COMPARISON OF DIFFERENT MODELS FOR DETERMINATION OF EROSION WEAR IN CENTRIFUGAL PUMPS

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ABSTRACT

Due to long operating time, the efficiency of centrifugal pumps is decreasing gradually. A decreasing efficiency can be originated from different wearing processes, why a detailed knowledge of these processes and their influence can be advantageous for a smooth operating behavior. In this context the erosion induced by solid particles in a centrifugal pump is investigated with the help of computational fluid dynamics. The erosion wear is calculated with two different models. Furthermore, the location of erosion wear and the influence of using a one-way and fully coupled solid phase are investigated. The results show similar locations and distributions of the predicted erosion damage for both examined models. The variation of the particle concentration suggests the assumption that a one-way coupling leads to inaccurate results for high solid concentrations. At least the investigations show an approximated linear scaling of the erosion rate density with the particle concentration and the prevailing volume flow.

KEYWORDS

CENTRIFUGAL PUMPS, SLURRY EROSION WEAR, EROSION MODELS

NOMENCLATURE

E erosion rate density \( \text{kg m}^{-2} \text{s}^{-1} \)
\( M_{\text{Ero,dim}} \) dimensionless mass of eroded material -
m particle mass \( \text{kg} \)
K ratio of force components acting on a particle -
\( K_1, K_2, K_3, K_{12} \) varying constants of the Grant-Tabakoff model -
U particle velocity \( \text{m s}^{-1} \)
\( U_{1N} \) normal velocity component of incoming particle \( \text{m s}^{-1} \)
\( U_{1T} \) tangential velocity component of incoming particle \( \text{m s}^{-1} \)
\( U_{2T} \) tangential velocity component of rebounding particle \( \text{m s}^{-1} \)
\( V_{\text{Ero}} \) volume of eroded material \( \text{m}^3 \)
Y plastic flow stress \( \text{kg m}^{-1} \text{s}^{-2} \)
\( \alpha \) angle of impact \( ^\circ \)
\( \psi \) ratio of depth of contact to depth of cut -

INTRODUCTION

Wearing is a not preventable process during long operating time of centrifugal pumps. Depending on the fluid properties and operating conditions different wearing processes occur, e.g. erosion, abrasion and corrosion. When pumping slurry, the impact of solid particles against the pump’s surfaces induces the so called slurry erosion wear. The rate of eroded material caused by
slurry erosion is a function of a wide range of different parameters. Sommer et. al. (2010) named the characteristic of the two-phase fluid, the condition of flow and the characteristic of the target material as the main parameters. Furthermore, More et. al. (2017) as well as the majority of research specified the impact angle, solid concentration, impact velocity and the particle size and shape as the most affecting ones.

Since the computer technology is increasingly powerful, the use of Computational Fluid Dynamics (CFD) in the design process of turbomachinery is state of the art. In addition to the design of the hydraulic contour, CFD can be used to calculate erosion wear and therefore to locate highly stressed machine parts. The numerical simulation of slurry erosion requires the complete calculation of the particle movement as well as a model to predict the rate of eroded material. As Zhang and Chen (2007) summarized, the particle trajectories can be computed with the Eulerian or Lagrangian Method. For the calculation of slurry erosion wear the literature research of Meng and Ludema (1995) revealed a wide range of various models. The primary challenge for every model is the consideration and differentiation of all the influencing parameters and mechanisms. Hence, many models are developed for general purpose or specific test cases.

**EROSION WEAR CALCULATION**

Due to the variety of research on erosive wear, many of the developed models depend on different parameters. However, two points of intersection can be found.

Primarily the used parameters can be grouped into the already mentioned superordinate parameters named by Sommer et. al. (2010). For instance, similar classifications are stated by Humphrey (1970) or Finnie (1995). Secondly, in most of the studies the differentiation of two wear-mechanisms for high and low impact angles is declared. Some of the first publications about these mechanisms are presented by Bitter (1963a) and Bitter (1963b). The mechanisms are classified as cutting and deformation wear, whereby cutting wear dominates the wear process for low impact angles and ductile materials. In this case the particle slides over the target surface and leaves striations and cavities. Conversely, deformation wear outweighs for high impact angles and brittle materials. The impingement of particles under high angles results in a form of hardening work.

Therefore, an erosion model for general purpose has to consider both of these mechanisms and a selected range of parameters of the three parameter groups. For ductile materials or especially metals Hutchings (1979) introduces a general form of erosion models. Under the assumption that the erosion wear just varies with the angle of impact $\alpha$ and the particle velocity $U$, the general form can be written as

$$M_{\text{Ero}, \text{dim}} = C U^n f(\alpha),$$  \hspace{1cm} (1)

where $M_{\text{Ero}, \text{dim}}$ is the dimensionless mass of eroded material, $f(\alpha)$ a function of the impact angle $\alpha$ and $C$ and $n$ are varying constants. It will be shown that the presented models in the next sections can be traced back to this general form.

**Finnie Model**

One of the first developed models to predict erosive wear was introduced by Finnie (1960). Despite its age, the Finnie model is one of the most widely-used erosion models for ductile materials. In its first version the model estimates the rate of eroded material accurate for the cutting wear-mechanism, but underestimates the influence of deformation wear. Hence, the erosion rate of ductile materials is mainly affected by particles impinging under a low angle of impact. But the additional wear induced by particles impacting under a high angle cannot be neglected. Therefore, Finnie (1972) introduced a second version of his model. The second version consists of two equations, whereby the choice which equation is used depends on the angle of impact. The use of separate equations for cutting and deformation wear leads to accurate results for both mechanisms. Thus, the volume of eroded material $V_{\text{Ero}}$ is calculated as
\[
V_{\text{Ero}} = \frac{m}{\psi Y K} U^2 \left( \sin(2\alpha) - \frac{6}{K} \sin^2(\alpha) \right) \quad \forall \alpha \leq \tan^{-1} \frac{K}{6}
\]  

and

\[
V_{\text{Ero}} = \frac{m}{\psi Y K} U^2 \left( \frac{K \cos^2(\alpha)}{6} \right) \quad \forall \alpha > \tan^{-1} \frac{K}{6}
\]

where \( m \) is the mass of the particle, \( Y \) the plastic flow stress of the material, \( K \) the ratio of force components acting on the particle and \( \psi \) the ratio of depth of contact to the depth of cut. Relating to equation (1), the first ratio in equation (2) and (3) can be interpreted as the constant \( C \). Furthermore, the Finnie model uses an exponent \( n \) equal two and the expressions in brackets correspond to the general function \( f(\alpha) \) in equation (1). Even if the ratio of force components \( K \) does not have to be constant, a resemblance of the Finnie model to the general form is apparent.

**Grant-Tabakoff Model**

Another widely-used model to predict erosive wear was established by Grant and Tabakoff (1973). Similar to the Finnie model, the Grant-Tabakoff model differentiates between the two wear-mechanisms cutting and deformation wear for low and high impact angles. In contrast, the Grant-Tabakoff model combines these two mechanisms in only one equation. The advantage when using one equation is the consideration of both wear-mechanisms for intermediate angles of impact. However, one equation including both mechanisms gets more complex and depends on several more constants accordingly.

The general form of the Grant-Tabakoff model to predict the erosion damage per unit mass of impacting particles \( E_{\text{Ero}} \) can be written to

\[
E_{\text{Ero}} = K_1 (U_{1T}^2 - U_{2T}^2) f(\alpha) + f(U_{1N})
\]  

where \( K_1 \) is a material constant, \( U_{1T} \) the tangential velocity component of incoming particle, \( U_{2T} \) the tangential velocity component of rebounding particle, \( f(U_{1N}) \) a general function to calculate the erosion due to the normal velocity component \( U_{1N} \) and \( f(\alpha) \) an empirical function of the impact angle. Again, equation (4) follows the general form of erosion models shown in equation (1) by depending on constants, the particle velocity and the angle of impact.

In order to use the erosion model, the general form in equation (4) has to be specified by defining the constants and functions. Therefore, Grant and Tabakoff (1973) took an experimental approach with 2024 aluminum alloy and silica sand particles. In this context, a second written composition with respect to the erosion in turbomachinery is given in Grant and Tabakoff (1975). The experimental approach was used to determine the absent constants and functions in order to fit the model results with the experimental data. Thus, the specified form of equation (4) is written to

\[
E_{\text{Ero}} = K_1 f(\alpha) U^2 \cos^2(\alpha)[1 - R_T^2] + f(U_{1N})
\]

where

\[
R_T = 1 - 0.0016 U \sin(\alpha)
\]

\[
f(\alpha) = \left[ 1 + K_2 \left( K_{12} \sin(2\alpha_0) \right) \right]^2
\]

\[
f(U_{1N}) = K_3 \left( U \sin(\alpha) \right)^4
\]
The factors $K_1$, $K_2$, $K_3$ and $K_{12}$ are empirical constants depending on the used materials and $\alpha_0$ is the angle of impact for maximum erosion damage, normally in the range of $20^\circ$ to $25^\circ$.

**SOLID PHASE TREATMENT**

Apart from the erosion model, the simulation of erosion wear with the help of CFD requires a method to calculate the particle movement. As stated by Zhang and Chen (2007), the particle movement can be calculated with the Eulerian or Lagrangian method.

When using the Eulerian method, the solid particles are treated as a continuous phase. Therefore, the appropriate equations similar to the fluid phase are solved. The Lagrangian method considers the solid phase as single particles, whereby the particle movement is a result of the forces acting on the particles. The considered forces in the used software package Ansys CFX 18.0 are specified to the viscous drag, buoyancy force, virtual mass and pressure gradient forces. In rotating domains the centripetal and Coriolis forces are calculated additionally. Supplementary details on the acting forces and furthermore the treatment of turbulence aspects can be found in Ansys (2017). Both methods have advantages and disadvantages and are therefore suitable for different applications. Durst et. al. (1984) summarized that the Eulerian method delivers a better approach for high particle concentrations. Furthermore, the Lagrangian method leads to better results for low particle concentrations and flows where large particle accelerations arise.

Irrespective of the calculation method of particle movement different coupling techniques of the fluid and solid phases are feasible. The so called one-way coupling neglected the influence of the solid phase on the fluid phase. Therefore, the resulting flow field of the fluid phase is identical whether a solid phase is present or not. When considering the interaction between both phases the coupling method is called two-way or fully coupled. In terms of a fully coupled solid phase the fluid momentum equations are extended by an additional source term. More information on how the used software package treated the interaction between the fluid and solid phase are stated in Ansys (2017). Crowe (1982) mentioned to use the one-way coupling for low particle concentrations and accordingly the full coupling for high particle concentrations. A transition concentration from one-way to full coupling is not stated.

**RESULTS**

The prediction of slurry erosion wear is investigated for a standardized water pump with a nominal size of 200-25 according to EN 733. This corresponds to an impeller diameter of 200 mm and a pressure joint diameter of 25 mm. Furthermore, the investigated pump has a nominal rotational speed of 2951 min$^{-1}$ and a specific speed of 7.8 min$^{-1}$.

The simulations are performed for unsteady conditions for the whole geometry of the pump including all side chambers, sealing gaps and balancing wholes being discretized with about 16 M nodes. The solid phase is defined as pure corundum particles with a mean diameter of 60 µm, a minimum diameter of 45 µm and a maximum diameter of 75 µm subjected to a Gaussian distribution. The density of the solid particles is 3980 kg m$^{-3}$. The particles are injected equally spaced at the pump’s inlet and the inlet-velocities of the fluid and solid phase are identical. Furthermore, a solid concentration of one and ten percent by mass as well as the use of a one-way and fully coupled solid phase are examined. As the particle concentrations are fairly low and the flow conditions inside the pump assume appreciable particle accelerations, all cases are computed using the Lagrangian method for particle tracking. The predicted erosive wear of each model is investigated for five different operating points in the permitted operation range of the pump. The five operating points are defined by 40%, 60%, 80%, 100% and 120% of the volume flow in the Best Efficiency Point (BEP). The used parameters in the Grant-Tabakoff model are set to the default values stated in Grant and Tabakoff (1973). Correspondingly, the parameters of the Finnie model are defined to the given values for aluminum in Ansys (2017).
In addition to the numerical simulations, the influence of slurry erosion wear is investigated with the help of an experimental test rig. The test rig includes the described pump in a stand-alone cycle, which is filled with a suspension of water and pure corundum. The properties of the solid particles in the experimental investigation correspond to the numerical setup. When pumping slurry, the machine operates in their BEP. Unlike the simulations, the solid concentration used in the experimental investigation is only one percent by volume. But, as will be seen in the following sections, the variation of the concentration seems to have no major influence on the general location of erosive wear. Solely the amount of eroded material varies with the concentration and time.

**Influence of Slurry Erosion Wear**

As an initial evaluation of slurry erosion wear in a standardized water pump the general locations where erosive wear occurs are investigated. Firstly the locations are exemplary presented for the BEP with a solid concentration of ten percent by mass and a fully coupled solid phase.

The main area where erosive wear occurs is located at the largest radius of the pump’s casing. The distributions of the time integrated erosion rate density after 50 impeller revolutions predicted by the Finnie and the Grant-Tabakoff model are therefore shown in figure 1. The erosion rate density describes the amount of eroded material in kilogram per time and surface area. The time integration of the erosion rate density leads to the total amount of eroded material after the specified time in relation to the surface area. The distributions are referenced to a thousandth of the maximum value of the erosion rate density in each case. Furthermore, the shown range is limited to a maximum value of one. This limitation permits an emphasizing of areas with a low amount of erosive wear, which further on prevail after the computed 50 impeller revolutions. In addition, the emphasizing of areas with a low amount of erosive wear simplifies the comparison of the numerical results to the experimental outcomes, which are recorded after several hours of erosion.

Figure 1 indicates that both models predict nearly the same area inside the casing and volute where erosive wear arise. Furthermore, both models lead to quite the same distribution of erosion rate density in relation to their reference value. In general, it seems that the Finnie model predicts a
slightly greater area of erosion. The major differences occur near the diffusor outlet, where the Finnie model predicts a higher amount of erosive wear in comparison to the Grant-Tabakoff model. But, regarding to the flow conditions inside the volute and the two wear-mechanisms, both models seem to predict the erosion rate as a result of the cutting wear-mechanism and therefore low impact angles fairly similar.

Figure 2: Erosive Wear after 162 Hours of Operation with Slurry

In comparison to figure 1, the experimental results of erosive wear in the pump’s casing after 162 hours of operation with the defined slurry are shown in figure 2. The experimental outcomes reveal a comparable distribution and especially location of eroded material as predicted by the erosion models. The pump’s casing and volute show multiple striations and cavities. Furthermore, the unilateral damage of the drainage-outlet can be clearly identified. In detail even the non-uniform damage of the volute’s nose is similarly apparent in the experimental and numerical results.

Although the numerical results in figure 1 and the experimental outcomes in figure 2 are gained with different solid concentrations, the general locations of erosive wear in the pump’s casing seem to be consistent. Obviously the extent of damage in the experimental results is more pronounced since the operation time of 162 hours substantially exceeds the simulated time of 50 impeller revolutions. To confirm the assumption that different solid concentrations do not have a major influence on the general location where erosive wear occurs, figure 3 compares the numerical predictions of the Finnie model for the BEP with a solid concentration of one and ten percent by mass and a fully coupled solid phase. Both distributions are now referenced to a thousandth of the maximum erosion rate density of the case with a solid concentration of ten percent by mass. As before, the range is limited to a maximum value of one and the shown erosion rate density is time integrated after 50 impeller revolutions. The direct comparison of the two solid concentrations in figure 3 reveals that in both cases the general locations of erosive wear are similar. Due to the same reference value, the amount of eroded material in case of a small concentration of one percent by mass is even lower. In conclusion, the comparison of the two solid concentrations confirms the assumption that the general locations where erosive wear occurs are not primarily affected by the solid concentration. Solely the extent of damage varies.
Next to the pump’s casing, further areas where erosive wear occurs can be located inside the impeller. As shown in figure 4, especially the leading edges of the blades are affected. The experimental outcomes are recorded after 18 hours. The numerical predictions of the two erosion models are shown for the BEP with a solid concentration of ten percent by mass and fully coupled solid phase. As before, the erosion rate density is time integrated after 50 impeller revolutions. Both cases are referenced to a thousandth of the maximum value of the Grant-Tabakoff model. Furthermore, the range is limited to a maximum value of one.

The comparison between the numerical and experimental results shows a distinctive difference in the amount of erosive wear especially on the blade’s suction side near the balancing holes. On the experiment the red coating mostly disappeared around the balancing hole and on the blade’s suction side. In contrast the simulations do not show extensive values of the erosion rate density in this area. Again, this difference can be traced back to the different points in time. But nonetheless the
flow through the balancing holes seems to influence the amount of erosion on the impeller hub downstream the channel in the numerical and experimental results. On the blade’s leading edge the distributions of the erosive wear are comparable between the experimental and numerical outcomes. However, it can be noted that the Finnie model predicts a lower extent of damage in comparison to the Grant-Tabakoff model. Regarding to the BEP, the flow direction should be blade congruent at the leading edge. Therefore, the impingement angle should be relatively high and deformation wear should be the dominating wear-mechanism. This leads to the presumption that the Grant-Tabakoff model predicts a higher erosion rate for deformation wear than the Finnie model. To examine this presumption, figure 5 shows the predicted variation of eroded material with the impingement angle for the Finnie and the Grant-Tabakoff model normalized to their maximum erosion.

![Erosion Curves Comparison](image)

**Figure 5: Erosion Curves of the investigated Models as a Function of the Impingement Angle**

Since both models depend on different parameters, a wide range of curves is possible. Therefore, the parameters for the Grant-Tabakoff model are set to the default values described in Grant and Tabakoff (1973). The parameters of the Finnie model are then chosen to obtain nearly the same value of maximum erosion. The particle velocity U is set to 10 m s⁻¹ for both models. The dashed lines represent the curve progressions of equation (2) and (3) of the Finnie model outside their scope of application.

Obviously, the difference between both models for low angles of impact is fairly insignificant. Substantial differences only occur for high impingement angles. Interestingly, the differences set in after the Finnie model switches to its second equation. Relating to figure 4, the presumption that the Grant-Tabakoff model predicts a higher amount of damage for the deformation wear-mechanism seems to be confirmed.

**Differences due to Coupling-Method**

In contrast to the decision of using the Eulerian or Lagrangian method to calculate the particle movement, the choice which coupling method leads to more accurately results cannot be founded directly. Furthermore, the evaluation with the help of the experimental test rig seems to be unfeasible, since the detailed particle trajectories inside the pump cannot be measured and the total amount of eroded material cannot be extracted from the suspension. However, the numerical investigation of both coupling methods leads to different predictions of erosion damage for all operating points and particle concentrations.

In this context figure 6 shows the area and time integrated erosion rate density for all operating points and the two particle concentrations. The area and time integrated erosion rate density is defined as the whole mass of eroded material after a specific time and for a specific surface area of target material. In this case the specific surface area corresponds to the pump’s surface and the
specific time equates to 50 impeller revolutions after the first particle injection. Again, all quantities are referenced to the BEP of each model with a solid concentration of ten percent by mass and a fully coupled solid phase. The calculations using the full coupling method are stated in blue color. Equally, the results using the one-way coupling method are shown in green color.

What is apparent, the predicted erosion damage when using a one-way coupling is clearly lower than when using a full coupling method for all investigated cases. The most obvious differences are evident for the high particle concentration. The difference between the two coupling methods for the Finnie model and the BEP is around 11% and even 25% for the Grant-Tabakoff model. In case of the low particle concentration, the differences decrease but are still present. Again, the Grant-Tabakoff model shows greater discrepancies as the Finnie model.

Figure 6: Time and Area Integrated Erosion Rate Density

With regard to Crowe (1982), the results show the stated differences for one-way and full coupling methods with respect to the particle concentration. On the assumption that the calculation of high particle concentrations is more accurate using a full coupling method as stated in Crowe (1982), a particle concentration of ten percent by mass seems to be too high for using a one-way coupling.

Time Response of the predicted Erosion Wear

The area and time integrated erosion rate density shown in figure 6 displays the extent of damage after a specific time. But since a smooth operating behavior of the pump is recommended, also the temporal evolution of erosive wear could be relevant. For this purpose, figure 7 shows the temporal evolution of the erosion rate density for the investigated erosion models with a fully coupled solid phase. Therefore, the area and time integrated erosion rate density was calculated for a number of time steps within a defined timescale. The timescale is about 50 impeller revolutions, where \( t_0 \) refers to the time of the first recorded erosive wear after the injection of solid particles and \( t_1 \) corresponds to the state shown in figure 6. Again, for each model the erosion rate densities are referenced to the BEP at time step \( t_1 \). For the sake of clarity, only the BEP and the partial load with 40% of the BEP volume flow are displayed.

Initially all curves in figure 7 show a conspicuous kink in the area around \( t_0 \). With respect to the described main areas of erosive wear and the presented timescale, these kinks correspond to the first recorded erosion wear inside the machine, which takes place inside the impeller accordingly. At this time, the particles did not reach the pump’s volute. Therefore, the erosion rate density is lower since not all machine parts are affected.

With the exception of the area around \( t_0 \), figure 7 shows a linear dependency between time and the predicted erosion rate density for all cases. Furthermore, no significant differences between the Finnie and Grant-Tabakoff model are apparent. For both models, the gradient of the shown curves scales with the solid concentration and the chosen operating point of the pump or rather the
prevailing volume flow. In a first approximation the erosion rate density for a constant operating point behaves proportional to the ratio of the solid concentrations. Moreover, for a constant particle concentration the erosion rate density roughly corresponds to the ratio of volume flows according to the investigated operating points. However, these correlations are just a first approach and are subjected to a certain uncertainty. Furthermore, how far and to what extent the consideration of surface deformation will influence this approach cannot be stated.

CONCLUSIONS

For a standardized water pump the erosive wear caused by solid particles has been investigated with the help of two different erosion models. The analysis of the most effected machine parts showed that the erosion wear in general takes place in the same areas independent of the solid concentration and the prevailing operating point. At least as long as the operating point fits the permitted operation range of the pump. Outside the permitted operation range new or rather undesired flow conditions could lead to further areas of erosive wear. Obviously, the extent of damage in these general areas varied with the amount of solid concentration and the flow velocity caused by the operating conditions.

The distributions of the erosion rate density predicted by the Finnie and Grant-Tabakoff model revealed no significant differences for areas where the cutting wear-mechanism and therefore particle impingement under a low angle of impact dominates. In contrast, the Grant-Tabakoff model forecasted a higher amount of erosive damage for areas where the deformation wear-mechanism outweighs.

The simulations were performed for a solid concentration of one and ten percent per mass and either using a one-way and fully coupled solid phase. The literature recommends using a full coupling method for high particle concentrations and accordingly a one-way coupling for low concentrations, whereby no transition concentration is stated. In case of a centrifugal pump the results showed decisive differences between the predicted erosive wear for the two coupling methods and the high solid concentration. Thus, using just a one-way coupled solid phase seems to lead to inaccurate results for a particle concentration of ten percent per mass and a full coupling should be preferred in this case. For a concentration of one percent per mass the differences between the two coupling methods were still present, although the deviation was much smaller. Therefore, a solid concentration of one percent per mass could be considered as the transition concentration between using a one-way and full coupling method for this present case. But this assertion has to be treated with some reservation since a validation with experimental results is not feasible at this point.

An increase of erosive wear for rising solid concentrations is not exceptional. Furthermore, with respect to the varying velocities, a dependency of the erosion rate on the operating conditions can
be retraced. Accordingly, the analysis of the temporal evolution of the erosion rate density indicated that the erosive damage scales with the solid concentration and the prevailing volume flow. Furthermore, the erosion rate showed a linear temporal behavior in general. In a first assumption, the scaling seems to be proportional. Though, an extended evaluation showed deviations of these proportional scaling in a range up to 25%. Unfortunately, an overall relation between the operating conditions, the particle concentration and the area-integrated erosion rate density at a specific time could not be found yet. But a proportional scaling seems to be appropriate for a first approach.

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