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Reliability assessment of the vertical well system subjected to erosion and tubing failure

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ABSTRACT
Tubing is part of a typical vertical well system which functions to transport hydrocarbon from the producing formations to the field surface facilities for processing. With its exposure to the harsh sandstone reservoir environment, erosion is likely to be present in the tubing. Regardless of this, the existing burst design models have not considered the impact from erosion when carrying out the assessment of the tubing. This paper proposes an erosion model to be integrated into the existing burst strength models and the assessments to be carried out using probabilistic approaches. Herein, limit state functions were introduced for the tubing and reliability assessment of the structure was computed by means of probability of failures (P_f) under varying reservoir pressures (P_{op}). Comparisons were made between the models computed with and without the inclusion of erosion models, for a well currently operated in the Peninsular Malaysia Operation.

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Reliability; limit state function; well; tubing; erosion

1. Introduction

A typical well system is composed of two main parts, namely casing and tubing, as shown in Figure 1. Their function is not only to ensure the smooth extraction of hydrocarbon from the reservoir, but also to provide housing for the whole well system. The tubing structure, in particular, is the conduit through which hydrocarbons are brought from the producing formations to the field surface facilities for processing. It should be designed and sized to be adequately strong to resist loads and deformations associated with the production and workovers.

Failing to withstand the right amount of loads would allow several well failures, for instance blowout or leakages. For instance in Pennsylvania alone, Vidic et al. (2013) detected around 3.4% wells drilled having leakage between year 2008 and 2013. For the offshore of the United Kingdom, a study conducted by Douglas-Westwood Ltd., had found that 10% of the wells had been shut down in the last 5 years due to 'structural integrity issues' (Fletcher 2005). Statistics prepared by Haaland (2017) for the Norwegian continental shelf supported the fact that the issue of well integrity was mostly contributed by tubing (29%), followed by casing, cement, packer among others (all less than 10%). These statistics have somehow triggered an alarming issue related to well tubing failures, thus special attention should be given for tackling the issue in the right assessment manner.

As sandstone is one of the common reservoir compositions and characteristics, sand and fine particles are always known to be by-products in the extraction of hydrocarbon from the wells. The sharp texture of sand coupled with its fast travelling speed has given it great potentials to erode any surface materials it touches, especially the tubing and pipeline walls. In the case of tubing, the occurrence of wall thinning anywhere would eventually progress to tubing burst, leakage and blowout.

The extent and impact erosion gives to the tubing structure are mainly governed by parameters associated with the operations. For instance, while sand particles are entrained in the liquid droplets in vertical annular flow, the particles would easily impinge on the pipe wall at a higher velocity in the gas core (Mazumder et al. 2008). In two-phase flows (fluid–sand), the eroding particle characteristics are easier to be estimated as compared to the multiphase flows (oil–water–sand) as the behaviour of eroding particles is only affected by a single fluid characteristic (Kesana et al. 2014). In a different work by Okonkwo and Mohamed (2014), it was reported that the erosion process is usually influenced by the properties of eroding particles, target materials and conditions of impingement. Properties of eroding particles such as size, shape, hardness and density can have a significant influence on the behaviour of solid particle erosion. The shape of the eroding particle, in particular, has some effect on the rate of erosion, for instance angular shape particles would give an impact of four times greater compared to the round shaped particles (Levy and Chik 1983) and a larger eroding particle size will produce a larger kinetic energy which will result in a higher rate of erosion in comparison to the smaller size particles (Parsi et al. 2014). Furthermore, erosion damages could occur through the impingement of solid particle on the material surface, abrasion by slurry or suspended particles in fast flowing liquid and the

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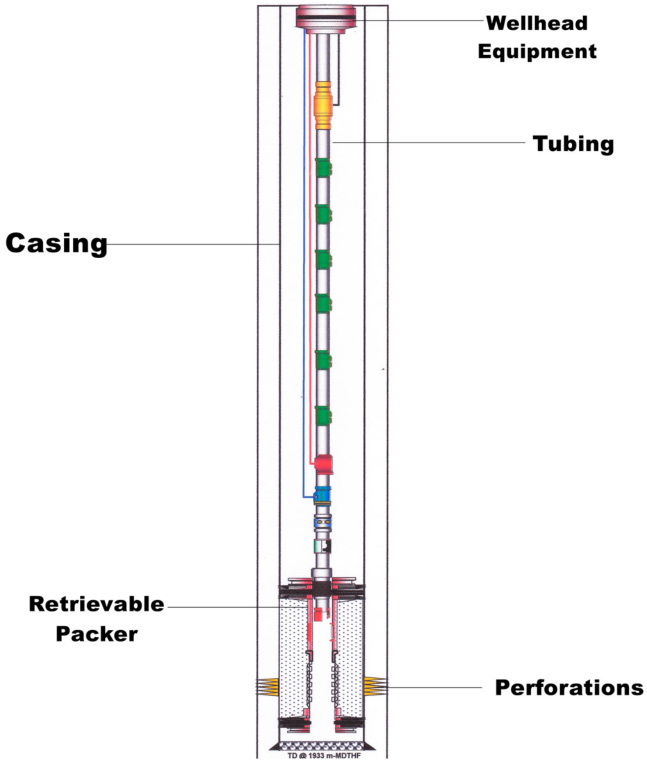

Figure 1. Sketch of a typical well system comprises casing and tubing (not to scale). (This figure is available in colour online.)

cavitation process that would be formed within the well tubing (Neville and Wang 2009; Kesana et al. 2014; Hemmati et al. 2016). Note that both ductile and brittle materials have always been the favourite material surfaces that are studied. Impact angles of the particles, on the other hand, are defined relatively to the plane of the target metal surface. In ductile materials, the erosion rate will be greater at lower impact angles. This is because at lower angles, the impact of the eroding particle will be more accurate and efficient compared to the impact of the eroding particle at higher angles. On the contrary, for brittle materials, a higher erosion rate usually occurs at higher angles or near the vertical angle. Since cracking is the dominating source of erosion in brittle materials, the impact of eroding particles at higher angles would result in greater cracks on the target metal surface. Okonkwo and Mohamed (2014) further added that increasing the impact velocity of erodent particles would influence the rate of erosion at which the solid material strikes the target surface (Islam and Farhat 2014; Okonkwo and Mohamed 2014).

Various remedial actions and solutions have been proposed to control and eliminate sand occurrence, for instance the installation of sand screens and gravel packs. Nevertheless, these installations do not seem to be effective enough to block and trap smaller particles which are less than 50 µm from entering the facilities. Since it is difficult to prevent erosion from entering the oil and gas facilities, proper prediction on the estimation of erosion is then necessary.

Recently, due to the development of computer performance and computer technology, data processing techniques including artificial intelligence, machine learning, deep learning and probabilistic approaches, their application based on various data have been highlighted in a variety of ways (Lotsberg et al. 2016; Wong and Kim 2018; Kim et al. 2019a, 2019b). For recent studies related to reliability assessment one may refer to ISSC (2012, 2015, 2018). Especially, quasi-static response (Technical Committee II.1), dynamic response (Technical Committee II.2) and ultimate strength (Technical Committee III.1) parts in the ISSC reports could be recommended.

In structural design as well as assessment methods, the traditional deterministic method has been widely used with the assumptions of partial safety factors embedded to their models or equations (Paik et al. 2009). This is normally classified as the Level I method (refer Table 1). As summarised in the work by Mustaffa et al. (2009), for instance, some of the disadvantages of the deterministic method are (i) unknown how safe the structure is, (ii) no insight on the contribution of different individual failure mechanisms, (iii) no insight on the importance of different input parameters, (iv) uncertainties in variables cannot be taken into account and (v) uncertainties in the physical models cannot be taken into account. With these limitations, industries begin to acknowledge different assessment methods in the classification of Levels II and III, which are formed by knowledge of probability and reliability theory concepts. Herein, this paper adapts the knowledge of Level III in carrying out the assessment of tubing failure. In the context of offshore structures for instance, works on reliability assessment have been proven through the assessments made to jacket platforms (Bai et al. 2016; Elsayed et al. 2016; Jahanmard et al. 2017; MoratÓ et al. 2019), pipelines (Mustaffa and Van Gelder 2010; Elosta et al. 2014 Mohd et al. 2014; Mustaffa et al. 2018), ships (Ivanov 2013; Kim et al. 2016; Obisesan et al. 2016; Shi et al. 2016), risers (Guo et al. 2014) amongst others. Therefore,

Table 1. Safety levels applied in structural design.

Safety level	Description
Level 0	• Deterministic method • Should not be applied
Level I	• Semi-probabilistic approach • Also known as *load resistance factored design* • Standard design procedures (codes and guidelines) • Utilises a single partial coefficient (safety factor) to represent an uncertainty variable • Design strength < design load × safety factor
Level II	• Approximations of the full probabilistic approach • Each variable (strength and load) is approximated by a standard normal distribution • Probability of failure computation is simplified by idealising (linearising) a failure surface
Level III	• Full probabilistic approach (more advanced) • Each variable (strength and load) is defined by its own probability density functions • All variables are treated based on the knowledge of (joint) distribution • Utilises the exact failure surface which requires numerical integration or simulation • Information needed for this method is not always available and even if they were, the calculations would be overwhelming

this paper attempts to introduce the application of the probabilistic approach to tubing structure with the consideration of erosion, which in particular would become one of the earliest efforts made to tubing assessments in the present date.

2. Erosion models in tubes

Various studies have been carried out to describe and estimate the rate of erosion in tubes. For the context of hydrocarbon fluids, the American Petroleum Institute Recommended Practice (API RP 14E, 1981) had initiated the idea of the erosion model with the inclusion of a constant fluid density. It was obvious that the high density of the hydrocarbon fluids (as compared to normal fluid) was the only concern during the time of development of this erosion model. While this model seemed to be overly simplified, the extension was then made by other literatures in the sequence of time, i.e. 1983, 1989, 1998 and finally 2000, a summary of which is shown in Table 2.

Special attention herein is given to the works by Salama and Venkatesh (1983). In 1983, they have developed an erosion model for ductile materials. Their erosion model had incorporated other associated parameters related to sand flow rate, fluid, pipe/tube diameter as well as material hardness. Sometimes later in 2000, Salama had extended his erosion model by considering particle diameter, fluid density as well as the geometry-dependent constant, as given by Equation (1)

$$\mathrm{ER} = \frac{1}{S_\mathrm{m}} \frac{W_\mathrm{p} V_\mathrm{m}^2 d_\mathrm{p}}{D^2 \rho_\mathrm{m}}, \qquad (1)$$

where ER is the erosion rate (mm/yr), W_p is the sand flow rate (kg/day), D is the diameter of the pipe (mm), d_p is the particle diameter (in microns), V_m is the mixture velocity (m/s), ρ_m is the fluid mixture density (kg/m^3) and S_m is a geometry-dependent constant. Apparently, the work of Salama (2000) seemed to be the last work involving erosion models in tubes/pipes. This paper then utilises the work of Salama (2000) in modelling erosion in the tubing.

3. Designs of tubing

A tubing located within the wellbore is always subjected to varying external loads, internal loads and axial force during its service life. The tubing is always designed to be adequately strong to resist any loads (pressure) imposed on it. A severe surrounding environment of tubing will cause the pressures and loads imposed on the tubing to increase. For instance, wells with high hydrogen sulphide content, high temperature and high pressure will cause the surrounding environment for the tubing to become more complicated and harsh (Lin et al. 2014). Continuous pressures and loads imposed to the tubing will result in failures which later cause blowouts or leakages to occur.

Burst pressure (P_b) is a pressure experienced by an inner diameter due to the internal pressure imposed to any kinds of pipes/tubes. The burst pressure usually arises due to the larger increment of pressure inside the pipes/tubes rather than the pressure outside. The pressure inside pipes/tubes will undermine the integrity of the wall thickness, resulting in ruptures to happen. The burst pressure in the tubing is the pressure that accumulates inside during drilling, production and workover operations. The highest burst pressure normally takes place during drilling operations, since the pressure build-up from the reservoir when hydrocarbon is being extracted will enter directly.

Over the years, there were various design models developed for the tubing, particularly based on different failure modes experienced by the structure. Discussion presented herein, however, is limited to the design subjected to burst only, with special attention given to the models developed by Klever and Stewart (1998) and Lin et al. (2014). These selections were in favour of a defect parameter that they have considered in representing the strength of the tubing, when other literatures seemed to have ignored it. Klever and Stewart (1998) had proposed the idea of having a higher nominal pipe strength, while Lin et al. (2014) had assumed a twin shear unified strength theory.

The burst strength model developed by Klever and Stewart (1998) is given by Equation (2), specifically for *oil country tubular goods* (OCTG).

$$P_\mathrm{b} = 2\sigma_\mathrm{uts}(t_\mathrm{min} - K_\mathrm{a} a_\mathrm{N}) \left[\frac{\left(\frac{1}{2}\right)^{n+1} + \left(\frac{1}{\sqrt{3}}\right)^{n+1}}{D_\mathrm{o} - (t_\mathrm{min} - K_\mathrm{a} a_\mathrm{N})} \right], \qquad (2)$$

where P_b is the burst pressure (MPa), σ_uts is the tubing tensile strength (MPa), t_min is the minimum wall thickness of tubing (mm), K_a is a coefficient of internal pressure resistance (2.0 for rotary calibrating and unknown tubing), a_N is the lower limit of defect detention (5% of wall thickness), n is the stress strain hardening factor (0.1) and D_o is the outer diameter of tubing (mm).

A revised burst strength model for casing and tubing was later proposed by Lin et al. (2014), given by

$$P_\mathrm{b} = \frac{4}{3}\sigma_\mathrm{y} \times \ln \left[\frac{\left(\frac{D_\mathrm{o}}{0.875 t_\mathrm{dc}}\right)}{\left(\frac{D_\mathrm{o}}{0.875 \times t_\mathrm{min} - 2}\right)} \right], \qquad (3)$$

with

$$t_\mathrm{dc} = t_\mathrm{min} - aK_\mathrm{a}, \qquad (4)$$

where σ_y is the tubing yield strength (MPa), D_o is the outer diameter of the tubing (mm), t_min is the minimum wall

Table 2. Summary of different parameters considered in erosion models.

Authors	Model considerations
API RP 14E (1981)	Fluids (density)
Salama and Venkatesh (1983)	Fluids (velocity), Sand (flowrate), Tube (diameter, hardness)
Bourgoyne (1989)	Fluids (gas velocity, volume fraction), Sand (density, flowrate), Tube (density, area)
Jordan (1998)	Fluids (gas velocity), Sand (flowrate), Tube (radius of curvature)
Salama (2000)	Fluids (velocity, density), Sand (diameter, flowrate), Tube (diameter)

thickness of the tubing (mm), a is the crack depth (mm) (5% of wall thickness) and K_a is the burst strength factor.

Note that Equations (2) and (3) were developed in the absence of any erosion parameters, despite erosion occurrence in sandstone wells being reported to report failures in the structure. Thus, as mentioned earlier, this paper attempts to incorporate the influence of erosion in describing the strength of a tubing structure. The next section illustrates the assumptions made to integrate erosion damage to the existing burst strength models of Klever and Stewart (1998) and Lin et al. (2014). The erosion parameter estimated by Salama (2000) was proposed to be inserted into the defect terms of a_N and a of Klever and Stewart (1998) and Lin et al. (2014), respectively. Such an assumption was considered valid because the two models have assumed a fixed tubing wall loss regardless of any defects causing it. This paper assumes that the wall loss reduction in tubing burst strength models is subjected to erosion damage.

4. Reliability analysis

The use of reliability analysis for the purpose of improving designs has the advantage that it provides a complete framework for the safety analysis, in which the actual probability of failure and not some empirical safety rules is used as a measure of the performance of a design (Plate, 1993). Reliability analysis involves two major steps: (1) to identify and analyse the uncertainties of each of the contributing parameters and (2) to combine the uncertainties of the random variables to determine the overall reliability of the structure. The second step may be further carried out in two ways: (i) directly combining the uncertainties of all the parameters and (ii) separately combining the uncertainties of parameters belonging to different disciplines or subsystems.

4.1. Uncertainties

Design of structures is subjected to uncertainties due to randomness of natural phenomena, data sample limitations and errors, modelling reliability and operational variability. Uncertainties in decision and risk analysis can primarily be divided into two categories: uncertainties that stem from variability in known (or observable) populations and therefore represent randomness in samples (inherent uncertainty), and uncertainties that come from basic lack of knowledge of fundamental phenomena (epistemic uncertainty) (Van Gelder 1999). It is not possible to reduce inherent uncertainties but epistemic uncertainties may change as knowledge increases (Van Gelder 1999). Analysing uncertainties is essential as it is the prerequisite for reliability analysis.

4.2. Random variables

The probabilistic method deals with uncertainties described earlier and are represented as random variables in the load (L) and strength (S) terms. In statistics, these random variables are normally presented in the form of probability density functions (PDFs). Some typical PDFs used in the probabilistic methods are uniform distribution, normal distribution, log normal distribution, Weibull distribution, Gamma distribution among others. Interested readers are recommended to refer to the statistical theories related to PDF for further understanding of the subject matter. Note that each PDF is normally characterised by a mean (μ), standard deviation (σ) or coefficient of variation (CV). The former is a measure of average values, while the latter two parameters describe the dispersion of a random variable.

4.3. Limit state function

A structure is said to be well designed when it has the ability to withstand certain loads without failure. Failure occurs when the strength (S) term of the structure is exceeded by the load (L) term, as shown by Equation (5). The state just before failure occurs is the limit state. The reliability is the probability (P) that this limit state is not exceeded. The general form of a limit state function (Z) can then be written as

$$Z = R - S. \quad (5)$$

The limit state is described by $Z = 0$. Failures take place when the failure surface falls in the region of $Z < 0$, while $Z > 0$ is a survival region. The probability of failure (P_f) can be computed from here and is given by Equation (6):

$$P_f = P(Z \le 0) = P(S \ge R). \quad (6)$$

Note that the probability of failure in Equation (6) may be solved in many ways. Some of the approaches include analytical approximation methods like the first-order reliability method (FORM) and second-order reliability method (SORM) or simulation method like Monte Carlo simulation (MCS). In this study, Equation (6) was simulated using the analytical approximation methods called the MCS method using MATLAB Programming Language.

Recalling that the two previously described equations developed by Klever and Stewart (1998) and Lin et al. (2014) were selected previously, the equations were later translated into the limit state function, Z models. These equations were assumed to represent the strength term (R) of the tubing, while the operating pressure (P_{op}) of the reservoir as the load term (S). The erosion parameter, a_N, in Klever and Stewart (1998) has been previously assumed as the tubing defect depth which generally sets to be 5% of the wall thickness. In this paper, however, such a constant was proposed to be translated into a defect governed by erosion, with the ability to describe the loss of wall thickness with time, i.e. mm/yr. Through the use of the erosion model developed by Salama (2000), the ER term of Eq. (1) is then replaced by a_N term in Equation (2). The revised limit state function model for Klever and Stewart (1998) was then rewritten as

$$Z = \left\{ 2\sigma_{uts}(t_{min} - K_a a_N) \times \left[\frac{\left(\frac{1}{2}\right)^{1.1} + \left(\frac{1}{\sqrt{3}}\right)^{1.1}}{D_o - (t_{min} - K_a a_N)} \right] \right\} - P_{op}, \quad (7)$$

with,

$$a_N = \frac{1}{S_m} \times \left[\frac{W_p V_m^2 d_p}{D_i^2 \rho_m} \right] \times \text{year}, \quad (8)$$

with an additional parameter D_i as the internal diameter of the tubing.

For Lin et al.'s (2014) model, the defect term, a, introduced in the equation was also previously assumed as a constant described by 5% of the wall thickness. By following a similar assumption made to the Klever and Stewart (1998) model earlier, the limit state function model of Lin et al. (2014) was then rewritten as

$$Z = \left[\frac{4}{3}\sigma_y \times \ln \frac{\left(\frac{D_o}{0.875 \times t_{dc}} \right)}{\left(\frac{D_o}{0.875 \times t_{min} - 2} \right)} \right] - P_{op}, \quad (9)$$

with,

$$t_{dc} = t_{min} - ak_a \quad (10)$$

and

$$a = \frac{1}{S_m} \times \left[\frac{W_p V_m^2 d_p}{D_i^2 \rho_m} \right] \times \text{year}. \quad (11)$$

For the sake of illustration, the analysis presented in this paper assumes only 1-year assessment carried out by Equations (7) and (9).

4.4. Sensitivity analysis

Sensitivity analysis is used to determine how 'sensitive' a model is to changes in the value of the parameters of the model, as well as to changes in the structure of the model. By showing how the model behaviour responds to changes in the value of parameters, sensitivity analysis is a useful tool in any model building as well as in model evaluation. The sensitivity analysis allows one to determine what level of accuracy is necessary for a parameter in order to make the model sufficiently useful and valid.

5. Methodology

This paper utilises a horizontal well system in one of the existing wells located in the Offshore Peninsular Malaysia operation. The horizontal well system comprises three sections, namely vertical, curve and horizontal as shown in Figure 2. Data pertaining to the well operations, tubing properties and dimensions are presented in Tables 3 and 4, respectively.

The vertical section of the well system comprises casing and production tubing. The tubing in particular is equipped with a (i) retrieval safety valve (TRSV) used to isolate the production tubing from the wellhead and production line, (ii) pressure downhole gauge (PDG) used to measure and provide readings of hydrostatic pressure inside the production tubing and (iii) the packer/seal element used to isolate the rest of the production strings from the hydrocarbon zone. The packer also helps in diverting hydrocarbon flows into the production tubing. In this type of well, the hydrocarbon usually flows into the casing and fills it before flowing into the production tubing. The hydrocarbon product will then be transported to the wellhead facilities through the production tubing.

In carrying out the probabilistic assessment, all random variables applied for the limit state function models are as described in Table 5.

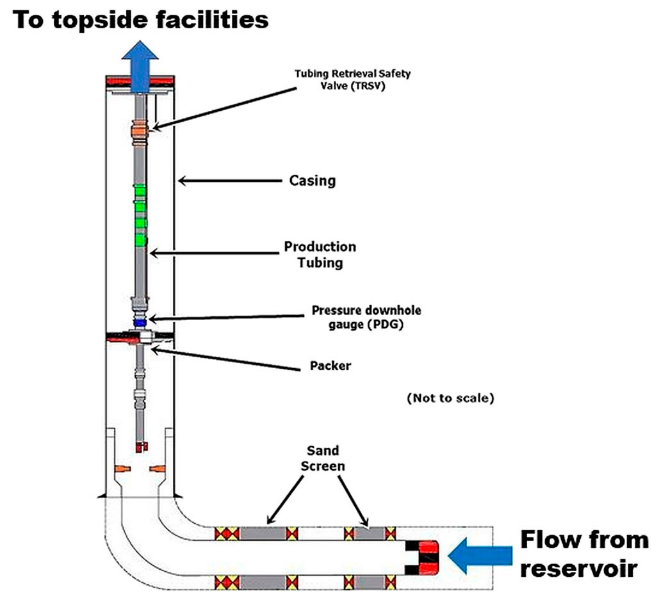

Figure 2. Sketch of a horizontal well system for one of the reservoirs in Peninsular Malaysia Operation (not to scale). (This figure is available in colour online.)

Table 3. Well operational data.

Well type:	Subsea well
Well depth	2652 m
Water depth	69 m
Maximum deviation	90°
Reservoir pressure	2300 psi (15.86 MPa)

Table 4. Tubing properties and dimensions.

Grade:	L-80 steel pipe
Size	3.5 inch. (88.9 mm)
Weight	92 lb/ft (13.69 kg/m)
Tubing wall thickness	0.254 inch. (6.45 mm)
Tubing inner diameter	2.992 inch. (76.0 mm)
Yield strength	80 ksi (552 MPa)
Tensile strength	95 ksi (655 MPa)

6. Results and discussion

Equations (7) and (9) with the inclusion of Salama erosion models were used in assessing the reliability of the tubing. All these models are computed and summarised in Figure 3. The figure shows the computation of probability of failure under various reservoir pressures. The figure shows that tubing failure for the Klever and Stewart (1998) model with the inclusion of the Salama erosion model seemed to give a slightly higher probability of failure as compared to the Lin et al. (2014) model. To illustrate this for instance, when reservoir pressure was set to be 18 MPa, the Lin et al. (2014) model resulted in a probability of

Table 5. Statistical models and random variables.

Variable						
Symbol	Description	Unit	Mean	Standard deviation	Distribution	References
P_{op}	Operating pressure	MPa	10–20	0.3–0.6	Normal	Operational data
σ_y	Tubing yield strength	MPa	552	16.56	Normal	Design data
σ_{uts}	Tubing ultimate strength	MPa	655	19.65	Normal	Design data
D_o	Outer tubing diameter	mm	88.9	2.667	Weibull	Design data
D_i	Tubing internal diameter	mm	76	2.28	Normal	Design data
t_{min}	Minimum wall thickness of tubing	mm	6.45	0.1935	Weibull	Design data
W_p	Solid particle flow rate	kg/day	47001.6	1410.048	Normal	Sanni et al. 2015
V_m	Mixture velocity	m/s	28.34	0.8502	Uniform	Sanni et al. (2015); Zhang et al. 2013
d_p	Particle diameter	micron	50	1.5	Normal	Li and Wilde 2005
ρ_m	Fluid mixture density	kg/m^3	784.43	23.5329	Normal	Sanni et al. (2015)
S_m	Geometry-dependent constant	–	33	–	Deterministic	Constant
K_a	Coefficient of internal pressure resistance	–	2.0	–	Deterministic	Constant
n	Stress strain hardening factor	–	0.1	–	Deterministic	Constant

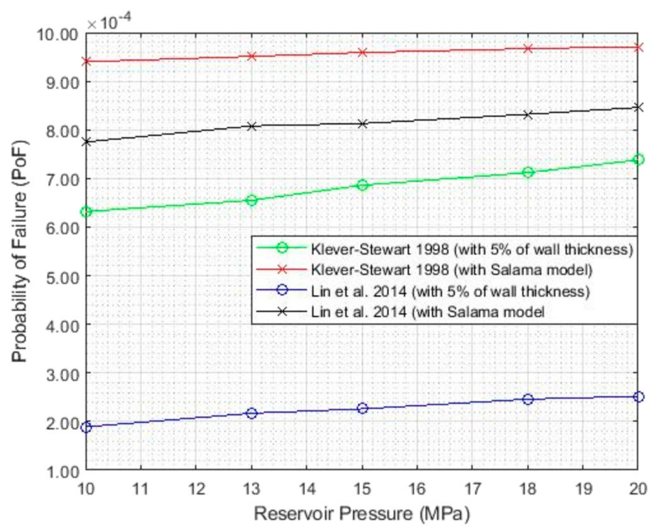

Figure 3. Probability of failure, P_f, for tubing under various reservoir pressure, P_{op}, for different models with the inclusion of erosion values. (This figure is available in colour online.)

failure of 8.32×10^{-4}, while Klever and Stewart (1998) of 9.67×10^{-4}. The difference between the two models was due to the fact that Lin et al. (2014) had utilised yield strength (σ_y) while Klever and Stewart (1998) had adopted ultimate tensile strength (σ_{uts}) as the strength parameter. The mechanics of materials have always been in favour of the ultimate tensile strength in giving a longer reliability span as compared to the yield strength.

While doing the analysis, results obtained from the Klever and Stewart (1998) and Lin et al. (2014) models with erosion values were also compared with a fixed value assumption (i.e. 5% of wall thickness reduction in defect terms, a_N and a) of the two models described earlier. These were also captured and presented in Figure 3.The Klever and Stewart (1998) and Lin et al. (2014) models which assumed a fixed 5% of wall thickness reduction gave the lowest probability of failure as compared to the models which have taken erosion into consideration. From this result, it could be implied that when erosion is considered in the assessment of burst strength of a tubing, the probability for it to fail is higher than those without any erosion estimates. This is indeed a revision to the current assessment approaches and would be able to provide a better result in understanding the remaining strength of the eroded tubing.

A more detailed analysis was later carried out to understand the response of each governing parameter towards the reliability models. One of the best approaches to observe such a response would be in the form of a sensitivity analysis, as shown in Figure 4. For the sake of illustration, only the reliability model developed by Klever and Stewart (1998) is presented in this paper. Figure 4 shows the response given by different governing parameters towards the reliability model developed by Klever and Stewart (1998), with and without the inclusion of the Salama (2000) erosion model. The latter

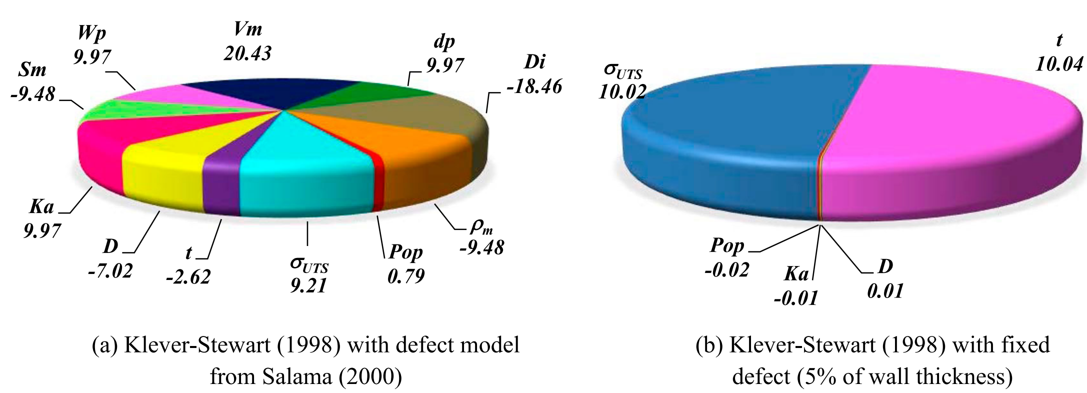

Figure 4. Sensitivity analyses (in %) obtained from Klever and Stewart (1998) model, with and without the inclusion of Salama (2000) erosion model. (a) Klever and Stewart (1998) with defect model from Salama (2000). (b) Klever and Stewart (1998) with fixed defect (5% of wall thickness). (This figure is available in colour online.)

was based on a fixed defect taken as the 5% value of the given wall thickness. From Figure 4(a), it is proven that the mixture velocity, V_m, parameter is positively significant and correlated to the failure with the highest value of +20.43, while the least influence was found to be the internal tubing diameter, D_i, with −18.46. Oppositely, when erosion was not considered in the model, failures would depend on the tubing properties solely, *i.e.* ultimate tensile strength, σ_{uts}, and wall thickness, t_{min}, as shown in Figure 4(b).

7. Conclusions

This paper attempts to analyse the impact of erosion on the burst strength calculation of a tubing placed in a vertical well system. Herein, the assessment was proposed to be carried out in the form of a limit state function equation. While doing so, the model allows governing parameters to be treated as random variables, which suit the actual operational and environmental conditions better. Two established burst strength models were selected and later integrated with another erosion model. Results presented in this paper showed that the inclusion of erosion in estimating the remaining strength of a tubing was significant as compared to the one without. It is further suggested that such a consideration needs to be taken seriously by the industry when carrying out the assessment of any particular tubing structure of a vertical well system.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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