

Effect of Flow Pattern at Pipe Bends on Corrosion Behaviour of Low Carbon Steel and its Challenges

Muhamadu Masin Muhammadu^{a*}, Jamaluddin Md Sheriff^b, Esah Hamzah^b

^aDepartment of Mechanical Engineering, Federal University of Technology, Minna

^bFaculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: jamal@fkm.utm.my

Article history

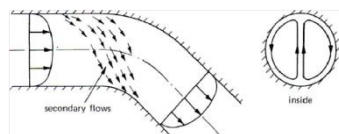
Received :12 July 2012

Received in revised form :

4 April 2013

Accepted :15 April 2013

Graphical abstract



Abstract

Recent design work regarding seawater flow lines has emphasized the need to identify, develop, and verify critical relationships between corrosion prediction and flow regime mechanisms at pipe bends. In practice this often reduces to a pragmatic interpretation of the effects of corrosion mechanisms at pipe bends. Most importantly the identification of positions or sites, within the internal surface contact areas where the maximum corrosion stimulus may be expected to occur, thereby allowing better understanding, mitigation, monitoring and corrosion control over the life cycle. Some case histories have been reviewed in this context, and the interaction between corrosion mechanisms and flow patterns closely determined, and in some cases correlated. Since the actual relationships are complex, it was determined that a risk based decision making process using selected 'what' if corrosion analyses linked to 'what if' flow assurance analyses was the best way forward. Using this in methodology, and pertinent field data exchange, it is postulated that significant improvements in corrosion prediction can be made. This paper outlines the approach used and shows how related corrosion modelling software data such as that available from corrosion models Norsok M5006, and Cassandra to parallel computational flow modelling in a targeted manner can generate very noteworthy results, and considerably more viable trends for corrosion control guidance. It is postulated that the normally associated lack of agreement between corrosion modelling and field experience, is more likely due to inadequate consideration of corrosion stimulating flow regime data, rather than limitations of the corrosion modelling. Applications of flow visualization studies as well as computations with the $k-\epsilon$ model of turbulence have identified flow features and regions where metal loss is a maximum.

Keywords: ALARP (As Low As Reasonably Practicable) CO_2 corrosion; corrosion resistant alloy (CRA); decision gates; erosion-corrosion; life cycle performance; risk basis

Abstrak

Kerja rekabentuk mutakhir ini mengenai aliran air laut telah menekankan keperluan untuk mengenal pasti, membangun dan mengesahkan hubungan kritikal antara ramalan kakisan dan mekanisme rejim aliran di selekoh paip. Dalam amalan ini sering mengurangkan kepada tafsiran pragmatik kesan mekanisme kakisan pada selekoh paip. Paling penting mengenal pasti kedudukan atau laman web, dalam kawasan sentuhan permukaan dalaman di mana rangsangan karat maksimum yang dijangka akan berlaku, sekali gus membolehkan pemakanan, pengurangan, pemantauan dan hakisan kawalan yang lebih baik ke atas kitaran hayat paip. Beberapa sejarah kes telah dikaji dalam konteks ini dan interaksi antara mekanisme kakisan dan corak aliran rapat ditentukan dan dalam beberapa kes kedua-duanya berkait rapat. Walaupun hubungan sebenarnya sangat kompleks, ia telah ditentukan bahawa proses membuat keputusan menggunakan berasaskan risiko dipilih 'apa' jika analisis kakisan dikaitkan dengan 'apa jika' analisis jaminan aliran adalah cara terbaik ke hadapan. Menggunakan ini dalam metodologi, dan bidang berkaitan pertukaran data, ia mengandaikan bahawa peningkatan yang ketara dalam ramalan kakisan boleh dibuat. Kertas kerja ini menggariskan pendekatan yang digunakan dan menunjukkan bagaimana hakisan data perisian model yang berkaitan seperti yang terdapat dari model hakisan Norsok M5006, dan Cassandra selari model aliran pengiraan dengan cara yang disasarkan boleh menjana hasil yang sangat perlu diberi perhatian dan trend jauh lebih berdaya maju untuk panduan kawalan hakisan. Ia mengandaikan bahawa kekurangan yang biasanya berkaitan antara model hakisan dan pengalaman bidang, adalah lebih mungkin disebabkan oleh pertimbangan yang tidak mencukupi hakisan merangsang data rejim aliran dan bukannya had model hakisan. Aplikasi kajian visualisasi aliran serta pengiraan dengan modek K-E pergolakan telah mengenal pasti ciri aliran dan kawasan berlaku kerugian logam adalah maksimum.

Kata kunci: ALARP (serendah munasabah) CO_2 kakisan; asas risiko; aloi tahan kakisan (CRA); pintu keputusan; hakisan karat; prestasi kitaran hidup paip

© 2013 Penerbit UTM Press. All rights reserved.

1.0 INTRODUCTION

Computational fluid dynamics (CFD) has advanced to the stage where the modelling of transport processes in wall bounded turbulent flows as well as the resolution of particle/wall interactions have enabled the initial steps being attracted in the development of predictive models for corrosion under conditions of fluid flow [1-8].

Most probably, the most severe erosion-corrosion problems familiar with industry involve flow pattern at sudden modifications within the flow geometry, where there's frequently flow separation based on recirculation, and reattachment, and secondary flow. Inside the situation of flow separation, for example inside a sudden expansion in the pipe, turbulence is moved downstream from the objective of separation. There is no simple relation involving the bulk flow parameters as well as the local near-wall, hydrodynamic, mass transfer and erosion-corrosion conditions as well as the latter ought to be determined either experimentally [1,8,9,12-13] or by record simulation both by [1,8,9,12,13]. This paper focuses the bond between flow pattern and corrosion behaviour at pipe bends as well as the advances in using turbulence models for the record simulation of erosion-corrosion throughout yesteryear decade.

The development of water pipeline infrastructure in a few part of world remains rapid growth within the last few years. It is crucial to acknowledge, identify, and develop, the critical relation between corrosion conjecture and flow systems at pipe bends. Most substantially the identification of web sites where maximum corrosion stimulus can be expected thus enabling better understanding, minimization, monitoring and corrosion remedies for the whole existence cycle. Some situation histories are actually examined in this particular context, as well as the interaction between corrosion systems and flow designs carefully determined for a number of design campaigns. The specific associations are complex, too for basic reasons some risk based making choices procedure using "what if" corrosion analyses connected with "what if" flow assurance analyses was considered our advice [14-23].

The experience based on formerly looked into work by authors [24,25] has generated an instantaneous final results of corrosion rate of low carbon steel loss and fluid flow designs. A modification of flow pattern can lead to significant improvements in tube existence by remaining from impinging flow. The mechanism in the internal corrosion rates aren't fully understood but appears being linked strongly towards the particulate matter inside the flow [24-29]. Even if pollutants are simply inside the micrometre size range, they could still deviate from fluid streamlines to make sure that glancing flow can lead to abrasion in the protective surface layer [30-37]. Rapid positioned on by corrosion-erosion will result when the layer is soft in compliance while using particulate matter.

By using this methodology, and area data exchange, it's thought significant enhancements in corrosion behaviour are achievable. This paper outlines the approach used and shows

how relevant corrosion modelling software data for example that supplied by corrosion models available Norsok M5006, and Cassandra Software [21] to parallel computational flow modelling within the specific manner can generate very significant results, and sometimes unforeseen trends for corrosion control guidance. The methodology offers good semi-quantitative arguments for justification and a variety of references are really used.

It's postulated the normally connected insufficient agreement between corrosion modelling and area experience, is much more likely because of insufficient acceptance within the impact of corrosion stimulating flow programs, instead of restrictions within the corrosion modelling itself, thus trending to switching the immediate onus for corrosion conjecture precision and reliability from corrosion modelling for the flow regime side. The topic matter or research area is totally new as well as on going that's envisaged those things will most likely be benchmarked against real area data as research advance into each existence cycle and generate area data and experience [8,9,15].

This method is anticipated to greater measure the training learnt a part of each research, therefore helping improve future designs within the less pricey manner, furthermore to attending better to challenges within the areas of water and future artic pipeline bend corrosion and integrity management, whereupon the advantages of naturally safe designs has turned into a much more stressed [15,20,21].

Usually low carbon steel is often the material of first option for pipeline, within the problem of internal liquids being too corrosive, passive corrosion control measure may be engaging internal films or internal corrosion allowance lining. Nonetheless although carbon steel might be attempted round the extender includes harder needs, like the advantages of better understanding, precision and robustness of materials and corrosion performance. Normally made available the primary obstacles are frequently seen to become connected while using corrosion allowance (CA) aspect. The CA may be the designer's tool delivering contingency for corrosion control. The parameter basically supplies a margin of safety to pay for corrosion wall loss with the look existence [15-21].

The happy couple of more mm (frequently minimal 3mm plus much more 10mm, and frequently a preventive 1mm for dry non corrosive lines) useful for this unique purpose can be significant for long flow lines. Hence technical arguments and history or experience based data is vital to help justify such additional steel. Clearly this is best done by an improved understanding of corrosion due to cavities at pipe bends or corrosive gasses/liquids erosion at bends, microbial activity (MIC), dead leg corrosion and in particular flow assisted corrosion (FAC).

Having considered the basic characteristics of flow in curved open channels are fairly understood, theoretically and numerically the configuration of the side wall has significant effects on the flow structures [29].

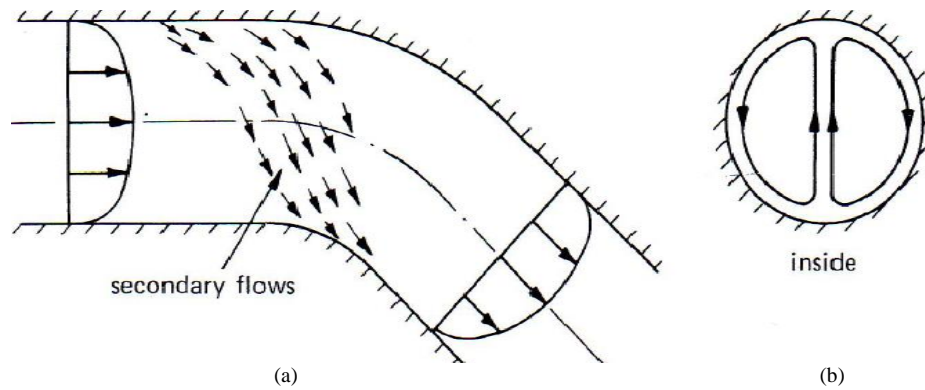


Figure 1 Ideal fluid flow through a bend

The Figure 1 shows ideal fluid flow in pipe through a bend, since the streamlines ought to be curved inside the same sense since the pipe itself there is a radial pressure gradient, so pressure is bigger round the outer wall in the pipe compared to the related point round the inner wall.

The mechanism which supplies birth for the stagnation pressure gradient is not considered incorporated within the secondary flow phenomena, although there's evidence of mutual interaction involving the two inside the turning passage to ensure that as result causes turbulent which in turns involve some unwanted effects round the pipe bend.

This paper is tried to give consideration towards the approaches and techniques familiar with identify, develop, and verify critical associations between corrosion behavior and flow programs systems. Used this frequently reduces with a practical interpretation in the outcomes of flow on corrosion turbulence systems.

2.0 TURBULENCE MODELS AND METHODS

The task of turbulence models is always to provide equations that will enable calculation in the Reynold stresses, $\overline{u_i u_j}$, as well as the turbulent diffusion fluxes, $\overline{u_i \phi}$, which arise when the time-averaged equations for turbulent flow and mass transport are acquired within the immediate equation [14]. The $k-\epsilon$, turbulence models [15] which are currently [16] broadly useful for the computation of business flows are eddy viscosity model which be a consequence of the concept recommended by Boussinesq and assumes caused by turbulence round the mean flow can be considered through viscosity. The turbulent viscosity, μ_t , is made the decision within the kinetic energy of turbulence, k , which is rate of dissipation, ϵ :

$$\mu_t = C_\mu f_\mu (\rho k^2 / \epsilon) \quad (1)$$

The effective viscosity is provided by

$$D_{\text{eff}} = \mu + \mu_t \quad (2)$$

similarly the effective diffusivity is given by

$$D_{\text{eff}} = \mu / \rho \sigma_t + \mu_t / \rho \sigma_t \quad (3)$$

Where σ_t is the turbulent Schmidt number [7,13].

The conservation equations for mass, momentum, kinetic energy of turbulence which is dissipation, and species, m , might be written in the general form. For axisymmetrical flow in 2D round co-ordinates [7]:

$$\frac{\partial}{\partial x} (\rho \phi u) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho \phi v) = \frac{\partial}{\partial x} (\tau_\phi \frac{\partial \phi}{\partial x}) + \frac{1}{r} \frac{\partial}{\partial r} (r \tau_\phi \frac{\partial \phi}{\partial r}) + s_\phi \quad (4)$$

Where $\phi = u, v, k, m$ and ϵ

The values of τ_ϕ , general diffusion coefficients and s_ϕ , the source terms.

Flow separation with recirculation and reattachment for example inside a sudden expansion and understanding in the concentration area enables the rate of mass transfer being calculated [6,13] with the expansion. The calculation in the concentration area near the wall requires utilizing a low Reynolds number [LRN] $k-\epsilon$ model since the mass transfer boundary layer is deeply embedded within the viscous sublayer. The concentration is required at $y^+ \sim 1$, insidewithin all the viscous sublayer where the mass transport is diffusion controlled, to have the ability to calculate the wall mass transfer rate. The 2nd requirement is because of the bit of turbulence inside the viscous sublayer obtaining a significant effect on mass transfer within the high Schmidt amounts $Sc \sim 1000$ frequently familiar with aqueous mass transfer. Low reynold number (LRN) models utilize turbulence damping functions [13,32] as the easiest way of modelling wall-bounded flow with warmth/mass transfer under separated flow conditions [33]. The option wall function (WF) closure places the initial computation mode inside the logarithmic law region ($30 < y^+ < 150$) and bridges over the important viscous sub-layer.

Furthermore, the motion of a dispersed particulate phase within a turbulent flow field can be modelled by either a Lagrangian or Eulerian approach [34]. He further lamented that in Lagrangian models a large number of individual particle trajectories are calculated in the flow domain whereas in the Eulerian approach the particles are treated as a second fluid. From an erosion modelling standpoint the direct calculation of particle/wall interaction statistics, impact frequency, angle and velocity with the Lagrangian approach is an advantage; at least in dilute particulate suspensions. As pointed out by Nesic [7], the Eulerian approach would be more appropriate in concentrated suspensions.

Also [55] review and revealed that particle breakage may cause quality control problems, whereas wall erosion increases equipment maintenance costs and environmental burden, and causes loss of productivity and a requirement to replace damaged components. Under normal operating conditions, erosion rates in pipe bends are much higher than those in straight pipe sections due to local turbulence and unsteady flow behaviour. Lamented that therefore, the time for failure piping systems is often dependent on the life of pipe fittings (valves,

bends, elbows, flow metres), flow pumps, turbines, and compressors [56–59]. It is, therefore imperative to improve the protection of these components from solid particle erosion by better understanding the physics of particulate flows.

Many investigators [68–71] have carried out both physical and numerical modelling of the erosion of pipe bends, elbows, tees and related geometries. Since the early 1990's, computational fluid dynamics (CFD) has been widely used for solid particle erosion prediction in curved pipes and ducts, with various analytical, semi-empirical and empirical models having been developed. In 1995 [71] provided a critical review of some of the erosion models that had been developed since Finnie (1960) proposed the first analytical approach, and found 28 models that were specifically for solid particle-wall erosion. The authors [71,73] reported that 33 parameters were used in these models, with an average of five parameters per model. These parameters influence the amount of material eroded from a target surface and the mechanism of erosion. The review revealed that each model equation was the result of a very specific and individual approach, hence it is clear that no single equation exists that can be used to predict wear from all known standard material or particle parameters, and that some reliance on experimental measurement will always be required to provide empirical constants necessary in the various erosion models. The following review is limited to models that have been used in CFD-based erosion modelling and which have received wide usage in applications to erosion in pipes bends and pipe fittings.

In 1987 [69] developed an empirical erosion model for AISI 1018 steel. McLaury (1993–1996) extended this model for aluminium and used it to predict particle erosion resulting from both direct and random impingements in two-dimensional geometries. This erosion model was developed at the Erosion-corrosion Research Centers. In 1996 [71] predict erosion in elbows, plugs, tees, sudden contractions, and sudden expansions for pipes with circular cross-sections, and was subsequently referred to as erosion -corrosion Research Centres models. Also in 1996 [72] applied this model to investigate the effects of elbow radius of curvature on erosion rates in circulate pipe. Meanwhile, [60] developed mechanistic models for predicting erosion in elbows based on the E/CRC model. In 1998 and 2001, [67] and [68] used a commercial CFD code to model fluid-solid flow and added routine to predict erosion on particle impact using the E/CRC models. The [73] and [74] also modelled the erosion in oilfield control valves using a commercial CFD code, accounting for both deformation and cutting erosion. They obtained a good agreement for the predicted wear rates and wear locations in pipe bends with the experimental gas-solid erosion results of Bourgoyne, added [63 and 64] the stochastic rebound model of [61 and 62] and the E/CRC model [56] to a commercially available CFD code and investigated the relative erosion severity in elbows and plug tees found in oilfield geometrics. Numerical simulations showed that particle rebound behaviour played an important role in determining the motion of the particle [65 and 72].

The performed their erosion research on 90 degree elbows and bends of circular cross-section. The fluid phase was modelled using a simple modified mixing-length model. The predicted fluid axial velocity was validated against the experimental data of [56], with erosion modelled using the E/CRC model [68]. They compared their predicted penetration rates with the experimental data of [65], obtaining good qualitative agreement but poor qualitative agreement between the predictions and data. The poor agreement occurred because most of the data available were from erosion experiments with high particle rates. The authors also found that erosion in long

radius bends was reduced when the carrier phase was changed from liquid to gas. They further reported that the effect of the squeeze film, secondary flows and turbulent flow fluctuations may all play important roles in erosion prediction when the carrier fluid is a liquid.

In 1991 studied [3] the local erosion in chokes and determining the local fluid velocity and particle impingement. Also, in 2006 [19] used a commercial CFD code coupled with an in-house particle tracker to predict fluid particle flow in a full 180 bend. He further implemented two erosion models, namely those of finite (1960) and [1 and 66] investigated erosion-corrosion problems in U-bends. However, there was no comparison was made with experimental data ; hence, the validity of the model could not be ascertained. Attempted to account for the shape of wear scars in predicting the life of pneumatic conveyor bends undergoing erosive Wear. However, these Authors did not use the shape of the scar to alter the computational mesh used in the fluid phase calculations.

Fan and co-workers [70] used Eulerian-Lagrangian approaches with the empirical restitution coefficient of [75] to model particle rebound velocities, and subsequently employed the semi-empirical erosion equation of [76] to study erosion in a vertical-to-horizontal bend. The authors used this technique to predict the erosion of tube banks in heat exchangers (70 and 76), to study protection techniques against tube erosion (77), and to investigate anti-erosion in 900 bends (78, 79, 80 and 81). In all the studies, the authors used the standard k- ϵ turbulence model, except in [82] where the authors used large eddy simulation LES to obtained flow and turbulence field predictions. The LES solution was not, however, validated against previous experimental or numerical results. In 1994 and 2004 [85 and 86] also used the semi-empirical erosion equation of [84] in 1995 to estimate the erosion rate in tube banks.

In 2007 [87] conducted a number of CFD-based erosion modelling investigations using a commercial CFD code. The erosion equation developed at the University of Tulsa (Albert, 1994; Edwards *et al.*, 2001; McLaury 1993, 1996; McLaury and [83] in 2000; [84] in 1995; [70] in 1995 and [77] in 2006, were included in the through user-defined-function. Particle trajectories were validated against the authors' experimental data for liquid-solid flows obtained using laser diagnostics. The entire CFD -based erosion authors' modelling procedure was then validated by comparison with the authors' experimental data obtained in 900 standard elbows with air flows, measured using a sensitive electrical-resistance probe. In 2009 [88] investigated particle motion in the near-wall region using a commercially available CFD code, modifying the code to account for particle size effects in this region before and after particle impact. For turbulent flow in a 90° bend, their results showed that the near-wall modifications and turbulent particle interactions significantly affect simulation results when compared with experimental data.

In 2009 [90] applied an Eulerian-Lagrangian approach with particle-particle interaction and a erosion model to simulate solid particle movement as well as the particle erosion characteristics of a solid-liquid two-phase flow in a choke. The authors used the standard k- ϵ model to treat the turbulence, the discrete particle hard sphere model to accommodate inter-particle collisions and the semi-empirical correlations of [91] in 1979 to study anti-erosion effects.

Despite all this work, there is continued interest in pipe wall erosion modelling because the prediction of erosion, in particular, is of value in estimating the service life of pipe bends systems, as well as in the identification of those locations in a particular pipe geometry most prone to erosion. In this review, [55] a study on three-dimensional computational fluid dynamic

model of erosion is developed to investigate the erosion of both the concave and the convex walls of cross-sectioned ducts of different bend geometries and orientations due to particle collisions with the wall surfaces. Results are discussed in terms of eroded depth and the location of primary and secondary wear, and are compared with available experimental data [92].

In term of erosion-corrosion simulations, modelling of phenomena such as erosion-corrosion and flow-induced corrosion in general is done with the immediate objective [35] of gaining a greater understanding of the mechanism involved. With this objective in mind the models should be based on fundamental equations and involve as few empirical relationships as possible. The ultimate objective of modelling is to develop predictive models that can be used for design purposes, and the more fundamentally based the greater generality and utility of the model.

The k- ϵ turbulence model meets these criteria. There are more fundamental models such as the Reynolds stress transport model (RSTM) which solves the transport equations for the turbulent stress directly. However, the improvements in mimicking the behaviour of the turbulent flow are offset by the complex problem of the prescription of boundary conditions for all stresses along the various boundaries.

Also, for the purposes of estimating the best corrosion allowance it is reasonable to use a baseline CO₂ dominated general or uniform corrosion rate using more than one model to determine uniform corrosion allowance (CA) and a total or true CA predicted based on CA plus margins to allow for localized corrosion mechanisms, namely erosion, MIC and pitting attack. In the absence of corroborated relationships and for simplification these are considered additive, rather than synergistic, for example: Total CA = Uniform CA + Erosion Allowance + Pitting allowance + Crevice allowance MIC allowance stagnation allowance (topographical) + flow-induced allowance (link) [16,24].

In practice after corrosion risk appraisal, this can be reduced to: Total CA = Uniform CA + erosion allowance + localized (pitting) allowance. The predictive corrosion rates can be based on the predicted temperature profiles and the published top of line corrosion correlations for example, the Nyborg-Dogstad correlation [95]. There are few published such [equation 5] can be used on an iterative basis, to determine top of line activity [50,93].

$$\text{Corrosion rate} = 0.004 \cdot R_c \cdot C_{fe} \cdot (12.5 - 0.09 \cdot T) \quad (5)$$

Where:

Corrosion rate: given in mm/y, R_c: Condensation rate g/m²/s, C_{fe}: Saturation iron levels in condensation (difficult variable, 50 - 200ppm often select), and T: Temperature in degree centigrade (°C) respectively.

■3.0 FLOW ACCELERATED CORROSION

The key factor response to determine flow faster corrosion (FAC) might be the oxide film on structure surfaces, which evolves consequently of corrosion and, simultaneously, controls the corrosion rate within the role like a protective film [47]. The primary parameters to discover FAC they fit into material parameters, flow dynamics parameters and atmosphere parameters (48). Metallic ions, mainly ferrous ions (Fe²⁺), are released for the water within the boundary layer where a number of within the supersaturated Fe²⁺ ions become oxide pollutants and in addition they deposit over the metal surface being

magnetic oxide layer [48]. The oxide layer plays an important role in preventing further relieve Fe²⁺ (corrosion reaction). The thickness inside the boundary layer is impacted by flow dynamics of people processes, oxygen concentration (O₂) inside the boundary layer plays an important role for oxidizing magnetite to hematite, which contributes to achieving much greater corrosion resistance [49].

Generally, subsea pipelines flow assurance covers all multiphase transport phenomena. Diligent design techniques, understanding and capabilities are very important to make sure safe, continuity of fluids transport from reservoir to topsides processing plant. The main areas involve steady condition and transient multiphase flow hydrates, sand, oil, emulsions, wax, scale and corrosion phenomena. The interaction between corrosion/scaling and flow assurance can therefore be instrumental in determining true production rates, and software packages such as the Scand energy or Non-destructive test types codes can certainly give reliable predictive modelling. Delivering an exact and reliable advantages of flow assurance and corrosion modelling is regarded as as one of the primary challenges facing the today. The overriding performance fingerprint is often best known to as tub curve and also to help facilitate this better, corrosion needs to be recognized to love an operating hazard. Once that's recognized the benefits of a soundly planned and faithfully applied corrosion management strategy becomes self apparent along with a pronounced reliance upon important water subsea infrastructure and tie back [25,27, and 30].

The beginning of issues with corrosion integrity throughout early existence is important, though mid existence is often better handled since area existence is extremely frequently well below design existence and for your reason options and time can be expected to favour planned retrofit as needed. Existence extension beyond the situated on out zone is generally more tightly related to older researches whereupon original design life's are actually exceeded and continuing production needed [28,31].

3.1 Challenges

The primary problems that arise connect with the modelling within the particular erosion-corrosion processes within the wall and pipe bends [35]. Also, undertaking research inside the relationship such as the dwelling inside the flow and corrosion in disturbed flow, Nesic and Postlethwaite [3] present in conclusion the region near-wall turbulence might be the controlling factor rather than wall shear stress inside the disruption inside the protective corrosion layer mentioning that in simple undisturbed flows the sorts of wall shear stress overlap using the sorts of near-wall turbulent intensity. The mechanical characteristics of in situ and developing corrosion product films aren't well recorded. Further tasks are needed in this area to describe the steadiness of corrosion product films under conditions of disturbed flow which are amenable to both experimental observation and record simulation [49].

Also, decision concerning time dependent factor stated by [38] might be the interrelation such as the wall geometry, erosion-corrosion and flow structure. As erosion-corrosion proceeds the computational energy power grid that could begin like a simple Cartesian energy power grid will not be acceptable, for example sharp edges are rounded requiring the introduction of curvilinear coordinates within the sudden constriction. Bends which might be initially modelled using analytically produced curvilinear coordinates will require numerically created grids since the asymmetrical erosion progresses [38].

Fluid flow is much more reproducible in comparison to kinetics of corrosion reactions together with the best barrier for your predictive modelling of erosion-corrosion will not be getting less ability to calculate the complex interaction between fluid and suspended solids when using the corroding wall however getting less ability to calculate totally or partially activation controlled corrosion rates acquiring a amount of confidence [39]. Moving the multiphase mixture helps to make the corrosion problems worse. If you have been flow programs in regards to the various flow rate of liquid and gas. Within the high product rate, the slug flow regime is prominent. Slug flow may seriously enhance internal corrosion in pipeline bends due to the mixing vortex and bubble impact inside the mixing zone of slug [40–43]. Slug flow is indicated obtaining a dimensionless Froude number (F_r) [44]. The turbulence levels and bubble impact on the pipe wall increase with the increase in Froude number. The most effective rate of wall shear stress due to the turbulence and bubble impact has the ability to decrease the performance of inhibitors that could have otherwise produced over the pipe wall and result in corrosion behavior [43].

It's recognized the main threat for your flow line resource is internal corrosion, rather than exterior cathodic protection (Clubpenguin) issues, which are quite effectively addressed by code compliance to coating and Clubpenguin standards. The information vary but overall it's discovered that internal corrosion causes around 15% of onshore and around 50% of offshore pipeline failures (45).

But you will find no generally recognized codes of practice to deal with internal corrosion, so the only re-course should be to take advantage of the highest quality available corrosion models. Normally provided CO_2 corrosion systems are dominant, and often the designs have tended therefore being based on empirical studies or even the deterministic approach of P-Waard and Milliams [9].

However used every models rarely match real-time, faster, or area results, that's credited most often to mistakes in modelling reliability, inappropriate presumptions and inaccurate data inputs, leading to unfitting safety margins, together with the skewing of performance data by secondary parameters for instance biofilming, microbially affected corrosion (MIC), crevicing sanding, etc. [8,15].

A terrific way to address this mismatch should be to assume bigger amounts of safety margin by searching at worst situation conditions situated around the look existence. However this may lead to over-conservatism with pricey reliance on even under-conservatism with premature failures. Meaning the main concentrate the job, to help better represent the pertinent parameters for instance flow assurance inside the detail design and verification of evaluation process. Another variable affecting existence cycle performance happens when large pipe, since the development of flow programs is not just time dependent but additionally length dependent, as well as for your reason highly influential over the corrosion activity through the introduction of water quit (wetted) zones. Furthermore this gives a loss of profits of profits of inhibitor filming, since the elevated area impacts the driving forces for slow, fast and spontaneous localized corrosion or passivity. Normally provided inhibition injection may require multiple dosing and monitoring points, to help better evaluate true efficiency and robustness in the corrosion management programs.

As recognized to earlier, the corrosion issues when incorporated for that new or existing designs are often hotly contested and strongly debated, frequently not easily resolved. Consequently solutions appear being best developed using risk based techniques. Too for carbon steels semi quantitative techniques using number option for top, medium, low, risk are

actually made to include better more repeatable revisions as new data are created [3]. These risk based techniques are constantly under review to help evaluate critical physical parameters, and corrosion systems for specific design and operating conditions for instance high water cut developments, non-steady physical/chemical activities, or bursts of MIC/biofilming (laminar flow phenomena), moved corrosion products furthermore for his or her re-adding (turbulent flow phenomena), and payments of sanding (erosive high flows). The impact of people upset or non-steady phenomena has additionally tended to produce database or software driven data management programs somewhat redundant oftentimes since the predictive trending can become less reliable. To counter that effect a bigger reliance on profile reasoning appears better, thus the implication that flow related systems must be interpreted situation by situation, and through consensus.

In another review, states [55] despite its frequent found in many chemical and process engineering application, the pneumatic transport of dilute headgear of particle in gas flows through bends is loaded with lots of defects. Because bends introduce an adjustment of flow direction and lots of scales of curvilinear motion inside the internal flow. On approaching an adjustment of flow direction, a particle's inertia helps it be deviate within the streamlines inside the carry fluid, resulting in particle management over the walls inside the pipe. Consequently, energy is moved for your impact zone and, in regards to the comparative strength inside the particle together with the wall material, either the particle is damaged (attrition) or even the pipe begins to take advantage of (erosion) [56].

3.2 Development of Corrosion Allowance

The easiest approach to search for the optimum corrosion allowance (CA) value may be subjective but it's been possible over numerous situation studies to build up a appropriate and realistic methodology. This may still (45) be referred to like a contentious issues, along with the corrosion analyst must therefore take account of inputs, opinions, where possible supporting standards, codes and suggestions. Typically permitting a defensible CA evaluation, it's normally simpler to list out the primary presumptions to prevent later confusion.

Although most pipelines or flow line is horizontal, servings of these may be vulnerable to modifications in elation and undulation, frequently to date because the major effect on corrosion may be introduced through full water quit, or intermittent wetting at low relaxing points. The upward sections may also be mindful to water slide back because the final results of gravity appear [16]. The task thus remains to search for the extent of localized corrosion that may occur at pipe bend, and most importantly where. This burden is way better addressed by historic, history, and judgment ideally based on mix resource area data inevitably this could just be reasonably completed through the ALARP process. The person localized corrosion risks may be examined and risk rankings used rank up or rank lower the corrosion allowance assessment [52]. Frequently the risk rankings high, medium and safe might be designated to mirror such forecasts. These are typically subjective qualitative understanding, but sometimes be semi-quantified if enumerated [53]. However, there's an excellent argument to help keep matters simple through getting an identical 3×3 matrix, without risking output. Other helpful recommendations, and failure mechanism definitions can also be established while using API 380 [54].

3.3 Enabling Presumptions

Uncover the dominant corrosive species usually CO_2 , with defined or understood water chemistry content.

Review, verify, and prioritize or assume the dominant flow programs, e.g. single or multiphase flow, stratified, slug, annular flows etc. forecasted while using existence cycle. This might require review of the steady condition and non-steady activities or transient flow situations. Frequently the flow assurance report examines the likely situations and phone connection, and with this judgment [37].

Validate the H_2S souring inclination because this greatly impacts cracking and corrosion behavior. As being a this is often less influenced by flow programs provided the most effective scales remain intact.

Corroborate dissolved chloride and oxygen levels, and the existence of aggressive organic species for example acetic/formic chemicals additionally for their types.

Assume the bottom corrosion is uniform but validated by real-time inspection and monitoring and via analysis of coups/probes, and deposits. However anticipate to witness localized corrosion when unsteady conditions occur.

Confirm threat and chance of biofilm formation assuming pattern of growth follows laminar or fluid stagnation sites, identify microbe species and MIC within the existence cycle.

Corroborate the extent of sand production (steady and episodic), along with the effect on materials degradation. Determine sand concentration, and particulate dimensions, and review interactions with inhibitor performance [53].

Determine the role of small-stagnant zone corrosion under primary flow conditions per small locations where pollutants and biofilms may proliferate [37].

Establish extent of pitting and inhibitors to both create sustainable inhibitor films and repair such inhibitor films even at high flow rates under sanding and erosion conditions [54].

3.4 Affecting on Key Drivers

The complex quantity of responses is competitive because certain species frequently promote existing CO_2 corrosion although others frequently promote passivation (alleviate) corrosion. These influencers have effect on all corrosion systems but possess a particular stimulus for flow aided systems, for example the following:

Accelerators affecting on flow dynamics: against bare steel the enhanced flux of moved species for example CO_2 , O_2 , chlorides (break lower passivity), and moved iron oxides etc.

Passivators affecting on flow dynamics: Surface condition eliminating, residual inhibition, oil wax films, sulphate/calcite precipitation, pH loading bicarbonates [1,6,7,8].

4.0 IMPACT OF TEMPERATURE AND FLOW

Temperature and flow regime are carefully linked since CO_2 corrosion is dynamics and very mindful to electro-chemical and physical fluctuations (for example changing P, T, V). Generally steady condition (P, T, V) Conditions frequently promote protective film compaction as well as for your reason passivation, and low corrosion rates. Lower temps < 1200F (500C) tend to promote patchy corrosion with softer multi-layer iron carbonate scales providing some barrier protection increasing up to 140 to 160°F (60-70°C). Above these temperatures damaging localized corrosion is observed as films lose stability and spall off giving rise to galvanic 'mesa' attack. Though there is evidence of a down turn in the plateau after

800C for certain cases. In reality the project design basis usually insists on a maximum value for temperature, as it does for other critical parameters such as pressure, materials characterization (yield stress, hardness, toughness, etc.). Regarding flow, the production rates can be influenced by flow regimes such as slug flows and annular gas flows. This can prove critical for vertical risers connecting the flowline to the offshore structure or topsides. The geometry can act almost like a 'specification break' whereupon the flow regime shifts largely due to the effects of gravity as the flowline transforms from a horizontal to a vertical member. The sag bend at the touch down zone can become a high risk corrosion component warranting greater degree of corrosion control, such as a thicker section, increased local CA, internal coating epoxy or increased monitoring routines etc.

The leading edge of slugging flows is to extreme highly turbulent shear stresses (> 200 Pa) capable of wrecking positive inhibitor films. For liquid slugs the phenomena is called associated with dissolved gas breakout effects, instead of wave leading to forces, though much studies still on-likely to check understand slugging flow behavior within multiphase liquids. In similar manner annular flow programs can enhance the extent of surface wall wetting [51] even under lower water cut values, thus again reducing oil phase wetting and undermining inhibitor contact for that wall. Annular flow may also pull primary flow entrained sand pollutants for that steel, thus harmful passive films no less than which inspires physical erosion at worst. Other flow programs for example mist flows can also be important poor direct droplet impingement, however, these do seem to become rare within the coal and oil industry [8].

Hence it's contended that for process steady states (constant P, T, V) steady uniform corrosion should be expected, whereas for unsteady states, transient states and activities will promote localized corrosion, frequently while using inhibition of pitting/crevice activity then progression of same throughout future steady conditions [29]. This is often largely because of difficulties with mixed inhibitors known to as cocktailing performance under variable flow programs [20,24].

Furthermore, as lamented earlier most likely probably the most challenging conjecture is less whether localized corrosion will occur but much more likely at this point you request, generally where? An thorough study on the expected flow regime curves and maximum flow velocities might help help with that judgment [25, 26]. It's also likely that whenever flow line localized corrosion starts, then it is more probably being self propagating (auto catalytic) and is less influenced by modifications inside the majority conditions though more jobs are needed in this region (42,45 50).

For operating profiles examined in that way, for example stratified flow, annular flow, slug flow and bubble flow, it should be assumed that essence turbulent as with line using the typical flow line Reynolds number, but realize that within each flow regime you will observe complex inter-facial behavior, including laminar, stratification and turbulence. The level of smoothness of people activities isn't necessarily expected, however reliable online monitoring results might help minimization and control, given to seize control of the feelings at a great choice.

5.0 INTERNAL CORROSION DIRECT ASSESSMENT

Harmful internal corrosion in addition to failures have happened on pipelines carry gas /liquid specified being dry [37]. The process referred to as internal corrosion direct assessment (ICDA) remains designed to look at the corrosion impact of

short-term upsets on pipeline integrity. The process is anticipated to boost pipeline integrity, reliability, and public safety. ICDA might come to terms with enhance the assessment of internal corrosion in gas transmission pipeline and help ensure pipeline integrity. The process is primarily positioned on gas transmission lines that normally carry dry gas/liquid but they're affected from temporary upsets of wet gas/liquid water (or electrolyte). The understanding basis must be readily transferrable together with other media liquids.

■6.0 SINGLE PHASE FLOW

An low Reynolds number (LRN), $k-\epsilon$ model has lately been positioned on the calculation of pipe-wall mass transfer rates in the sudden change or expansion [5], an immediate constriction [3] and flow round the groove [8]. They pointed out, in addition mass transfer rates are really calculated for that pipe wall in the sudden bend where small patches in the protective 'rust' film were assumed to possess been removed. The above mentioned pointed out stated results indicate the mass transfer regions of erosion-corrosion processes in flow pattern conditions may be satisfactorily laboured with through turbulence models.

A much more intractable issue is an chance to calculate protective film removal under single phase aqueous flow conditions. The partial elimination of a protective surface film is frequently the precursor to rapid corrosion and component failure. For instance failures in copper piping in apartment structures frequently connect to rapid corrosion in the sudden difference in the geometry in which the normally protective film remains broken using the enhanced turbulence. Recent findings have proven that although point about this kind of corrosion happens near the outlet of 90° bends the film breakdown and subsequent failure began inside the sudden step in which the downstream pipe was soldered towards the elbow. The idea of an essential shear stress for eliminating protective layers remains asked for because the small stresses involved wouldn't be sufficient to robotically remove a surface oxide film. As

pointed out by Launder, B. E., 1998 pressure fluctuations unlike velocity fluctuations don't vanish inside the wall. In 1991, [7] has recommended that pressure fluctuations inside the wall, in flow pattern, raise the overall shear stress and could produce mechanical damage.

■7.0 LIQUID/SOLID FLOW

The presence of solid particles enhances the destruction of protective films giving rise to increased corrosion rates and may add to the overall metal loss by the mechanical erosion of the underlying metal. As with single phase flow these destructive effects are more pronounced under flow pattern condition.

In 1991 [4] have developed a predictive model for localized erosion-corrosion under flow pattern conditions based on the application of a two phase flow version of an low Reynolds number (LRN), $k-\epsilon$ model of turbulence. The motion of the particles was predicted by means of a Lagrangian Stochastic-Deterministic (LSD) model. The model which was applied to various pipe geometries including a sudden expansion, constriction and a groove was based on an oxygen-mass-transfer controlled corrosion model with the assumption that the particles removed the protective rust film, and an erosion model based on the cutting wear erosion equations [84].

The successfully applied a two phase $k-\epsilon$ model to the numerical simulation of uniform CO_2 erosion-corrosion under separated flow conditions at a sudden expansion. The particles were modeled by an Eulerian approach [88].

■8.0 SUMMARY OF PREVIOUS WORKS

Year(s)	Researcher(s)	Method(s)	Flow Pattern	
			Reynolds number	Size(D=depth/L=length)
1966	Burgraff O.	Numerical: modified relaxation	Up to 400	Square bend (D/L = 1)
1979	Benjamin A., <i>et al.</i>	Numerical: ADI Scheme for linear system and Newton-like method for non-linear system	Up to 10000	D/L = 1 and 2
2004	Yao H., <i>et al.</i>	Numerical: Finite difference for unsteady 3D incompressible Navier-Stoke equation	1000 to 10000	D/L = > 0.1
2005	Cheng M., <i>et al.</i>	Numerical: Lattice Boltzmann	Range of 0.01 to 5000	D/L range from 0.1 to 7
2006	Thierry M., <i>et al.</i>	Experimental: Doppler Velocimetry	$1150 < \text{Re} < 10670$	$0.5 < \text{D/L} = 2$
2009	Ozalp A., <i>et al.</i>	Experimental: PIV	1230, 1460, and 1700	Rectangular, Triangular and Semi-circular with D/L = 2
2011	Muhammad R. M.	Experimental: PIV (tape as fluid) and Numerical: 2-D fluent	23144, 32963 and 39275	D/L = extend surface, $X = 0, 5, 10, 15, 20\text{cm}$
2012	Muhammadu M. M.	Experiment: PIV (Seawater as fluid) and Numerical: 3-D fluent	On going	On going
Corrosion Behaviour				
1960	Bitter J. G.A.	2-D model	the result could not ascertained	
1993 to	Fan J., <i>et al.</i>	E/CRC and Eulerian-	Investigate Concave and Convex walls of square duct, and no	

1996		Lagrangian 3-D models	significant results
1990	Nesic S., <i>et al.</i>	K- ϵ model (under gas flow)	Determined gas flow pattern near-wall turbulence intensity
1991	Nesic S.	K- ϵ model to low Reynolds number	Determined wall-pipe mass transfer rates
1993	Postlethwate S., <i>et al.</i>	2-D (under disturbed flow)	Determined local mass rates and s Products at sudden expansion
2009	Binder S., <i>et al.</i>	Norsok M506 (Multiphase gas /liquid flow)	Generate noteworthy results but lack agreement b/w modelling and field data
2011	Mamat M. F.	Immersion and Salt spray tests	Determined corrosion rate of the welded and unwelded joint
2012	Muhamadu M. M.	Non-destruction test (NDT) and X-ray test	To determine the effects of fluid flow at pipe bends on the corrosion behaviour of low carbon steel

9.0 FURTHER WORK

Further work is required to clarify the stability of corrosion behaviour under the condition of turbulence fluid flow at pipe bend where are amenable to both experiment observation and numerical simulation in relation to Reynolds number or particle image velocimetry (PIV). Also, identification of positions or sites, within the internal surface contact areas where the maximum corrosion stimulus may likely to occur, thereby allowing better understanding, mitigation, monitoring and corrosion control over the life cycle.

10.0 CONCLUSION

Corrosion and its interactions with the flow phenomena is a complex discipline, neither one dominates the other. Corrosion modelling results are often found not to agree with field data. The discrepancy is often blamed on the inadequacy of the models. However, this article or review has concluded that the differences are better explained by the rationalization of the effects of flow pattern on the base and localized corrosion rates. The core postulate is that the lack of agreement between corrosion modelling data and field experience is due more to inadequate account of corrosion stimulating flow regimes, rather than limitations of the modelling: thus reverting the onus for corrosion prediction away from corrosion modelling to the flow regime side.

The arguments are new and on going and a paradigm shift in thinking is needed to explore further the links between flow pattern and corrosion behaviour. In other word, a computational fluid dynamic model coupled to a Lagrangian particle tracking routine and a number of erosion models have been used to predict the solid particle erosion in square cross-section bends for dilute particle-laden flow. The results obtained were clearly affected by uncertainties in the empirical restitution coefficients. However, the results obtained do demonstrate the ability of the CFD techniques employed to predict erosion location and the depth of material eroded, and hence their usefulness in providing estimate of the service life of pipe systems as well as in the design of mitigation measure.

References

- Pourahamadi F. and Humphrey J. A. 1983. *Physico Chem. Hydrodynamics*. 4: 191.
- Zeisei H. and Durst F. 1990. Computations of Erosion-corrosion Processes in Separated Two-phase Flows Corrosion/90. Paper no. 29. National Association of Corrosion Engineers, Houston, Texas.
- Nesic S. and Postlethwate J. 1990. *Corrosion*. 46: 874.
- Nesic S. and Postlethwate J. 1991. *Can. Chem. Engineering*. 69: 698.
- Nesic S. and Postlethwate J. 1991. *Corrosion*. 47: 582.
- Nesic, Ph.D. 1991. Thesis, University of Saskatchewan, Saskatoon.
- Roco M. C. 1990. *Corrosion*. 46: 424.
- Blati M. and et- atel. 1989. *Corrosion*. 45: 793.
- Lotz U. and Postlethwate J. 1990. *Corrosion Science*. 30: 95.
- Syderger T. and Lotz J. 1982. *Electrochem Society*. 129: 276.
- Blatt W. and Hetz E. 1990. Hydromechanical Measurements for Erosion-corrosion. Corrosion/90, paper no. 25, National Association of Corrosion Engineers, Houston, Texas.
- Nesic S., Postlethwate J. and Bergstrom D. J. 1992. *Int. J. Heat Transfer*. 35.
- Patankar S. V. 1990. *Numerical Heat Transfer and Fluid Flow*. New York: McGraw Hill.
- Singh B., Folk T., Jukes P., Garcia J., Perich, W. 2007. Engineering Pragmatic Solutions for CO₂ Corrosion Problems, paper 07310 NACE Corrosion.
- Olsen S. 2003. CO₂ Corrosion Prediction by Use of Norsok M506 Model Guidelines and Limitations, paper 2336, NACE Corrosion.
- Nybong R. 2003. Understanding and Prediction of Mesa Corrosion Attack, paper 42036 NACE Corrosion.
- Singh B., Folk T., Jukes P., Garcia J., Perich W. 2006. Research in Progress Symposium, presentation, 06R206, NACE Corrosion.
- Tang C., Ayello F., Cai J., Nesic S. 2006. Experimental Study on water wetting and CO₂ Corrosion in Oil-water two phase flow, paper 06559, NACE Corrosion.
- Nesic S., Cai J., Lee K. L. 2005. Multiphase Flow and Internal Corrosion Prediction Model for Mild Steel Pipeline, paper 06555, NACE Corrosion.
- Poblete B., Singh B. 2005. Risk, Rust and Reliability, paper 05555, NACE Corrosion.
- IONIK-J Kenny Reports. 2008. Internal Spreadsheets and Toolboxes (2005-).
- Norsok M506 Software and BP Cassandra Software Modelling and Support Literature (2003-2007).
- Hedges B., Paisley D., Woollam R. 2001. The Corrosion Inhibitor Availability Model, paper 0043, NACE Corrosion.
- Ai 14E RP, Offshore Piping Design Section 2.5, Version (1991).
- IONIK Consulting T4B Private Venture Studies Materials, Corrosion Modelling, and Fitness for Service (2005-2007).
- DNV RP 0501, Erosive Wear in Piping Systems 1999 (updated 2002).
- Rippon I. 2001. Carbon Steel Pipeline Corrosion Engineering : Life Cycle Approach , paper 01055, NACE Corrosion.
- Hedges B., Sprague K., Bieri T., Chen J. H., 2006. A Review of Monitoring and Inspection Techniques for CO₂ and H₂S Corrosion in Oil and Gas Production Facilities: Location, Location, Location paper 06120.
- Deizell A, G. 2004. Inherently Safe Design paper 85698, Society of Petroleum Engineers, Convention.
- Kelly G. 2006. IONIK Klips Internal Reliability and Integrity Study.
- Nagano y., and Hishida M. 1987. *ASME J. Fluids Engineering*. 109: 156.
- Laurder E. B. 1988. *Trans. ASME J. Heat Transfer*. 110: 1112.
- Durst T., et-atel. 1984. *Applied Mathematics Modelling*. 8: 101.
- Postlethwate J., Nesic S., and Bergstrom D. J. 1998. Predictive Models for Erosion-Corrosion under Disturbed Flow Conditions. 1-4.

- [35] Singh B., Krishnathan K. 2009. Making the Link between Inherently Safe Design, Integrity Management and Piping. The pipeline Piggings and Integrity Management Conference, Houston.
- [36] Singh B., Krishnathan K. 2010. Pragmatic Effects of Flow on Corrosion Prediction.
- [37] Lotz U., and Henz E. 1983. *Werkstoffkorros.* 34: 454.
- [38] Berger P. F., and Hauk K. F. 1997. *International Journal Heat Transfer.* 20: 1185.
- [39] API 17D Specification for Subsea Wellhead and Christmas Tree Equipment.
- [40] UK HSE/TUV-NEL. 2003. Erosion Research Report 115.
- [41] Shreir L. L. 1994. *Corrosion Handbook.* Butterworth Heineman. 3rd Edition.
- [42] DNV Offshore Standard-Submarine Pipeline Systems OS-F 101 (2000).
- [43] Federal Registrar – DOI/MMS Proposed Rules- 30 CFR parts 250, 253, 254 and 256 (2007).
- [44] Fontana M. G. and Greene N. D. 2000. *Corrosion Engineering.* McGraw Hill orig. pub. 1967, re-publish.
- [45] Czajkowski C. Z. 1987. Metallurgical Evaluation of an 18 inch Feedwater Line Failure at the Surry unit Power Station.
- [46] Dooley K. B. 2010. Flow Accelerated Corrosion in Fissile and Combined Cycle/HRSG Plants Power Plant Chemical. 10: 68.
- [47] Fujiwara K., Domae M., Ohira T. 2011. Electrochemical Measurements Carbon Steel under high Flow Rate condition and Thermodynamic solubility of Iron. Inc. Proceeding of the 16th Pacific Basin Nuclear Conference.
- [48] Shunsuke U., et al. 2011. Evaluation of Flow Accelerated Corrosion by Coupled Analysis of Corrosion and Flow Dynamics. Relationship of Oxide Film Thickness, Hematite/Magnetite Ratio, ECP and Wall Thinning Rate.
- [49] Nyborg A. R., et al. 2010. Corrosion and Water Condensation Rates in Wet Gas Pipelines, paper 07554 NACE Corrosion.
- [50] Waterhouse I. R. 2008. Developments in Spray Pig Inhibitor Application. The Pipeline Piggings and Integrity Management Conference, Houston.
- [51] Andersen T. R., et al. 2007. The Influence of Condensation Rate and Acetic Concentration on Corrosion in Multiphase Pipelines, paper 07312 NACE Corrosion.
- [52] Vitse F. S., et al. 2003. Mechanistic Model for the prediction of the Line Corrosion Risk, paper 03633.
- [53] API 580 Risk-based Inspection, Recommended Practice, First Edition May (2002).
- [54] Derrick O. N., Michael F. 2012. Modelling of Pipe bend erosion by Dilute Particle Suspensions.
- [55] Ablert K. L. 1994. Effects of Particle Impingement Angle and Surface Wetting on Solid Particle Erosion of AISI 1018 Steel, Tuis, OK.
- [56] Badr H. M., et al. 2003. Numerical Investigation erosion Threshold Velocity with Sudden Contraction Computers Fluids.
- [57] Badr H. M., et al. 2006. Erosion in The Tube Entrance Region of an Air-cooled Heat Exchanger. *International Journal of Impact Engineering.* 32(9): 1440–1463.
- [58] Bergevin K. 1984. Effect of slurry velocity on the Mechanical and Electro-chemical components of erosion-corrosion in vertical pipes (M.sc. thesis) University of Saskatchewan, Saskatoon, Canada.
- [59] Bitter J. G. A. 1963a. A study of Erosion Phenomena: Part 1. *Wear.* 6(1): 5–21.
- [60] Bitter J. G. 1963b. A. A Study of Erosion Phenomena: Part 2. *Wear.* 6(3): 169–190.
- [61] Bourgoyne A. T. 1984. Experimental study of erosion in diverter systems due to sand production, Paper presented at the SPE/IADC drilling conference, SPE/IADC 18716, New Orleans, LA.
- [62] Chen X. H., McLaury B. S. and Shirat S. A. 2004. Application and Experimental Validation Of A Computational Fluid Dynamics (CFD)-Based Erosion Prediction Model in Elbows and Plugged Tees. *Computers and Fluids.* 33(10): 1251–1272.
- [63] Chen. X. H., et al. 2006a. A Comprehensive Procedure to Estimate Erosion in Elbows for Gas/Liquid/Sand Multiphase Flow. *Journal of Energy Resources Technology.* 128(1): 70–78.
- [64] Chen. X. H., et al. 2006b. Numerical and Experimental Investigation of the Relative Erosion Severity Between Plugged Tees and Elbows in Dilute Gas/Solid Two Phase Flow. *Wear.* 261(7–8): 715–729.
- [65] Dianat M., et al. 1996. Reynolds Stress Closure Applied to Axisymmetric, Impinging Turbulent Jets. *Theoretical and Computational Fluid Dynamics.* 8(6): 435–447.
- [66] Edwards J. K., McLury R. S. 1998. Supplementing a CFD Code with Erosion Prediction Capabilities. American Society of Mechanical Engineers (ASME) Fluid Engineering Division Summer Conference, paper FEDSM 98-5229 Washington, DC.
- [67] Edwards J. K., et al. 2001. Modelling solid particle erosion in elbows and plugged tees. *Journal of Energy Resources Technology.* 123(4): 227–284.
- [68] Eyley R. 1987. Design and Analysis of a Pneumatic Flow Loop (M.sc. thesis). West Virginia University, Morgantown, WV.
- [69] Fan J. R., et al. 2004. Large eddy simulation of the anti-erosion characteristics of the ribbed-bend in gas-solid flows. *Journal of Engineering for Gas Turbines and Power.* 126(3): 672–679.
- [70] Meng H. C. and Ludema K. C. 1996. Wear Models and Predictive Equations. Their Form and Current Content. *Wear.* 181–183(2): 443–457.
- [71] Wang J., Shirazi S., Shadley J. and Rybick E. 1996. Application of Flow Modelling and Particle Tracking to Predict Sand Erosion Rates in Elbows. ASME Fluids Engineering Division. 236: 725–735.
- [72] Forder A., A. 2000. Computational Fluid Dynamics Investigation Into the Particulate Erosion of Oilfield Control Valves (Ph.D. thesis) University of Southampton, Southampton, UK.
- [73] Forder A., et al. 1998. A Numerical Investigation of Solid Particle Erosion Experienced within Oilfield Control Valves. *Wear.* 216(2): 184–193 ().
- [74] Grant G. and Tabakoff W. 1973. An Experimental Investigation of the Erosion Characteristics of 2004 Aluminium Alloy (Tech. rep. 73-37), Cincinnati: Department of Aerospace Engineering University of Cincinnati.
- [75] Fan J. R., et al. 1998. Numerical Investigation of a New Protection Method of the Tube Erosion by Particles Impingement. *Wear.* 223(1–2): 50–52.
- [76] Habib M. A., Badr H. M., Said S. A. M., Ben-Mansur R. and Al-Anizu S. S. 2006. Solid Particle Erosion in the Tube End of the Tube Sheet of a Shell and Tube Heat Exchanger. *International Journal for Numerical methods in fluids.* 50(8): 885–909.
- [77] Fan J., Sun P., Zhang X., and Cen K. 1999. A numerical study of a protection technique against tube erosion. *Wear.* 223–229: 458–464.
- [78] Fan J. R., Yan J. and Cen K. F. 2002. Anti-erosion in 90 Degrees Bend by Particle Impaction. *AIChE Journal.* 48(8): 1401–1412.
- [79] Fan J., Zhang X. and Cen. K. 2001. Experimental and Numerical Investigation of a New Method for Protecting Bends from Erosion in Gas-Particle Flows. *Wear.* 251(1–12): 853–860.
- [80] Fan J., and et al. 1997. New Stochastic Particle Dispersion Modelling of a Turbulent Particle-laden Round Jet. *Chemical Engineering Journal.* 66(3): 207–215.
- [81] Fan J., Zhang D. D., Jin J. and Cen K. 1991. Numerical Simulation of Tube Erosion by Particle Impaction. *Wear.* 142(1): 1–10.
- [82] Finnie I. 2000. Erosion of surfaces by solid particles. *Wear.* 3(2): 87–103.
- [83] Finnie I. 1995. Some reflections on the past and future of erosion. *Wear.* 186–187(1): 1–10.
- [84] Jun Y. D. and Tabakoff W. 1994. Numerical-simulation of a Dilute Particulate Flow (Laminar) over Tube Banks. *Journal of fluids Engineering.* 116(4): 770–777.
- [85] Moris Y. S., et al. 2004. Principal Characteristics of Turbulent Gas-Particulate Flow in the Vicinity of Single Tube and Tube Bundle Structure. *Chemical Engineering Science.* 59(15): 3141–3157.
- [86] Zhang Y., Reuterfor E. P., McLaury B. S., Shirazi S. A. and Rybicki E. F. 2007. Comparison of Computed and Measured Particle Velocities and Erosion in Water and Air Flows. *Wear.* 263: 330–338.
- [87] Zhang Y., McLaury B. S., Shirazi S. A. 2009. Improvement of Particle Near-wall Velocity and Erosion Predictions Using a Commercial CFD Code. *Journal of Fluids Engineering.* 13(3): 031303– 031309.
- [88] Zhang Y., McLaury B. S., Shirazi S. A., and Rybick E. F. 2010. A two-dimensional mechanistic model for sand erosion prediction including particle impact characteristics, in NACE international annual conference, CORROSION 2010 (paper No. 10378) San Antonio TX.
- [89] Li G., Wang Y., He R., Cao X., Lin C., and Meng T. 2009. Numerical Simulation of Predicting and Reducing Solid Particle Erosion of Solid-Liquid Two-phase Flow in a Choke. *Petroleum Science.* 6(1): 91–97.
- [90] Menguturk M. and Sverdrup E. F. 1979. Calculated tolerance electric utility gas turbine to erosion damage by coal gas ash particles. In W. F., Alder (Ed). Erosion prevention and useful application (Pp 193–224), Philadelphia; American Society for Testing and Materials, ASTM-STP-664.
- [91] Njubuenwu D. O., Fairweather M. and Yao J. 2012. Prediction of turbulent gas-solid flow in a duct with a 90° bend using an Eulerian-Lagrangian Approach. *AIChE Journal.* 58(1): 14–30.
- [92] IONIK-J P Kenny Reports, Internal Spreadsheets and Toolboxes (2005–2008).

- [93] Singh B., *et al.* 2005. Risk, Rust and Reliability, paper 05553, NACE Corrosion.
- [94] Nyborg R., Dugstad A. 2003. Understanding and Prediction of Mesa Corrosion Attack, paper 03642, NACE Corrosion.
- [95] Olsen S., 2003. CO₂ Corrosion Prediction by Use of Norsok M506 Model, Guidelines and limitations, paper 03623, NACE Corrosion.