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# ASSESSING LIQUID DROPLET EROSION POTENTIAL IN CENTRIFUGAL COMPRESSOR IMPELLERS

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## ABSTRACT

This paper presents a method for estimating the potential for liquid droplet erosion in compression system components, such as the impeller of centrifugal compressors. The erosion model selected is used to calculate a threshold velocity that represents the limit for the onset of erosion damage. The parameters used in the model include the liquid phase density and viscosity, impeller geometry, shaft rotational speed, impeller material hardness, maximum droplet diameter size, and sonic velocity of the liquid phase. The potential for erosion is assessed by comparing the threshold velocity with the maximum expected impact velocity. The model was benchmarked against several industry standards and the original equipment manufacturer's (OEM) own expertise regarding blade protection from liquid erosion in steam turbines. The results from the proposed erosion potential method agreed closely with the steam turbine experience.

## INTRODUCTION

The oil and gas industry faces a great opportunity in wet gas compression as a mean of improved, cost-effective production from existing and future fields. Under wet gas conditions the compression package must handle a mixture of liquid and gaseous phases. Production of nearly depleted fields and development of subsea production are increasing the likelihood of liquids present in the gas stream. Typically, the liquid phase is removed using scrubbers and separators located upstream of the compressor. These devices are large and heavy, resulting in significant installation costs, particularly for topside offshore and subsea applications. The objective for this OEM is to reduce the size and weight of the compression package by performing the separation process within the compressor casing.

Separation technologies have improved and will continue to advance. Regardless of the separator performance, some carryover of liquids always occurs. Conventional static separators are known to experience a decrease in performance as the process pressure increases (Brigadeau, 2007) leading to significant liquid carryover. Performance targets for the separation process require a complete understanding of the potential for erosion damage. A method for calculating a threshold velocity and comparing it to the maximum expected impact velocity was developed. The component risk analysis determined that, should there be liquid carryover, the first stage impeller in the compressor would be the most likely to suffer erosion damage. Therefore, the application of this method has been focused on impellers. The method could be adapted to any other components to study erosion caused by liquid droplet impact. The erosion model selected for the purpose of this paper only considers liquid droplet impacts. Solid particles are not analyzed in this study, neither are erosion-corrosion mechanisms.

The benefit of having developed a method for estimating erosion potential is that, for the first time, users are able to analyze each individual application and then properly select and apply the equipment. Knowing the liquid erosion potential allows the OEM to design and manufacture compression system components such as impellers in accordance with the criteria established for various specific process conditions so as to avoid compromising equipment availability and reliability.

## EROSION MODEL

An extensive literature search was performed for liquid droplet erosion models. Three models were studied and analyzed based on applicability and suitability for centrifugal compressor use: Krzyzanowski (1974, 1988), Krzyzanowski and Weigle (1976), Krzyzanowski and Szprengiel (1978), and Krzyzanowski, et al. (1971), Shubenko and Kovalsky (1987), Pouchot (1970), and Pouchot, et al. (1971). The erosion model developed by Pouchot (1970), and Pouchot, et al. (1971), was selected because it was calibrated based on experimental results from Pearson (1964a and 1964b) at the Central Electricity Generating Board (CEGB) of Great Britain, one of the largest studies of droplet erosion in steam turbines.

Erosion caused by droplet impingement does not develop uniformly over time. Different phases characterize the loss of material. An initial stage where no material is removed is commonly called the incubation stage. This is followed by a sharp increase in material removal referred to as the accumulation stage or acceleration period. There is debate about the specification of the next stage(s). Some believe there is an attenuation zone followed by a steady-state zone, while others assume there is a steady-state period first followed by a deceleration stage (Figure 1). The variation over time obstructs the comparison of reported results because it is not always clear from which stage of the erosion process the data were obtained. The analysis and results of this study are for the maximum rate of erosion unless otherwise indicated. The maximum rate of erosion is obtained at the end of the accumulation or acceleration stage, which is taken as a worst case scenario.

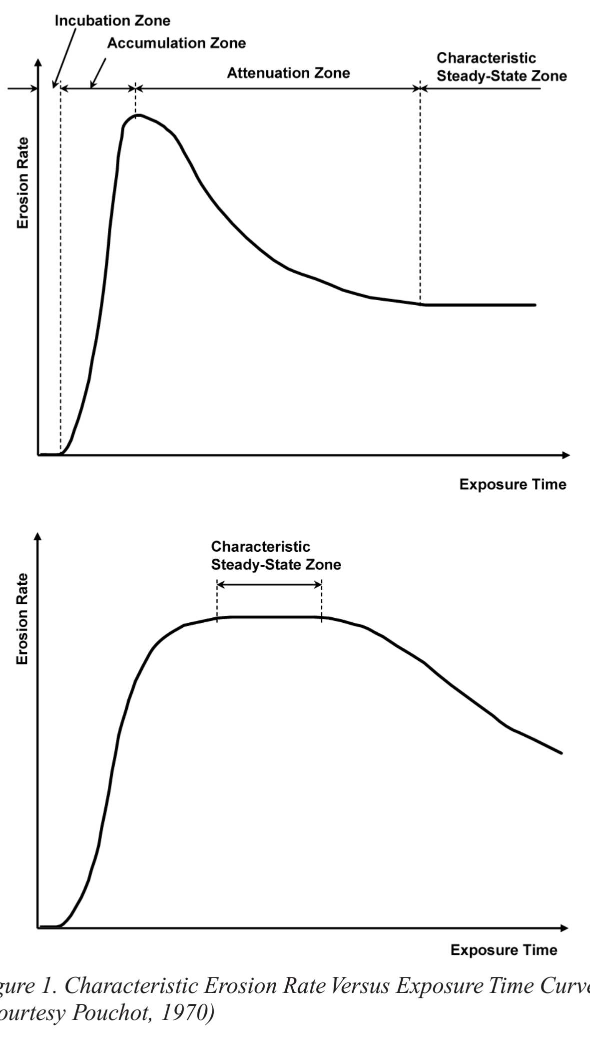


*Figure 1. Characteristic Erosion Rate Versus Exposure Time Curves. (Courtesy Pouchot, 1970)*

The mechanism of erosion from liquid droplet impact comprises two forces. First, the initial impact pressure, and second, pressure created by the deformation or lateral movement of the droplet. These two pressure levels are modeled as a "waterhammer pressure," which is a function of the shock wave velocity of the liquid. These forces cause plastic deformation on the material that builds up over time until stress concentration exceeds the tensile strength and cracks form. The result is material breakdown as the cracks spread and interconnect.

Most of the literature on liquid impact erosion agrees that there seems to be a threshold value for the impact velocity under which no erosion occurs. The value of the threshold velocity is a function of the particular material, liquid, and droplet size. The difficulty in determining an impact threshold velocity is the fact that erosion is a prolonged process. Therefore, most experiments are "accelerated" tests where impact conditions are increased to measure erosion in a shorter period of time or the impact conditions are such that erosion is measurable in a reasonable amount of time. As the conditions are lessened to approximate the threshold limit, the time restriction becomes prohibitive. Hence, an impact velocity under the threshold value does not mean that damage or material loss would not occur, but rather that damage or material loss does not occur during any "practical" exposure time. The proposed erosion potential method includes elements in its derivation that reduce the uncertainties in the model.

The erosion model selected is developed based on the assumption of a liquid layer retained on the surface of the impacted material. The existence of a liquid film explains the droplet diameter effect observed in the experimental results and why smaller droplets cause less damage than large droplets on an energy per volume basis. This liquid film attenuates the blow from smaller droplets more than larger droplets. The liquid layer thickness would change as the surface is eroded and becomes roughened.

The following model equations are valid for impingement conditions that are more severe than what is expected to occur in a centrifugal compressor (i.e., droplet size and impact velocities). Therefore, a confidence margin or safety factor is built into the model. This safety factor reduces the effect of the uncertainties developed by the assumptions made in the model.

The liquid layer thickness (δ) calculation shown in Equation (1) was developed for samples tested in a rotating arm erosion test setup. This equation is a force balance between viscosity forces and centrifugal forces. The parameters are: liquid viscosity (μ), liquid density ($\rho_l$), specimen diameter ($D_s$) and specimen velocity ($U_s$). The specimen diameter includes the length of the rotating arm.

$$\delta = \sqrt{\frac{3 \cdot \mu \cdot D_s}{4\pi \cdot \rho_l \cdot U_s}} \tag{1}$$

The threshold velocity ($U_{cd}$) shown in Equation (2) is a function of the stress capability of the material for droplet impact (S) taken to be the Vickers hardness, the sonic velocity in the uncompressed liquid ($C_0$), liquid density ($\rho_l$), empirical proportionality constant (K), liquid layer thickness (δ), droplet diameter (D), and an empirical exponent (n).

$$U_{cd} = K\left(\frac{S}{\rho_l \cdot C_0}\right)\left(\frac{\delta}{D}\right)^n \tag{2}$$

## THRESHOLD VELOCITY CALCULATIONS

There are nine parameters that need to be determined to calculate the threshold velocity using Equations (1) and (2). The liquid density ($\rho_l$) and liquid viscosity (μ) are obtained from a simulation software for chemical and hydrocarbon processes with the gas-liquid mixture pressure, temperature, and composition as inputs. The thermodynamic methods use the Benedict-Webb-Rubin modified by Starling equation of state (BWRS) and corresponding states technique developed by Ely and Hanley (1981) for viscosity and thermal conductivity calculations.

The sonic velocity of the liquid phase is obtained from a process dynamic simulation software that uses a patented extended Lee-Kesler equation of state. The sonic velocity calculation uses a method by Starling, et al. (1987), for gases and is extended to liquids using the Beattie and Bridgeman (1928) derivative tables in terms of the pressure, temperature, and normal compressibility. The inputs are the pressure, temperature, and gas composition of the gas-liquid mixture.

The liquid layer thickness is a function of centrifugal and viscous forces. These forces are dependent on the tangential velocity (specimen velocity), length of the surface (specimen diameter), density, and viscosity of the liquid. In the case of a centrifugal compressor's impellers, the impacts are expected to occur at the leading edge of the blade (Figure 2). Therefore, the tangential velocity and the length of the surface are calculated using the shaft rotational speed and the impeller's leading edge geometry.

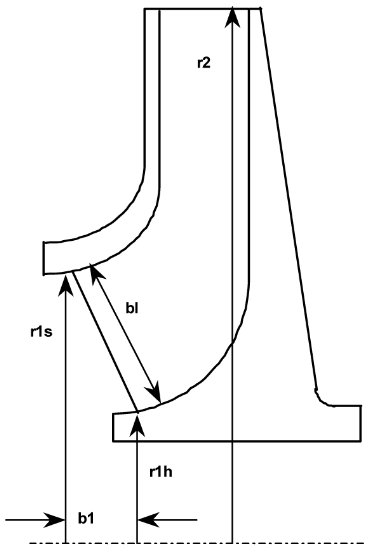


*Figure 2. Impeller Geometrical Parameters.*

The droplet diameter has been estimated from computational fluid dynamics (CFD) simulations using a fluid flow analysis and design optimization software. The simulations used the Eulerian-Eulerian approach with the Luo and Svendsen (1996) model for droplet breakup. The droplet distribution used to calculate the maximum droplet diameter was taken from Hoffmann and Stein (2002).

There are different opinions about the appropriate parameter to use to characterize the stress capability of the material for droplet impact (S). Some authors suggest using the material's yield strength, Vickers hardness, ultimate tensile strength, ultimate resilience, or modified resilience. There is no agreement on this subject in the published literature. The authors selected the Vickers hardness because it adjusts closely in most cases and it was the parameter used in the CEGB study. The empirical proportionality constant (K) and the empirical exponent (n) were taken from Pouchot, et al. (1971). These coefficients were adjusted from experimental data from the CEGB study.

The maximum leading edge impact velocity is calculated from the impeller geometry and the shaft rotational speed. The erosion potential factor (EPF) is determined using Equation (3), where $U_{cd}$ is the threshold velocity calculated from Equation (2) and $V_{max}$ is the leading edge maximum impact velocity. This equation uses the natural logarithm of the ratio of velocities. The criterion for defining a particular configuration as without erosion damage potential is an EPF larger than one. The natural logarithm larger than 1 is used as a safety factor that accounts for uncertainties in the model. In other words, the velocity ratio should be larger than 2.7183 to estimate no erosion potential.

$$EPF = LN\left(\frac{U_{cd}}{V_{max}}\right) \tag{3}$$

Part of the selection process for the OEM equipment includes the calculation of the erosion potential factor. Table 1 shows the evaluation of the erosion potential factor for two recent applications. Configuration 1 does not have a potential for erosion damage; the EPF is larger than one (EPF = 3.17). Configuration 2 has a potential for erosion damage because the EPF is 0.158. Having this information available during the selection of the equipment enables the OEM to make the necessary modifications before component manufacturing, thus satisfying the equipment availability and reliability goals. For Configuration 2, the impeller material can be modified to increase the threshold velocity, or the compressor can be selected to operate at lower shaft rotational speeds. Under certain conditions of severe erosion, the end-user process may need to be modified to reduce the factors that affect the erosion potential.

*Table 1. Example of Erosion Potential Factor Calculations.*

| Parameters | Configuration #1 | |
|---|---|---|
| Pressure | 2148.2(psia) | 14.81($MPa_a$) |
| Temperature | 111.2(°F) | 44(°C) |
| Vickers hardness | 6.98 E7($lbf/ft^2$) | 3295(MPa) |
| Empirical proportionality constant | 1.14 | |
| Empirical exponent | 0.57 | |
| Droplet diameter size | 1.97(mils) | 50(microns) |
| Sonic velocity | 2171(ft/s) | 651.4(m/s) |
| Liquid density | 1.1236($slugs/ft^3$) | 579.09($kg/m^3$) |
| Liquid viscosity | 1.316 E-4(lbm/ft*s) | 1.958 E-4(Pa.s) |
| Shaft rotational speed | 9255(RPM) | |
| Erosion potential factor | 3.17 | |
| | Configuration #2 | |
| Pressure | 200(psia) | 1.38($MPa_a$) |
| Temperature | 200(°F) | 93.3(°C) |
| Vickers hardness | 3.78 E7($lbf/ft^2$) | 1784.8(MPa) |
| Empirical proportionality constant | 1.3 | |
| Empirical exponent | 0.57 | |
| Droplet diameter size | 1.97(mils) | 50(microns) |
| Sonic velocity | 5100.5(ft/s) | 1555(m/s) |
| Liquid density | 1.7798($slugs/ft^3$) | 917.25($kg/m^3$) |
| Liquid viscosity | 2.04 E-4(lbm/ft*s) | 3.038 E-4(Pa.s) |
| Shaft rotational speed | 22825(RPM) | |
| Erosion potential factor | 0.158 | |

## BENCHMARK AND COMPARISON

One of the oil and gas industry's most used standards for selecting scrubbers and separators is NORSOK Process Systems Standard P-100 (2001). This NORSOK standard is developed by the Norwegian Technology Center with broad industry participation. It specifies the following with regard to maximum allowable liquid entrainment and droplet size.

- *Section 5.3.1.2*

"The specification for maximum allowable liquid entrainment from the scrubber, shall be set in agreement with the downstream equipment vendor and the operating company. A design margin (overlap) shall be included. A typical general specification of maximum liquid entrainment has historically been 13 liter/$MSm^3$ (0.1 US gallon/Million SCF)."

- *Section 5.3.3.2*

"Mesh demisters typical minimum droplet removal size is:
Metal mesh: 10 micron
Plastic/fiber: 3-5 micron"

- *Section 5.3.3.4*

"For axial cyclones, typical minimum droplet removal size is 5-10 microns depending on swirl velocity."

Therefore, using this specification the scrubbers or separators should allow a maximum of 0.1 US gallons per million SCF (13 liter/MSm$^3$) to enter the centrifugal compressor with a maximum droplet size of 10 microns (0.394 mils). This assumes the separation equipment would operate at the design conditions and that the process conditions would not change, which is not always the case.

Another standard that was used for comparison was the OEM's own specification for solvent injection in centrifugal compressors. This specification indicates a maximum droplet size of 25 microns (0.984 mils) and a liquid maximum rate of 3 percent by weight flow of total gas flow. This will help reduce, but not eliminate, the erosive effects.

The threshold velocity calculated with Equation (2) was developed to set the boundary where erosion damage is not determined by the amount of impacts. In other words, under threshold conditions the impacts do not create enough damage that cracks would develop regardless of the number of impacts. This proposed method for assessing erosion potential does not specify the maximum amount of liquid that can impact the impeller.

The maximum droplet size that can impact the impeller without potential for erosion damage can be calculated for each particular application using the proposed method. NORSOK standard P-100 (2001) specifies 10 microns (0.394 mils), and the OEM solvent injection standard recommends all droplets be less than 25 microns (0.984 mils) in diameter. But neither of these specifications suggests that this would eliminate the potential for liquid erosion damage. The proposed method allows the calculation of the maximum droplet size taking into consideration the key liquid and impeller material parameters that influence erosion damage. The criterion for defining a particular configuration as without erosion damage potential is an EPF larger than 1. By setting the erosion potential factor to 1 in Equation (3), the threshold velocity can be defined as 2.7183 times the maximum leading edge impact velocity ($V_{max}$). This ratio is used as a safety factor to account for the uncertainties in the model. Using Equations (1) and (2), the maximum droplet size can be calculated as shown in Equation (4). For example, the recent oil and gas application shown as Configuration 2 in Table 1 has an EPF of 0.158 using 50 microns (1.97 mils) as maximum diameter. For this application the maximum diameter calculated from Equation (4) to obtain an EPF >1 is 11.4 microns (0.448 mils).

$$D_{max} = \left(\frac{3\mu \cdot D_S}{4\pi \cdot \rho_l \cdot U_S}\right)^{1/2} \left[\frac{K}{2.7183 \cdot V_{max}} \left(\frac{S}{\rho_l \cdot C_o}\right)\right]^{1/n} \quad (4)$$

The OEM's excellent record of erosion protection for steam turbine blades is a good indication that the method used to assess erosion is reliable. The proposed method of calculating an erosion potential factor is compared with the method for determining blade protection. The criterion for blade protection is based on the experimental work of Moore and Sieverding (1976). To determine if a blade requires protection (i.e., flame hardening) the erosion index (EI) shown in Equation (5) is calculated based on the blade tip velocity (U), pressure entering the stage (P), and the moisture content (Q). Moore and Sieverding (1976) indicate that, based on a series of experiments on the last stage of large steam turbines, standard quenched and tempered 403 stainless steel did not show erosion damage for erosion index values less than eight (m$^4$/kg.s).

$$EI = \frac{2 \cdot Q^2 \cdot U^3}{P} \quad (5)$$

A set of 17 steam turbine applications that required blade protection is used as data for this comparison. The erosion potential factor is calculated for each application and its erosion damage prediction is compared with the erosion index. Table 2 shows the parameters used in calculating the EPF.

*Table 2. Parameters Used for Calculating Erosion Potential Factor.*

| Parameter | US customary units | SI units |
|---|---|---|
| Viscosity | 0.00031 (lbm/ft.s) | 4.613 E-4 (Pa.s) |
| Density | 1.9 (slugs/ft$^3$) | 979.22 (kg/m$^3$) |
| Sonic velocity | 5050 (ft/s) | 1539.24 (m/s) |
| Vickers hardness | 4.7 E7(lbf/ft$^2$) | 2216.3 (MPa) |

Table 3 shows the values of tip speed, moisture content, and pressure ahead of stage from the 17 examples used. The comparison between erosion index and erosion potential factor is shown in Table 4. The erosion potential factor is a function of droplet size. Two calculations of the EPF are shown in Table 4. The first calculation uses the maximum droplet size reported by Moore and Sieverding (1976) of 400 microns (15.7 mils). The range given by the authors is droplets between 50 microns (1.97 mils) and 400 microns (15.7 mils). The comparison between EI and EPF at 400 microns (15.7 mils) indicates good agreement. Both methods predict all samples would require blade protection due to the potential for erosion damage. All the EI values are larger than eight and all the EPF at 400 microns (15.7 mils) values are less than one. A plot of the correlation between these two parameters is shown in Figure 3. The trend observed indicates a good correlation but there is some spread of the data points. This is because the EPF values are calculated at a fixed droplet size that does not consider the influence of the moisture content and pressure ahead of stage on droplet diameter. The EI values shown in Table 4 take into consideration this influence on droplet size. To verify this analysis, the authors calculated the droplet diameter that would result in a correlation EI versus EPF with an $R^2$ of one. The diameter values are shown in Table 4 as Dcalc. All the diameters are within the range reported by Moore and Sieverding (1976) of 50 (1.97 mils) to 400 microns (15.7 mils). The EPF values calculated with Dcalc are shown in Table 4. The correlation EI versus EPF at Dcalc is illustrated in Figure 3.

*Table 3. Steam Turbine Examples Used for Comparison.*

| Examples | Tip Speed | | Moist. content | Press. ahead of stage | |
|---|---|---|---|---|---|
| | ft/s | m/s | % | $psi_a$ | $kPa_a$ |
| 1 | 1210 | 368.7 | 9.5 | 4.14 | 28.54 |
| 2 | 1132 | 344.9 | 9.3 | 5.32 | 36.68 |
| 3 | 1068 | 325.6 | 10.7 | 2.84 | 19.58 |
| 4 | 1068 | 325.6 | 11.3 | 2.01 | 13.86 |
| 5 | 1492 | 454.9 | 10.7 | 3.23 | 22.27 |
| 6 | 1414 | 430.9 | 9.8 | 3.37 | 23.24 |
| 7 | 1068 | 325.6 | 10.1 | 2.36 | 16.27 |
| 8 | 1414 | 430.9 | 10.8 | 3.52 | 24.27 |
| 9 | 1414 | 430.9 | 10.8 | 2.93 | 20.20 |
| 10 | 877 | 267.3 | 6.7 | 2.52 | 17.37 |
| 11 | 1414 | 430.9 | 11.7 | 3.46 | 23.86 |
| 12 | 1355 | 413.1 | 9.3 | 4.14 | 28.54 |
| 13 | 1024 | 312.2 | 11.1 | 2.38 | 16.41 |
| 14 | 1219 | 371.5 | 10.5 | 4.4 | 30.34 |
| 15 | 1244 | 379 | 11.6 | 3.03 | 20.89 |
| 16 | 877 | 267.3 | 6.8 | 2.57 | 17.72 |
| 17 | 1492 | 454.9 | 7.7 | 4.28 | 29.51 |

*Table 4. Comparison Erosion Index Versus Erosion Potential Factor.*

| Examples | *EI* | *EPF@ 400 microns* | Dcalc | | *EPF @ Dcalc* |
|---|---|---|---|---|---|
| | $m^4$/kg.s | (15.7 mils) | microns | mils | |
| 1 | 31.68 | -0.347 | 196 | 7.72 | -0.204 |
| 2 | 19.36 | -0.401 | 149 | 5.87 | -0.100 |
| 3 | 40.36 | -0.259 | 261 | 10.3 | -0.277 |
| 4 | 63.59 | -0.259 | 367 | 14.4 | -0.472 |
| 5 | 96.75 | -0.543 | 364 | 14.3 | -0.752 |
| 6 | 66.14 | -0.503 | 248 | 9.76 | -0.494 |
| 7 | 43.27 | -0.259 | 272 | 10.7 | -0.301 |
| 8 | 76.91 | -0.503 | 291 | 11.5 | -0.584 |
| 9 | 92.39 | -0.503 | 366 | 14.4 | -0.715 |
| 10 | 9.87 | -0.020 | 252 | 9.92 | -0.020 |
| 11 | 91.82 | -0.503 | 363 | 14.3 | -0.710 |
| 12 | 42.71 | -0.652 | 135 | 5.31 | -0.296 |
| 13 | 45.69 | -0.295 | 265 | 10.4 | -0.321 |
| 14 | 37.27 | -0.752 | 105 | 4.13 | -0.251 |
| 15 | 70.15 | -0.312 | 368 | 14.5 | -0.528 |
| 16 | 9.97 | -0.020 | 253 | 9.96 | -0.021 |
| 17 | 37.81 | -0.543 | 152 | 5.98 | -0.255 |

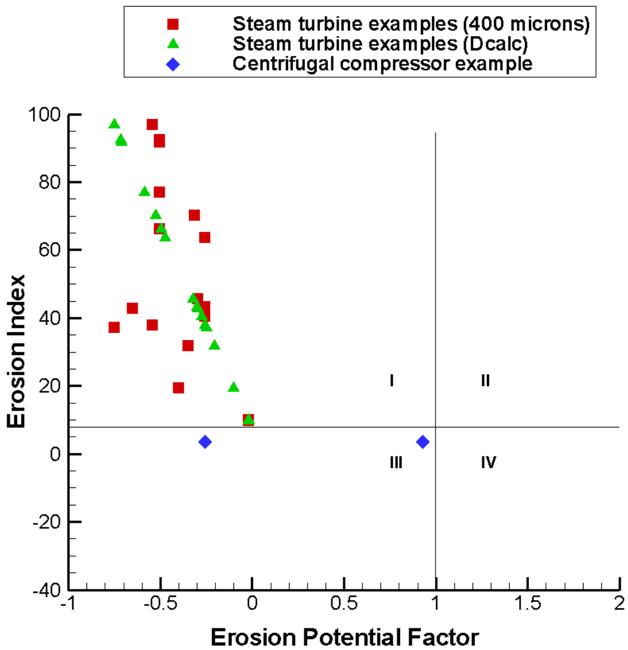


*Figure 3. Correlation of Erosion Index Versus Erosion Potential Factor.*

The previous comparison was performed for conditions typical for last stage steam turbines. For centrifugal compressors the leading edge maximum impact velocity is expected to be much lower than the tip velocity of a last stage steam turbine blade. A typical centrifugal compressor configuration was designed for evaluation using both methods. The configuration is specified as follows: A gas stream with water and hydrocarbon condensate as the liquid phase and a 15 percent liquid mass fraction is used. Other parameters used are: pressure 15 $psi_a$ (103.4 $kPa_a$), tip velocity (or maximum leading edge impact velocity) of 650 ft/s (198.12 m/s), sonic velocity 4103 ft/s (1250.6 m/s), 403 SS as material, and 400 and 50 micron (15.7 and 1.97 mil) droplets. Under this scenario, the erosion index obtained would be EI = 3.38 ($m^4$/kg.s) which means no erosion damage is expected, no protection required. The erosion potential factor calculated is EPF = 0.25 for droplets 400 microns (15.7 mils) in size and EPF = 0.93 for droplets 50 microns (1.97 mils) in size, which means erosion damage is possible. These two values of erosion potential factor are shown in Figure 3. In this example, the proposed erosion potential method appears to be more conservative than the steam turbine blade protection method. One aspect to consider is that the erosion index is designed for the last stage of steam turbines where the pressure would be subatmospheric. The use of pressure values larger than subatmospheric would result in an extrapolation that could skew the results.

Using the limiting values for erosion index of 8 and erosion potential factor of 1, the comparison space shown in Figure 3 can be divided into fours sections. The four sections are labeled I, II, III, and IV. Points located in section I denotes that both methods indicate potential for erosion problems. The 17 samples shown in Table 4 correspond to this category. Section II denotes that EI indicates erosion possibility while EPF does not or that EI is more conservative. Section IV means both methods indicate no erosion problem. Points in section III denote that EPF indicates erosion possibility while EI does not or that EPF is more conservative. The samples under centrifugal compressor conditions are located in section III. Therefore, the proposed method is more conservative for the applications targeted by this paper. This provides a measure of confidence in the calculations given the good experience of the OEM with the steam turbine blade protection method.

## SUMMARY AND CONCLUSIONS

This paper presented a method for assessing liquid droplet erosion potential on impellers of centrifugal compressors. The proposed method calculates a threshold velocity that represents the limit for the onset of erosion damage. The calculation is based on an erosion model developed by Pouchot (1970) and Pouchot, et al. (1971). The potential for erosion damage is assessed by comparing the threshold velocity with the maximum expected impact velocity. A criterion was developed for determining the conditions where potential for erosion damage existed as a natural logarithm of the ratio of the velocities. This was selected to create a safety margin around the calculations. The erosion modeling tool was embedded in the OEM's equipment selection process for long-term product success.

The proposed method was compared against NORSOK standard P-100 (2001) and the OEM specification for solvent injection. Most standards set the maximum droplet size based on experience as a generic rule to cover all applications. The erosion potential method can be used to determine the maximum droplet size for each particular application. This allows users to properly select and apply the equipment. Additionally, the OEMs can design and manufacture the compression system in accordance with the process conditions while limiting possible erosion damage and maintenance problems. The proposed method was also benchmarked against the OEM's own expertise regarding blade protection from liquid erosion in steam turbines. The results from the proposed erosion potential method agreed closely with the steam turbine experience and the erosion potential method was found to be more conservative.

This paper was focused on erosion damage from liquid droplet impacts. Other factors that can result in damage to the compressor internals due to liquids in the gas stream were not considered in the scope of this study, but have been analyzed as parts of other development projects. The findings of these other studies will be shared in future presentations at conferences and in other technical publications.

## DISCLAIMER

## NOMENCLATURE

$U_{cd}$ = Threshold condition velocity (ft/s)
K = Empirical proportionality constant (dimensionless)
S = Average stress capability of the material for droplet impact ($lb/ft^2$)
$\rho_l$ = Liquid density ($slugs/ft^3$)
$C_0$ = Sonic velocity in the uncompressed liquid (ft/s)
$\delta$ = Liquid film thickness over specimen (ft)
D = Droplet diameter (ft)
n = Empirical exponent (dimensionless)
$\mu$ = Liquid viscosity ($lb.s/ft^2$)
$D_s$ = Specimen diameter (ft)
$U_s$ = Specimen velocity (ft/s)
EI = Erosion index ($m^4/kg.s$)
Q = Moisture content (percent)
U = Blade tip velocity (m/s)
P = Pressure ahead of the stage ($Pa_a$)
EPF = Erosion potential factor (dimensionless)
$V_{max}$ = Maximum leading edge impact velocity (ft/s)

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