



Experimental insights into sweep-induced mechanism of erosive wear in a straight pipe section with turbulent slurry flow

Ariel Espinoza-Jara^{a,b}, Magdalena Walczak^{a,e}, Gianandrea Vittorio Messa^b, Wernher Brevis^c, Alessandro Pascone^d, Cristina Tedeschi^b

^a Department of Mechanical and Metallurgical Engineering, Escuela de Ingeniería, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Santiago, 7820436, Chile

^b Department of Civil and Environmental Engineering, Politecnico di Milano, Milano, 20133, Italy

^c Department of Hydraulic and Environmental Engineering, Pontificia Universidad Católica de Chile, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Santiago, 7820436, Chile

^d Telemed Medical Systems S.r.l, Via Eugenio Villoresi 24, Milano, 20143, Italy

^e Millennium Institute on Green Ammonia as an Energy Vector (MIGA), Vicuña Mackenna 4860, Santiago de Chile, RM, Chile

ARTICLE INFO

Keywords:

Erosive wear

Slurry

Turbulent flow

Ultrasound particle image velocimetry (UPIV)

ABSTRACT

Reliable design and operation of slurry handling systems are critical in industries such as mining. This study examines erosion due to solid particle impacts in a straight pipe section, introducing the concept of “turbulent erosive wear”. Ultrasound particle image velocimetry (UPIV) is used to observe flow at the surface of a ductile target (copper). Experiments are conducted at flow velocities of 1.97 and 2.15 m/s, with particle sizes of 500 and 700 μm . Sweep events are identified, and their frequency, intensity, and duration are analysed using wavelet analysis. The results show that velocity impacts of solid particles during sweeps correlate with the geometry of wear scars. Turbulent erosive wear is linked to a characteristic threshold value of impact velocity. This value provides a measurable parameter to enhance predictive modelling and material selection for pipeline design.

1. Introduction

Slurry pipelines carry a mixture of solid particles suspended in a fluid and are crucial for the normal operation of several key industries, such as the oil, gas, and mining [1,2]. Compared to other alternatives for the transportation of slurries, such as trucks or trains, pipelines offer a cost-effective option with a potentially reduced risk of failure. However, transporting slurry in a pipeline presents unique challenges, one of the most important being the monitoring and reduction of pipe wear caused by the impacts of solid particles. Erosion wear can produce structural failures, leading to leakages, or the collapse of the pipe, which can be highly detrimental to the environment [1–4].

The mechanisms of wear in particle-laden pipelines are determined by several factors, including particle size, shape, concentration, fluid velocity, and pipeline geometry [2,5–8], and their understanding is crucial for developing effective strategies to minimise erosive wear and to improve operational reliability. The physical mechanisms that lead to material loss in particle-laden pipelines can be classified as follows [7,9–11]: (i) abrasive wear, resulting from the action of a bed of particles that slides over the bottom part of the cross-section,

during extended or pseudo-continuous periods. Abrasive wear is mainly related to the removal of material caused by cutting damage [7,9,12], (ii) erosive wear, which occurs when solid particles impact the wall. The mechanism is characterised by a short contact between the particle and the wall, but also by the transfer from the particle to the wall of enough momentum for the particle to be able to remove material from the wall [7,11], and (iii) corrosive wear, in this case the material is removed due to chemical reactions between the fluid and the wall [13,14]. It is necessary to highlight that synergistic effects may arise as a result of the simultaneous action of two or more of the aforementioned mechanisms [8,13–15]. The effect of the action of a sliding bed can be avoided by using a proper selection and control of flow parameters [16]. Corrosion can be mitigated by implementing physical or electrochemical strategies. The erosive action, however, is unavoidable as it is inherent to the flow [17].

Depending on the flow condition, wear can be classified as impact or turbulent erosion wear. Impact erosion is associated with jet flow [18, 19], sudden changes in the flow direction, or the presence of obstructions such as valves [20–22]. On the other hand, turbulent erosion wear

* Corresponding author.

E-mail address: mwalczak@uc.cl (M. Walczak).

<https://doi.org/10.1016/j.wear.2025.206221>

Received 22 November 2024; Received in revised form 17 June 2025; Accepted 23 June 2025

Available online 7 July 2025

0043-1648/© 2025 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

arises from the turbulent nature of the flow, where local turbulence is high enough to produce significant near-wall events associated with the onset of coherent structures [5,23]. These turbulent coherent structures can induce short but highly energetic momentum fluxes between the bulk flow and the wall, leading to significant damage to the latter, which in the case of a pipe is its inner surface [24], similar to the effect of vortices [25].

In this work, we hypothesise that turbulent erosion is a significant wear mechanism in a straight section of a pipe and that it is mainly caused by highly energetic burst events, in particular sweeps, in the near-wall region. The presence of such short but highly energetic exchanges between the bulk flow and the wall region was shown in the literature to convey a considerable percentage, up to 87%, of the velocity at the centre line as shown in similar cases [26–29]. The implication for velocities typical of mining pipelines is that the burst events might increase the amount of energy conveyed by the flow through the solid particles. Although the idea of erosive wear by turbulence has been suggested in literature [30], the influence of sweep and ejection events on the wear mechanism in the straight section of a pipe has not been demonstrated experimentally so far. The hypothesis is tested by a novel application of ultrasound imaging to directly identify and quantify individual sweep events that effectively result in wear. In particular, flow parameters are measured in the near-wall region, i.e., internal surface of the pipe, by ultrasound particle image velocimetry (UPIV) [31–35] and then compared in statistical terms with equivalent data obtained by inverse analysis of the worn target surface as described by Molina et al. [36].

2. Material and methods

The experimental design consists of running a particle-laden flow loop, with tap water as the liquid phase and glass beads as the solid phase (Table 1). The test matrix includes two levels of flow velocity and two particle size distributions (Table 2), which are among the most influential parameters in erosive wear phenomena [13] and their values were determined to demonstrate their relationship with wear scars. The selection of velocity and particle size levels in the pipe loop experiments was guided by both measurement constraints and physical erosion mechanisms. Two velocity levels (2.17 m/s and 1.97 m/s) were established: the higher level (V_H) was optimised to match the operational capabilities of the ultrasound particle image velocimetry (UPIV) system, ensuring reliable flow characterisation, while the lower level (V_L) was selected to remain above the threshold that would induce a stationary deposit, or a collision-dominated transport regime (heterogeneous flow), thus maintaining a fully suspended flow condition. Similarly, particle size levels were chosen to balance transport dynamics and erosion potential [13,36]. The larger particle size distribution (600–800 μm , labelled according to the mean value as D_{700}) was selected to ensure full suspension within the flow, while the smaller particle size distribution (400–600 μm , labelled as D_{500}) was chosen to retain sufficient kinetic energy under the tested velocities to induce surface impacts with erosive potential, considering the necessary mass-velocity combination for material wear.

In order to ensure the reproducibility of the experiment and for the estimation of experimental error, some of the level combinations (runs) were repeated. The experiment for V_L and D_{500} were executed three times (Runs 2, 5, and 7), for V_L and D_{700} twice (Runs 3 and 6), and the remaining combinations only one (Table 2).

2.1. Experimental set-up

The exposure to turbulent flow was conducted in an experimental set-up consisting of a pipe-loop formed by 5 elements as shown in Fig. 1: (1) mixing tank, (2) inlet pipe with flow-meter, (3) outlet vertical pipe, (4) pipe straight section, and (5) flow return to mixing tank. The fully developed flow was produced in the straight section

Table 1

Summary of boundary conditions of the experimental setup.

Condition	Value
Pipe Length	1400 mm
Pipe Diameter	32 mm
Pipe Material	Acrylic
Sample Material	Copper C11000
Surface Preparation	Polished (sandpaper to 0.04 μm colloidal silica)
Liquid Phase	Tap water at 18°C
Solid Phase	Glass beads (400–600 μm and 600–800 μm)
Flow Velocities	1.97 m/s (V_L) and 2.17 m/s (V_H)
Solid Concentration	0.28–0.34 vol.%

Table 2

Summary of test runs of the experiment design. Variability and repeatability were considered by repeating the experiments for the same combination of parameters. Flow velocity and particle size are average values.

Particle Size (μm)	Flow Velocity	
	1.97 (m/s) (V_L)	2.17 (m/s) (V_H)
400–600 (D_{500})	Run 2	Run 4
	Run 5	
	Run 7	
600–800 (D_{700})	Run 3	Run 1
	Run 6	

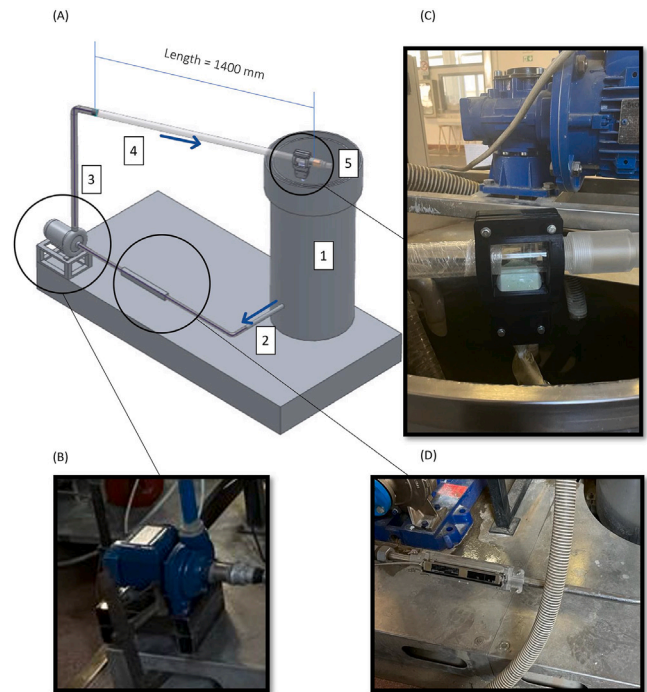


Fig. 1. Experimental set-up of the pipe loop: (A) Schematic overview; (B) Detail of the pump; (C) Location of ultrasound transducer and copper test coupon detailed in Fig. 2; (D) Detail of the inlet section with flow meter sensor.

made of polycarbonate tubing of 32 mm internal diameter and a total length of 1400 mm. The characteristics of the experimental set-up correspond to an entrance length equal to 43.75 pipe diameter, which is considered sufficient to ensure the fully developed flow condition. At the downstream part of the straight section, the transducer of the UPIV measurement system was attached, followed by a removable copper ring as shown in Fig. 2.

The removable copper ring was used for capturing the wear scars produced by particle impacts. The ring was electrolytic tough pitch copper C11000 (Cu-ETP) of the same inner diameter as the pipe (32 mm), 40 mm long. One ring was used per experimental run. Prior to exposure, the inner surface of the ring was polished to a surface quality

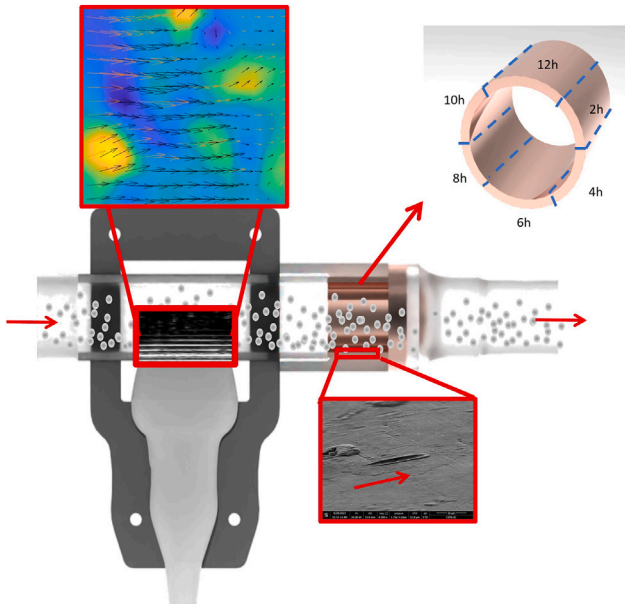


Fig. 2. Detailed view of the experimental setup: (left-side) linear ultrasound transducer of the UPIV system, and (right-side) copper ring at which wear scars were produced. An example of flow field is shown using colour scale of radial velocity component: yellow — positive (towards pipe wall), blue — negative (toward pipe centre).

sufficiently smooth to observe the scars produced by the glass beads. The polishing process was conducted on a vertical driller at 300 rpm in three stages using: (1) SiC grinding paper with grits increasing from 600 to 3000 at a standard speed, (2) polycrystalline diamond (PCD) suspensions of 3 μm and then 1 μm , and (3) colloidal silica suspension of 0.04 μm .

The flow was impulsed by a pump with a variable frequency drive. The discharge was measured with a Proline Prosonic Flow 91 ultrasonic flowmeter (Endress+Hauser). The discharge was recorded every 15 min using a data logger (National Instruments) over a sampling time of 5 min. The readings were converted into units of m/s by dividing the discharge by the cross-section of the pipe.

Before initiating the flow, glass beads were mixed with water in the tank to achieve the desired static concentration of particles. Throughout the experimental runs, slurry samples were collected every 15 min at the pipe return to the mixing tank, using a graduated volume flask. The instantaneous content of the solid phase was determined using the procedure of Messa et al. [37], and the measurements were used to adjust the quantity of glass beads in the system to keep the desired concentration levels throughout the experimental runs.

2.2. Experimental procedure

Each run consisted of 105 min exposure to flowing slurry during which measurement of flow rate, sampling of concentration and acquisition of ultrasound data were conducted with a temporal scheme summarised in Fig. 3A.

2.3. Ultrasound image velocimetry (UPIV)

UPIV was conducted using an ArtUs EXT-1H Rev.C1s ultrasound system, equipped with a digital beamformer provided by Teled. This system is based on a linear array transducer, model L12-5N40-A4, which has a length of 40 mm and operates within a frequency range of 5.0–12.0 MHz. The acoustic images were generated by mounting the transducer on the surface of the pipe using a custom-designed support visible in Fig. 1C. This set-up allowed the observation and recording of the flow in the axial cross-section as shown in Fig. 2. The transducer was operated at a working frequency of 12 MHz, activating a segment

of 20 mm (50% of the transducer crystals), which allowed increasing the acquisition rate to 419 frames per second (fps) as compared to 336 fps when operating all the transducer crystals. The ultrasound images generated by the system were recorded directly using the Echowave II 4.1.0 software provided by Teled.

The raw ultrasound images were corrected for two types of aberrations: (1) the delay associated with the sweep velocity of the image formation was improved following the method of Poelma et al. [32], and (2) the discretization error due to low line density of the images causing delayed representation of actual particle position was corrected using the half-distance between two adjacent transducer crystals. The value was determined by observing cumulative images following the method of Bone et al. [38]. In this work, the line density for ultrasound acquisition was held constant, and the position correction in the axial direction (along the pipe and perpendicular to ultrasound sweep) was determined to be 0.61 mm. The correction of the V_x velocity component was thus +0.26 m/s for the entire flow field.

2.4. Surface characterisation

After completing the exposure time, the worn surface was characterised on coupons dissected from the copper test rings via electrical discharge wire machining (EDM). Detailed analysis was conducted on the coupon of the 6 o'clock section corresponding to the radial location of the velocity plane characterised by UPIV.

The overall morphology of the surface was examined using field emission scanning electron microscopy (FE-SEM, FEI-Quanta 250 FEG). Conventional e-beam incidence was used for the top-view observation of the wear scar location and lateral shape. The topography of the wear scars was visualised in SEM using a high-tilt approach. In addition, a quantitative topography analysis was conducted using white light optical profilometry (Rtec WLI integrated to a multifunctional tribometer, model MFT5000).

The WLI data were processed using the Gwyddion software version 2.63. The sequence of applied filters included 'flatten base' (to level the image background), 'median value filter' (to denoise the images), and 'shift minimum data value to zero' (to standardise the starting data point). Following this pre-processing, the data were exported in a matrix format as a text file, with pixel calibration preserved for subsequent processing in a Python environment. The algorithm was based on the work of Molina et al. [36] to which automated search for local minimum and maximum neighbours was added. The search consisted of moving a square window of 15 $\times$ 15 pixel (px) by the lateral distance of 7 px and identifying paired local minima and maxima points. For each pair of identified points, an ellipse was fitted to depict the scar topology. The cross-sectional profiles of the major and minor axes of each fitted ellipse were extracted. The parameters of each ellipse, including the angle, lengths of the major and minor axes, and their profiles, were recorded in a new list. Approximately 200 potential impact scar candidates were identified per image. Each candidate was manually selected to compile a comprehensive dataset of impact scars for each image. Each post-processed image was subsequently analysed to determine the impact angle and impact velocity, which are defined as the angle formed by the particle velocity vector just before impact with the wall, as shown later in Fig. 11. The values of impact angles were determined directly from the topography of the wear scars. The values of impact velocities were determined by inverse analysis of wear scar depth using the deformation model of Cheng [36,39].

2.4.1. Ultrasound data processing

The sequence of acoustic images, corrected for ultrasound aberration, was processed using PIVLab [40] to determine the instantaneous velocity field using interrogation windows diminishing from the initial 380 $\times$ 380 pixel (px) to the final size of 48 $\times$ 48 px. For increased accuracy in the velocity estimation, the Gauss 2 $\times$ 3 point sub-pixel estimator was used. Standard distance rule available in each ultrasound

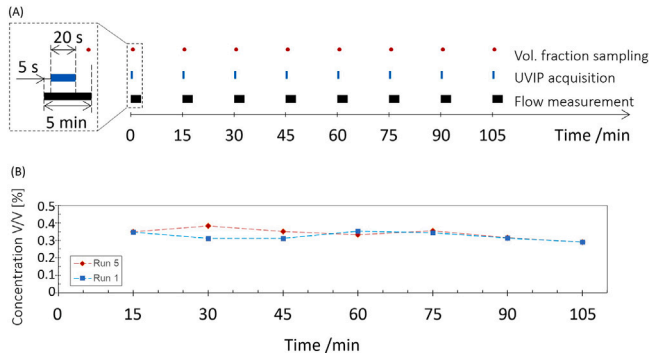


Fig. 3. Temporal scheme of measurements and data acquisition (A) with an example of volume fraction determined by sampling (B).

image was used for distance calibration. The estimated velocity vectors were validated by applying limits to the magnitude of the instantaneous velocity fields in both the axial (x) and radial (y) directions. The V_x and V_y velocity fields from each frame were exported as text files and then post-processed in the R language. It should be kept in mind that the so estimated flow fields correspond flow of the inertial particles carried by the flow and not to the presence of tracer particles. A detailed analysis of the flow field was focused on a region of interest (ROI) located in the near-wall region.

The UPIV data was also used for the estimation of particle concentration by analysing pixel density on cumulative images. These images were obtained by adding up all frames of the time series in which the value of a pixel is proportional to the concentration averaged over time. The average particle concentration in the radial direction was obtained by adding rows of data corresponding to the same radial distance from the wall, which is equivalent to marginalizing out the axial direction (along the pipe). It should be noted that only relative values can be analysed because there is no direct quantitative relationship between physical particle concentration and pixel density, as discussed by Espinoza-Jara et al. [31].

2.4.2. Analysis of sweep events

In this study, an erosive sweep event is defined as the impingement of multiple particles onto the same location of the boundary wall associated with a sweep of the fluid phase as defined by the corresponding quadrant [41] and occurring in a temporal sequence [42]. The sweep events were identified by observing the flow field in the ROI located approximately 1 mm from the target surface, in which negative values of radial velocity component ($V_y < 0$) are the condition necessary for producing a wear scar.

The time series of the radial velocity component (V_y) in the ROI was subject to wavelet analysis using the Morlet mother function. The presence of periodic events of significant magnitude and duration of the $V_y(t)$ signal power was interpreted as sweep events [43,44].

3. Results

3.1. Global flow parameters

Fig. 3B summarises the evolution of particle concentration over the duration of the exposure experiment for the conditions of lower velocity–smaller particles ($V_L - D_{500}$) and higher velocity–larger particles ($V_H - D_{700}$). The concentrations are consistently fluctuating with an average value 0.3 vol.%. Similar behaviour was observed for all other runs, for which the average concentration values are summarised in Table 3. Additionally, the table shows the corresponding average flow velocity determined experimentally.

The time evolution of the experimental flow velocity is shown in Figs. 4A and 4B with the detail of fluctuation in time. The fluctuation of

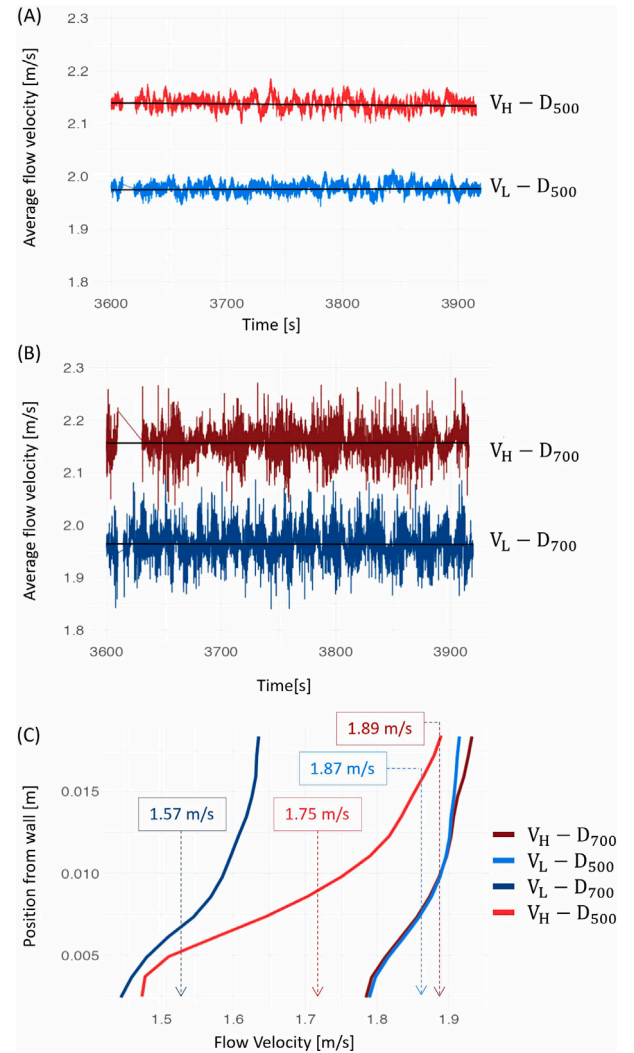


Fig. 4. Comparison of flow velocities determined by two methods: Evolution average values measured by flow meter for (A) smaller particles (D_{500}) and (B) larger particles (D_{700}). (C) Representative velocity profile determined by UPIV, data average for 20 s. Mean values of the flow profiles are indicated in the corresponding boxes.

the bulk velocity is notably smaller in case of the smaller particles (D_{500} , Fig. 4A) as compared to the larger particles (D_{700} , Fig. 4B), potentially indicating the interference of the particles with the flow meter device.

The global flow parameters were also estimated from the temporal and spatial averaging of the velocity fields estimated from the UPIV measurements. Fig. 4C shows the time-averaged profiles of the particle velocity along the radial dimension. In all cases, and as expected, the velocity increases with the distance from the wall region towards the centre of the pipe, approaching a uniform profile typical of turbulent particle-laden flows. However, for the case of higher velocity with smaller particles ($V_H - D_{500}$), the increase in velocity towards the centre is steeper, i.e., with a pronounced difference in average particle velocity between the wall region and the centre. The mean velocities from UPIV data are systematically lower, by about 0.5 m/s, when compared to the corresponding readings of the flow meter (Table 3). The profiles of faster flow with larger particles ($V_H - D_{700}$) seems similar to slower flow with larger particles ($V_L - D_{500}$). Both observations are consistent with the expected trends and discussed in Section 4.1.

3.2. Concentration profile

Fig. 5A shows an example of the summation of B-mode image frames for the case of lower velocity–larger particles ($V_L - D_{700}$). It

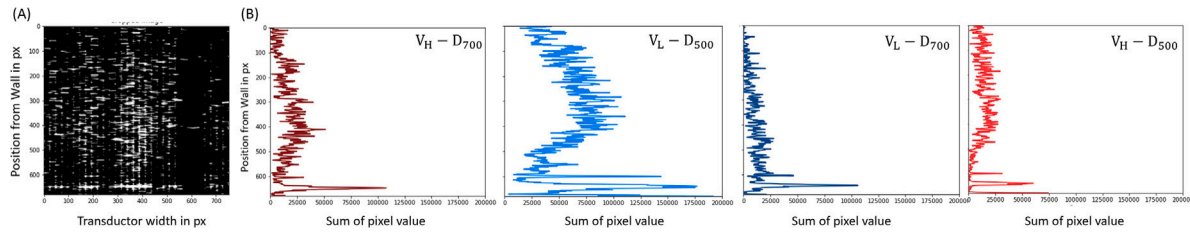


Fig. 5. Cumulative concentration distribution profile during UPIV analysis time: (A) Representative B-mode image addition, (B) Pixel values obtained for radial direction by marginalizing out the axial direction (along the pipe), representing the radial concentration profile for the indicated combinations of velocity (V_H — higher, V_L — lower) and particles sizes (D_{700} — larger, D_{500} — smaller).

Table 3

Summary of volume fraction and measured average flow velocity at section 4 of the loop (see Fig. 1).

Run	Levels	Volume fraction (%)	Average flow velocity (m/s)
1	$V_H - D_{700}$	0.32 ± 0.03	2.15 ± 0.15
2	$V_L - D_{500}$	0.31 ± 0.04	1.98 ± 0.05
3	$V_L - D_{700}$	0.32 ± 0.01	1.97 ± 0.17
4	$V_H - D_{500}$	0.28 ± 0.05	2.14 ± 0.08
5	$V_L - D_{500}$	0.34 ± 0.04	1.97 ± 0.05
6	$V_L - D_{700}$	0.33 ± 0.04	1.97 ± 0.05
7	$V_H - D_{700}$	0.33 ± 0.02	1.98 ± 0.06

visualises the average over time, with brighter pixels indicating areas of higher particle concentration, typically found in specific locations on average. The statistical distributions of particles across the diameter of the pipe (0 to 700 px, equivalent to 0 to 17.75 mm, i.e. the distance from the inner wall to the centre) determined from the average sum of the pixels are summarised in Fig. 5B. The particle distribution profiles observed in all flow conditions present a heterogeneous concentration but with different distributions for each flow condition, consistent with the observation of Gurung and Poelma [33]. The common pattern is the presence of higher concentration in the near-wall region, where the condition of lower velocity and smaller particles ($V_L - D_{500}$) shows the highest concentration. The latter might be indicative of particle flow close to a sliding bed condition for this case, with a pseudo-parabolic concentration distribution towards the centre of the pipe. For the case of lower velocity and larger particles ($V_L - D_{700}$), a pseudo-constant decreasing pixel value is observed from the wall to the centre of the pipe. For the cases of higher velocity and larger particles ($V_H - D_{700}$) and lower velocity–smaller particles ($V_L - D_{700}$), three characteristic regions are observed: in the near-wall region there is a local peak similar to other conditions, then an intermediate region located between the near-wall and the centre in which the total number of pixels increases, followed by decrease towards the centre of the pipe.

3.3. Velocity in radial direction

The near-wall velocity field revealed by UPIV was analysed in the near-wall region indicated at an example frame in Fig. 6A. The velocity components V_x and V_y correspond to axial (along the pipe) and radial (towards the pipe wall) directions, respectively. Time evolution of the $V_y(t)$ signal is shown in Fig. 6B at which peak exceed 0.5 m/s indicating events at which the particles impinge the surface ($V_y > 0$) or are ejected from it ($V_y < 0$). The cumulative average of the $V_y(t)$ signal is shown in Fig. 6C in which convergence towards a constant value is observed, which is an indication of the statistical significance of the sampling time.

3.4. Characterisation of wear scars

Wear scar morphology

Fig. 7 shows representative SEM micrographs of surfaces worn at different conditions in which the presence of elongated scars, predominantly aligned with the direction of flow, is observed, different to the

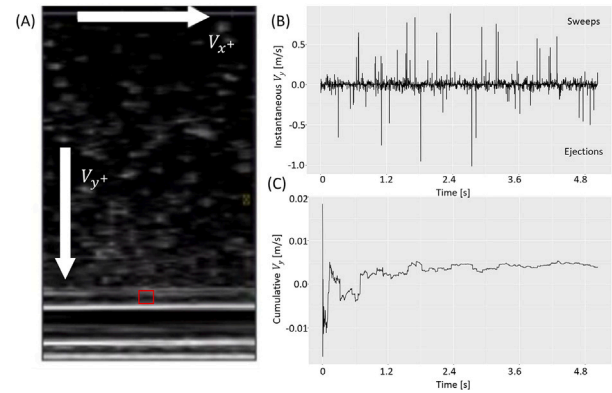


Fig. 6. Example evolution of velocity in the near-wall region as observed in Run 5: (A) Definition of axes and location of ROI, (B) Evolution of instantaneous value of radial velocity (normal to target surface, V_y) observed in the ROI, and (C) Cumulative value of V_y observed in the ROI.

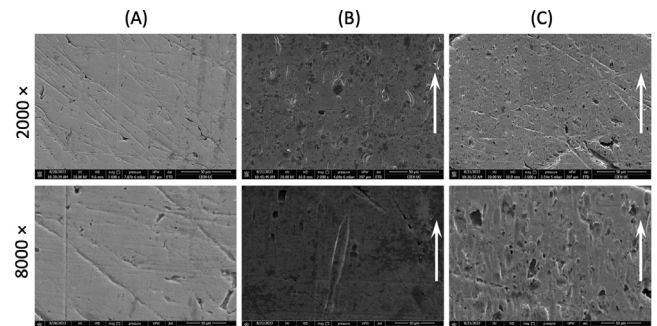


Fig. 7. Representative SEM micrographs of the inner surface of the pipe: (A) Prior to exposure (reference), (B) After completing Run 1 ($V_H - D_{700}$), (C) After completing Run 2 ($V_L - D_{700}$). The flow direction is indicated by the arrow.

characteristic longitudinal grooves remaining from polishing. A typical morphology of an individual wear scar observed at high tilt in SEM is shown in Fig. 8A. An example analysis of an individual wear scar by optical profilometry is shown in Figs. 8B and C, demonstrating the selection of the scar from an overview and its detailed analysis, respectively. On the depth profile along the major axis of the scar a deformation lip is observed from which the direction of impact is deduced. The very presence of wear scars is consistent with the observation of sweeps. However, the density of the wear scars is lower than the number of sweep events, indicating that not all the sweeps result in a measurable plastic deformation.

Statistics of impact parameters

Fig. 9 summarises the statistical distribution of particle impacts in terms of impact angle and normal component of impact velocity. The values determined by UPIV are compared with the results obtained by

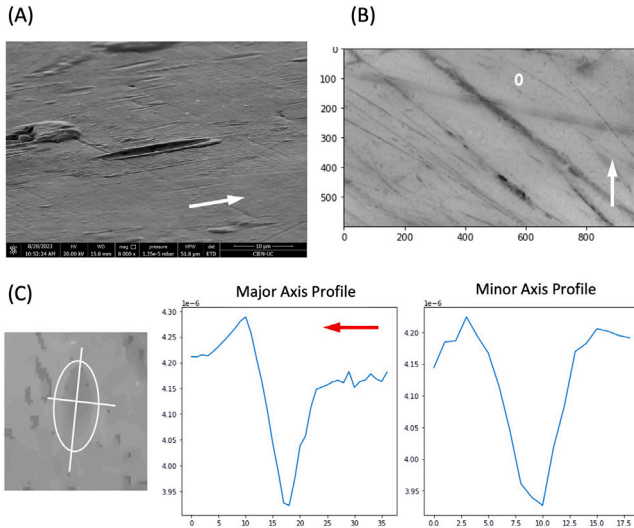


Fig. 8. Representative wear scar topography observed by (A) SEM using high tilt and (B) optical profilometry (top view). The small red ellipse at the top of (B), whose zoomed view is given in (C), indicates a wear scar. The depth profiles along the major and minor axes are also shown in (C). The red arrow in all figures indicates the direction of pipe flow. Example data from Run 1 ($V_H - D_{700}$).

inverse analysis of the wear scars. In all cases, the amount of data obtained from scar analysis is smaller than that obtained from UPIV; however, the range of values and the overall shape of the frequency distributions are comparable. Also, it is observed that the lowest measured value is characteristic of a specific flow condition, whereas the effect of flow velocity is more pronounced than the effect of particle size. The lowest value of velocity is further referred to as threshold velocity and discussed in Section 4.3 as a nuanced relationship between flow condition, set by the nominal flow velocity, and the characteristics of particle impacts in terms of impact velocity and impact angle.

4. Discussion

4.1. Validity of experimental data

The two principal aspects of data validity are the stability of the flow within the observation time and the uncertainty of the measured values. In this study, the straight section of the pipe upstream of the UPIV observation is assumed to be sufficient to produce fully developed flow, such that its characteristics do not change with the longitudinal position. The uniform profile of average velocity is shown in Fig. 4C, which is typical of fully developed turbulent flows [45]. On the other hand, the time of acoustic image acquisition (5 s) is considered sufficient to provide statistically valid data, which is supported by the convergence of cumulative average of V_y shown in Fig. 6C. Also, the UPIV data acquired for different time intervals (Fig. 3A) was analysed for statistical consistency to ensure that it is representative of the entire duration of erosion exposure (110 min). The stability of sampled volume fraction (Fig. 3B) and flow rate (Figs. 4A and B) further supports the steadiness of the flow, which is crucial for the comparative analysis of impact velocities and impact angles.

The aspect of data uncertainty can be assessed by analysing the error associated with the determination of velocity by UPIV and by analysing the consistency of the determined values with the flow rate measurement. The systematic error is inherent in ultrasound image generations, and the PIV algorithm, which on average is less than 5% and with sweep correction could be around 1% [32]. Notably, this study applies an additional line density correction, resulting in a 21.6% reduction in measurement error compared to validated Optical PIV techniques [38]. However, the values of average flow velocity determined by UPIV (Fig.

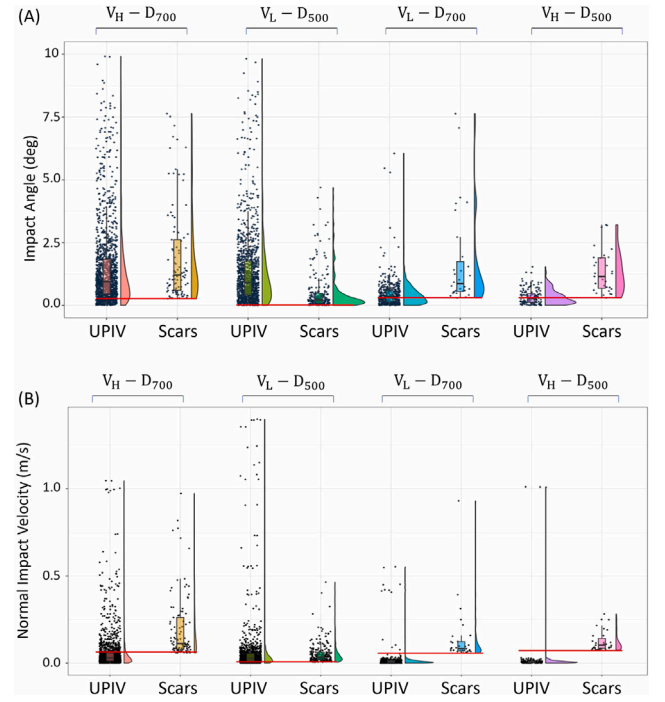


Fig. 9. Comparison on particle impact statistics obtained by UPIV and inverse analysis of wear scars for the different flow conditions (Table 2: (A) Particle impact angle, and (B) Component of impact velocity normal to target surface.

4C) do not coincide exactly with the respective values measured by the flow meter (Fig. 4A and B). This discrepancy can be explained by the difference in measuring principle of the two methods. Whereas the flow meter captures the signal of the entire flow by the principle of the Doppler effect and determines the average cross-sectional velocity, the UPIV data is specific to the flow field of abrasive particles as measured directly on the observed displacement of particles. Further, the values of particle impacts determined by UPIV are consistent with the values estimated by the inverse analysis of wear scars.

4.2. Coherent flow structures

The presence of sweep events is demonstrated by recurrent peaks of positive value in the evolution of velocity component V_y observed in the near-wall region (Fig. 6B). Also, the cumulative value of V_y is slightly positive on the time average (Fig. 6C), indicating that, at the particular location under observation, sweep events are predominant. Thus, the presence of a spatially coherent structure at this location, in particular sweeps, is evidenced. The frequency and intensity of such sweep events vary for the different flow conditions as represented by the evolution of V_y filtered for positive values shown in Fig. 10. In the case of higher velocity and larger particles ($V_H - D_{700}$), the interaction of particles projected from bulk flow onto the surface is characterised by the highest number of events with high-velocity magnitude (Fig. 10A). The magnitude of the events is lower for the smaller particles, which at the higher velocity ($V_H - D_{500}$) produce only two events of relatively low magnitude (Fig. 10D, note the scale of velocity axis).

The temporal coherence of the sweep events can be observed in the wavelet analysis shown in Fig. 12 where the heat map reveals the periodicity and duration of sweep-containing events in terms of the relative magnitude of the $V_y(t)$ signal. The time step used for the analysis corresponds to the inverse of the acquisition frame rate (1/fps), which in this study was equivalent to 2.4 ms. Thus, considering the duration of the UPIV recording (5 s), the longest period that can be identified is about 0.61 s. The enclosed areas represent events of temporal coherence within the statistical significance of $\alpha \leq 5\%$, which

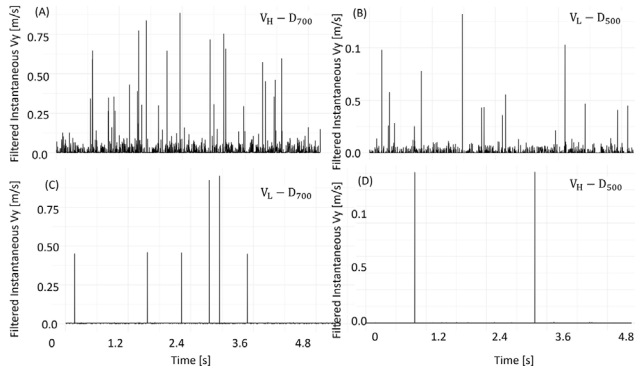


Fig. 10. Periodicity of sweep events observed in the near-wall region for the indicated flow conditions revealed by filtering positive values of V_y .

is naturally consistent with the number of sweep events represented in terms of temporal occurrence $V_y > 0$ in Fig. 10. The high-magnitude events are revealed by the wavelet analysis to be characterised by relatively short duration, and the duration of the sweeps is longer for events occurring with lower periodicity (longer periods). In the case of higher velocity and smaller particles ($V_H - D_{500}$), there are only two events observed. In the case of larger particles at both velocities ($V_H - D_{700}$ and $V_L - D_{700}$), there is one event of constant intensity occurring with the same periodicity (ca. 0.61 s) for an extended duration, ca. 2 s and 1.5 s, respectively. In all cases, most of the events have a characteristic time of duration (vertical features), whereas a characteristic periodicity is found only in flows with larger particles (horizontal features), indicating that maintaining a homogeneous suspension of larger particles is more difficult.

The frequency of high coherence events is consistent with the concentration profiles shown in Fig. 5B. In the case of the lower velocity and smaller particles ($V_L - D_{500}$), there is a higher concentration of particles in the near-wall region, leading to increased interactions at low velocity V_y . However, there are still some periodic events with high velocity. In contrast, when the particles are larger ($V_L - D_{700}$), there are fewer events compared with the smaller particles ($V_L - D_{500}$), but similar periodicity in high-velocity events. These observations evidence how the different flow conditions and particle size influence the periodicity and intensity of sweep events, which are directly related to erosive wear. The interaction of larger particles results in higher kinetic energy transfer per sweep event but occurs less frequently, highlighting the balance between impact intensity and frequency across various flow conditions as shown in Fig. 12.

The energy transfer from sweeps is evidenced by the presence of the wear scars produced by particle impingements on the pipe wall. In turbulent pipe flow, large-scale motions (LSMs) extend from the outer region toward the wall, where they interact with near-wall structures and generate sweep events. These sweeps carry high-momentum fluid and entrained particles downward, which result in erosion, i.e., surface deformation or cutting, when sufficient inertia is conveyed by the particles as explained schematically in Fig. 11. This dynamic process links the structure of turbulence to surface damage through intermittent but energetically significant events. The impact velocities calculated from the depth of the wear scars are consistent with those obtained from UPIV. The range of particle impact velocities measured by UPIV, however, is generally broader than those determined from the wear scars. This discrepancy can be attributed to the energy dissipation of the mechanical system. Higher impact velocities result in a wider range due to greater energy dissipation, while lower velocities may not cause damage because the impact deformation occurs within the elastic region of the target material or the resulting damage is not detectable by the measurement tool.

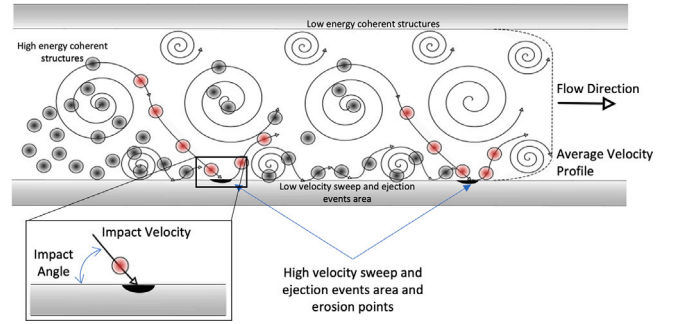


Fig. 11. Conceptual illustration of coherent flow structures in a turbulent particle-laden pipe flow. High-energy structures generate sweep events capable of entraining particles and projecting them onto the wall with sufficient velocity to cause wear. In contrast, low-energy structures may also generate sweeps, but with insufficient energy to produce significant material damage. The figure also describes the particle impact velocity and impact angle relative to the pipe's wall.

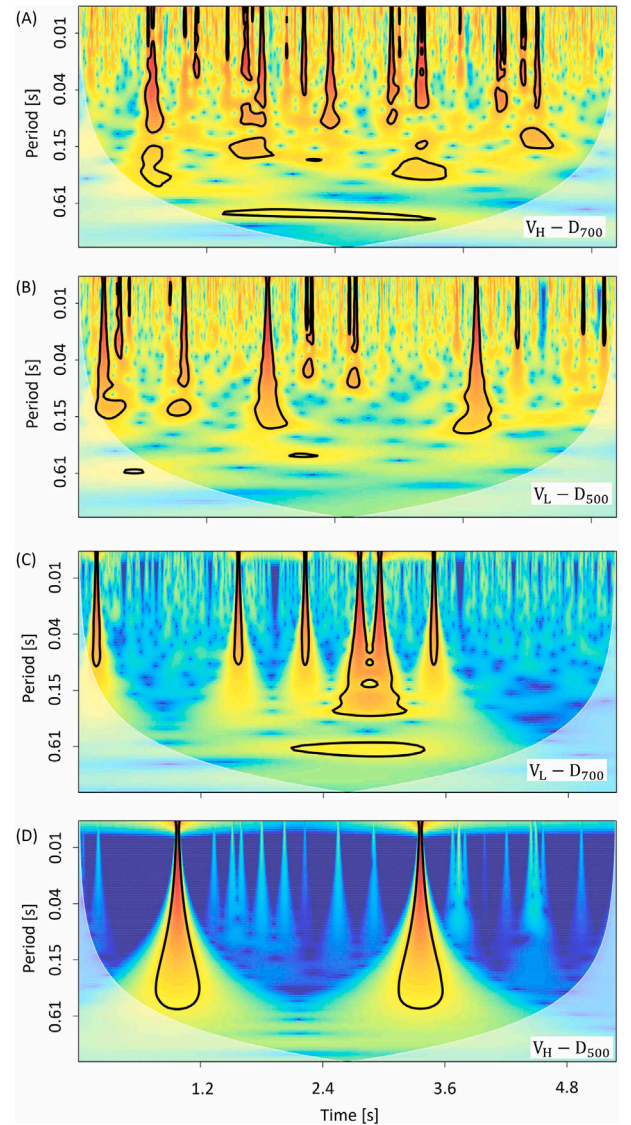


Fig. 12. Wavelet analysis of time evolution of V_y showing periodicity and duration of sweep-containing events for the indicated flow conditions (A–D). The heat map indicates the relative magnitude of V_y associated with a given periodicity and duration.

The share of energy transferred from the flow into the target surface is relevant for erosive wear and the values found in our work are generally consistent with literature data on similar systems. Sekar and Bennett reported that up to 87% of the central line velocity can be transferred as sweep [15,26] and Smiths et al. found that sweeps, together with ejections, may correspond to 70% of all coherent flow structures. [23].

4.3. Conditions for erosive wear

Only some of the sweeps produce measurable wear. For low velocity and smaller particles ($V_L - D_{500}$), the flow profile tends to be more uniform and it is significantly altered by particle size (Fig. 4C). The lower average velocity observed in the velocity profiles compared to the corresponding flow rate values (Figs. 4A and B) can be attributed to the fact that whereas the profiles represent the velocities of the abrasive particles, the flow meter measures the total volume of both phases. Consequently, the particles are concluded to be slower, which can be expressed by a slip ratio lower than 1. This ratio between the solid particle velocity and the fluid velocity when < 1 indicates deceleration of the solid phase with respect to the carrier fluid observed in some multiphase systems due to difference in inertia.

Previous numerical studies, e.g., Messa et al. [45], have demonstrated how the average velocity of the solid phase profile is related to the particle concentration profile. In this study, Fig. 5 exhibits similar behaviour in the average solid phase concentration profile, particularly in the near-wall region (pixels 500 through 680 in Fig. 5), where differences between experimental runs can be identified. The conditions of higher velocity and large particles ($V_H - D_{700}$) and low velocity and smaller particles ($V_L - D_{500}$) are extremes of factor combinations but the resulting profiles of solid phase concentration are similar in shape and values in the near-wall region. This similarity can be explained by the high concentration of large particles at the bottom of the pipe in the case of $V_H - D_{700}$, which may temporarily reduce the effective cross-sectional area due to the formation of a particle bed, which would increase the velocity of the liquid phase and consequently enhance the drag on particles in that area.

Particle size and global flow velocity significantly influence the flow pattern, which in turn affects the conditions for erosive wear by the temporal evolution of particle impact angle and impact velocity, which are the fundamental parameters in most erosion models [46]. The general capacity of small particles to interact with the fluid turbulence, in particular, to remain trapped in the near-wall eddies and impinge against the wall multiple times, has been discussed by Parsi et al. [47]. However, to the best of our knowledge, this interaction was not shown for the case of turbulent erosion wear in straight pipes in which the turbulent flow causes particles to interact with the pipe wall in a more distributed manner, resulting in varying impact angles and velocities. This complexity is less pronounced in elbows, where the flow pattern leads to more consistent and directed impacts, simplifying the wear analysis [48,49]. Therefore, a comprehensive study of turbulent erosion wear in straight pipes is essential to accurately model and predict erosion rates and patterns in these environments.

4.4. Relevance of sweep events for turbulent erosive wear

Sweep events emerge directly from turbulent behaviour, representing a form of order translating the chaotic nature of the flow in an ordered process of wear, giving rise to the concept of “turbulent erosive wear”. Analysing these coherent structures provides information on the angle and velocity of particle impacts, which characterise the turbulent flow and determine the extent of erosive wear. The significance of sweep events rests on their ability to convey particles onto the target surface with sufficient kinetic energy to cause wear. Both the frequency of sweep events and the amount of energy conveyed per event are thus relevant.

Fig. 10 presents evidence of the recurrence of high-impact velocities associated with sweep events. The repeated peaks in the radial (wall-perpendicular) velocity signal near the wall indicate localised bursts of downward momentum transfer, consistent with the signature of Q4-type sweep events [29]. These events are driven by coherent structures such as large-scale motions (LSMs), which intermittently transport high-momentum fluid from the outer region toward the wall. The temporal recurrence and spatial localisation of these peaks across all runs suggest a statistically robust mechanism of particle–wall interaction driven by turbulent structures. On the other hand, Fig. 9 compares the impact velocity and impact angles as measured directly in the near-wall region with equivalent values inferred by inverse analysis of wear scar morphology, showing similarities but also differences in the two independent data sets. The ranges of the measured values are generally comparable, but there is a marked minimum measured value observed in the data inferred from wear scars, which is not observed in the values determined by UPIV. This minimum value, i.e., the threshold value, is not the same for the different flow conditions. For instance, scars measured at higher velocity and larger particles ($V_H - D_{700}$) exhibit a higher threshold value of both impact angle and normal impact velocity as compared to those obtained at lower velocity and smaller particles ($V_L - D_{500}$). This observation is indicative of the threshold to be determined by the flow condition rather than the precision of the method. Also, the hypothesis of erosive wear to be determined by coherent flow structures, in addition to direct particle–wall interactions, is thus supported.

The recurrence of high-impact velocities shown in Figs. 10 and 12 demonstrates the temporal coherence in the evolution of velocity over the measured time range. Because the evolution of high-impact velocities is not a random effect, the observation of sweeps could be, in principle, used for increasing the precision of modelling and predicting erosive wear. Such models would rely on the calculation of energy carried by each particle from the impact velocity and particle mass, which is transferred to the target surface and divided into restitution energy from elastic deformation and energy lost due to plastic deformation and heat dissipation. Analysing such data would enable the development of new erosion models in which characterisation of sweep events would be essential.

4.5. Limitations

This exploratory study provides experimental basis for linking sweep events with erosion wear. There are several limitations that should be kept in mind when projecting the results to other flow systems:

- Spatial inference of velocity fields. The velocity patterns observed by UPIV and those determined on the copper section, located further downstream along the test line and on which UPIV cannot be performed, are assumed to be statistically equivalent. This introduces uncertainty that should be considered in further studies.
- UPIV resolution and range. The limited spatiotemporal resolution and penetration depth of the UPIV system restricts the ability to capture the entire spectrum of turbulent structures (across the diameter). Future work should aim to enhance the temporal and spatial resolution and explore alternative imaging modalities.
- Dimensionality of flow field. In this study only one transducer was used providing data in a single one plane. However, coherent structures are 3D in nature, which could be addressed by including additional transducers.
- Projection to actual wear rate. The present work focuses on single-event impact analysis rather than cumulative wear rate quantification. Surface evolution due to progressive erosion was not tracked over time. Experiments of extended duration and time-resolved erosion assessment would be necessary to develop an erosion model suitable for incorporation in a CFD framework.

- Narrow particle size distribution. The use of a single particle size range limits the identification of critical thresholds for erosion. Expanding the study to include different sizes, concentration and particle morphology is necessary to project the studies for real slurries.
- Sample-induced flow disturbance. Although the sample preparation was carried out with high mechanical precision, slight surface imperfections may have altered the local turbulence characteristics near the wall.
- Flow rate stability. The pumping system exhibited periodic variations in flow rate, which could have introduced unintentional flow pattern fluctuations. Since the analysis of erosion is closely tied to these flow dynamics, this could affect the repeatability of certain observations.

5. Conclusions

In this study, flow structures of turbulent slurry containing abrasive particles were studied by ultrasound particle image velocimetry (UPIV) and compared with the actual wear scars caused by the particles carried by the flow. Analysis of the obtained results allows to conclude that:

- The method of UPIV is applicable to characterise the flow of abrasive particles carried by a turbulent flow at velocities relevant to the transport of mining slurries. In particular, both the distribution of abrasive particles and their flow field can be measured with sufficient spatial and temporal resolution to directly visualise burst events, in particular sweeps.
- The presence of sweep events leading to wear was demonstrated in the near-wall region by wavelet analysis of the UPIV data and evidenced by the formation of wear scars of topography consistent with the impact of solid particles rather than abrasive sliding.
- The flow rate in the pipe and the size of the erosive particles do affect the formation of coherent flow structures. In this study, higher velocity and smaller particle sizes resulted in a smaller number of sweep events with sufficient energy to cause wear.
- The values of minimum impact velocity and impact angle resulting in measurable wear scar are determined by the flow structures rather than by the precision of optical profilometry, which is evidenced by the dependence of the respective threshold values on the flow condition. In particular, the lowest threshold of the normal velocity component was observed for the slower flow of smaller particles in which, on time average, a higher concentration of particles was observed near the target surface.

This work has shown that in a straight section of a pipe, turbulent erosion is a distinctive mechanism of wear governed by the formation of coherent flow structures. The direct observation of such structures, in particular sweeps, by UPIV could be used to develop advanced erosion models that account for this wear mechanism. However, the study presents certain experimental constraints, such as the use of a single target material, a limited range of particle sizes, and the absence of long-term wear tracking. While the observed flow structures and their correlation with erosion are consistent and physically grounded, further research involving extended tests, enhanced measurement resolution, and broader parameter ranges is necessary to deepen the understanding of turbulent erosion and strengthen its application in the surface engineering of erosion-resistant materials and structures.

CRedit authorship contribution statement

Ariel Espinoza-Jara: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Magdalena Walczak:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding

acquisition, Formal analysis, Data curation, Conceptualization. **Gianandrea Vittorio Messa:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Wernher Brevis:** Writing – review & editing, Supervision, Resources. **Alessandro Pascone:** Validation, Resources, Methodology, Investigation. **Cristina Tedeschi:** Writing – review & editing, Supervision, Resources, Methodology.

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.

Acknowledgments

This research was funded by ANID (Agencia Nacional de Investigación y Desarrollo de Chile) through the grant FONDECYT Regular 1241722. The authors extend special thanks to the Erosion-LAB group for the many constructive discussions, particularly to Edwin Bone, Millaray Araya, and Dr. Igor Wilk. Additional gratitude is owed to the “Gaudenzio Fantoli” Hydraulics Laboratory of DICA PoliMi, especially to Prof. Stefano Malavasi, Ing. Gianluca Crotti and the entire support team, for their invaluable assistance and collaboration in sample preparation and laboratory support. Finally, the support provided by the Telemed Italy team during the laboratory measurements is deeply appreciated.

Data availability

Data will be made available on request.

References

- [1] C. Belvederesi, M.S. Thompson, P.E. Komers, Statistical analysis of environmental consequences of hazardous liquid pipeline accidents, *Heliyon* 4 (11) (2018) e00901, <http://dx.doi.org/10.1016/j.heliyon.2018.e00901>.
- [2] J.W. Calderón-Hernández, A. Sinatorra, H.G. de Melo, A.P. Chaves, E.S. Mano, L.S. Leal Filho, J.L. Paiva, A.S. Braga, T.C. Souza Pinto, Hydraulic convey of iron ore slurry: Pipeline wear and ore particle degradation in function of pumping time, *Wear* 450–451 (November 2019) (2020) <http://dx.doi.org/10.1016/j.wear.2020.203272>.
- [3] M.A. Adegboye, W.-K. Fung, A. Karnik, Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches, *Sensors* 19 (11) (2019) 2548, <http://dx.doi.org/10.3390/s19112548>.
- [4] H. Yu, H. Liu, S. Zhang, J. Zhang, Z. Han, Research progress on coping strategies for the fluid-solid erosion wear of pipelines, in: *Powder Technology*, vol. 422, 2023, <http://dx.doi.org/10.1016/j.powtec.2023.118457>.
- [5] H. Clark, Particle velocity and size effects in laboratory slurry erosion measurements OR... do you know what your particles are doing? *Tribol. Int.* 35 (10) (2002) 617–624, [http://dx.doi.org/10.1016/S0301-679X\(02\)00052-X](http://dx.doi.org/10.1016/S0301-679X(02)00052-X).
- [6] M.A. Islam, T. Alam, Z. Farhat, Construction of erosion mechanism maps for pipeline steels, *Tribol. Int.* 102 (2016) 161–173, <http://dx.doi.org/10.1016/j.triboint.2016.05.033>.
- [7] V. Javaheri, D. Porter, V.T. Kuokkala, Slurry erosion of steel – Review of tests, mechanisms and materials, *Wear* 408–409 (2018) 248–273, <http://dx.doi.org/10.1016/j.wear.2018.05.010>.
- [8] A. Espinoza-Jara, I. Wilk, J. Aguirre, M. Walczak, An AI-extended prediction of erosion-corrosion degradation of API 5L X65 steel, *Lubricants* 11 (10) (2023) <http://dx.doi.org/10.3390/lubricants11100431>.
- [9] G. Truscott, A literature survey on abrasive wear in hydraulic machinery, *Wear* 20 (1) (1972) 29–50, [http://dx.doi.org/10.1016/0043-1648\(72\)90285-2](http://dx.doi.org/10.1016/0043-1648(72)90285-2).
- [10] B.E.A. Jacobs, *Design of Slurry Transport Systems* by B.E.A. Jacobs, Taylor & Francis Ltd, 2019.
- [11] P.P. Shitole, S.H. Gawande, G.R. Desale, B.D. Nandre, Effect of impacting particle kinetic energy on slurry erosion wear, *Journal of Bio- and Tribo-Corrosion* 1 (4) (2015) <http://dx.doi.org/10.1007/s40735-015-0028-6>.
- [12] O.E. Adediji, L. Zhang, D.E. Breakey, R.S. Sanders, Investigation of abrasive wear in contact load-dominated slurry flows using a toroid wear tester, *Wear* 477 (2021) <http://dx.doi.org/10.1016/j.wear.2021.203767>.
- [13] J. Aguirre, M. Walczak, Multifactorial study of erosion-corrosion wear of a X65 steel by slurry of simulated copper tailing, *Tribol. Int.* 126 (2018) 177–185, <http://dx.doi.org/10.1016/j.triboint.2018.04.029>.

- [14] R. Kuruvila, S.T. Kumaran, M.A. Khan, M. Uthayakumar, A brief review on the erosion-corrosion behavior of engineering materials, *Corros. Rev.* 36 (5) (2018) 435–447, <http://dx.doi.org/10.1515/corrrev-2018-0022>.
- [15] A. Sekar, A.R. Bennet, A comprehensive review on synergistic and individual effects of erosion-corrosion in ferrous piping materials, *Corros. Rev.* 41 (4) (2023) 399–416, <http://dx.doi.org/10.1515/corrrev-2022-0063>.
- [16] R. Visintainer, V. Matoušek, L. Pullum, A. Sellgren, Stratification of slurry flow and deposition of solids in pipes, in: *Slurry Transport using Centrifugal Pumps*, Springer International Publishing, Cham, 2023, pp. 81–114, http://dx.doi.org/10.1007/978-3-031-25440-6_4.
- [17] J. Jiang, M.A. Islam, Y. Xie, M.M. Stack, Some thoughts on modeling abrasion-corrosion: Wear by hard particles in corrosive environments, *Journal of Bio- and Tribo-Corrosion* 10 (1) (2024) 12, <http://dx.doi.org/10.1007/s40735-023-00811-3>.
- [18] Y. Yuan, J. Chen, H. Gao, Surface profile evolution model for titanium alloy machined using abrasive waterjet, *Int. J. Mech. Sci.* 240 (2023) <http://dx.doi.org/10.1016/j.ijmecsci.2022.107911>.
- [19] L. Han, C. Guo, F.K. Osman, D. Li, H. Wang, Y. Liu, D. Qin, Effect and mechanism of erosion in Pelton turbine and case studies-A review, *Phys. Fluids* 36 (3) (2024) <http://dx.doi.org/10.1063/5.0191051>.
- [20] G.V. Messa, S. Malavasi, The effect of sub-models and parameterizations in the simulation of abrasive jet impingement tests, *Wear* 370 (2017) 59–72, <http://dx.doi.org/10.1016/j.wear.2016.10.022>.
- [21] R.J.K. Wood, T.F. Jones, J. Ganeshalingam, N.J. Miles, Comparison of predicted and experimental erosion estimates in slurry ducts, *Wear* 256 (9–10) (2004) 937–947, <http://dx.doi.org/10.1016/j.wear.2003.09.002>.
- [22] R.J.K. Wood, T.F. Jones, N.J. Miles, J. Ganeshalingam, Upstream swirl-induction for reduction of erosion damage from slurries in pipeline bends, *Wear* 250 (2001) 770–778, [http://dx.doi.org/10.1016/S0043-1648\(01\)00715-3](http://dx.doi.org/10.1016/S0043-1648(01)00715-3).
- [23] A.J. Smits, B.J. McKeon, I. Marusic, High-Reynolds number wall turbulence, *Annu. Rev. Fluid Mech.* 43 (Volume 43, 2011) (2011) 353–375, <http://dx.doi.org/10.1146/annurev-fluid-122109-160753>.
- [24] M. Alletto, M. Breuer, Prediction of turbulent particle-laden flow in horizontal smooth and rough pipes inducing secondary flow, *Int. J. Multiph. Flow* 55 (2013) 80–98, <http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.04.009>.
- [25] G. Su, J. Zhang, Failure analysis of erosion wear of the pipeline after 30° elbow by adsorbent particles, *Eng. Fail. Anal.* 166 (2024) 108883, <http://dx.doi.org/10.1016/j.engfailanal.2024.108883>.
- [26] K. Meyer, J. Westerweel, Advection velocities of flow structures estimated from particle image velocimetry measurements in a pipe, *Exp. Fluids* 29 (S) (2000) S237–S247, <http://dx.doi.org/10.1007/s003480070026>, 3rd International Workshop on Particle Image Velocimetry, Santa Barbara, California, September 16th–18th, 1999.
- [27] K.-T. Wu, C.W. Tsai, M.-J. Wu, Probabilistic characterisation of sweep and ejection events in turbulent flows and its implications on sediment transport, *Water Resour. Res.* 58 (5) (2022) <http://dx.doi.org/10.1029/2021WR030417>.
- [28] J. Jeong, F. Hussain, W. Schoppa, J. Kim, Coherent structures near the wall in a turbulent channel flow, *J. Fluid Mech.* 332 (1997) 185–214, <http://dx.doi.org/10.1017/S0022112096003965>.
- [29] D. Fiscaletti, R. de Kat, B. Ganapathisubramani, Spatial-spectral characteristics of momentum transport in a turbulent boundary layer, *J. Fluid Mech.* 836 (2018) 599–634, <http://dx.doi.org/10.1017/jfm.2017.841>.
- [30] A. Abdelbary, *Extreme Tribology: Fundamentals and Challenges*, CRC Press, 2020, URL <https://books.google.cl/books?id=SmrIDwAAQBAJ>.
- [31] A. Espinoza-Jara, M. Walczak, W. Brevis, G.V. Messa, Erosion by turbulence: Discovering the counter-wise vortex events and their effect on wear, *Wear* (2023) 204988, <http://dx.doi.org/10.1016/j.wear.2023.204988>.
- [32] C. Poelma, Ultrasound imaging velocimetry: a review, *Exp. Fluids* 58 (1) (2016) 3, <http://dx.doi.org/10.1007/s00348-016-2283-9>.
- [33] A. Gurung, C. Poelma, Measurement of turbulence statistics in single-phase and two-phase flows using ultrasound imaging velocimetry, *Exp. Fluids* 57 (11) (2016) 171, <http://dx.doi.org/10.1007/s00348-016-2266-x>.
- [34] C. Tan, Y. Murai, W. Liu, Y. Tasaka, F. Dong, Y. Takeda, Ultrasonic Doppler technique for application to multiphase flows: A review, *Int. J. Multiph. Flow* 144 (2021) 103811, <http://dx.doi.org/10.1016/j.ijmultiphaseflow.2021.103811>.
- [35] F. Ahmadi, M. Ebrahimi, R.S. Sanders, S. Ghaemi, Particle image and tracking velocimetry of solid-liquid turbulence in a horizontal channel flow, *Int. J. Multiph. Flow* 112 (2019) 83–99, <http://dx.doi.org/10.1016/j.ijmultiphaseflow.2018.12.007>.
- [36] N. Molina, M. Walczak, M. Kalbarczyk, D. Celentano, Erosion under turbulent slurry flow: Effect of particle size in determining impact velocity and wear correlation by inverse analysis, *Wear* 474–475 (2021) 203651, <http://dx.doi.org/10.1016/j.wear.2021.203651>.
- [37] G.V. Messa, Y. Wang, M. Negri, S. Malavasi, An improved CFD/experimental combined methodology for the calibration of empirical erosion models, *Wear* 476 (2021) 203734, <http://dx.doi.org/10.1016/j.wear.2021.203734>.
- [38] E. Bone, A. Espinoza-Jara, M. Walczak, I. Lira, W. Brevis, Ultrasound particle velocimetry: Validation and limitation for monitoring erosion by opaque abrasive particles, *Int. J. Multiph. Flow* (2024).
- [39] J. Cheng, N. Zhang, L. Wei, H. Mi, Y. Dou, A new phenomenological model for single particle erosion of plastic materials, *Materials* 12 (1) (2019) <http://dx.doi.org/10.3390/ma12010135>.
- [40] W. Thielicke, R. Sonntag, Particle image velocimetry for MATLAB: Accuracy and enhanced algorithms in PIVlab, *J. Open Res. Softw.* (2021) <http://dx.doi.org/10.5334/jors.334>.
- [41] R.A. Antonia, Conditional sampling in turbulence measurement, *Annu. Rev. Fluid Mech.* 13 (1981) 131–156, <http://dx.doi.org/10.1146/annurev.fl.13.010181.001023>.
- [42] N. Aubry, P. Holmes, J.L. Lumley, E. Stone, The dynamics of coherent structures in the wall region of a turbulent boundary layer, *J. Fluid Mech.* 192 (1988) 115–173, <http://dx.doi.org/10.1017/S0022112088001818>.
- [43] R. Kellnerová, L. Kukačka, Š. Nosek, V. Uruba, K. Jurčáková, Z. Jaňour, Wavelet analysis of the turbulent flow over the very rough surface, *EPJ Web Conf.* 67 (2014) 02051, <http://dx.doi.org/10.1051/epjconf/20146702051>.
- [44] A. Guo, D. Floryan, M.D. Graham, Self-similar, spatially localised structures in turbulent pipe flow from a data-driven wavelet decomposition, *J. Fluid Mech.* 971 (2023) A9, <http://dx.doi.org/10.1017/jfm.2023.639>.
- [45] G.V. Messa, Q. Yang, M.G. Rasteiro, P. Faia, V. Matoušek, R.C. Silva, F. Garcia, Computational fluid dynamic modelling of fully-suspended slurry flows in horizontal pipes with different solids concentrations, *KONA Powder Part. J.* 40 (2023) 219–235, <http://dx.doi.org/10.14356/kona.2023008>.
- [46] A.M. Lospa, R.G. Ripeanu, A. Dinita, Erosion modelling: a systematic review of available models and equations, *IOP Conf. Ser.: Mater. Sci. Eng.* 724 (2020) 012037, <http://dx.doi.org/10.1088/1757-899x/724/1/012037>.
- [47] M. Parsi, K. Najmi, F. Najafifard, S. Hassani, B.S. McLauri, S.A. Shirazi, A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications, *J. Nat. Gas Sci. Eng.* 21 (2014) 850–873, <http://dx.doi.org/10.1016/j.jngse.2014.10.001>.
- [48] Y. Wang, X. Wang, P. Shang, Z. Xu, Q. Huang, A numerical study of the slurry erosion in 90° horizontal elbows, *J. Pipeline Sci. Eng.* 4 (1) (2024) 100149, <http://dx.doi.org/10.1016/j.jpse.2023.100149>.
- [49] L. Ba, R. Fu, J. Wang, H. Ma, B. Xiao, Experimental research on influence of pipeline wear in high-density solid waste backfill, *Discov. Civ. Eng.* 2 (1) (2025) 73, <http://dx.doi.org/10.1007/s44290-025-00237-5>.