Literature review relevant to particle erosion in complex geometries

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Abstract. Erosion is a challenge in many industries where fluid is transferred through pipe and valve arrangements. Wear can occur in a variety of systems and is often related to the presents of droplets or solid particles in the fluid stream. Solid particles are in many cases present in hydropower systems, and can cause severe damage to system components. Flow conditions, particle size and concentration vary greatly and can thus cause a vast variety of damage, ranging from manageable wear to component failure. The following paper will present a summary of literature relevant to the prediction of erosion in complex geometries. The intention of the review is to investigate the current state of the art, directly relevant to the prediction of wear due to solid particle erosion in complex geometries.

1. Introduction
An understanding of erosion patterns and rates is crucial for designing equipment that can manage challenging erosive flow conditions. Numerical analysis alone can be an adequate tool for predicting erosion rates, however, the quality and accuracy of such methods can be challenging to predict. Experimental methods are a powerful means of calibrating such models for specific geometries and flow conditions, furthermore give more precise predictions of wear and product lifetime.

By understanding the fundamentals of erosion, approaches to validation and application of erosion models, a method may be developed in order to accurately predict erosion rate in specific complex geometries. The following paper will present central literature relevant to identifying the main developments and focus of the current available research related to the prediction of erosion in complex geometries.

2. Mechanism of erosion
The erosion phenomenon is widely studied and several theories have been produced in order to describe the mechanisms that occur as particles impact and remove material from a surface. Based on the study of free moving particles and particle deformation upon impact, Bitter [1],[2], proposed a two-part representation describing the modes of wear. Deformation wear, \( W_d \), wear on surface due to particles impacting normal to the surface and Cutting wear, \( W_{C1}, W_{C2} \), due to particles impacting at an acute angle relative to surface. Deformation wear and cutting wear occurs, in most cases, simultaneously. It was identified that the cutting wear, is the dominating erosion in ductile materials, whereas deformation wear, is the dominating erosion in brittle materials. This is presented graphically in Figure 1 and Figure 2. According to Bitter [2], the plastic deformation of the surface occurs when the elastic limit of the surface material is reached as a result of repeated particle impact. In this process the surface is
deformed plastically and work hardened. As the area cannot deform any further the surface cracks and small fragments are detached. As particles impact on a surface at an acute angle, cutting wear can occur due to shear stress of the surface material being exceeded. Particle velocities are divided into two components, vertical and horizontal, relative to the surface. When velocity normal to the surface is large enough to plastically deform the surface layer, cutting and scratching can occur due to the addition of the horizontal particle velocity component. Bitter [1] divides cutting wear further into two equations dependent upon the velocity of the particle after impact. When horizontal velocity of the particle is present post impact, the erosion is represented by \( W_{C1} \). When the particle has no horizontal velocity after impact the erosion is represented by \( W_{C2} \). The total wear, \( W_t \), is defined as the sum of deformation wear and cutting wear \([2], [1]\).

\[
W_D = \frac{1}{2} \cdot M \cdot \left( V \cdot \sin(\alpha) - K \right)^2 \cdot \varepsilon
\]

\[
W_{C1} = \frac{2 \cdot M \cdot C (V \cdot \sin(\alpha) - K)^2}{(V \cdot \sin(\alpha))^{1/2}} \cdot \left( V \cdot \cos(\alpha) \cdot \frac{(V \cdot \sin(\alpha) - K)^2}{(V \cdot \sin(\alpha))^{1/2}} \cdot \varepsilon \right)
\]

\[
W_{C2} = \frac{1}{2} \cdot M \cdot \left[ V^2 \cdot \cos^2(\alpha) - K_1 \left( V \cdot \sin(\alpha) - K_2 \right) \right] \cdot \varepsilon
\]

\[
W_t = W_D + W_{C1} \text{ or } W_D + W_{C2}
\]

**Figure 1.** Characteristic erosion of ductile material [1].

**Figure 2.** Characteristic erosion of brittle material [1].
Finnie [3] proposed that erosion of a ductile surface material, due to solid particle impact in a fluid stream, is dependent on the fluid flow and on the mode of material removal. Erosion of ductile and brittle materials were identified as diverse mechanisms and only a model for erosion of ductile materials was considered.

Finnie introduced a model describing the removal of material as a result of micro-cutting of the surface. Based on micro-geometry of an impacting particle on surface, and the impingent angel, Finnie proposed two equations. The two equations, (5) and (6), present a prediction of the volume of removed material \( Q \) as a function of a single particle impact. The two erosion modes are dependent on the velocity of the particle after cutting.

\[
Q = \frac{M \cdot V^2}{\rho \cdot \varphi \cdot K^2} \left( \frac{\sin(2 \cdot \alpha) - 6}{K^2} \cdot \sin^2(\alpha) \right) \quad \text{If,} \tan(\alpha) \leq \frac{K^2}{6}
\]

\[
Q = \frac{M \cdot V^2}{\rho \cdot \varphi \cdot K^2} \left( \frac{K^2 \cdot \cos^2(\alpha)}{6} \right) \quad \text{If,} \tan(\alpha) \geq \frac{K^2}{6}
\]

Finnie [4] based much of his study on realistic fluid flow erosion issues. Thus, considering the fluid flow aspect and particle shape in depth. Finnie’s early model underpredicts the erosion at high impingement angles as can be seen in Figure 3. Later Finnie [3] introduced a modified model to address the issue of wear at high impingement angles. Additionally, identifying several parameters that may affect the erosion, and concluding that not all parameters can be measured or controlled, furthermore not being implemented in a model.

Tilly [5] introduced the terms primary and secondary erosion, which is caused by the first impact and fragmentation of the particle respectively. Particle impact angle and erosion rates for primary and secondary erosion is presented in Figure 5. Addressing the mechanism occurring at high impingement angles has shown to be challenging to predict analytically. Tilly [5] presents a theory that introduces an erosion mechanism of ductile materials at large particle impingement angle. In circumstances where particle impact angle is high, the particle can fracture upon impact and the fragments can wear the surface surrounding the larger impact area. Figure 4 show a microscope image where the primary and secondary damage can be observed.
Figure 4. Primary indentation surrounded by secondary damage produces by 700 μm quartz particle against H 46 steel at 800 ft.sec⁻¹ (x200). [5].

Figure 5. Ductile erosion curve. The influence of impact angle for 135 μm quartz against H 46 steel at 1200 ft.sec⁻¹. [5].

Tilly [5] derived his erosion model from the equation of motion and kinetic energy. The two stage mechanism is represented by the following equations.

$$
\varepsilon_1 = \hat{\varepsilon}_1 \cdot \left( \frac{V}{V_{ref}} \right)^2 \cdot \left[ 1 - \left( \frac{d_0}{D} \right)^3 \cdot \left( \frac{V_0}{V} \right) \right]^2
$$

(7)

$$
\varepsilon_2 = \hat{\varepsilon}_2 \cdot \left( \frac{V}{V_{ref}} \right)^2 \cdot F_{d,v}
$$

(8)

$$
\varepsilon_{total} = \varepsilon_1 + \varepsilon_2
$$

(9)

Further, Tilly[5] identified that the wear was dependent on the particle size. For particle size larger than 100μm the relationship become linear, hence the ratio of mass erode material / mass erosive material becomes constant. This relationship is shown in Figure 6.

Figure 6. Erosion ratio versus particle size and particle impact velocity [5]. Curves derived from equation (9), points from experiment data.

Tabakoff and Grant [6] proposed a semi empirical model for predicting erosion. In the presented model the erosion rate is dependent on the particle impingement angle and velocity. In addition, several constants related to the particle-surface interaction was incorporated. Tangential particle velocity post impact is taken into account as a restitution factor. It was assumed that the erosion occurs in two stages dependent on the impingement angle and that the models is representative for both small and large particle impingement angle as well as a combination. The Tabakoff and Grant model allows for great
adjustment to specific erosion challenges. However, the accuracy of the model strongly depends on the
determination of a variety of constant that is required.

\[
E = k_7 \cdot f(\alpha) \cdot V^2 \cdot \cos^2(\alpha) \cdot \left[1-R_t^2\right] + f(V_{PN})
\]  

(10)

\[
f(\alpha) = \left[1+k_5 \cdot k_6 \cdot \sin\left(\frac{\pi}{2} \cdot \frac{\alpha}{\alpha_0}\right)\right]^2
\]  

(11)

\[R_t = 1-k_4 \cdot V \cdot \sin(\alpha)\]  

(12)

\[f(V_{PN}) = k_3 \cdot (V \cdot \sin(\alpha))^4\]  

(13)

\[k_5 = \begin{cases} 1.0, & \text{if } \alpha \leq \alpha_0 \\ 0.0, & \text{if } \alpha > \alpha_0 \end{cases}\]  

(14)

3. Erosion in valves and complex geometries
Later literature introduces models that are developed in correlation with modern techniques such as computational fluid dynamics simulations (CFD).

DNV recommended practice 0501 [7], present a guideline for material selection and erosion evaluation for a selection of pipe geometries. The general equation allows for great adjustability to different factors related to materials and particles. The correlation between erosion rate \(E\), particle mass \(m\), velocity \(U\) and surface material function / angle is given by:

\[
\dot{E} = \dot{m_p} \cdot K_8 \cdot V^n \cdot F(\alpha)
\]  

(15)

\[
\dot{E}_i = \frac{(\dot{m}_p \cdot K_9 \cdot V^n \cdot F(\alpha))}{\rho_t \cdot A_i} \cdot C_{Unit}
\]  

(16)

\[F(\alpha) = \sum (-1)^{(i+1)} \cdot A_i \cdot \left(\frac{\alpha \cdot \pi}{180}\right)^i\]  

(17)

Figure 7. Parameters characterising erosion impact on a surface, ref. equation (15), [7].

Figure 8. Function \(F(\alpha)\) for “typical” ductile and brittle materials [7].

The DNV model correlates with Haugen’s work [8] and was developed by the use of CFD analysis in parallel with experimental tests. Haugen introduced experimental data for a wide range of materials as presented in Figure 9. The barchart show a comparison of erosion rate of different materials such as ceramics and hard metals, extensively used in industry, relative to steel.
Figure 9. Relative erosion resistance of solid WC and ceramics relative to C-steel. [8]

One of the more recognized CFD software used for erosion prediction in fluid systems is Ansys and Fluent. These software packages enables many models to be implemented, Finnie [4] and Tillly [5] to mention some. However, the default model used in the Fluent code as shown in equation (18), is similar to equation (15), [9]. The model display similarities with the DNV Haugen model [8]. However, with the distinction of a particle size function, \( d_p \). This allows for a more realistic representation of particle distribution, as the size and number of impinging particles can vary vastly in real life events.

\[
\dot{E} = \sum_{p=1}^{N_{\text{particles}}} \frac{\dot{m}_p \cdot C(d_p) \cdot f(\alpha) \cdot V_p(v)}{A_{\text{face}}} \quad (18)
\]

McLaury[10] presents a three-part investigation by the means of CFD in the attempt to create a comprehensive method for erosion rate estimation for valve designers in industry. The CFD method is described in short as follows: 1. Solving the Navier-Stokes equation, and turbulence model, 2. Applying the Euler-Lagrangian method for particle trajectory tracing, and 3. Applying an erosion model to estimate the erosion rate.

Erosion model and constants used for the test was based on Finnie [4] and Bitters [1] work. By comparing numeric predictions and experimental data, a relatively large discrepancy was found. A proposed reason for the difference in results was related to the turbulence as calculated in the computational dataset. Furthermore, the change in geometry as a function of erosion was not considered in the CFD analysis resulting in a potential inaccuracy of the prediction.

Zhang [11] used similar approach as McLaury [10] by implementing a three stage method. Results from the experimental setup with erosion probes and laser Doppler velocimetry was compared with CFD predictions. A nozzle projecting particles on to an erosion probe (and LDV field) in a tank was used as experimental setup. It was found that the velocities and particle trajectories had good correlation. Zhang claim that the CFD based method as described is a sufficient way to predict erosion, especially in complex geometries.

Mansouri [12] developed a methodology for predicting erosion and implement relevant variables into an equation set that was applied in a CFD code. The aim was to predict wear and erosion material wastage with a high accuracy by combining CFD analysis and empirical data. The three stage technique as presented by Mansouri is in short described as following: 1. Measure erosion depth on a specimen via 3D profilometry, 2. Calculate the particle speed, angle and frequency of impact as a function of...
radial position via CFD simulation and 3. Fit an equation which correlates the particle impact information to thickness loss (erosion depth). The particle flow was investigated by the means of particle image velocimetry (PIV) measurement technique to quantitatively determine particle distribution and velocity. PIV, CFD and erosion test-parameters was combined with an erosion prediction equation which produced a profile that was compared with experimental data. A difference of less than 14% between prediction model and test data was found.

Fordere [13] presents a numerical study of a complex needle – seat control valve based on parameters representative for typical oil and gas fields. The CFD based approach is similarly defined as in Zhang [11] and McLaury[10]. It is argued that the standard erosion equation is not satisfactory for complex geometries such as choke valves. A design philosophy at which impingement angles and velocities in the diverging section of the choke are reduced, is applied and tested with success [13]. Comprehensive testing was completed in order to validate results, however, a limited amount of results was presented.

Wallace [14] presents an in-depth study on prediction of wear in complex geometries such as control valves. Experimental erosion parameters were obtained by jet type erosion tests. Three stages of modelling were discussed: flow field, particle dynamics and wear models. The models used in this study show that CFD could predict the flow characteristics of complex geometries. It can also be concluded that the location of erosion is well predicted by CFD, however, this study demonstrates that the modelling underpredicts (by 10-15 times) erosion compared with experimental values. For complex geometries such as choke valves used in the study, a significant difference between prediction and measured values was found.

The study presented by Nøkleberg and Søntvedt [15] was focused towards lifetime prediction of valves to reduce cost related to maintenance. Nøkleberg and Søntvedt present a comparison of a numerical study and experimental tests of a choke valve for oil and gas applications, Figure 10. The oil and gas sector is an industry with challenging conditions such as high flow velocities, erosive – corrosive fluids, extreme pressures and temperature. Erosion by droplets was considered to be a major contributor to the erosion of choke valves. Droplets can often occur in two or multiphase flow, and it can be difficult to establish whether observed erosion is due to solid particles or by droplets.

The erosion model and CFD correlated well with field studies and the results was used to develop a modified choke design. The modified design, Figure 10, introduces a reduction in particle impingement angles, to optimize the lifetime of the equipment. Nøkleberg and Søntvedt [16] made a quantitative

![Figure 10. Modified needle-seat choke valve](Image)

![Figure 11. Maximum erosion on steel seat and of modified needle and seat Choke, 25% open](Image)

The erosion model and CFD correlated well with field studies and the results was used to develop a modified choke design. The modified design, Figure 10, introduces a reduction in particle impingement angles, to optimize the lifetime of the equipment. Nøkleberg and Søntvedt [16] made a quantitative
comparison in their modelling of a modified needle and seat choke, and showed that the technique (using the structured Fluent code was able to adequately predict wear location.

In later work Nøkleberg and Søntvedt [16] compared numerical models and experimental data, considering erosion by solid particles only. The tests were performed on the modified choke valve at DNV flow loop which was purpose built for the application. The experiment was conducted with supersonic velocities that reflect real life operating conditions for many choke valves. It was found that the erosion model and parameters used for the application underestimated the real erosion depth magnitude (by 2-3 times) as shown in Figure 11. By comparing wear in an optimized needle-seat valve with an external sleeve valve it was found that the erosion rate reduction of the needle-seat valve was as much as 50-100 times.

Wang [17] presents a method of predicting wear in a throttle valve, which is prone to erosion due to sand slurry flow. A CFD analysis was made and compared with empirical results. The study revolves around a specific complex valve geometry. The aim of the study was to validate a prediction method, parameters, and to optimized design based on modelling. A good correlation between test and simulation was found, however, it was identified that the erosion prediction and experimental results had a diverging correlation with time. Change in surface geometry as a function of erosion, which is not considered by the CFD analysis, was considered to be the main contributing factor of the discrepancy.

4. Discussion
Predicting erosion accurately is a challenge, and many models have been made to account for variables that effect the particle – surface interaction in the erosion process. Meng and Ludeman [18] introduced an overview of 28 different erosion models accounting for up to 34 variables. The strive to derive models that represent erosion accurately have led to a wide range of models that allow for vast range of parameters. [18]. However, the most relevant parameters contributing to erosion is identified as the particle velocity, mass, impingement angle and surface material properties.

Bitter, Finnie and Tilly among others, produces some of the most recognized models for predicting erosion by solid particles. Later literature introduces models and methods that are developed in correlation with modern techniques such as CFD.

The particle trajectories and impingement statistics is in present methods commonly done by CFD simulation, and the erosion models are generally applied to calculate the erosion based on the particle – surface interaction only. This method has been presented in available literature and has good predictive capabilities with respect to erosion location. However, it is the belief that with the growing availability of CPU power, the accuracy of both erosion location and magnitude can be studied in detail.

The importance of precise test results in addition to accurate CFD models has shown to be critical in the prediction of wear. When evaluating erosion in complex geometries and determining component lifetime a high level of accuracy is required. Based on a “comprehensive literature review of solid particle erosion modelling in oil and gas”, Paris [6] concluded that the available generic erosion models, method and parameters are not adequate for predicting wear in complex geometries such as choke valves. In such cases, it is required to do experimental erosion tests and CFD model validation for the specific geometries in order to produce accurate erosion predictions.

5. Conclusion, discussion and further work
The current methods for erosion modelling and wear prediction is found to be sufficient for establishing the location of erosion. However, the magnitude and rate of erosion is often underpredicted. This is challenging with respect to product lifetime prediction for erosion prone components. This applies particularly to complex geometries such as control valves.

Based on the available information, it is concluded that in order to investigate the discrepancy between numerical model prediction and experimental data for erosion rates, the fluid flow has to be analysed for specific geometries. When detailed numerical analysis can be compared with experimental data, it is believed that factors adding to discrepancy between results may be identified. Furthermore, a
justified correction can be made to the models or parameters in order to achieve a more accurate erosion prediction for the specific geometry.

In order to better understand the erosion rates for a specific complex geometry, the primary step is to investigate the flow characteristics, and how these characteristics are represented by different numerical parameters and simplifications. When a numerical dataset is obtained, laboratory studies is required in order to validate numerical parameters. Upon the comparison and potential correction of numerical models and the specific flow structure, the particle trajectories can be calculated, measured and further used for accurate prediction of erosion rate in the specific geometry.

Table 1. Nomenclature.

| Parameter | Description                                                  | Unit               |
|-----------|--------------------------------------------------------------|--------------------|
| A_t       | Area exposed to erosion                                      | [ m^2 ]            |
| A_i       | Dimensionless parameter group                                |                    |
| A_face    | Cell face area                                               | [m^2]              |
| b(v)      | Function of relative particle velocity                       |                    |
| C(d_o)    | Particle distribution function                               |                    |
| C_Unit    | Unit conversion factor                                       |                    |
| d_o       | Threshold particle diameter below which no erosion occurs    | [ µm ]             |
| D         | Particle diameter                                            | [ µm ]             |
| e         | Cutting wear factor                                          | [ g f cm / sec^3 ] |
| E_p       | Erosion parameter, ratio of metal penetration and mass of sand hitting the material | [ mm / kg ] |
| E         | Erosion rate                                                | [ mm / year ]      |
| Ė         | Erosion rate, mass loss / impact mass                        |                    |
| F_{d,v}   | Fragmentation                                                |                    |
| F(α)      | Material function                                            |                    |
| K         | Velocity at with plastic deformation occurs                 | [ cm / sec ]       |
| K_{1,7}   | Constant                                                    | [ m / s ]          |
| K_9       | Material constant                                           | [ (m/s)^-n ]       |
| m_p       | Mass flow rate of sand                                       | [ kg / s ]         |
| M         | Total mass of impinging particle                             | [ g f sec^2 /cm ]  |
| ρ_t       | Target material density                                      | [ kg / m^3 ]       |
| V         | Particle velocity prior to impact                            | [ m/s ]            |
| V_0       | Threshold particle velocity below which no erosion occurs    | [ m / s ]          |
| V_{ref}   | Reference velocity                                           | [ m / s ]          |
| W_D       | Wear due to repeated deformation impact                      | [ cm^3 ]           |
| W_{C1}    | Deformation wear                                            | [ cm^3 ]           |
| W_{C2}    | Deformation wear                                            | [ cm^3 ]           |
| α         | Particle impact angle                                        |                    |
| ε         | Deformation wear factor, energy required to remove a unit volume of surface material by deformation of scratching | [ g f cm / sec^3 ] |
| ε_1       | Primary erosion rate                                         |                    |
| ε_2       | Primary erosion rate                                         |                    |
| φ         | Ratio of depth of contact to depth of cut                    |                    |
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