necessary to describe and measure the individual particle impacts. Although the transition from individual impacts to cumulative damage has been described for macroscopic impacts [25], up to date, no such attempt was reported for the slurry flow.

The conventional erosion models build on multifactorial analysis, through which velocity magnitude and impact angle are consistently found to be the most significant factors [9]. On the other hand, the mechanics of damage based on the premise of energy exchange between the particle motion and the eroded surface comprises the interdependence of force, velocity, and impact energy, making the formal description of erosive wear difficult [9,26]. According to the energy framework, particles impacting form turbulent flow require sufficient energy to produce erosive/abrasive effect in the target surface, and, in case of our slurry pot geometry, this energy originates from turbulent structures. The spatial components of each impact are relevant because the perpendicular and parallel components of impact energy (Eq. (9)) are associated with different wear mechanisms, namely, deformation and cutting, respectively [23,25]. The mechanism of erosive wear could then be described as the energy exchange between a turbulent flow and

the eroded surface, where the particle act as exchange medium. Since kinetic energy of individual particles can be measured prior and after impact events by the method presented here, this approach could be used for development of models based on this premise. Such analysis is not conducted in this paper however, focusing instead on the phenomenon of counter-wise impacts, which are relevant to the statistics of impact velocity and, *per se*, statistics of impact energy.

Our results show a significant number of counter-wise impacts, between 6% and 21% depending on the rpm level. Because these impacts occur at velocity magnitudes higher than the input velocity of the moving target surface, their kinetic energy could account up to 30% of the cumulative impact energy (Table 3). This observation is similar to the experimental data of Molina et al. [5,6] in which discrimination between wear scars caused by normal impacts from those caused by counter-wise impacts was possible through analysis of their morphology (Fig. 2(b and c)). From the statistics of the wear scar types and statistics of the impact velocity, it is possible to determine the corresponding impact energies. The experiment of Molina et al. [5,6] was conducted at slightly different flow conditions to privilege the production of individual wear scars, i.e., higher rpm level, lower particle concentration, and longer exposure time. However, the 26% fraction of counter-wise impacts at 12,732 rpm (Table 4) is esteemed reasonable compared with the lower number of 8% at 3300 rpm (Table 3) as the difference can be explained by the fact that not all the impacts (detected by the direct observation in our study) convey sufficient energy to produce a measurable wear scar (detected by profilometry by Molina et al. [5,6]). Because the fraction of impacts associated with counter-wise impacts is always that of highest kinetic energy (Fig. 11) their potential to produce a measurable wear scar also increases. To provide a quantitative analysis, the absolute value of minimum energy necessary to produce a measurable wear scar, i.e., contribute to wear, would be necessary. However, as of current, this threshold value remains unclear, as discussed by Espinoza-Jara et al. [7].

In addition to particle concentration, the fraction of counter-wise impacts also depends on particle size and density. At a fixed level of flow-field time scale, larger and/or denser particles are generally less affected by the turbulent flow having a longer response time. In our study, only a single particle size was studied, selected from the range investigated by Molina et al. [5]. In their work, different particle sizes were studied and for the same rotational frequency, the number of impacts with velocity higher than system's input, i.e., associated with counter-wise impacts, decreased with increasing particle size (Fig. 2(a)). This observation is consistent with the higher probability of the smaller particles to be efficiently conveyed by and projected from counter-wise vortices.

Table 4

Contribution of counter-wise impacts to kinetic impact energy evaluated from profilometry data of Molina et al. [5]. Compare with data in Table 3.

	12,732 rpm	
Impact	Cumulative energy (J)	Fraction (%)
Counter-wise	0.076	26.4%
Normal	0.0273	73.6%
Total	0.1033	100%

The capacity of ultrasound technology to provide direct insights into the geometry of individual impacts, both before and after they occur, is an innovative application of the otherwise known ultrasound imaging to the study of erosive wear. In particular, an experimental study of rebound is technically feasible in principle, allowing for comprehensive study of the wear mechanisms if further developed. It also provides a chance for developing algorithms capable of identifying particle breakage, which would be helpful for elucidating the key factors influencing this process. However, it should be kept in mind that particle trajectories is only one piece of the puzzle in the context of complex and interdependent phenomena.

Finally, the fact that the moving wall generates the flow is relevant to the effect of counter-wise impacts on erosive wear. In principle, counter-wise vortices could be formed in various geometries or flow conditions, but our work demonstrates their existence at least in the Taylor-Couette flow generated in slurry pot tests, which is of particular importance to rotatory machinery such as pumps, mixers, and impellers. As a future work, a more detailed fluid dynamic characterization of such flow might be useful to predict the formation of counter-wise events and include their effects in erosion models through integral time scale, integrating the space and time period of recurrence. This would allow further improving the existing models consistent with the known factors of particle size, turbulence condition, and target wall velocity. On the other hand, our discussion of counter-wise impacts stresses the importance of properly accounting for these flow structures in the modelling of turbulence by the CFD-based slurry erosion prediction. It remains to be determined whether this consideration would demand for more advanced approaches in turbulence modelling compared with the ones which are typically used at current.

6. Conclusions

Direct observation of abrasive particle impacts in slurry pot tests by means of ultrasound B-mode imaging was reported in this study, extended by the velocimetry analysis to characterize the vortices from which the particles were projected. The visualization techniques confirmed the existence of counter-wise turbulent eddies from which particles can be projected as inferred from a previous study based on a different method (namely, inspecting individual erosion scars posterior to exposure reported by Molina et al. [5]). The results of the present study allow formulating two types of conclusions, those specific to the method used for discovering the counter-wise particle impacts and those specific to their relevance for erosive wear.

Concerning the characterization of particle impacts by ultrasound velocimetry.

- Both the techniques of B-mode image analysis, i.e., Ultrasound Particle Tracking Velocimetry (U-PTV) and Ultrasound Particle Image Velocimetry (U-PIV), are applicable for characterising turbulent structures in the relevant time scale. In particular, both algorithms allowed the identification of counter-wise vortex events.
- Counter-wise events were detected as vortices such that produce impact of particles onto a moving target surface with tangential direction contrary to surface motion. This type of particle impacts was previously hypothesised but not observed directly.
- The maximum acquisition rate of the ultrasound system imposes a limit to the range of velocity and particle content that can be analysed:
 - The maximum particle velocity that can be measured at the acquisition rate of 336 fps is about 2.7 m/s.
 - The U-PTV algorithm is more suitable for lower concentrations (up to $\Phi_p \sim 0.5\%$) observed at the two lowest flow velocities. The limit derives from the capacity of the algorithm to follow (track) particles on a sequence of images produced at the maximum acquisition rate.

- The U-PIV algorithm is more suitable for higher particle concentrations (higher than $\Phi_p \sim 0.5\%$) observed at the two highest flow velocities. The limit derives from the capacity of the algorithm to correlate interrogation windows in consecutive images produced at the maximum acquisition rate.
- The exact limits of particle velocity measurable by the U-PTV and U-PIV algorithms are yet to be explored in function of ultrasound acquisition technique relative to the structure of the turbulent flow near a target surface.

Concerning the relevance of counter-wise particle impacts for erosion.

- Velocity of particles impacting from counter-wise vortices is higher than the system's input velocity, which is not taken into account by the multifactorial models of erosive wear.
- Depending on the system's input velocity (rpm level in this study) the fraction of counter-wise impacts may be as high as 22% of the total number of impacts. Because the higher velocities convey more kinetic energy, the counter-wise fraction may convey a significant fraction of the impact energy, estimated here to be up to 30%.
- The energy of counter-wise particle impacts is conveyed mainly through the tangential component of impact velocity, indicating that some turbulent structures may be more relevant for the erosive wear in materials susceptible to cutting.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wear.2023.204988>. Videos of the image sequences associated with Figs. 9 and 10. Fig. 11(S): The normal and counter-wise components of energy distributions for the four levels rotation frequency. The green lines are added for visual guide of the relation between the distributions.

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