Technical Condition Assessment and Remaining Useful Life Estimation of Choke Valves subject to Erosion

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ABSTRACT

Components that are part of an industrial process are normally degraded after some time in use. Efficient maintenance is of fundamental importance to the safety and economics of the plant operation. Predicting the future evolution of the degradation of components and estimating their remaining useful life are central elements for the implementation of optimal maintenance strategies. To achieve this, one must first identify the parameters providing a reliable indication of component performance or technical condition and then develop models for predicting their future trend. This paper presents an approach to tackle a practical problem concerning the estimation of remaining useful life of choke valves located topside at wells on the Norwegian Continental Shelf. Choke valves suffer from erosion due to sand production in mature fields and eventually need to be replaced. One indicator of the erosion process is the increase of the difference between the theoretical and estimated valve flow coefficients. To achieve a reliable estimate of this parameter an empirical model-based approach is used accounting also for the historical well test measures collected during the choke valve life. A gamma process is then devised to model the temporal variability trend of the erosion. Finally, the choke valve remaining useful file is estimated based on an erosion threshold established by expert judgment.*

1 INTRODUCTION

Predicting the remaining useful lifetime of industrial and structural components bears recognized valuable advantages in improving the safety and economical aspects in the industrial facilities. Ideally, when the condition of a component can be monitored, inspection and condition-based maintenance planning can be devised to maintain the component dynamically on the basis of the observed condition. This requires the capability of predicting the evolution of the component's degradation state over time.

Prognostics deals with the task of predicting the probable failure time of a component during plant operation, thus offering a frame to support the decision on whether/when fixing or replacing a component based on the estimation of its Remaining Useful Life (RUL).

One or more parameters carry the information about the current health state of a component and the dynamic evolution of its performance and can be used for assessing its RUL. The variation (or degradation) in time of the performance parameters can give indications of a possible future component failure, once a specified parameter threshold is reached. Hence, if the degradation path of the performance of the component is predicted, the failure time and RUL of the component can be estimated.

Model-based estimation methods are often used for inferring the RUL of a component on the basis of a sequence of measurements related to its state. In practice, the RUL estimate of a component may be difficult to obtain, since its degradation state may not be directly observable and/or the measurements may be affected by noises and disturbances. In these cases, model-based estimation methods like Bayesian methods (Doucet, 1998; Doucet *et al.*, 2001) or the Kalman filter (Anderson and Moore, 1979) offer interesting potentials for inferring the dynamic degradation trend on the basis of sequences of noisy measurements, ensuring reliable quantifications of the RUL estimation uncertainties. On the other hand, one could tackle earlier in the process the problem of noisy or lacking measurements of the performance parameters by providing an estimate using common filtering techniques or empirical models.

In this paper, we tackle a practical prognostic problem proposed by the Norwegian oil company Statoil and regarding the RUL estimation of choke valves located topside at wells on the Norwegian Continental Shelf. In fact, choke valves are subject to erosion due to the sand carried along with the oil-gas-water mixture during the extraction process.

The primary performance parameter which indicates the choke valve erosion state is identified as the difference between the theoretically designed (C_V^{theor}) and actually calculated (C_V^{calc}) valve flow coefficients (Andrews *et al.*, 2005; Bringedal *et al.*, 2010; Haugen *et al.*, 1995; Hovda and Andrews, 2007; Hovda and Lejon, 2010). Based on such performance parameter, the goal is here to estimate the functional shape of the erosion in time, the probability distribution of the choke valve replacement time and finally the choke valve RUL.

In this respect, it is fundamental to obtain continuous, stable and reliable measurements (or estimates) of the performance parameter. To this aim, an empirical model-based technique developed at the Institute for Energy Technology on which a patent is currently pending (PCT/NO2008/00293, 2008) has been applied. Further, a gamma process approach (van Noortwijk and Pandey, 2003) has been deployed to carry out the prognostics assessment.

The paper is organized as follows. In Section 2, the technical aspects related to choke valves used in the oil industry are briefly illustrated. Section 3 provides a detailed insight on the performance parameters effectively used to assess the choke valve technical condition and, finally, Section 4 presents the results of the choke valve RUL estimation. Notice that, in this research, measurements of parameters related to one single choke valve are available. Further analyses are planned to extend and generalize the choke valve prognostics as measurements related to other similar valves will be provided. Conclusions on the advantages and limitations of the proposed approach are drawn in the final Section.

2 CHOKE VALVES IN OIL INDUSTRY

In Figure 1, a choke valve is sketched. As a common practice in the oil industry, liquid and gas mixtures are flown through chokes to control flow rates and protect equipment from unusual pressure fluctuations. Both surface and subsurface chokes are utilized. At the surface all chokes are of the rotating disk type. Here the throttle mechanism consists of two circular disks each with a pair of circular openings to create variable flow areas. One of the disks is fixed in the valve body, the other being rotated either by manual operation or by actuator, to vary or close the aperture. The mating surfaces of both disks are precision lapped to ensure tight sealing and prevention of ingress of grained grit, sand and scale between the disks.

Prolonged exposure to abrasive flow conditions will eventually lead to erosion on sealing surfaces and the valve body. The rotating disk valves are designed to produce near linear flow characteristics making them ideal for e.g. control applications. Erosion is a slow process and will produce a gradual change from the design characteristics. For a specific opening the valve flow coefficient will increase as the valve circular openings erode (change in geometry). Calculation of the erosion rate development is a complex task and is in general dependent on factors like the design and build quality (design geometry, materials used), operational history (particle impact angle, velocity, fraction of abrasion particles and change in geometry) and the current state of the valve as measured by a set of indicators. An important indicator is the deviation between designed flow coefficient and the estimated flow coefficient. Erosion management is vital to avoid failures that may result in loss of containment, production being held back, and increased maintenance costs.

3 CHOKE VALVE TECHNICAL CONDITION ASSESSMENT

In many existing fields of the Norwegian Continental Shelf, it is common for the choke valve erosion process to sharply increase toward the end of the well life due to decreasing reservoir pressure and increasing sand extraction. Inspection, maintenance intervals and methods are decided based on a detailed assessment of the erosion rates of different components. From an economical point of view, an increase in the extraction/production line can be obtained by reducing the downstream pressure at choke valves, which increases the flow rate, but also the erosion for more sand passes through the choke valve at higher velocity. Hence the design and material selection of such components is crucial (Andrews *et al.*, 2005; Bringedal *et al.*, 2010; Haugen *et al.*, 1995; Hovda and Lejon, 2010).

Much research has been carried out on erosion in choke valves. Procedures for calculation of erosion rates in pipe components based on extensive experiments and computational fluid dynamic modeling are outlined in a DNV Recommended Practice (Det Norske Veritas, 2005). Wallace (Wallace *et al.*, 2004) compared flow coefficients and mass removal rates with measurements from a parallel experimental program, emphasizing that neglecting the modeling of geometry changes due to erosion can partly account for poor prediction of wear rates.

So far no generally accepted method has been devised for online calculation of the erosion rate in choke valves due to multiphase flow. One way to evaluate the erosion and to assess the choke valve technical condition is to refer to the valve flow coefficient C_v. In fact, the difference $\delta_{C_v} = C_v^{calc} - C_v^{theor}$ between the actual and theoretical C_v is a trustworthy indicator of the valve technical condition. The actual calculated C_v^{calc} is based on the choke opening and other process parameters, while the theoretical C_v^{theor} is given as a technical parameter from the vendors data sheet and is dependent on the valve type and opening. The process parameters used to calculate δ_{C_v} are daily mean values of:

- Allocated oil flow rate (Sm^3/d)[†]
- Allocated water flow rate (Sm^3/d)
- Allocated gas flow rate (Sm^3/d)
- Upstream well head pressure (bar)
- Downstream well head pressure (bar)
- Choke opening angle set point (°)
- Design valve flow coefficient from data sheet , C_v^{theor}
- Calculated valve flow coefficient C_v^{calc} from Insight software, ABB[‡]

[†] Sm^3/d stands for standard cubic meters per day

[‡] *Insight – Erosion Management System* is a commercial software product from ABB Oil & Gas. See http://www05.abb.com/global/scot/scot267.nsf/veritydisplay/a19574f541925d408525771b004ba78b/$File/TP002_Insight_erosion_management_system.pdf

Allocated production flow rates are not measured, but calculated with software which accounts for measurements of pressures, temperatures and other parameters whose variability causes large uncertainties in the calculation.

The physics equations that describe the behavior of isentropic multiphase flow through chokes are deduced from the general energy equation and are presented in (Perkins, 1993). The equations are valid for both critical and subcritical flows. Under subcritical flow conditions, if the pressure upstream of the choke is held constant, the mass flow rate of a stream is a function of the pressure downstream of the choke. If the pressure drop across the choke becomes sufficiently large, the flow regime will become critical and, if the upstream pressure is held constant, the mass flow rate will be independent of the downstream pressure.

The actual valve flow coefficient C_v^{calc} is calculated by the Insight software. Homogeneous flow theory based on average parameter values can be used in multiphase flows to calculate the valve flow coefficient (Metso Automation, 2005). The density of the mixture ρ_E is formulated as:

$$\rho_E = \left(\frac{f_g}{\rho_g \cdot J^2} + \frac{f_w}{\rho_w} + \frac{f_o}{\rho_o} \right)^{-1} \qquad (1)$$

where $f_g = w_g / w$, $f_w = w_w / w$ and $f_o = w_o / w$ are the fractions of gas, water and oil mass flow rates, respectively, over the total mass flow rate, ρ_g, ρ_w and ρ_o are the densities of the gas, water and oil-phases, respectively, on the valve inlet side and J is the gas expansion factor.

The actual valve flow coefficient C_v^{calc} is then computed as:

$$C_v^{calc} = \frac{w}{N_6 F_p \sqrt{\Delta P \rho_E}} \qquad (2)$$

where $w = w_g + w_w + w_o$ is the total mass flow rate of the mixture, N_6 is a constant equal to 27.3, F_p is the so-called piping geometry factor and ΔP is the pressure drop across the valve (bar).

Besides the indications provided by the performance parameter C_v^{calc}, also measurements directly obtained during periodical well tests are valuable to be used for developing and validating the prognostic model for RUL estimation. In fact, these measurements help assessing the performance of current condition indicators like C_v^{calc} and can be used as feedback to the system designer for improving the design itself or modifying the condition indicators. Well tests have been performed at regular intervals and the measurements retained during the well tests (especially the flow rates) are considered more accurate than corresponding values available during regular operation[§].

Figure 2 illustrates the operational history of the choke valve under analysis in terms of the calculated C_v^{calc} and theoretical C_v^{theor} valve flow coefficients. A period of 384 calendar days has passed from the valve installation at November 26, 2005 (dark star) until December 15, 2006 when erosion was confirmed, and the choke was replaced (light star)[**]. In between, there has been 7 well tests (squares) and the corresponding measures of C_v^{calc} (black dots) and C_v^{theor} (red dots) are indicated in the graph. Blanks spots indicate absence of measurements due to process shutdown.

As clearly shown, the difference δ_{C_v} observed at subsequent well test increases due to erosion until a threshold is reached and the choke valve is replaced. Since C_v^{theor} is a design parameter only related on the valve opening, if the opening does not change, the trend of δ_{C_v} is directly dependent on the variations of C_v^{calc} caused by the erosion process.

Measurements of C_v^{calc} obtained at well tests during the valve life are indeed accurate, yet too few to effectively capture in details the evolution of C_v^{calc} (i.e. the proceeding of the erosion process) and to be eventually used in a model-based RUL estimation technique based on the gamma process. In fact, to reduce the uncertainty of the RUL estimation, a large amount of reliable information is needed and thus it is fundamental to determine the values of the actual daily C_v between the well tests.

In this view, daily measurements of C_v^{calc} can be obtained by interpolation/extrapolation of the known measures (dark dashed line in Figure 2). Nevertheless, such procedure would require waiting for the following well test to be able to interpolate measurements with the previous one and due to the long gaps between well tests it would not allow a prompt assessment of the valve technical condition.

Another solution, actually adopted by ELF[††], can be the analytical calculation of C_v^{calc} based on other process parameters. The inaccuracy and high uncertainty of the measurements of the process parameters lead the model outcome (the dark line in Figure 2) to be very noisy and in some parts inconsistent. In fact, in some time intervals it indicates a decrease of C_v^{calc} which contrasts with the physical assumption that erosion is a continuous monotonic process. Furthermore, the resulting noisy difference δ_{C_v} cannot be used as the performance parameter within the gamma process for RUL estimation.

In this work, an empirical model-based approach (PCT/NO2008/00293, 2008) has been used to obtain reliable estimates of C_v^{calc}. In general, given a number of input parameters correlated to a quantity of interest (in this case C_v^{calc}), the method aims at providing a reliable estimate of that quantity.

Six parameters are here available for estimating C_v^{calc}: the upstream and downstream valve pressures, the valve opening and the daily allocated rates of oil, gas and water. Two models are considered, one using as inputs only the two pressures and the valve opening and one obtained by adding as inputs the allocated rates. The training target is the C_v^{calc} obtained by interpolation/extrapolation of the valve flow coefficient measurements at the well tests (dark dashed line in Figure 2)[‡‡]. Once trained, the models are fed with new measures of the input process parameters as they become available and they are expected to provide an accurate estimate of C_v^{calc}.

[§] Well tests are performed with a three phase flow meter which is not constantly installed. During the tests the flow from one or several wells is fed into a test separator for analysis and detailed flow measurements. This normally takes place when the well is taken into production and later at regular intervals. Since the test separator is much better instrumented and furthermore laboratory analyses are performed, the accuracy of the data after a well test is much higher than that of the data recorded between the well tests.

[**] Replacement of the choke valves are performed when the choke is worn out or due to some other criteria such as the potential production gain achieved by changing to a larger opening.

[††] Former French oil company ELF Petroleum now renamed Total.

[‡‡] The measurements corresponding to sharp variations of the theoretical valve flow coefficient (spikes in the light line in Figure 2) have been removed and therefore not used in the model training. This is motivated by the fact that they correspond to short (1 or 2 days) valve opening variations, most likely intended as tests for the valve mechanisms. Correspondingly sharp variations are expected to occur in the calculated valve flow coefficient. These trends are hard to model and negatively affect the model performances. Furthermore, they are not meaningful for estimating erosion since erosion is a slow process unaffected by sharp events.

Figure 3 illustrates the trends of the performance parameter $\delta_{C_v} = C_v^{calc} - C_v^{theor}$ when using C_v^{calc} estimates provided by the ELF model and by the empirical models with three and six input parameters, respectively. The ELF model provides inconsistent indications of the erosion state (negative and extremely noisy values of δ_{C_v} - light dashed line in Figure 3), whereas using C_v^{calc} obtained by the empirical models provides a reliable indication for assessing the choke valve technical condition. In particular, the trend of δ_{C_v} obtained using the model with six input parameters (dark line in Figure 3) appears as the most suitable to be used in the gamma process for RUL estimation.

4 EROSION AND CHOKE VALVE RUL ESTIMATION

The cumulative operational time-dependent erosion is here modeled by the gamma process method (van Noortwijk and Pandey, 2003) which bears the advantage of capturing the uncertainty of the erosion process over the choke valve lifetime.

From the point of view of condition-based maintenance, the operational time and not the calendar time is considered[§§]. The δ_{C_v} estimate of the empirical model has been further filtered to obtain a monotonic increasing function which is required for using δ_{C_v} within the gamma process[***].

In general, the probability density function of the generic quantity $Y(t)$ is obtained by the gamma process as:

$$f_{Y(t)}(y) = \frac{u^{v(t)}}{\Gamma(v(t))} y^{v(t)-1} e^{-uy} \tag{3}$$

where u is a constant scale parameter, $\Gamma(v(t))$ is the complete gamma function[†††] and $v(t)$ is the shape parameter and is a monotonically increasing, positive-defined, right-continuous, real-valued function with initial condition $v(0)=0$ which is established based on the knowledge of the degradation process and therefore is intended to reflect the physical nature of the erosion process. Notice that in this case $Y(t)$ is the filtered choke valve performance parameter $\delta_{C_v}(t)$ modeled as a random quantity.

By setting an erosion threshold ρ, one can obtain from (3) the choke valve cumulative lifetime distribution function, i.e. the first hitting time T_ρ of threshold level ρ:

$$F_{T_\rho}(t) = \Pr(T_\rho \le t) = \Pr(Y(t) \ge \rho) = \\ = \int_{y=\rho}^{\infty} f_{Y(t)}(y)\,dy = \frac{\Gamma(v(t), \rho u)}{\Gamma(v(t))} \tag{4}$$

where $\Gamma(v(t), \rho u)$ is the incomplete gamma function. The parameters of the gamma process are established using the Method of Moments (van Noortwijk and Pandey, 2003) assuming the functional form of the expected value of $Y(t)$ to be $E(Y(t)) = ct^b/u$. Two different parameters estimations are carried out considering 220.8 and 305 operational days, respectively. Figures 4 and 5 show the erosion predictions in the two cases. Notice that the choke valve has been replaced after 314 operational days.

The erosion trend appears concave if 220.8 operational days are considered, whereas it is convex when 305 operational days are used. Given a threshold value $\rho = 7$ based on Statoil expert judgment, the choke valve lifetime distribution can be estimated. In the first case, the median of the lifetime distribution is estimated to be 246 operational days (68 operational days before the actual choke valve replacement). Nevertheless, a two-sided 95% confidence interval corresponding to [99, 496] operational days clearly reveals a large prediction uncertainty. In the second case, the estimated median of the lifetime distribution is 190 operational days (124 before the choke change) with a 95% confidence interval ranging in [149, 229] operational days, which is a much smaller prediction uncertainty.

These results show the crucial trade-off between the amount of information to collect for increasing the precision of the erosion trend prediction and the risk of getting too close to the erosion threshold. In fact, if the erosion indication parameter is close to or has passed the threshold value, the gamma process returns a very

[§§] The operational time is defined as the time during which the choke opening is different from zero. The daily operational time is calculated as the fraction of hours the choke valve has been effectively open during one day and it is equal to zero if the valve has never been open.

[***] A two-step filtering is here adopted. First a centered moving average with time window set equal to ±4 is deployed to smooth out the noisy peaks. Then moving maxima filtering is used to generate a monotonic trend of δ_{C_v}.

[†††] The generic shape of the gamma function is: $\Gamma(v(t), x) = \int_{z=x}^{\infty} z^{v(t)-1} e^{-z} dz$, where $x \in [0, \infty)$. If $x = 0$ the gamma function is called complete, otherwise it is called incomplete.

narrow remaining lifetime distribution, i.e. the valve should be instantly replaced.

In this respect, establishing the value for the threshold is an open problem. In fact, a correct combination of the threshold value, the amount of operational days used in the gamma process and the functional trend (concave/convex) of the erosion process is crucial to provide a reliable lifetime distribution and RUL estimate. In this respect, the threshold setting can be improved by considering erosion trends from similar choke valves and by accounting also for economical and safety requirements.

5 CONCLUSIONS

In this paper, a practical prognostic problem has been presented concerning the remaining useful life estimation of choke valves used in the oil industry and subject to erosion due to sand grains.

Two issues have been here considered: (1) how to obtain reliable and stable measurements of the performance parameter (in this case the valve flow coefficient) that is effectively giving the indication of the state of the erosion process at a specific operational time and (2) how to predict the trend of the erosion process and estimate the choke valve remaining useful life.

To this aim, two methods have been combined. Concerning the first problem, an empirical model-based method has been deployed and has provided reliable estimates of the performance parameter which then have been effectively used within the gamma process to tackle the second problem. In this respect, the uncertainty of the estimation of the remaining useful life has shown to be closely dependent on the amount of data used within the gamma process, the functional shape and the value of the threshold which defines the severity of the erosion. Collected or simulated erosion measurements of similar choke valves can be used to define an optimal value for the erosion threshold and to generate a more comprehensive statistics in order to reduce the uncertainty and increase the accuracy of the remaining useful lifetime estimation.

ACKNOWLEDGMENTS

The authors wish to thank the IO Center for Integrated Operations in the Petroleum Industry for funding this research project; Erling Lunde, Morten Løes, Kjell Lejon and Jamie Stuart Andrews at Statoil ASA for proving us with the operational choke valve data; Knut Hovda and B. Bringedal at ABB Oil & Gas for providing the results of the *Insight – Erosion Management System* software.

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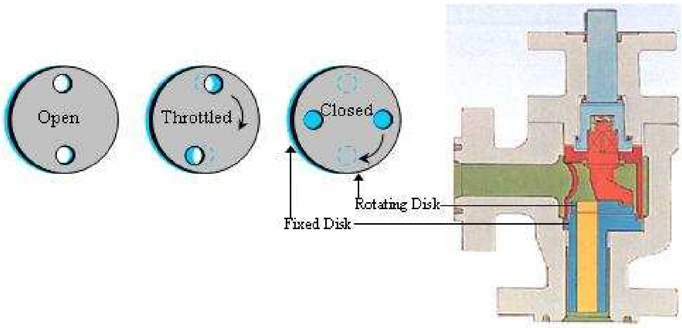

Figure 1: Typical choke valve of rotating disk type: by rotating the disk the flow will be throttled (picture taken from www.vonkchokes.nl)

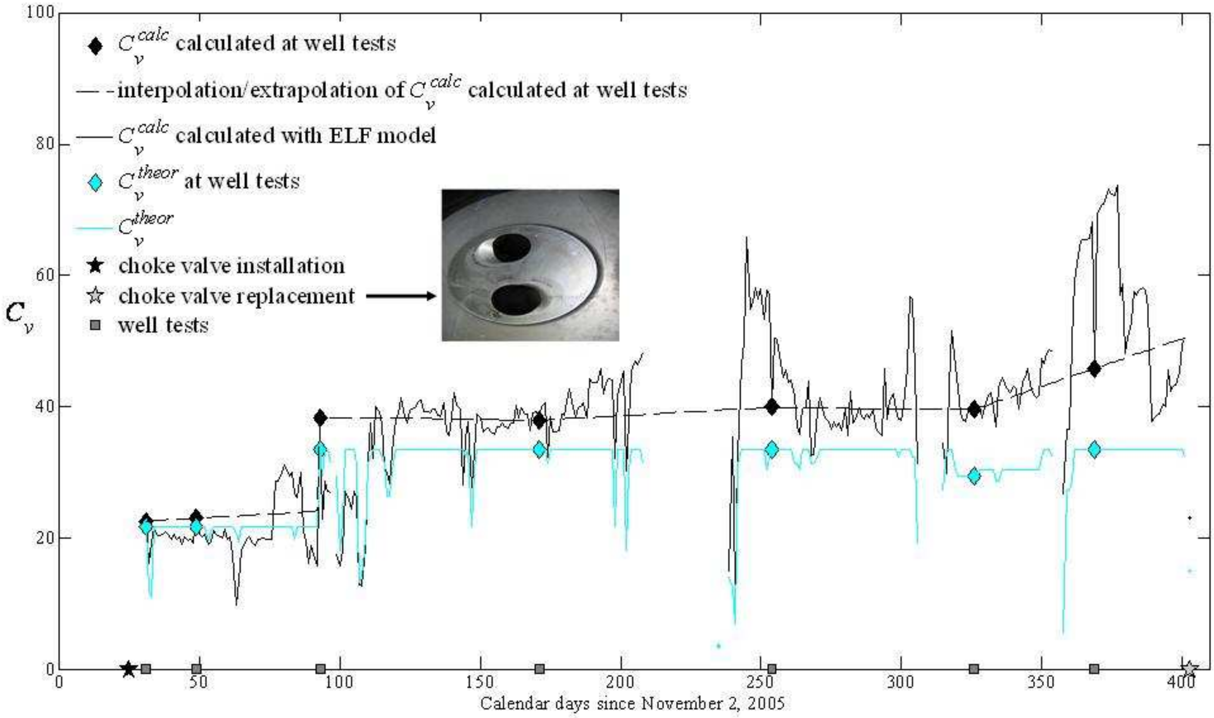

Figure 2: Choke valve operational history from installation to replacement in terms of C_v^{calc} and C_v^{theor}

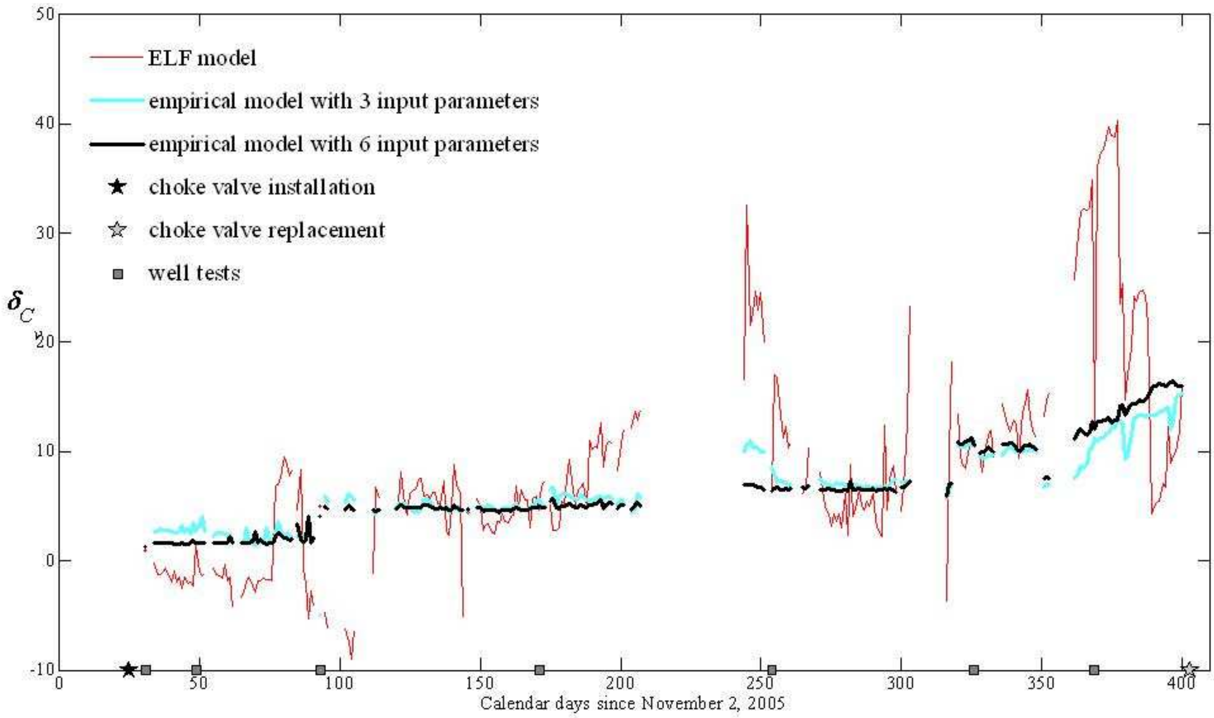

Figure 3: Trend of the performance parameter δ_{C_v} using different C_v^{calc}

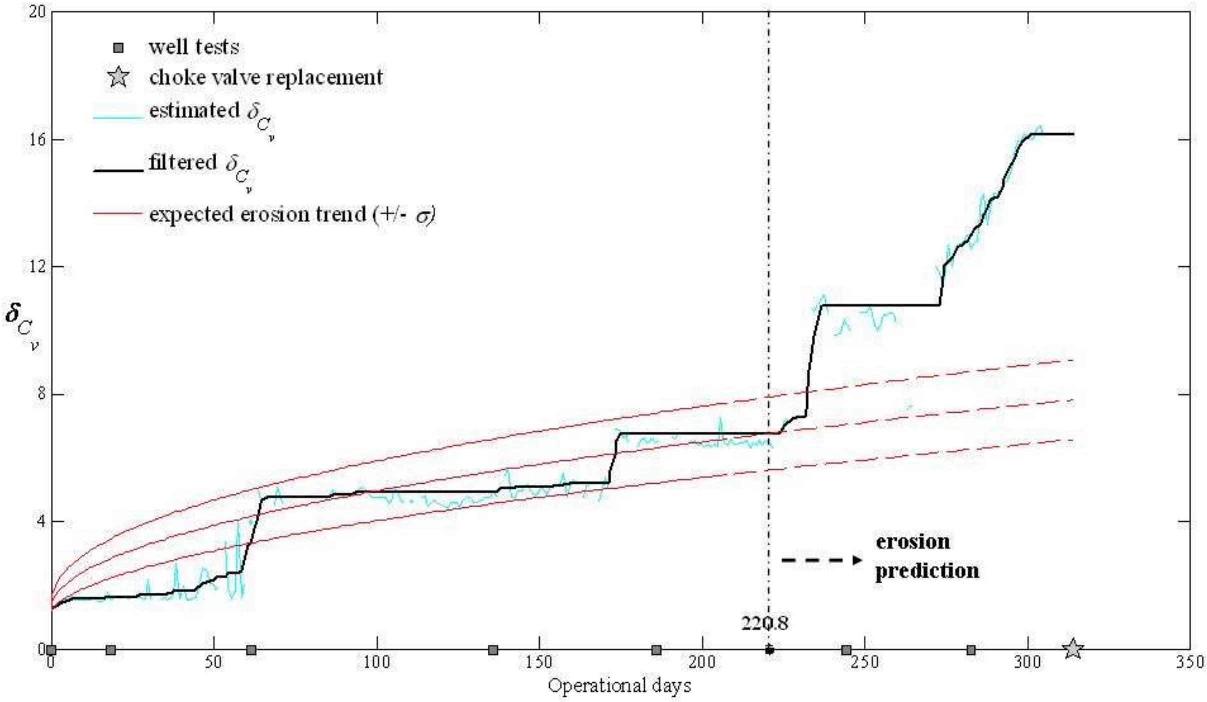

Figure 4: Expected functional shape of the erosion process using data related to the first 220.8 operational days ($\hat{b}$ =0.5, $\hat{u}$ =4.20057, $\hat{c}$ =1.55727)

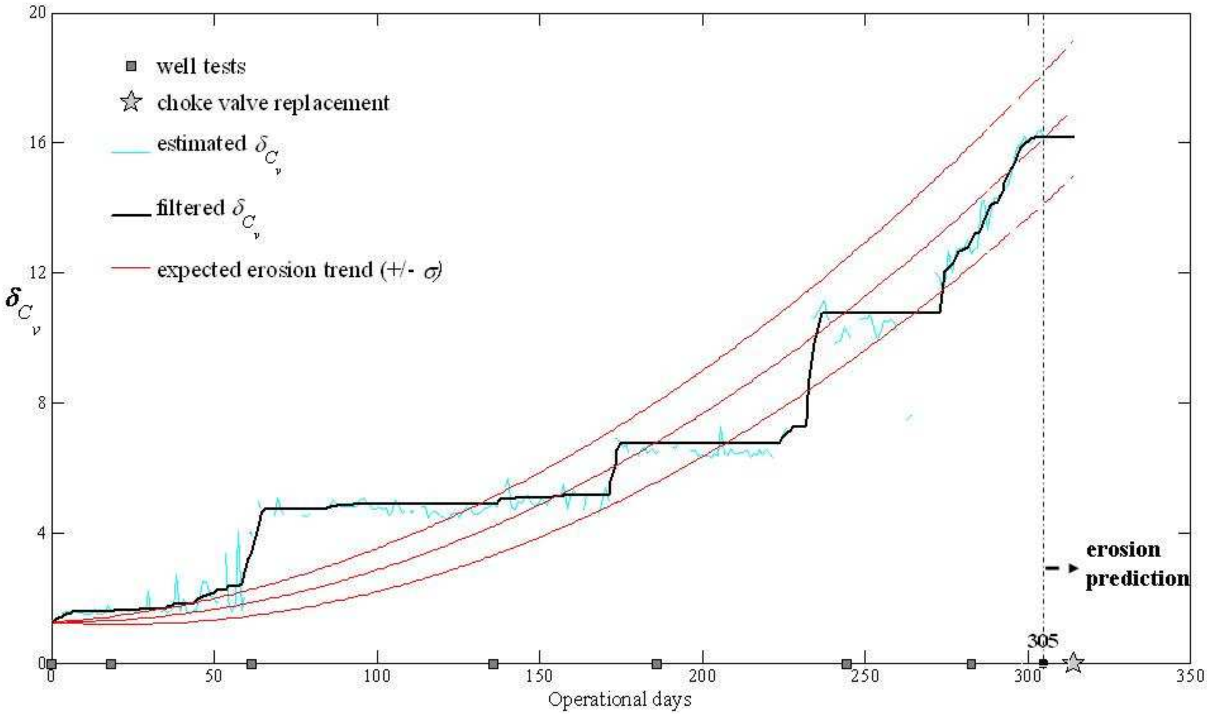

Figure 5: Expected functional shape of the erosion process using data up to 305 operational days ($\hat{b}$ =2, $\hat{u}$ =3.65543, $\hat{c}$ =0.00059)