Chapter

Erosion-Corrosion in Pipe Flows of Particle-Laden Liquids

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Abstract

The transmission of particle-bearing liquids in pipes has motivated continuing research into erosion mechanisms and the distribution of erosion rates over wetted surfaces. This chapter covers these initiatives with particular reference to erosion-corrosion modelling within bends and straight sections of cylindrical pipes manufactured in a variety of materials and transporting a variety of liquids. Erosion-corrosion modelling techniques such as submerged slurry jets and rotating cylinder electrodes have been used to study factors influencing material degradation. Improvements in computational fluid dynamics (CFD), such as the development of a moving deforming mesh (MDM) have improved the accuracy of CFD models in predicting pipe wall erosion rates. Combined discrete phase tracking approaches such as the CFD-DPM-DEM (discrete phase-discrete element model) have helped improve computational efficiency. Wall impact erosion models are calibrated using laboratory scale tests. Validation of CFD models using full-scale test data is rare, meaning their accuracy is still largely unreported. Material testing has helped to identify the resilience of prospective pipeline materials to erosion-corrosion, while modifications to internal geometry and pipe section have shown potential to improve erosion-corrosion resistance.

Keywords: erosion-corrosion, computational fluid dynamics, pipelines, slurry, modelling, state-of-the-art

1. Introduction

Erosion-corrosion (E-C) is recognised as one of the most significant threats to the integrity of pipelines carrying fluids mixed with solid particles. It affects numerous industries including mining, oil and gas, power generation and sediment transport. Marine, aero and food production industries are also affected [1]. Pipework, turbines, pump components and valves can all become heavily damaged by E-C. Improper management can lead to loss of productivity, unplanned downtime, or complete component failure, with obvious environmental and safety concerns. Erosion-corrosion is said to be the primary cause of fluid leakage in pipelines and is estimated to cost the Canadian oil sands industry $1bn a year in damages [2, 3]. Owing to its importance within industry, the field of erosion-corrosion has enjoyed plentiful research over several decades.

Material type	Angle of impingement		
	<20°	**45°**	**90°**
Elastic	No effect	Negligible	Surface deformed
Ductile	"Cutting" wear dominates	Mixed regime	Deformation wear dominates
Brittle	Negligible	Intermediate	Maximum

Table 1.
Material response to solid particle impact (adapted from [7]).

Since the first focused work on theoretical mechanisms at least 28 different erosion equations have been proposed, including a total of 33 different parameters [4]. Erosion rate is defined as the rate of mass loss from a surface due to particle impingements. The response of pipeline materials to solid particle impacts depends on the nature of the target material and the treatments to which that material has been subjected. Environmental parameters such as flow velocity [5], pressure [6], temperature, impact angle, solid particle concentration, size and shape are also known to influence erosion [7]. The influence of impact angle depends on the mechanical characteristics of the pipe material. Brittle materials such as ceramics experience maximum erosion at impact angles of 90°. In ductile materials, cutting wear dominates at low impact angles (<20°) while deformation wear is most prominent at high impact angles [7]. This is summarised in **Table 1**.

Finnie [8] suggested that the volume loss due to erosion was proportional to the square of velocity. This comes because kinetic energy is likely the dominant factor governing erosion. Despite this, values of the exponent have been reported between 0.34 and 4.83 [9]. This variation has likely come in part due to difficulties accurately determining the impact velocities of particles in laboratory experiments. Other parameters that affect this number are particle size and its shape. The roundness of particles is often described using the circularity factor (CF). In perfectly spherical particles this factor is equal to 1, reducing as particles become more angular. It has been found that the circularity factor and erosion rate hold an inverse power law relationship [10]. A similar relationship has been found for particle size, with the exponent value quoted ranging between 0.2–4.0 depending on test conditions [9]. The behaviour of particles entrained within a flow is described by the Stokes number. Particles with Stokes numbers close to 1 tend to follow streamlines of the continuous phase. In flows with higher stokes numbers, particle motion is largely inertia-dominated and wall collisions are more likely, leading to increased erosion rates [11]. Particles of higher hardness are known to cause higher erosive wear, although the ratio of particle to pipe hardness is perhaps the more important factor governing erosion rate [12].

Corrosion is an electrochemical process, caused by the interaction of the conveying fluid with the pipe material. As was the case with erosion, corrosion strongly depends on the nature of the pipe material. It has been found that the combined effects of erosion and corrosion can lead to significantly higher material loss rates than the summation of both processes separately [13, 14]. In the past decade, most erosion-corrosion research has been driven by the oil and gas industry. However, additional sectors have also been subject to investigation. In recent years, erosion-corrosion has been studied in concentrating solar power systems [15], engine cooling systems [16], fertiliser/mineral processing [14, 17] and geothermal power generation

[18] to name a few. The focus of research in these fields has been varied. Influencing factors such as pipe material, geometry and flow conditions have been studied. Methods of studying E-C due to particle-laden fluids can be broken down into pipeline tests, laboratory simulations and numerical simulations. The first two methods were reviewed in by Vahid Javaheri et al. [9]. Numerical simulation using computational fluid dynamics (CFD) was reviewed in 2014 by Mazdak Parsi et al. [19], and later by Messa et al. [20] in 2021. Recent developments in erosion-corrosion research were reviewed in 2017 [1]. This chapter will review developments in the modelling and management of erosion-corrosion subsequent to these works. The scope of this work will be limited to E-C of pipelines containing liquid-solid flows. Three-phase, gas-liquid or gas-solid flows will not be considered.

2. Numerical and laboratory scale modelling

2.1 Laboratory techniques

After the review in [1], various researchers have published work in which the erosion-corrosion behaviour of pipeline materials has been tested. Owing to their existing popularity, pipeline steels have been the focus of the majority. Due to their low cost, compact size, easy setup and short test durations, bench-scale laboratory tests are the most popular method for investigating E-C. Of these, the jet impingement test and slurry pot testers are the most popular techniques used today [9]. Other techniques used include the submerged jet impingement test [17, 21], pin-on-disk test [22], electrode cells [23] and rotating cylinder electrode [24] to name a few. Aside from the latter two techniques, these experimental methods have been recently reviewed in [9, 25].

Submerged jet impingement tests are a popular means of testing different materials. Results from jet tests are commonly used to calibrate erosion models in CFD packages, as will be discussed later in this chapter. While the high velocities required make the method unsuitable for simulating erosion in real pipelines, they are a valuable tool for evaluating material performance [9]. For example, Karafyllias et al. [17] used a submerged direct impact jet to investigate the performance of two stainless steels (UNS S31600 and UNS S42000) and two white cast irons (27WCI and 37WCI). Tests were carried out in a neutral and acidic (pH 3) environment. They found that the austenitic grain structure of the UNS S31600 and WCI37 samples better-resisted corrosion at pH 3. At neutral pH, the increased hardness of both WCI alloys led to increased erosion resistance over the softer stainless steels. Their tests were carried out at 90° impact angles and 21 m/s jet velocities. This limits the applicability of the results to real-world scenarios where a wide range of slurry velocities and impact angles are common. Using a similar methodology, Brownlie et al. [18] investigated the performance of various engineering materials for use in geothermal power generation. The performance of three grades of stainless steel, a carbon and low-alloy steel, Inconel 625 and Ti-6Al-4 V were evaluated. They found that low-carbon and low-alloy steels are especially vulnerable to erosion-corrosion at shallow impingement angles. Inconel 625 and super austenitic stainless steel UNS S31254 exhibited the greatest E-C resistance. Cathodic protection was employed and found to have a profound effect on erosion rate, reducing volume loss due to E-C of low alloyed ATSM A470 Grade C steel by nearly 6 times. Mostafa et al. [26] investigated the wear rate of HDPE as a function of impact velocity and angle using slurry impingement tests.

Impact angles between 30 and 90° were studied at velocities of 4, 5 and 6 m/s. The erodent particles were silica sand. Mass change measurements were used to quantify material loss from target samples. Erosion was found to peak at impact angles around 45–50° and increased proportionally with slurry velocity.

The popularity of the slurry pot apparatus is owed to the ease at which the influence of slurry velocity, concentration and impact angle can be studied on sample materials. By substituting test specimens, the performance of different materials can be easily evaluated. However, hydrodynamic differences limit this method's ability to predict erosion rates within real-world pipe flows [9].

Chung et al. [27] used a slurry pot tester to study E-C in a variety of different pipeline steels. API 5 L X65, X70 and X80 steels were compared with ASTM A1053 dual phase stainless steel and AR400 hard plate. Tests were carried out at two speeds and dissolved oxygen levels. The steels were characterised using electron microscopy, X-ray, micro-mechanical probing, and electrochemical testing techniques. At the lowest oxygen level (0.6 ppm) corrosion was mainly suppressed. At high oxygen levels and slurry velocities, dual-phase stainless steel suffered enhanced damage to its passive film and E-C resistance decreased. They concluded that E-C resistance is a function of a combination of mechanical properties including hardness, strain hardening capability, ductility, toughness, and deformation before failure. The high E-C resistance exhibited by AR400 was attributed to its finer microstructure (when compared to the X series steels) obtained after the tempering and quenching process. The author recommended the use of fine micro-structured steels for slurry transport.

A slurry pot tester was also used by Singh et al. [28]. They investigated the influence of particle type and circularity factor on erosion wear of stainless steel (SS 316L). Samples of fly ash, bottom ash and sand were compared. Particle characteristics were measured using digital image processing on SEM images. It was discovered that the value of erosion wear decreased with the circularity factor. The relationship between erosion rate and circularity factor appeared to follow the inverse power law. The exponent value was predicted as 2.668 for multisized slurry.

Rotating disk/cylinder electrode systems are a popular choice for those wishing to establish the effect of flow velocity and solid concentration on corrosion in pipeline steels. Aguirre et al. [24] used a rotating cylinder electrode (RCE) to investigate the mechanism of corrosion-accelerated erosion in carbon steel API 5 L X65 in alumina slurry doped with mineral quartz. Tests were carried out at different fluid velocities and dissolved oxygen (DO) concentrations. SEM and electron backscatter diffraction (EBSD) inspection was used to analyse surface wear patterns. DO availability increased the wear rate of steel. It was proposed that plastic deformation due to particle impingements increased the formation of anodic/cathodic sites to an order of magnitude larger than the original impact site. This led to further increases in corrosion rate.

A multifactorial study by the same author [29] used similar apparatus to investigate the influence of velocity, particle concentration, temperature, pH, dissolved oxygen, and copper ion content on E-C in pipes of the same material. Sample degradation was measured using a combination of gravimetric techniques and surface morphology measurement using SEM imaging and energy dispersive X-Ray spectroscopy (EDX). Also using an RCE, Molina et al. [30] assessed the directionality of wear scars at different velocities when API 5 L X65 steel is exposed to quartz slurry. This was done by applying Fast Fourier Transform (FFT) to SEM images. They found that patterns in erosion wear scars could be successfully identified. Implementation of this technique could be used to enhance understanding of erosion wear.

Using combined wire beam and coupon electrodes, Xu et al. [23] investigated the influence of pre-corrosion on E-C in X65 pipeline steel. Pre-corrosion is common in pipelines where residual moisture is present following pressure testing. While they found that the E-C rate was similar in pre-corroded and non-pre-corroded samples, their findings cannot be extended beyond X65 steel.

2.2 Numerical methods

Computational fluid dynamics (CFD) is a popular method of wall impact erosion modelling in particle-laden fluids. Erosion modelling procedures generally follow three steps: First, the continuous phase is resolved. The motion of elements within the discrete phase is then calculated. Finally, by using element motion in the near wall region estimates of material removal due to collisions can be generated at each wall node. By following this procedure, detailed erosion maps can be generated for geometry analysis [2]. While CFD simulations can yield highly detailed results, their accuracy has come under scrutiny in many papers [31]. The main sources of uncertainty lie within accurately modelling particle wall impact behaviour and estimating the material loss due to particle wall impingement. Particle tracking has also proven difficult and computationally expensive. Two main methods of multiphase modelling exist in CFD packages today. An overview of each is provided below.

2.2.1 Eulerian-Eulerian approach

The Eulerian-Eulerian methodology, often referred to as the two-fluid model, treats both phases equally. This approach is computationally efficient and allows models containing numerous phases to be resolved. The downside of the Eulerian approach is that individual particle motion cannot be calculated. This limits the use of the Eulerian-Eulerian approach in erosion modelling. Despite this, the approach remains useful in applications where high solid concentrations are present or when the coupling between the fluid-particle or particle-particle is important [3].

2.2.2 Eulerian-Lagrangian approach

The Eulerian-Lagrangian formulation allows the trajectories of particles within the discrete phase to be tracked. As before, the carrier fluid (continuous phase) is modelled following the Eulerian framework. To model the erosion process in turbulent flows, steady state Reynolds-averaged Navier-Stokes (RANS) equations have been combined with a variety of turbulence models to simulate fluid flows [32]. This approach has been used somewhat successfully over the past couple of decades [2, 33]. While the RANS approach can be used to establish the time-averaged erosion characteristics of a particle-laden fluid, it is unable to establish the unsteady nature of turbulent flows being modelled. To simulate unsteady properties of pipe flows such as the evolution of vortices and recirculation, large eddy simulation (LES) algorithms have been developed. A detailed description of LES can be found in [32]. The performance of both algorithms has been evaluated. Wang et al. [34] studied erosion in pipe elbows using an LES Euler-Lagrange model. Results obtained using the RANS and LES were compared. Results were verified using experimental results taken from [35]. Good agreement between velocity profiles predicted by the LES method and experimental values was noted. In comparison, the RANS method was found to overpredict the fluid velocity in the near-wall region. The increased accuracy of the LES model was attributed to its ability to model the unsteady secondary flow at the inner radius.

The Lagrangian framework resolves the motion of particles based on a translational force balance for each entity. The Discrete Phase Model (DPM) tracks the movement of particles through the continuous phase. In the DPM each modelled entity represents a 'parcel' of particles having similar dynamic properties [36]. Another approach to particle tracking is the Discrete Element Method (DEM). Unlike the DPM, individual particles are tracked and their equations of motion solved. The benefit of this method is that information related to inter-particle collisions can be calculated using the 'soft sphere' approach, making the DEM suitable for flows with high solid concentrations. The applicability of the DPM is limited to solid concentrations where the influence of inter-particle collisions can be neglected. Wang et al. [2] found the influence of inter-particle collisions to be negligible at solid concentrations up to 5.37% wt., while Kloss et al. [37] limited their use of DPM modelling to below 5% by volume. Lagrangian inter-particle collision models have been used in [38, 39] to extend the range of applicability to higher concentrations of solid particles. However, their use remains limited due to the increased computational burden and the number of difficult-to-estimate parameters these models rely on [40].

Coupling between the DEM and DPM has been proposed to improve the accuracy of the CFD-DPM approach without the full computational expense of the CFD-DEM method. Kloss et al. [37] used the CFD-DPM-DEM approach to model the dispersed phase in air-particle flows. They showed that the simulation speed of various systems using DEM could be significantly increased by switching to the DPM methodology in regions of low particle concentration without a significant effect on the results of the simulation. By extending this technique to solid-liquid flows the ability of CFD packages to model regions of high concentration could be improved.

2.3 Advancements in CFD

2.3.1 Flow modelling

It is widely accepted that erosion is a time-dependent process. The formation of wear scars takes time to develop and is most severe in areas with highly disturbed flows (such as in elbows, contractions, and tees). It is known that deformations to wall geometry can modify the flow field and cause changes to the local erosion rate. Despite this, most CFD packages assume that cavities formed are insignificant to the flow field. This assumption can lead to significant errors in erosion field calculations, especially in areas with sharp geometrical changes. López [41], Dong [42] and Agrawal et al. [43] all proposed modifications to CFD solvers to dynamically change wall geometry based on the local erosion rate.

A López et al. [41] utilised open source CFD software OpenFOAM. Surface erosion was calculated using built-in functions to establish an erosion vector for each point on the surface. This material loss was used to calculate the change in the shape of the solid surface. The geometry of the solid surface was modified by moving points of the mesh depending on the material loss magnitude. This process was repeated at regular intervals, with the flow field being re-calculated at each instance.

Using commercial CFD software Ansys Fluent, Dong et al. [42] proposed a methodology using a dynamically deforming mesh to model the deformed surface profile due to material erosion. Material removal was converted into a wall deformation using a user-defined function (UDF) within Fluent. As in [41], the mesh was updated at regular time intervals. The flow field was updated according to the new deformed wall shape. Their methodology was implemented in the erosion modelling of an economizer bank used in coal-fired power plants. A good agreement between the erosion profile predicted using the CFD model and the on-site test sample was noted. By utilising the CFD model, the evolution of erosion profile and particle trajectories could be seen. While their results appeared promising, no comparison to CFD models without the moving mesh approach was made, meaning the accuracy increase with their methodology cannot be quantified.

Similarly, Agrawal et al. [43] developed a moving-deforming-mesh (MDM) model within CFD software Ansys Fluent. The mesh deformation was calculated using UDFs within the software. Based on the local erosion rate, the geometry of the solid wall and its computational mesh were updated at regular time intervals. The flow field was recalculated following each update. It was found that the dynamically changing flow fields were able to capture the development of flow features which were not present in the undeformed model. Their approach proved capable of predicting secondary erosion features not present in non-MDM CFD models. Agrawal concluded that the effect of the MDM was most pronounced at sharp geometrical features (such as changes in section or elbows) where erosion caused significant changes to the flow field. A case study of a mitre-bend was used to illustrate the differences between models with and without the MDM algorithm.

Additional challenges in CFD modelling come when trying to calculate particle motion near solid boundaries. For erosion estimates to be accurate, the motion of the particle must be equivalent to that found in real-world scenarios. Different researchers have tried to investigate near wall effects and rebound characteristics of the discrete phase. Issues in particle motion and rebound modelling were demonstrated by Karimi et al. [31]. From their review of literature, it was found that CFD packages over-estimated the true rate of erosion. They found that modelling errors led to small particles becoming trapped in eddies in the near wall region, leading to multiple wall impacts. This non-physical behaviour was thought to contribute to some of the over-estimates commonly seen in CFD modelling. It was found that more realistic erosion estimates could be obtained by limiting the number of impacts a given particle to one. It was concluded that current rebound models are not simulating small particle behaviour after wall impacts correctly. More work is therefore required in this area.

2.3.2 Wall erosion modelling

Accurately turning wall impingements into an estimate of material loss is perhaps the biggest challenge in CFD erosion modelling. The process is highly complex, and research is still ongoing to understand the exact mechanisms behind erosion. Since the 1990s computational methods have been used to simulate erosive wear [44]. Erosion modelling using the Finite Element Method (FEM) has been successfully implemented to produce fairly accurate results [44–47]. The advantage of FEM is that erosion is calculated directly from material properties and the underlying physics. The drawback of this method is that it is limited to domain sizes at the same scale of the particles and for only a handful of collisions. This limits its use in CFD packages where both the scale and number of collisions are orders of magnitude higher.

The approach taken by CFD modellers is to disregard the physics at the micro-scale, instead focusing on the macroscale model encompassing the domain of interest. Trajectories and velocities of particles are calculated. Material removal due to wall impingements is estimated using empirical relationships derived from jet impact test results. While popular due to the ease at which such relations can be incorporated into CFD packages, the validity of the results is limited. Empirical relations fail to account for the variation of particle size in naturally occurring materials and the non-linearity of the erosion process. Jet impact tests are carried out at higher velocities than most fluid flows, meaning that relationships drawn are often outside of the experiment's calibration range. Also, as was noted in the introduction, relations derived from experiments vary massively depending on methodology and test conditions. Even with careful application, it is not certain that test results are representative of the environment to be modelled.

Leguizamón et al. [47] proposed a multi-scale approach to surface erosion modelling. They created a database of physically determined micro-scale erosion results, calculated using the FEM approach. Particle collisions were modelled under a variety of conditions. These results were used to calculate material loss due to collisions within a macroscale model. The main benefit of this method is that erosion rates are based on detailed impact simulations as opposed to experimentally determined erosion correlations. To ensure the accuracy of this method a reliable and comprehensive set of erosion tests were carried out at the microscale. Validation results proved encouraging with significant improvements in accuracy over correlation-based approaches. Unfortunately, the proposed approach comes at a massive computational expense meaning that the method is unfeasible for full-scale modelling.

An alternative approach to improve the accuracy of wall material removal models was proposed by Mansouri [48] and later modified by Messa et al. [40]. Their solution consisted of an upgraded CFD/experimental methodology to calibrate coefficients used in the empirical erosion models based on slurry jet impingement tests. The slurry jet tests were performed on aluminium and curved glass reinforced epoxy samples. One-way coupling was used in the simulation owing to the relatively low volume fraction of solid. This was done to reduce the computation time as the trajectories of fluid parcels could be decoupled from the solution of the carrier fluid flow. The CFD simulation was carried out using ANSYS FLUENT and particle trajectories were calculated using the Lagrangian method. Modifications to the CFD code were implemented to account for the influence of particle shape on particle-wall impingement characteristics. Additionally, to reduce uncertainty due to the point-particle approximation, impact characteristics were evaluated at half of the particle diameter from the wall. This methodology was originally proposed by Messa and Wang [49], who found that a region of high drag near the wall resulted in an underestimation of impact velocity. An improvement in the reliability of CFD-based erosion predictions was noted. It was concluded that the method represented a practical compromise in the prediction of erosion using empirical models without the need for modelling at the micro-scale.

Wee et al. [11] sought to improve erosion damage prediction of CFD approaches by implementing the Rosin Rammler particle size distribution model. Simulations were carried out using Ansys Fluent 17.2. Two-phase flow and particle wall interactions were solved using the Euler-Lagrange model. Simulations were carried out using both water-sand and air-sand flows, to compare the influence of carrier-fluid on erosion rate. Results from the CFD simulation were compared with experimental results. Implementation of the Rosin Rammler particle size model reduced the error in CFD results from between 6.81–24.31% and below 5% for all test cases. Erosion wear was found to be up to 97.44% lower when using water as the carrier fluid. This is because sand particles follow the streamlines in the water much better than air, as characterised by their respective Stokes numbers.

2.4 Studies using CFD

To reduce costs associated with erosion damage in sections of pipeline, many have turned their attention to optimising pipe geometry. Changes in cross-section, curvature and internal profile have all been suggested as methods of reducing E-C [50]. Internal ribs, a vortex chamber and twisting sections have been found to reduce erosion in elbows by modifying flow conditions within the pipe. However, in all these studies only gas-solid mixtures were considered. Li et al. [50] used a CFD-DEM simulation to model the influence of wall shape on wear rates in the vicinity of a pipe bend. The working environment consisted of a two-phase flow with particle concentrations of 1–10% and 1–3 mm in diameter. By adding a solid protrusion to the internal surface of the bends outer radius at the region at which particles first contact the wall it was found that the wear rate could be reduced significantly. The 'bump' reduced the kinetic energy of particles entrained in the flow and the number of times particles collide with the wall. The effectiveness of the bump in reducing wall wear was subject to other factors, including particle size, flow velocity and mass flow rate of particles.

Okhovat et al. [51] used a combined mathematical and CFD approach to model erosion-corrosion in straight and contracted pipe sections. COMSOL Multiphysics v3.5a was used to model fluid flow, while corrosion rate was determined as a function of oxygen concentration in the near wall regions. The pipe geometry used was a converging-diverging section, with an inlet diameter of 38.6 mm, contraction diameter of 21.2 mm and outlet diameter of 42.5 mm. When compared with experimental results, erosion estimates using the CFD model offered reasonably good agreements in the inlet and contracted region, but significantly underpredicted E-C in the expanded (downstream) section. This was put down to the momentum model used. Although the effects of both erosion and corrosion were predicted, their synergism was assumed negligible, which would likely have led to an underprediction of the true material loss rate.

It is not uncommon for the results of CFD simulations to be combined with experimental work. Many have used this approach to verify results from experimental tests. For example, More et al. [52] investigated the influence of impact angle on erosion wear in mild steel pipelines handling coal ash slurry. Findings from CFD simulations were verified against slurry pot test results. Impact angles ranged between 7 and 90°. All tests were carried out at slurry velocities of 4 m/s. While similar trends between impact angle and erosion rate were noted, CFD simulations were found to underpredict erosion rate by an average of 21%. The author suggested that difficulties exactly replicating the nature of coal ash particles in the CFD simulation may have attributed to this error. An underprediction of impingement velocity, or miscalculation of flow regime could have also attributed to this error. Speculatively, it could in part be due to inaccuracies in fluid models used by the CFD solver.

CFD has been used to model the influence of particle size on erosion rate. As part of his PhD thesis, Braut [36] studied the influence of nano-sized particles on erosion. CFD studies were carried out using commercial software STAR-CCM+ and verified using experimental data. Particle size varied between 1 and 500 μm. Erosion rate was found to increase with particle diameter, despite a larger number of particles at smaller diameters. This was put down to higher kinetic energies of larger particles. Erosion pattern was also found to change with particle size. It was suggested that this was because smaller particles were more affected by the fluid flow, as they had lower inertia.

Li et al. [53] used combined results from CFD and experimental testing to establish the effect of large particles on pipe erosion. The particles used were 3 mm in diameter at mass concentrations from 1 to 15%. An aluminium sheet was fixed to the inside of the test bend to establish the erosion profile. The resulting profile was found to be corrugated, a result of the 'bouncing' of the particles along the bends outer radius. The size of this 'erosion ripple' was found to be dominated by the concentration of solid particles. The observed periodic wave pattern was found to be consistent with that predicted by the numerical model.

Using a submerged impingement jet, Owen et al. [21] investigated the influence of impingement conditions on erosion-corrosion of X65 carbon steel. Particle trajectories within the jet were predicted using COMSOL Multiphysics CFD software. Impact angles and velocities of particles in the jet were predicted. Within the impingement zone, sites with differing degradation mechanisms were identified. The synergy between erosion and corrosion was investigated. Under these test conditions (60°C, pH 4.7 2% NaCl solution, 1 g/L sand particles at 20 m/s) corrosion-enhanced erosion was found to be much more significant than erosion-enhanced corrosion.

3. Full scale experimental and *in-situ* monitoring techniques

3.1 Recirculation tests

Closed loop pipeline recirculation rigs are a popular choice for those looking to accurately replicate industrial conditions. Tests are conducted within specimen sections which can be inspected periodically. Various techniques have been used to investigate E-C damage within the specimen section. For example, Wood et al. [54] used a combination of gravimetric, ultrasonic thickness and diameter measurements taken using a ball-ended micrometre to quantify material loss within stainless steel test sections. The latter two measurements allowed for damage mapping across the wetted area, which showed good agreement with results from a CFD model, demonstrating that their method could be used to predict erosion damage patterns within pipe sections.

Owen et al. [55] developed a 3D printed pipe elbow to aid with prototyping and flow mapping within pipe sections. Multiple samples of X65 carbon steel were inserted into the elbow. Mass loss measurements at each sample location were used to map erosion damage across the sample section. While their results showed reasonable agreement with those expected from existing literature, it is questionable if their methodology provides any benefit over that used by Wood et al. [54] for the following reasons: the samples were only installed on the inner and outer radius of the elbow, so are incapable of detecting erosion to the elbows sides; it is not certain that the 3D housing, its material, and the geometry of the samples in the housing accurately replicate the flow in real elbows. No measurement of material loss from the housing was provided, so changes in flow condition due to housing erosion could not be ruled out. Rebound characteristics from the 3D printed housing may also be different to a full steel elbow and could affect erosion rates downstream of the first particle-wall impingement. With this being said, due to the ease of 3D printing, this method may be of use in rapid prototyping applications. It also allows for rapid substitution of test material samples for comparison tests.

Elemuren et al. [14] used a continuous recirculation rig with four 1018 steel 90° elbows to investigate the influence of slurry velocity on E-C. A slurry of potash brine with silica sand was used. Gravimetric measurement was used to quantify mass loss from each elbow. The synergy between erosion and corrosion was investigated by comparing results from separate erosion (deoxygenated potash brine w/10% wt. solid) and corrosion (saturated potash brine w/0% wt. solid) tests. It was found that the synergy decreased with slurry velocity, reducing by 45% between 2.5 m/s to 4 m/s. At high velocities, surface impingement became the dominant mechanism of material loss. Erosion-corrosion was found to be a function of solid concentration and flow velocity.

Regions in which flow trajectories are severely altered are found to be the most prone to erosion damage. Such areas include tees, elbows, and contractions, where changes in flow direction mean entrained particles are more likely to cross streamlines and contact the solid walls. Bilal et al. [56] investigated the influence of pipe geometry on wear due to water-sand and water-air-sand flows in pipe bends. They aimed to investigate alternative geometries to standard 90° elbows, where the curvature radius is equal to 1.5 times the pipe diameter, *D*. Geometries of 2.5D and 5D along with a 45° elbow with a radius of 1.5D were investigated. Numerical studies were carried out using commercial CFD code ANSYS FLUENT. Results from the CFD study were compared against experimental results. The inner surfaces of acrylic pipe bends/elbows were painted with black paint primer. Solid particles entrained in the flow remove the paint from the internal surfaces and allow erosion patterns to be observed. The tests were run until no further change occurred in the paint pattern. This gave a qualitative indication of which pipe geometry is least susceptible to erosion. It was found that smoother transitions in pipe geometry reduced erosion rates as particles are less susceptible to hitting pipe walls. Additionally, smaller changes in direction (45°) led to lower erosion. Generally, CFD results were found to corroborate the experimental paint removal study. An exception to this was that CFD failed to predict some of the secondary erosion patterns downstream of elbows. Wall function (modelling of flow in the near wall boundary region) was also found to affect the observed erosion patterns, producing a secondary hotspot on the inside of the elbow that wasn't present in the paint removal study. This was put down to be an artefact of the turbulence model used.

In industry, a wide range of pipe geometries are used in a variety of orientations. It is known that erosion properties can be quite different depending on the orientation of a section. Reportedly, most studies examining erosion in elbows have placed the sections in the horizontal-vertical configuration. Wang et al. [2] studied the effect of orientation on erosion in pipe elbows in the horizontal-horizontal configuration. Two elbows connected in series were analysed. Additionally, the effect of particle concentration and inlet conditions were also examined. CFD simulations were verified against experimental results. The effect of gravity became less noticeable, and the erosion profile became more symmetric across the pipe section as inlet velocity increased. The downstream elbow was found to be severely influenced by the flow profile exiting the previous elbow. The distance between the two had a significant influence on this effect.

To accurately model pipeline decay in real-world operation, factors outside those discussed above should be considered. External factors such as human, geotechnical, and natural hazards are all known to pose a risk to pipeline integrity [57]. External corrosion related to environmental conditions is known to be one of the most significant factors governing pipe life. Methods of monitoring and inspecting pipelines were reviewed in [58]. The same article proposed a risk-based integrity management model.

Yang et al. [6] carried out a performance investigation for slurry erosion in high-pressure hydraulic fracturing pipelines. Unlike other papers which studied slurry erosion, the effects of tensile stress induced due to internal/external pressure was considered. Additionally, the effects of impact angle, particle velocity and concentration, and target material were also considered. Results from an experimental study were used to develop a random forest regression (RFR) algorithm to develop an erosion prediction model for fracturing pipelines. A jetting circulating erosion test rig was used to apply adjustable tensile stress on the specimen during erosion. Test samples consisted of 4 different hypereutectoid steels. The effect of impact angle was evaluated on a sample of unstressed 42CrMo steel. Erosion wear was found to reach its maximum at an impact angle of 30°. At low angles, micro-cutting was found to be the prominent erosion mechanism, while plastic deformation caused erosion at higher impact angles. Erosion rate was found to be proportional to tensile stress. At 30° the increase was approximately 70% between 0 and 500 MPa, while it nearly doubled for the same stress range at impact angles of 90°. This is due to a lower yield force under high stresses being more easily overcome by the kinetic energy of impacting particles.

3.2 *In-situ* damage monitoring

Online condition monitoring (OCM) allows for the health of critical components to be continuously monitored. OCM systems generally rely on an array of sensors linked to a processing device to display output parameters to the user. Readings can be used to schedule repairs and detect early signs of failure, reducing costs of manual inspection and safety/economic implications of unplanned downtime. The benefits of OCM are numerous and its implementation has become common practice in several industries. Liu et al. [59] proposed a system to allow for the online monitoring of metal loss in pipelines. Ring pair electrical resistance sensor (RPERS) arrays were used to monitor erosion loss around the diameter of the pipe, while linear polarisation resistance (LPR) was used to measure the corrosion rate in a pipe ring. Electronic measurements were compared to weight loss measurements. The X65 steel test pipe was embedded in a recirculation rig, and CFD studies were used to calculate flow distribution and sand concentration in the section. LPR, RPERS and gravimetric measurements showed good agreement for this configuration. It should be noted that the results cannot be generalised as they only relate to the specific configuration and conditions used.

4. Conclusion

Erosion-corrosion research in the past decade has been dominated by application-specific studies. Most of these papers have focused on comparing different materials or pipe geometries under specific flow conditions. Laboratory testing techniques such as slurry pot testers or electrode cells can be used to provide an understanding of factors influencing E-C within several materials. Due to the differences between laboratory and in-service conditions, the applicability of results obtained to real-world scenarios should be checked.

It is well known that pipe geometry has a significant effect on erosion rate. Despite this, relatively little research has been done to investigate alternative pipe geometries. Work by Li et al. [50] exploring the influence of internal bumps in a pipe elbow showed that erosion rate could be reduced with well-designed internal surface modifications. This could be implemented in particularly vulnerable pipe sections and should be explored further. As demonstrated by Wang et al. [2] pipe orientation and flow conditions entering pipe elbows can heavily influence the resulting erosion pattern. Despite this, few papers focus on the role of pipe geometry upstream of subject sections on erosion. By altering the upstream configuration, it is conceivable that one could alter the erosion pattern to increase component lifetime with relatively little difficulty. Perhaps this could be the subject of future work.

Recent improvements in the area indicate a promising future for CFD erosion modelling. Improved impact models, dynamically deforming geometry and more accurate particle tracking have all helped improve the accuracy of CFD erosion predictions. Despite these advancements, more work is required before CFD can be heavily relied upon. Errors in near-wall erosion models have been identified and require rectification. Loosely representative empirical erosion models are still heavily relied upon for wall erosion modelling and limit the applicability of the technique for a wide range of materials. While CFD-DEM allows the modelling of more dense slurry flows, the computational expense limits its use to small-scale modelling. To reduce computational expense, coupled DEM-DPM appears promising, but its application to liquid-solid flows is yet to be thoroughly explored.

List of abbreviations

E-C	erosion corrosion
DO	dissolved oxygen
CFD	computational fluid dynamics
EBSD	electron backscatter diffraction
SEM	scanning electron microscopy
EDX	energy dispersive X-ray spectroscopy
RCE	rotating cylinder electrode
RANS	Reynolds averaged Navier-Stokes
LES	large eddy simulation
DPM	discrete phase model
DEM	discrete element model
MDM	moving-deforming-mesh
UDF	user defined function
FEM	finite element model
CF	circularity factor
FFT	fast Fourier transform
OCM	online condition monitoring

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