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To cite this article: A M Lospa *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **514** 012009

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CFD Evaluation of sand erosion wear rate in pipe bends used in technological installations

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Abstract. In this paper are presented the results of the CFD analysis evaluations performed by the authors to determine the erosion rate in pipe bends used in technological installations that circulate fluids together with a small percentage of solid particles under the form of sand. The pipe bends that were analysed have different curvatures and diameters and the same wall thickness. The CFD analysis is focused on determining the areas where the erosion occurs together with the erosion rate values. The main area where erosion occurs is at the pipe bend extrados. The differences that have been noticed are influenced by the pipe bend type, as the maximum erosion rate increases as the bend curvature increases. The research will continue with designing an experimental test rig for erosion testing to compare the CFD and experimental program results.

1. Introduction

Erosion has been long recognized as a potential source of problems in oil and gas production systems, being a complex process affected by multiple factors present in the operational conditions. Potential mechanisms that could cause significant erosion damage are, [1]:

- Particulate erosion;
- Liquid droplet erosion;
- Erosion-corrosion;
- Cavitation.

Particulate erosion is defined as the loss of material or loss of material integrity as a result of solid particle impact on the material surface. A minimum tolerance for erosion needs to be considered when designing oil and gas production systems. This can be done by setting an acceptable erosion rate, based on which the remaining target service life of the system and the system maintenance costs can be computed, [2].

According to Venkatesh, [3], the most vulnerable parts of production systems are the components in which flow direction changes suddenly, high flow velocities caused by high volumetric flow rates are present or high flow velocities caused by flow restrictions are present.

Some of the most important factors that need to be taken into consideration when determining the rate of particulate erosion are, [1, 4]:

- Fluid velocity – Material wear is a function of the fluid velocity by the means of a velocity exponent, n : $Wear = f(velocity)^n$;
- The mass of sand and the sand flowrate;
- The average sand particle size, its shape, sharpness and hardness;
- The fluid flow regime, fluid viscosity and density;



- The system design and configuration, the flow path profile and shape;
- The materials used for the piping system;
- The angle of impingement of the sand particles.

Extensive research on erosion has been carried out, based on which theoretical and empirical erosion models were developed, see Table 1.

Table 1. Theoretical and empirical erosion models.

Erosion Model	Mathematical expression	Description
Finnie and McFadden - Theoretical [5]	$V = \frac{c \cdot M \cdot U^2}{4P(1 + m \cdot r^2 / I)} \left[\cos^2(\alpha) - \left(\frac{x'_0}{U} \right)^2 \right]$	V is the volume removed from surface, M the mass of eroding particle, m the mass of individual particle, I the moment of inertia of the particle, r the average particle radius, the impact angle, U the particle impact velocity, P the horizontal component of flow stress, c the fraction of particles cutting in an idealized manner, x'_0 the horizontal velocity of the particle after cutting
Neilson and Gilchrist - Theoretical [6]	$\alpha \leq \alpha_0 : W = \frac{M}{2} \left(\frac{V^2 \cos^2(\alpha) \sin(n\alpha)}{\phi} + \frac{V \sin(\alpha) - K^2}{\varepsilon} \right)$ $\alpha \geq \alpha_0 : W = \frac{M}{2} \left(\frac{V^2 \cos^2(\alpha)}{\phi} + \frac{(V \sin(\alpha) - K)^2}{\varepsilon} \right)$ $E = \frac{W}{M}$	M is the mass of erosive particles, W the eroded mass produced by M at impact angle of and velocity of V , K the velocity component normal to the surface below which no erosion takes place in certain hard materials
ANSYS Fluent Standard – Theoretical [7]	$R_{erosion} = \sum_{p=1}^{N_{particles}} \frac{m_p \cdot C(dp) \cdot f(\alpha) \cdot v^{b(v)}}{A_{face}}$	$C(dp)$ is the particle diameter function, the impact angle of the particle, $f(\alpha)$ the impact angle function, the relative particle velocity, $b(v)$ the relative particle velocity function, A_{face} the area of the cell face at the wall. Default values: $C = 1.8E-09$, $f = 1$, $b = 0$.
McLaury and Ahlert - Empirical [8]	$ER = A \cdot F_s \cdot V^n \cdot f(\alpha)$ $\alpha \leq a : f(\alpha) = a \cdot \alpha^2 + b \cdot \alpha$ $\alpha > a : f(\alpha) = x \cdot \cos^2(\alpha) \cdot \sin(\alpha) + y \cdot \sin^2(\alpha) + z$	a, b, c, w, x, y, z are impact angle function constants $A = 1559HB - 0.59E-09$, HB is the Brinell Hardness
Tulsa – Empirical [9]	$ER = \frac{A \cdot F_s \cdot F_p \cdot V^n \cdot m}{D_p^2 \cdot B^b}$	A is a constant, F_s the sand sharpness correction factor, F_p the wall material penetration factor, B the material Brinell hardness, n the velocity exponent, D_p the pipe diameter, b the hardness exponent
Salama and Venkatesh – Empirical [10]	$ER = \frac{S_k \cdot V^2 \cdot m}{d_{pipe}^2}$	S_k is a geometry dependent constant, $S_k = 0.038$ for short radius elbows and $S_k = 0.019$ for ells and tees d_{pipe} is the diameter of the pipe, m the sand flow rate, V the particle impact velocity
Oka et al. – Empirical [11]	$E(\alpha) = g(\alpha) \cdot E_{90}$ $g(\alpha) = (\sin(\theta))^{n_1} \cdot (1 + H \cdot v (1 - (\sin(\theta))))^{n_2}$ $E_{90} = K \cdot (H \cdot v)^{k_1} \cdot \left(\frac{V_p}{V} \right)^{k_2} \cdot \left(\frac{D_p}{D} \right)^{k_3}$ $n_1 = s_1 \cdot (H \cdot v)^{q_1}; n_2 = s_2 \cdot (H \cdot v)^{q_2}; k_2 = 2.3 \cdot (H \cdot v)^{0.038}$	$K, k_1, k_2, k_3, s_1, s_2, q_1, q_2, n_1, n_2$ are constants and exponent values for particles material and targeted material

According to [12], the flow velocity should be the main factor used for design calculations. A threshold for the pipeline flow velocity, V_e [feet/sec], called the “erosional velocity”, should be set, indicating the velocity above which erosion may occur.

$$V_e = \frac{C}{\sqrt{\rho}} \quad (1)$$

where: C represents an empirical constant; ρ is the fluid mixture density [lbs/ft³].

Considerations related to the values for C , the empirical constant [12]:

- Conservative approach for solid-free fluids: $C = 100$ for continuous service and $C = 125$ for intermittent service;
- For solid-free fluids, where corrosion is not anticipated or is controlled: $C = 150 \dots 200$;
- Values up to $C = 250$ have been successfully used for intermittent services.

According to Salama and Venkatesh, [10], erosion in solids-free fluids occurs only at very high velocities. To avoid this, a value of $C = 300$ must be used.

Based on [2], particle erosion in pipe bends can be estimated with the following expression:

$$E_{L,y} = \frac{K \cdot F(\alpha) \cdot U_p^n}{\rho_t \cdot A_t} \cdot G \cdot C_I \cdot GF \cdot m_p \cdot C_{unit} \quad (2)$$

where: $E_{L,y}$ represents the annual surface thickness loss [mm/year]; K - the material erosion constant [(m/s)⁻ⁿ]; U_p - the particle impact velocity [m/s]; n - the velocity exponent ($n = 2.6$ for ductile steels); ρ_t - the density of target material [kg/m³]; A_t - the area exposed to erosion [m²]; G - the particle diameter correction function [-]; C_I - a model/geometry factor [-], GF - the geometry correction factor [-], m_p - the mass rate of sand [kg/s]; C_{unit} - the unit conversion factor (from m/s to mm/year) [-]; α represents the particle impact angle [°] and $F(\alpha)$ characterizes the ductility of the pipe bend material and has the following expression (the maximum erosion is experienced for impact angles of 20°... 50°) [-]:

$$F(\alpha) = 0.6 \cdot \left[\sin(\alpha) + 7.2 \cdot (\sin(\alpha) - \sin^2(\alpha)) \right]^{0.6} \cdot (1 - e^{-20\alpha}) \quad (3)$$

According to [2], the preferred option for complex piping configurations or for situations where the erosion location is of utmost importance, the preferred option is to run CFD erosion simulations.

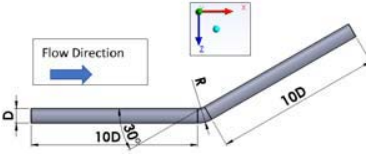
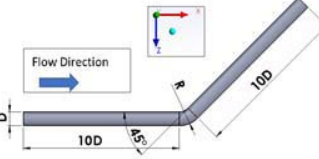
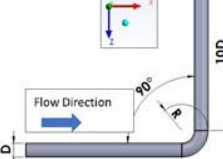
2. CFD Analysis

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to solve and analyse problems that involve fluid flows, [13]. A CFD analysis translates in solving the Reynolds averaged Navier-Stokes equations for a specified fluid domain, [2].

2.1. Geometric model

In order to evaluate the erosion impact on pipe bends, several configurations have been designed, taking into account different diameters and curvatures.

Table 2. Theoretical and empirical erosion models.

Bend Type	30° Bend	45° Bend	90° Elbow
Drawing			

Diameter (D_e), mm	76.1	88.9	114.3	76.1	88.9	114.3	76.1	88.9	114.3
Wall thickness, mm	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Bend radius, mm	95	114	152	95	114	152	95	114	152

The 9 bend configurations plus the specific dimensions can be seen in Table 2. Fluid flow enters through a straight section of $10D$ long, followed by a 30° , 45° or 90° bend section and continues through another $10D$ straight section.

Figure 1 shows the mesh details of the 30° , 45° and 90° bends for one of the diameters, $D_e = 114.3$ mm. Details about the number of cells and nodes of the mesh for all the bend configurations can be observed in Table 3.

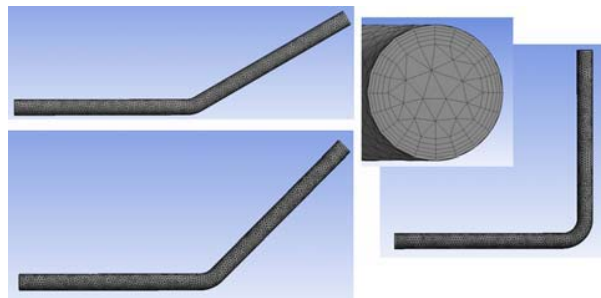


Figure 1. Mesh details for 30° , 45° and 90° pipe bends.

Table 3. Pipe bends mesh nodes and elements.

Bend Type	30° Bend		45° Bend		90° Elbow	
Mesh details	Nodes	Elements	Nodes	Elements	Nodes	Elements
$D_e=76.1\text{mm}$	22140	57168	22489	58199	22717	58191
$D_e=88.9\text{mm}$	21520	55609	22165	57196	22880	58958
$D_e=114.3\text{mm}$	21323	54970	21562	55701	22417	57872

2.2. Flow model

The problem is treated as the steady flow of water through the 9 bend configurations on the XZ horizontal plane, with gravitational effects included, $g = -9.8 \text{ m/s}^2$ on Y axis). The specified temperature is 20°C , water density $\rho = 998.2 \text{ kg/m}^3$ and viscosity $\eta = 0.001003 \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$. The flow velocity at the inlet on X direction is $U = 5 \text{ m/s}$.

A standard k - ϵ two equations turbulence model based on turbulence kinetic energy (k) and its dissipation rate (ϵ) transport equations is used to model the turbulence. The model is valid only for fully turbulent flows. Scalable wall functions are used to model the wall-bounded turbulent flows. The turbulence model is modified to enable the viscosity-affected region to be resolved with a mesh all the way to the wall, including the viscous sublayer, [7].

2.3. Simulation Conditions

The following parameters have been adopted for the boundary conditions:

- Inlet velocity - $U = 5 \text{ m/s}$;
- Solid Wall - wall roughness $R_a = 6.3 \text{ }\mu\text{m}$; Reflection coefficients are set as per [14]: 4 polynomial coefficients for the normal and tangent direction; Impact angle function as per [14]: 5 points piecewise linear; Diameter function $C(dp) = 1.8\text{E-}9$ as per [7]; Velocity exponent $n = 2.6$ as per [14];
- Outlet - Pressure Outlet.

2.4. Discrete phase modelling

The Euler-Lagrange approach is used to model the discrete phase. The fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles through the calculated flow field. The dispersed phase can exchange momentum, mass, and energy with the fluid phase, [7].

Sand is used as discrete phase, with a density of $\rho = 2500 \text{ kg/m}^3$, flow rate = 0.1 kg/s and a particle diameter of $1000 \text{ }\mu\text{m}$.

A Non-spherical Drag Law is used to model the non-spherical sand particles, [7]:

$$C_D = \frac{24}{\text{Re}_D} \cdot \left(1 + b_1 \cdot \text{Re}_D^{b_2}\right) + \frac{b_3 \cdot \text{Re}_D}{b_4 + \text{Re}_D} \quad (4)$$

where: C_D represents the drag coefficient and Re_D the Reynolds number.

The values for the b_1 , b_2 , b_3 and b_4 coefficients are calculated as follows:

$$b_1 = \exp(2.3288 - 6.4581\phi + 2.4486\phi^2) \quad (5)$$

$$b_2 = 0.0964 + 0.5565\phi \quad (6)$$

$$b_3 = \exp(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3) \quad (7)$$

$$b_4 = \exp(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3) \quad (8)$$

$$\phi = \frac{s}{S} \quad (9)$$

where: Φ represents the shape factor, s - the surface area of a sphere having the same volume as the particle and S - the actual surface area of the particle.

A value of $\phi = 0.9$ for the sand particle shape factor was adopted to run the CFD analysis.

3. Results and conclusions

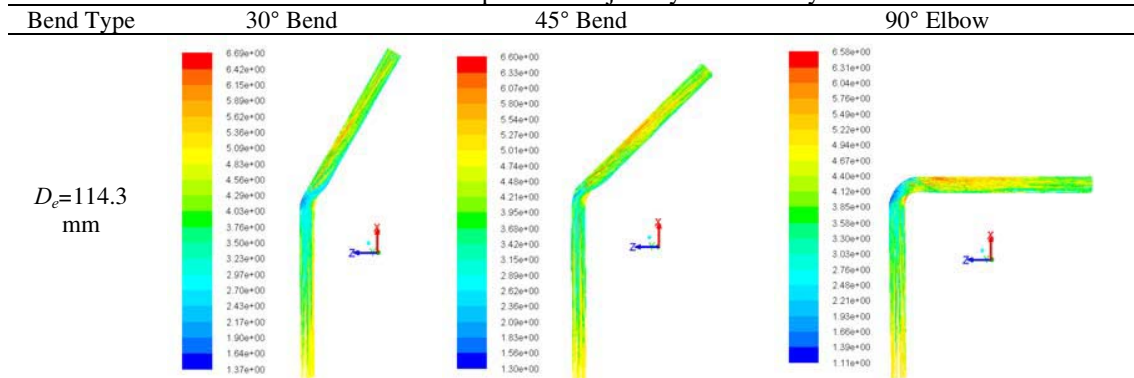
The maximum erosion rates in mm/year as per the CFD computation for steel pipe bends with density $\rho = 7850 \text{ kg/m}^3$ are shown in Table 4.

Table 4. Maximum erosion rates shown as mm/year.

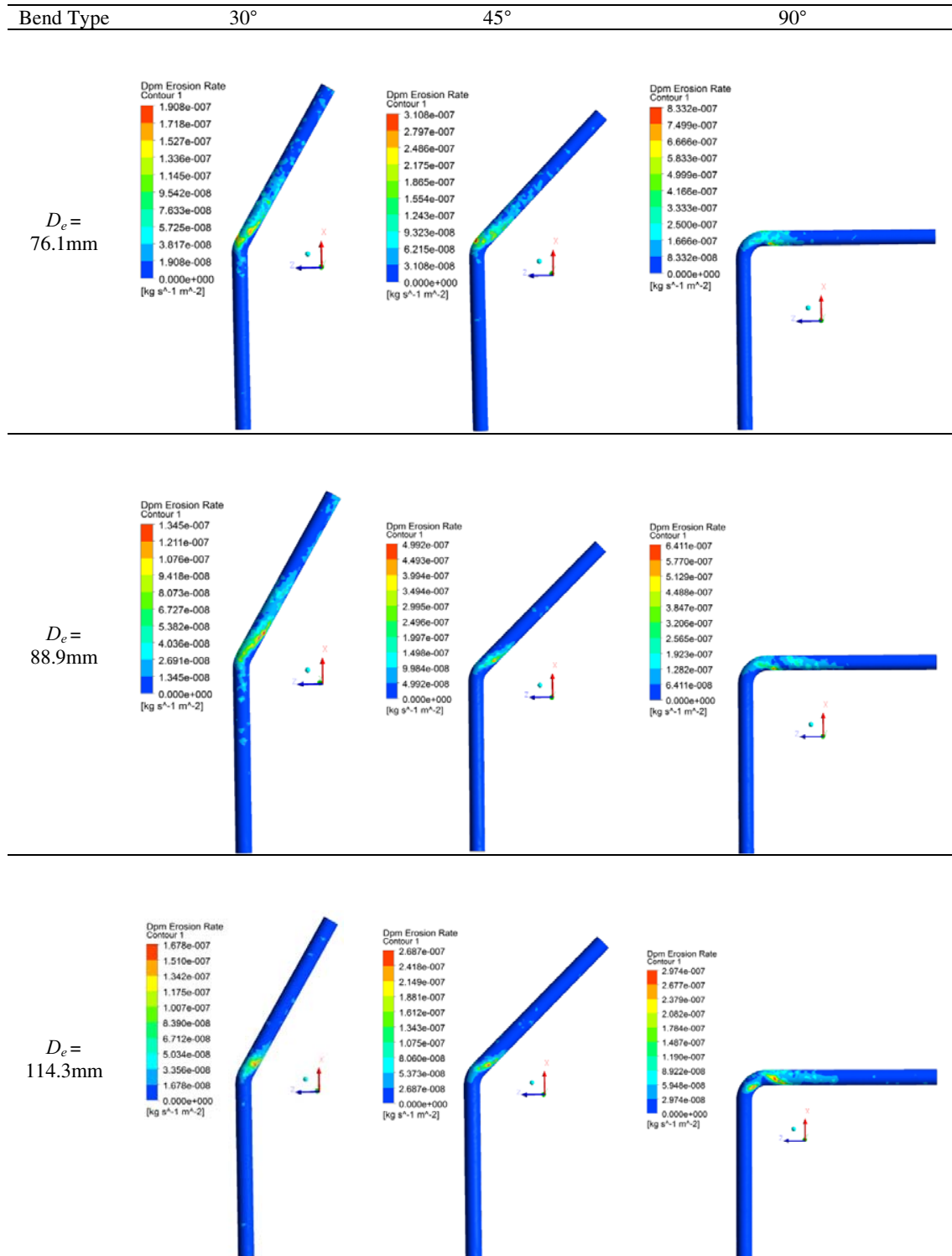
Bend Type	30°	45°	90°
$D_e = 76.1 \text{ mm}$	0.767 mm/year	1.25 mm/year	3.35 mm/year
$D_e = 88.9 \text{ mm}$	0.540 mm/year	2.01 mm/year	2.58 mm/year
$D_e = 114.3 \text{ mm}$	0.674 mm/year	1.08 mm/year	1.19 mm/year

The sand particle trajectories, together with the velocity magnitude, for the 30°, 45° and 90° bends, with $D_e = 114.3 \text{ mm}$ are presented in Table 5.

Table 5. Sand particles trajectory and velocity.



In Table 6, all the CFD simulation results for the 9 bend configurations are showcased.

Table 6. CFD Simulation Results – Erosion Rate.

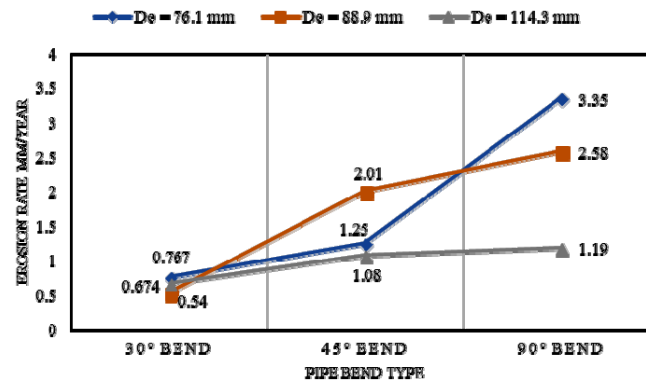


Figure 2. Maximum erosion rates based on bend types and diameters.

Simulation results are in good agreement with the experimental results of Bourgoyne [17] for 90° elbows conveying water and sand particles with an average diameter of 350 μm (see Table 7). Bourgoyne studied failure in diverter systems due to erosion produced by sand particles entrained in the flow stream. An experimental diverter system with various fittings was built to test and to compare erosion severity for different geometries (elbows and tees with a nominal diameter of 50.8 mm). The difference between simulation and experimental results is due to: different elbow diameters (76.1/88.9/114.3 mm vs. 50.8 mm), different sand flow rates (0.1 kg/s vs. 1.44/1.72/6 kg/s) and different sand particle diameters (1000 μm vs. 350 μm).

Table 7. Bourgoyne experimental data on erosion rate [17].

Geometry	r/D	U (m/s)	Sand flow rate (kg/s)	ER (kg/m ² s)	ER (mm/year)
Seamless elbow	1.5	9.45	1.44	3.42×10^{-9}	0.014 mm/year
Cast elbow	3.25	14.6	1.72	2.41×10^{-8}	0.1 mm/year
Cast elbow	3	11.5	6	3.49×10^{-9}	0.014 mm/year

Analysing the results from tables 4, 5 and 6, the following conclusion can be drawn:

- Maximum erosion rates are obtained for 90° bends, graphically shown in Figure 2;
- For 90° bends, the maximum erosion rate decreases as the pipe diameter increases;
- From a bend curvature perspective, the calculation is showing that the erosion rate increases as the bend curvature increases;
- After hitting the pipe bend wall, the sand particles are getting a swirl. The particles that are hitting the bend intrados are getting accelerated, the highest velocity increase being calculated for the 30° bend types;
- The working fluid type should be taken into consideration, for corrosive fluids the calculations need to account for erosion-corrosion;
- As next steps, the influence of the particle shape factor and the particle material type will be looked upon by the means of CFD analysis;

Experimental data availability for elbow erosion due to sand particles present in a liquid flow stream is quite rare based on the literature review performed by the authors. The research will continue

with designing and building of an experimental test rig for erosion testing to generate the experimental data to compare with the CFD simulation results.

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