EFFECTS OF FLUID FLOW ON CORROSION BEHAVIOUR IN PIPE BENDS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

NOVEMBER 2016

DEDICATION

This thesis dedicated to our noble and beloved Prophet – Prophet MUHAMMAD (S.A.W)

ACKNOWLEDGEMENT

In the Name of Allah, the Most Beneficent, the Most Merciful, All praises and thanks is due to Mighty Allah, the lord of the universals, may the peace and blessings of Allah continue to abide by our beloved prophet MUHAMMAD, his household, his company and those that following him till the last day.

This research project would not have been possible without the support of many people. First and foremost, I would like to express my deep appreciation and gratitude to my supervisor, Assoc. Prof. Dr. Kahar bin Osman for encouragement, close attention, comments and valuable critics. I am proudly grateful and feel honour to have you supervise my Ph.D. I am very grateful to my co-supervisor, Prof. Ir. Dr. Esah Hamzah for guidance, advices and motivation. My big thank goes to Assoc. Prof. Dr. Jamaluddin Md Sheriff to have as supervisor in the initial stage of my studies, thanks you for the advice and guidance. Big appreciation goes to Mr Johari Mohammad, Mr. Mohammad Iskandar and to all technical staff of aeronautic Laboratory and fabrication Laboratory for your consistent support with some helpful discussions, advices and ideas. The contributions my friends especially in CFM and CFD Lab. and Dr. Jafaru Usman for your invaluable assistance. Without your continued support and interest, this thesis would not have been the same as presented here.

I offer my immense debt of gratitude to my late father, Mallam Muhammadu Abubakar and my aged mother, Mallama Aishatu Muhammadu for their love to me. My thanks to our Sheikh, Sheriff Abubakar Musa, for his continuous prayers. My profound appreciation also goes to our Sheikh wife and all members of our Zawiyyah.

To someone who always stays beside me in better and worse time, my sincere love appreciation goes to my wife – Mrs Aminatu Muhammadu Al-Hassan, and my children Fatimatu Zahra’u, Muhammadu Hafizu, Muhammadu Taha, Fatimatu Batula and Ummu-Kulsum for your prayers, patience and support.

ABSTRACT

Correlation on flow induced corrosion (*FIC*) for straight pipes and bends have been obtained by researchers via a two-dimensional numerical method and experimental techniques. However, for pipe bends, the correlations require further improvements as the flow in bends are more complicated. The objective of this research is to obtain more accurate correlations for *FIC* in bends using two-dimensional and three-dimensional numerical and experimental techniques. In the numerical and experimental approach, several important parameters such as Reynolds number and selected discrete particle model (*DPM*) were used to obtain erosion rate for miter and smooth bend models. Validations for the modellings were compared with experimental results and locations of the eroded sections were observed to be in agreement. Then, the erosion rates were extracted and analyzed using shooting method. Finally, the new coefficients for the correlations were obtained. When the new equations were applied to the same two-dimensional models, it was shown that the previous two-dimensional models had over-predicted the mass transfer values. Furthermore, when comparisons were made between smooth and miter bends results under the same flow conditions, it was observed that mass transfer values calculated from miter bend models were much higher than that of smooth bends. Experimental results also showed similar behavior, when the surface morphology was examined under Field Emission Scanning Electron Microscope (*FESEM).* From numerical and experimental approach conducted, it is concluded that the inner diameter bends were the areas with the highest *FIC* behaviour for 30^0 and 45^0 smooth and mitre bends.

ABSTRAK

Korelasi terhadap aliran kakisan (*FIC*) untuk paip lurus dan bengkok telah diperoleh oleh penyelidik melalui kaedah berangka dua dimensi dan eksperimen. Walau bagaimanapun, penambahbaikan pada korelasi sedia ada amat diperlukan bagi paip bengkok disebabken oleh aliran yang lebih rumit. Objektif kajian ini adalah untuk mendapatkan korelasi yang lebih tepat bagi aliran kakisan (*FIC*) dalam paip bengkok dengan menggunakan kaedah berangka dua dan tiga dimensi dan eksperimen. Dalam pendekatan berangka, beberapa parameter penting seperti nombor *Reynolds* dan *particle* model diskret (*DPM*) terpilih telah digunakan untuk mendapatkan kadar kakisan untuk model paip licin bengkok dan *miter*. Validasi untuk model dicapai melalui perbandingan hasil eksperimen padu lokasi bahagian terkakis. Selain itu kadar kakisan diambil dan dianalisis menggunakan teknik *shooting*. Akhir sekali, pekali baru untuk korelasi telah diperolehi. Apabila persamaan baru telah digunakan untuk dua dimensi model yang sama, ia menunjukkan bahawa model dua dimensi yang sebelumnya telah terlebih dahulu meramalkan nilai pemindahan jisim. Nilai pindahan jisim menunjukkan nilai yang melangkaui ramalan pada model dua dimensi yang sedia ada apabila persamaan baru digunakan pada kedua-dua model dua dimensi yang sama. Tambahan pula, hasil perbandingan antara paip licin bengkok dan *miter* pada keadaan aliran yang sama menunjukkan nilai pindahan jisim pada model paip bengkok *miter* adalah lebih tinggi berbanding paip licin bengkok. Hasil eksperimen juga menunjukkan hasil yang sama pada permukaan bentuk apabila diuji di bawah Mikroskop Pelepasan Bidang Imbasan Elektron (*FESEM*). Daripada pendekatan eksperimen dan ujikaji yang dijalankan, dapat disimpulkan bahawa garis pusat dalam paip adalah kawasan kelakuan *FIC* yang tertinggi untuk 30^o dan 45^o kawasan lian dan *miter* selekoh.

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LIST OF ABBREVIATIONS

A	-	Area
ASME	-	American Society of Mechanical Engineers
ASTM	-	American Society for Testing and Materials
CFD	-	Computational Fluid Dynamics
De	-	Dean number
DPM	-	Discrete Phase Model
dp	-	diameter of the pipe
EDM	-	Electric Discharge Machining
EDX	-	Energy Diffraction X-ray
EIS	-	Electrochemical Impedance Spectroscopy
FAC	-	Flow Accelerated Corrosion
FESEM	-	Field Emission Scanning Electron Microscope
FIC	-	Flow Induced Corrosion
FVM		Finite Volume Method
GDS	-	Glow Discharge Spectrometer
GF	-	Geometry Factor
LDM	-	Lesser Doppler Anemometry
Log	-	Logarithm
LR	-	Long radius
MT	-	Mass Transfer
MTC	-	Mass Transfer Coefficients
MTCRE	-	Mass Transfer Coefficients Ratio Equation
MTCRMBE	-	Mass Transfer Coefficients Ratio for Mitre Bend Equation
MTCRSBE	-	Mass Transfer Coefficients Ratio for Smooth Bend Equation
NPP	-	Nuclear Power Plant
PIV	-	Particle Image Velocimetry

POD	-	Proper Orthogonal Decomposition
PVC	-	Polyvinyl Chloride
PWR	-	Pressure Water Rector
RANS	-	Reynolds Averaged Navier Stokes
RNG	-	Random Number Generator
RSM	-	Reynolds Stress Model
SR	-	Short radius
r/b	-	bend radius
r/D	-	Diameter ratio
SEM	-	Scanning Electron Microscope
TKE	-	Turbulent Kinetic Energy
USA	-	United States of America
WSS	-	Wall Shear Stress
XRD	-	X-Ray Diffraction

LIST OF SYMBOLS

J	-	Joule
μ	-	Viscosity
∞	-	Infinity
ρ	-	Density
ℓ	-	Exponential
θ	-	Angle
Q	-	Flow rate
G	-	Gram
O	-	Oxygen
H	-	Hydrogen
Re	-	Reynolds number
P	-	Pressure
P_1	-	Pressure 1
P_2	-	Pressure 2
Sh	-	Sherwood number
V	-	Velocity
V_1	-	Velocity 1
V_2	-	Velocity 2
Sc	-	Schmidt number
Mn	-	Magnesium
Cl	-	Chloride
C	-	Carbon
NaCl	-	Sodium Chloride
Fe	-	Iron
FeO	-	iron (ll) oxide
Fe_3SO_4	-	iron (lll) oxide

HCl	-	Hydrogen chloride
FeCl	-	Iron chloride
D	-	Diameter
D_f	-	diffusion coefficient
M	-	Metre
G	-	Gram
K	-	Constant
Kg	-	Kilogram
Pa	-	Pascal
τ	-	Shear stress
W	-	mass loss
%	-	Percentage
γ	-	Specific weight
2-D	-	2-Dimensional
3-D	-	3-Dimensinal
$k-\varepsilon$	-	k-epsilon
Mm	-	Millimetre
M	-	Metre
S	-	Second
λ	-	Wavelength
Cm	-	Centimetre
N	-	Integer
2-θ	-	2 –Theta
N	-	Newton
ε	-	Dissipation
μ_t	-	turbulent viscosity
C_μ	-	empirical constant

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

The research works presented in this thesis address character of fluid flow in pipe bends. The production and processing industries are currently facing with problems of fluid flow induced corrosion (FIC) which results into degradation or deterioration in pipe lines, especially in bends, joints and valves, where severe deterioration is found to occur. The reason for severe degradation or high rate of degradation in bends is due to recirculation of fluid flow behaviour in these regions as a result of high wall shear stress (wss), high turbulent intensity and secondary flow which are the attributes of the growth of this degradation in bends (Njobuenwu and Fairweather, 2012; Sun *et al.*, 2012). Furthermore, the problem in wide perspective, when fluid flow through the bends, is that the pipe usually experiences strong secondary flow and high wall shear stress in the plane normal to the pipe axis. This secondary flow and wall shear stress is believed to accelerate the mixing, and hence deterioration and degradation of the pipe wall elbow. Moreover, this may lead to excess vibrations of the pipe as a results of fluid flow.

Generally, fluid flow plays an important role in every industry associated with Mechanical or Chemical engineering. In these industries, huge fluid flow networks are important to attain continuous transportation of products. However, because of the importance of fluid flow behaviour in bends, many numerical and experimental works on the straight line pipe have been conducted by many researchers but due to the complexities, the numerical computation and experimental works in elbows have been untouched.

Therefore the present research focus is on effect of fluid flow on local deterioration rates to develop and modify the new correlation in relation to flow induced corrosion experiment and computational fluid dynamics method respectively. The study therefore, considers two (2) types of pipe bends, mitre and smooth bends, which are made up of low carbon steel (industrial grade).

The flow of fluids in networks of pipes is very common in many areas such as desalination plant, oil and gas industries, refineries, water cooling networks, steam and condensate networks, ventilation systems, and municipal water utilities (Tominaga and Nagao, 2000).

Aqueous degradation is often accompanied by the formation of deterioration products on the metal surface. Integral layers of degradation products or insoluble scale deposits on the pipe bend surface can act to protect the underlying metal from attack. Biofilms formed by the colonization of solid surfaces by microorganisms present a special case.

Meanwhile, the pipe bends as well as elbows in water plants are exposed to various deterioration mechanisms. Wall thinning, in particular, is considered as a key degradation mechanism in pipe elbows. In the past, researchers considered 90^0 bend with rectangular cross section as the main shape of configuration, but in this research a configuration of mitre bend and smooth bend was considered (Azzola *et al.*, 1986).

The study therefore, focused and aimed to obtain the effect of flow behaviour in pipe bends through the newly modified correlation analysis and fluid flow induced corrosion behaviour by weight loss.

1.2 Statement of the Problem

Flow degradation failures in pipe bends continue to occur despite the standards, connections, industry codes having been followed and proper base selected (Babu and Natarajan, 2008). The production and processing industries are currently facing problems of severe damage due to FIC that occurs in pipe fittings, turbines, pumps, flow line, valves and header especially in bends and joints, where severe degradation is found to occur (Schefski *et al.*, 1995; Wood, 2008). The reason for severe deterioration or high rate of degradation in bends is due to extreme fluid flow behaviour in these regions as the result of recirculation of flow, high turbulent intensity and mass transfer coefficient that are attributed to the growth of degradation of elbow (Schefski *et al.*, 1995; Ahmed, 2012). To put the issue in perspective, fluid flowing through the bends, experiences strong reverse flow in the plane normal to the pipe axis. This mass transfer and wall shear stress as well as high turbulent intensity is believed to accelerate the mixing, and hence the degradation of the pipe wall. However, subsequent degradation can cause sudden explosion and breakdown in the production and processing industries, thus requiring another better computational fluid dynamics (CFD) and experimental analysis. The degradation of flow line equipment costs the industry millions of dollars every year (Sun *et al.*, 2012). This research, therefore, intends to modify simplified correlation to predict maximum mass transfer coefficient in bends based on many simulations.

1.3 Objectives of the Research

The objectives of this research are categorized as follows:

1. To quantify maximum mass transfer coefficients with 2D and 3D models in mitre and smooth bends.
2. To characterize and correlate degradation parameters between the bends through the flow induced corrosion study.
3. To improve and modify for maximum prediction of maximum mass transfer coefficients in bends.

1.4 Significance of the study

Most published research works on the effect of fluid flow on degradation behaviour in pipe bends are concerned mainly with numerical analysis, while the experimental study and simplified correlation to predict maximum mass transfer coefficient for validation has received no much attention due to the difficult and complex nature of the process. Currently, reports on experimental analysis on flow effect on degradation behaviour in elbows are still lacking (Wood, 2008; Ahmed, 2012). Thus, bend geometries has become highly significant to be investigated and studied in detail in order to improve and correlates degradation parameters as it has practical implication in industries.

1.5 Research scope

1. Two types of bends were selected among types of bends used in production industries.
2. The flow degradation parameters in pipe bends geometry were obtained from CFD.
3. Modify simplified correlation to predict maximum mass transfer coefficient in bends.
4. Numerical results are validated with mass transfer coefficient predictions and experimental results.

1.6 Thesis outline

This thesis contains five chapters. The first chapter contains a general introduction and background of the thesis. Objectives, scope and significance of study are outlined. The rest of the chapters are described below.

Chapter 2 starts by quoting or reviewing several researches work on effect of fluid flow behaviour on fluid flow in pipe elbows and related areas. It then provides the review of literature and theoretical frame work of the research area done by the past researchers. The important theoretical background is included in this chapter.

Chapter 3 presents the research methodology and describes the CFD approaches, verified method through $k-\omega$ turbulence model combine with discrete phase models, techniques used for an experimental to analyse FIC and MTC modified equations.

Chapter 4 presents the results of CFD through $k-\omega$ combine with discrete phase models (DPM) that was conducted, verified by an experimental techniques will be used to analyse FIC test and the results will be correlated with MTC modified equation.

Chapter 5 is the concluding part of the research. This summarizes, recommends and concludes the research that has been carried out in this study. Further work will be suggested at the end of this chapter.

REFERENCES

Abdelmeguid, A. and Spalding, D. (1979). Turbulent Flow and Heat Transfer in Pipes with Buoyancy Effects. *Journal of Fluid Mechanics.* 94(02), 383-400.

Abdolkarimi, V. and Mohammadikhah, R. (2013). Cfd Modeling of Particulates Erosive Effect on a Commercial Scale Pipeline Bend. *ISRN Chemical Engineering.*2013.

Ablikim, M., Achasov, M., Ai, X., Albayrak, O., Ambrose, D., An, F., An, Q., Bai, J., Ferroli, R. B. and Ban, Y. (2013). Observation of a Charged Charmoniumlike Structure in E+ E−→ Π+ Π− J/Ψ at S= 4.26 Gev. *Physical ReviewLetters.*110(25),252001.

Achenbach, E. (1976). Mass Transfer from Bends of Circular Cross Section to Air. *Future Energy Production Systems, Academic Press, New York.* 1 327-337.

Adloff, C., Anderson, M., Andreev, V., Andrieu, B., Arkadov, V., Arndt, C., Ayyaz, I., Babaev, A., Bähr, J. and Baranov, P. (1999). Measurement of D∗ Meson Cross Sections at Hera and Determination of the Gluon Density in the Proton Using Nlo Qcd. *Nuclear Physics B.* 545(1), 21-44. (http:// www. science direct.com/science/article/pii/S0550321399001194) Assessed July, 2016

Ahmed, W. H. (2010). Evaluation of the Proximity Effect on Flow-Accelerated Corrosion. *Annals of Nuclear Energy.* 37(4), 598-605. (http:// www. science direct.com/science/article/pii/S0306454909003946) Assessed January, 2016

Ahmed, W. H. (2012). *Flow Accelerated Corrosion in Nuclear Power Plants.* INTECH Open Access Publisher.

Al-Hashem, A. and Riad, W. (2002). The Role of Microstructure of Nickel–Aluminium–Bronze Alloy on Its Cavitation Corrosion Behavior in Natural Seawater. *Materials characterization.* 48(1), 37-41. (http://www. sciencedirect.com/science/article/pii/S1044580302001961) Assessed March, 2016

Alabbas, F. M., Williamson, C., Bhola, S. M., Spear, J. R., Olson, D. L., Mishra, B. and Kakpovbia, A. E. (2013). Influence of Sulfate Reducing Bacterial Biofilm on Corrosion Behavior of Low-Alloy, High-Strength Steel (Api-5l X80). *International Biodeterioration & Biodegradation.* 78 34-42. (http://www.sciencedirect.com/science/article/pii/S096483051200323X) Assessed February, 2016

Azzola, J., Humphrey, J., Iacovides, H. and Launder, B. (1986). Developing Turbulent Flow in a U-Bend of Circular Cross-Section: Measurement and Computation. *Journal of fluids engineering.* 108(2), 214-221 Assessed January, 2016.

Babu, S. K. and Natarajan, S. (2008). Influence of Heat Input on High Temperature Weldment Corrosion in Submerged Arc Welded Power Plant Carbon Steel. *Materials & Design.* 29(5), 1036-1042. (http://www. science direct. com/science/article/pii/S0261306907000945) Assessed December, 2015.

Bagnold, R. A. (1954). Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid under Shear. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences.* 49-63.

Balan, C. and Redekop, D. (2005). The Effect of Bi-Directional Loading on Fatigue Assessment of Pressurized Piping Elbows with Local Thinned Areas. *International Journal of Pressure Vessels and Piping.* 82(3), 235-242. (http://www.sciencedirect.com/science/article/pii/S0308016104001929) Assessed August, 2014

Balbaud-Celerier, F. and Barbier, F. (2001). Investigation of Models to Predict the Corrosion of Steels in Flowing Liquid Lead Alloys. *Journal of Nuclear Materials.* 289(3), 227-242. (http://www.sciencedirect. com/ science /article /pii/S0022311501004317) Assessed June, 2015

Barker, R., Hu, X. and Neville, A. (2013). The Influence of High Shear and Sand Impingement on Preferential Weld Corrosion of Carbon Steel Pipework in Co 2-Saturated Environments. *Tribology International.* 68 17-25. (http:// www. sciencedirect.com/science/article/pii/S0301679X12003702) Assessed May, 2016

Barua, S. (1963). On Secondary Flow in Stationary Curved Pipes. *The Quarterly Journal of Mechanics and Applied Mathematics.* 16(1), 61-77 Assessed January, 2013.

Bendick, W., Gabrel, J., Hahn, B. and Vandenberghe, B. (2007). New Low Alloy Heat Resistant Ferritic Steels T/P23 and T/P24 for Power Plant Application. *International Journal of Pressure Vessels and Piping.* 84(1), 13-20. (http://www.sciencedirect.com/science/article/pii/S0308016106001591) Assessed February, 2016

Berger, F. and Hau, K.-F.-L. (1977). Mass Transfer in Turbulent Pipe Flow Measured by the Electrochemical Method. *International Journal of Heat and Mass Transfer.* 20(11), 1185-1194. (http://www. sciencedirect. com/ science/article/pii/0017931077901272) Assessed July, 2015

Bhadeshia, H. and Honeycombe, R. (2011). *Steels: Microstructure and Properties: Microstructure and Properties.* Butterworth-Heinemann. (http://www. science direct.com/science/article/pii/0257897289900522) Assessed January, 2013

Brooman, E. (2000). Corrosion Performance of Environmentally Acceptable Alternatives to Cadmium and Chromium Coatings: Chromium—Part Ii. *Metal Finishing.* 98(8), 39-45 Assessed May, 2012.

Caro, C., Fitz-Gerald, J. and Schroter, R. (1971). Atheroma and Arterial Wall Shear Observation, Correlation and Proposal of a Shear Dependent Mass Transfer Mechanism for Atherogenesis. *Proceedings of the Royal Society of London B: Biological Sciences.* 177(1046), 109-133 Assessed September, 2016.

Castaño, J., Botero, C., Restrepo, A., Agudelo, E., Correa, E. and Echeverría, F. (2010). Atmospheric Corrosion of Carbon Steel in Colombia. *Corrosion Science.* 52(1), 216-223. (http://www.sciencedirect. com/science/ article/ pii/ S0010938X09004399) Assessed March, 2015.

Chattopadhyay, D. and Webster, D. C. (2009). Thermal Stability and Flame Retardancy of Polyurethanes. *Progress in Polymer Science.* 34(10), 1068-1133. (http://www.sciencedirect.com/science/article/pii/S007967009000550) Assessed May, 2012.

Chen, H., Sun, Z., Song, X. and Yu, J. (2016). A Pseudo-3d Model with 3d Accuracy and 2d Cost for the Cfd–Pbm Simulation of a Pilot-Scale Rotating Disc Contactor. *Chemical Engineering Science.* 139 27-40. (http://www.science direct.com/science/article/pii/S0009250915006454) Assessed August, 2015.

Chen, J.-F. and Bogaerts, W. (1996). Electrochemical Emission Spectroscopy for Monitoring Uniform and Localized Corrosion. *Corrosion.* 52(10), 753-759 Assessed May, 2012 Assessed March, 2016.

Chen, X., Mclaury, B. S. and Shirazi, S. A. (2004). Application and Experimental Validation of a Computational Fluid Dynamics (Cfd)-Based Erosion Prediction Model in Elbows and Plugged Tees. *Computers & Fluids.* 33(10), 1251-1272. (http://www.sciencedirect.com/ science/article /pii/ S00457 93004 00043X) Assessed April, 2016.

Cheng, G. and Farokhi, S. (1992). On Turbulent Flows Dominated by Curvature Effects. *Journal of fluids engineering.* 114(1), 52-57 Assessed April, 2016.

Chilukoori, S. R. (2013). *Computational Study of Laminar Flow in Microchannels with Abrupt Expansion or Contraction at a 90° Miter Bend.* The University of Utah.

Choi, U. S., Talbot, L. and Cornet, I. (1979). Experimental Study of Wall Shear Rates in the Entry Region of a Curved Tube. *Journal of Fluid Mechanics.* 93(03), 465-489.

Coney, M. (1981). *Erosion-Corrosion: The Calculation of Mass-Transfer Coefficients.* CEGB Assessed April, 2016.

Couvert, A., Bastoul, D., Roustan, M., Line, A. and Chatellier, P. (2001). Prediction of Liquid Velocity and Gas Hold-up in Rectangular Air-Lift Reactors of Different Scales. *Chemical Engineering and Processing: Process Intensification.* 40(2), 113-119. (http://www.sciencedirect. com/science/ article/pii/S0255270100001306) Assessed December, 2015

Craft, T., Gant, S., Iacovides, H. and Launder, B. (2004). A New Wall Function Strategy for Complex Turbulent Flows. *Numerical Heat Transfer, Part B: Fundamentals.* 45(4), 301-318. ISSN: 1040-7790 Assessed April, 2016

Craft, T., Gerasimov, A., Iacovides, H. and Launder, B. (2002). Progress in the Generalization of Wall-Function Treatments. *International Journal of Heat and Fluid Flow.* 23(2), 148-160. (http://www.sciencedirect. com/ science/article/pii/S0142727X01001436) Assessed June, 2016

Csizmadia, P. and Hos, C. (2013). Predicting the Friction Factor in Straight Pipes in the Case of Bingham Plastic and the Power-Law Fluids by Means of Measurements and Cfd Simulation. *Periodica Polytechnica. Chemical*

Engineering. 57(1-2), 79. *57/1–2 (2013) 79–83 (http:// periodicapolytechnica.org/ch)* Assessed July, 2016

Cuming, H. (1955). *The Secondary Flow in Curved Pipes.* HM Stationery Office. **R. &** M. No. 2880 A.R.~. ~elmieal l~Imr~ Aeronautical Research Council Reports and Memoranda

Cziesla, T., Biswas, G., Chattopadhyay, H. and Mitra, N. (2001). Large-Eddy Simulation of Flow and Heat Transfer in an Impinging Slot Jet. *International Journal of Heat and Fluid Flow.* 22(5), 500-508. (http:// www. science direct.com/science/article/pii/S0142727X01001059) Assessed April, 2015

De Matos, A. and Franca, F. A. (2009). Bubbly Flow Segregation inside a U-Bend Pipe: Experimentation and Numerical Simulation. *Chemical Engineering Research and Design.* 87(5), 655-668. (http://www.sciencedirect. com/ science/article/pii/S0263876208002645) Assessed May, 2016

Dean, W. and Hurst, J. (1959). Note on the Motion of Fluid in a Curved Pipe. *Mathematika.* 6(01), 77-85.

Deslouis, C. (2003). Microscopic Aspects of Surfactants Action on Flow Induced Corrosion. *Electrochimica Acta.* 48(20), 3279-3288. (http://www. science direct.com/science/article/pii/S001346860300389X) Assessed July, 2016

Dooley, R. and Chexal, V. (2000). Flow-Accelerated Corrosion of Pressure Vessels in Fossil Plants. *International Journal of Pressure Vessels and Piping.* 77(2), 85-90. (http://www.sciencedirect.com/science/article/pii/S008016199000873) Assessed April, 2014

El-Behery, S. M., Hamed, M. H., El-Kadi, M. and Ibrahim, K. (2009). Cfd Prediction of Air–Solid Flow in 180 Curved Duct. *Powder Technology.* 191(1), 130-142. (http://www.sciencedirect.com/science/article/pii/S0032591008004476) Assessed January, 2016

El-Behery, S. M., Hamed, M. H., El-Kadi, M. and Ibrahim, K. (2010). Numerical Simulation and Cfd-Based Correlation of Erosion Threshold Gas Velocity in Pipe Bends. *CFD Letters.* 2(1), 39-53. *CFD Letters* www.cfdl.issres.net Assessed April, 2012

El-Gammal, M., Mazhar, H., Cotton, J., Shefski, C., Pietralik, J. and Ching, C. (2010). The Hydrodynamic Effects of Single-Phase Flow on Flow Accelerated Corrosion in a 90-Degree Elbow. *Nuclear Engineering and*

Design. 240(6), 1589-1598. (http://www.sciencedirect. com/science /article/ pii/S0029549309006451) Assessed March 2015.

Eliyan, F. F. and Alfantazi, A. (2014). On the Theory of Co 2 Corrosion Reactions–Investigating Their Interrelation with the Corrosion Products and Api-X100 Steel Microstructure. *Corrosion Science.* 85 380-393. (http://www. sciencedirect.com/science/article/pii/S0010938X14002261) Assessed April, 2016

Enayet, M., Gibson, M., Taylor, A. and Yianneskis, M. (1982). Laser-Doppler Measurements of Laminar and Turbulent Flow in a Pipe Bend. *International Journal of Heat and Fluid Flow.* 3(4), 213-219. (http://www. sciencedirect.com/science/article/pii/0142727X82900248) Assessed September, 2015

Ferng, Y. M. and Lin, B. H. (2010). Predicting the Wall Thinning Engendered by Erosion–Corrosion Using Cfd Methodology. *Nuclear Engineering and Design.* 240(10), 2836-2841. (http://www.sciencedirect. com/science /article /pii/S0029549310005042) Assessed August, 2014

Fokeer, S. (2006). *An Investigation of Geometrically Induced Swirl Applied to Lean Phase Pneumatic Flows.* University of Nottingham. http://eprints. nottingham.ac.uk/10256/1/An_Investigation_of_Geometrically_Induced_Swirl_ Applied_to_Lean_Phase_Pneumatic_Flows.pdf Assessed March, 2016

G1-03, A. (2003). Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens.

Ghali, E. (2010). *Corrosion Resistance of Aluminum and Magnesium Alloys: Understanding, Performance, and Testing.* John Wiley & Sons. num+ and +Magnesium+Alloys%3A+Understanding%2C+Performance%2C+and+Testing&btnG=&hl=en&as_sdt=0%2C5

Ghazali, M. and Rahim, M. (2013). Cfd Prediction of Heat and Fluid Flow through U-Bends Using High Reynolds-Number Evm and Dsm Models. *Procedia Engineering.* 53 600-606. (http://www. sciencedirect.com/science/ article /pii /S1877705813001963) Assessed April, 2015

Ghosh, S., Das, G. and Das, P. K. (2011). Simulation of Core Annular in Return Bends—a Comprehensive Cfd Study. *Chemical Engineering Research and Design.* 89(11), 2244-2253. (http://www.sciencedirect.com/science/article/ pii/ S0263876211001341) Assessed May, 2016

Golru, S. S., Attar, M. and Ramezanzadeh, B. (2015). Effects of Different Surface Cleaning Procedures on the Superficial Morphology and the Adhesive Strength of Epoxy Coating on Aluminium Alloy 1050. *Progress in Organic Coatings.* 87 52-60. (http://www.sciencedirect.com/science/article/pii/S0300944015001447) Assessed August, 2015.

Hadžiahmetović, H., Hodžić, N., Kahrimanović, D. and Džaferović, E. (2014). Computational Fluid Dynamics (Cfd) Based Erosion Prediction Model in Elbows. *Tehnicki vjesnik/Technical Gazette.* 21(2) Assessed May, 2016.

Haque, M., Hassan, A., Turner, J. and Barrow, H. (1983). An Observation on the Origin of Secondary Flow in Straight Noncircular Ducts. *Wärme-und Stoffübertragung.* 17(2), 93-95. (http://www.Februay, 2016

Hashimoto, T., Tanno, I., Yasuda, T., Tanaka, Y., Morinishi, K. and Satofuka, N. (2015). Higher Order Numerical Simulation of Unsteady Viscous Incompressible Flows Using Kinetically Reduced Local Navier–Stokes Equations on a Gpu. *Computers & Fluids.* 110 108-113. (http://www.sciencedirect.com/science/article/pii/S0045793014003508) Assessed April, 2016.

Hawthorne, W. R. (1951). Secondary Circulation in Fluid Flow. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences.* 374-387.

Hernández-Jiménez, F., Sánchez-Delgado, S., Gómez-García, A. and Acosta-Iborra, A. (2011). Comparison between Two-Fluid Model Simulations and Particle Image Analysis & Velocimetry (Piv) Results for a Two-Dimensional Gas–Solid Fluidized Bed. *Chemical Engineering Science.* 66(17), 3753-3772. (http://www.sciencedirect.com/science/article/pii/S0009250911002685) Assessed January, 2016

Hidayat, M. and Rasmuson, A. (2005). Some Aspects on Gas–Solid Flow in a U-Bend: Numerical Investigation. *Powder Technology.* 153(1), 1-13. (http://www.sciencedirect.com/science/article/pii/S0032591005000306) Assessed April, 2016.

Hille, P., Vehrenkamp, R. and Schulz-Dubois, E. (1985). The Development and Structure of Primary and Secondary Flow in a Cu. February, 2016.

Hirsch, C. (2007). *Numerical Computation of Internal and External Flows: The Fundamentals of Computational Fluid Dynamics: The Fundamentals of Computational Fluid Dynamics.* Butterworth-Heinemann February, 2016.

Hossain, A. and Naser, J. (2004). Cfd Investigation of Particle Deposition around Bends in a Turbulent Flow. *Governing.* 13 17.

Hosseini, A., Mostofinejad, D. and Hajialilue-Bonab, M. (2012). Displacement Measurement of Bending Tests Using Digital Image Analysis Method. *International Journal of Engineering and Technology.* 4(5), 642.

Hu, X., Alzawai, K., Gnanavelu, A., Neville, A., Wang, C., Crossland, A. and Martin, J. (2011). Assessing the Effect of Corrosion Inhibitor on Erosion–Corrosion of Api-5l-X65 in Multi-Phase Jet Impingement Conditions. *Wear.* 271(9), 1432-1437. (http://www. sciencedirect. com/science/ article/pii/ S0043164811003073) Assessed March, 2016

Huang, Y. H. and Zhang, T. C. (2005). Effects of Dissolved Oxygen on Formation of Corrosion Products and Concomitant Oxygen and Nitrate Reduction in Zero-Valent Iron Systems with or without Aqueous Fe 2+. *Water Research.* 39(9), 1751-1760. (http://www.sciencedirect.com/science/article /pii/ S00431354 050 00904) Asessed May, 2015

Ito, H. (1987). Flow in Curved Pipes. *JSME International Journal.* 30(262), 543-552.

Jacob, K. S. and Parameswaran, G. (2010). Corrosion Inhibition of Mild Steel in Hydrochloric Acid Solution by Schiff Base Furoin Thiosemicarbazone. *Corrosion Science.* 52(1), 224-228. (http://www.sciencedirect.com/science/ article/pii/S0010938X09004405) Assessed March, 2015.

Jang, B. S. and Oh, B. H. (2010). Effects of Non-Uniform Corrosion on the Cracking and Service Life of Reinforced Concrete Structures. *Cement and Concrete Research.* 40(9), 1441-1450. (http://www.sciencedirect.com/science/ article /pii/S0008884610000876) Assessed May, 2013

Jiang, H., Lu, L. and Sun, K. (2011). Experimental Investigation of the Impact of Airborne Dust Deposition on the Performance of Solar Photovoltaic (Pv) Modules. *Atmospheric Environment.* 45(25), 4299-4304. (http://www. science direct.com/science/article/pii/S1352231011005243) Assessed March, 2012

Jones, N. (1966). On the Design of Pipe-Bends. *Nuclear Engineering and Design.* 4(4), 399-405. (http://www.sciencedirect.com/science/article/pii/0029549366900689) Assessed February, 2016.

Jones, W. and Whitelaw, J. (1982). Calculation Methods for Reacting Turbulent Flows: A Review. *Combustion and flame.* 48 1-26.

Jyrkama, M. I. and Pandey, M. D. (2012). Methodology for Predicting Flow-Accelerated Corrosion Wear Using Unreferenced Multiple Inspection Data. *Nuclear Engineering and Design.* 250 317-325. (http://www. science direct.com/science/article/pii/S0029549312003214) Assessed March, 2016

Kain, V., Roychowdhury, S., Ahmedabadi, P. and Barua, D. (2011). Flow Accelerated Corrosion: Experience from Examination of Components from Nuclear Power Plants. *Engineering Failure Analysis.* 18(8), 2028-2041. (http://www.sciencedirect.com/science/article/pii/S1350630711001506) Assessed April, 2015

Kalpakli, A., Örlü, R. and Alfredsson, P. H. (2013). Vortical Patterns in Turbulent Flow Downstream a 90° Curved Pipe at High Womersley Numbers. *International Journal of Heat and Fluid Flow.* 44 692-699. (http://www. sciencedirect.com/science/article/pii/S0142727X1300194X) Assessed March, 2016

Kastner, W., Erve, M., Henzel, N. and Stellwag, B. (1990). Calculation Code for Erosion Corrosion Induced Wall Thinning in Piping Systems. *Nuclear Engineering and Design.* 119(2), 431-438.v (http://www.sciencedirect. com/ science/article/pii/002954939090182W) Assessed June, 2014

Kear, G., Barker, B. and Walsh, F. (2004). Electrochemical Corrosion of Unalloyed Copper in Chloride Media—a Critical Review. *Corrosion Science.* 46(1), 109-135. (http://www.sciencedirect.com/science /article/pii/S 0010938X 020 02573) Assessed March, 2015

Kim, J.-W., Na, M.-G. and Park, C.-Y. (2008). Effect of Local Wall Thinning on the Collapse Behavior of Pipe Elbows Subjected to a Combined Internal Pressure and in-Plane Bending Load. *Nuclear Engineering and Design.* 238(6), 1275-1285. (http://www.sciencedirect.com/science/article/pii/S002954930005572) Assessed March, 2016

Kuan, B., Yang, W. and Schwarz, M. (2007). Dilute Gas–Solid Two-Phase Flows in a Curved 90◦ Duct Bend: Cfd Simulation with Experimental Validation.

Chemical Engineering Science. 62(7), 2068-2088. (http://www.science direct .com/science/article/pii/S0009250907000085) Assessed March, 2015.

Kussmaul, K., Diem, H., Uhlmann, D. and Kobes, E. (1995). Pipe Bend Behaviour at Load Levels Beyond Design. *Transactions of the 13. International Conference on Structural Mechanics in Reactor Technology. v. 2.*

Lai, Y., So, R. and Zhang, H. (1991). Turbulence-Driven Secondary Flows in a Curved Pipe. *Theoretical and Computational Fluid Dynamics.* 3(3), 163-180 Assessed May, 2013.

Larsson, I., Lindmark, E., Lundström, T. S. and Nathan, G. (2011). Secondary Flow in Semi-Circular Ducts. *Journal of fluids engineering.* 133(10), 101206.

Lasiecka, I. and Triggiani, R. (1990). Exact Controllability of the Euler-Bernoulli Equation with Boundary Controls for Displacement and Moment. *Journal of mathematical analysis and applications.* 146(1), 1-33. (http://www. sciencedirect.com/science/article/pii/0022247X9090330I) Assessed February, 2016

Launder, B. and Sharma, B. (1974). Application of the Energy-Dissipation Model of Turbulence to the Calculation of Flow near a Spinning Disc. *Letters in heat and mass transfer.* 1(2), 131-137. (http://www.sciencedirect. com/ science/ article/pii/0094454874901507) Assessed March, 2015

Launder, B. E. (1988). On the Computation of Convective Heat Transfer in Complex Turbulent Flows. *Journal of Heat Transfer.* 110(4b), 1112-1128.

Launder, B. E. and Spalding, D. (1974). The N umerical Computation of Turbulent Flows. *Computer methods in applied mechanics and engineering.* 3(2), 269-289.(_http://www.sciencedirect.com/ science/article/pii/0045782574900292) Assessed May, 2015.

Lelièvre, C., Legentilhomme, P., Gaucher, C., Legrand, J., Faille, C. and Bénézech, T. (2002). Cleaning in Place: Effect of Local Wall Shear Stress Variation on Bacterial Removal from Stainless Steel Equipment. *Chemical Engineering Science.* 57(8), 1287-1297. (http://www. science direct.com /science/ article/pii/S0009250902000192) Assessed March, 2014.

Li, Q., Song, J., Li, C., Wei, Y. and Chen, J. (2013). Numerical and Experimental Study of Particle Deposition on Inner Wall of 180° Bend. *Powder Technology.* 237 241-254. (http://www.sciencedirect .com/science/ article /pii/ S0032591012007577) Assessed March, 2015

Li, T., Pannala, S. and Shahnam, M. (2014). Reprint of" Cfd Simulations of Circulating Fluidized Bed Risers, Part Ii, Evaluation of Differences between 2d and 3d Simulations. *Powder Technology*. 265 13-22. (http://www. sciencedirect.com/science/article/pii/S0032591014003027) Assessed July, 2015

Lin, C. H. and Ferng, Y. M. (2014). Predictions of Hydrodynamic Characteristics and Corrosion Rates Using Cfd in the Piping Systems of Pressurized-Water Reactor Power Plant. *Annals of Nuclear Energy*. 65 214-222. (http://www.sciencedirect.com/science/article/pii/S0306454913005902) Assessed June, 2015

Liu, Y., Zhang, Y. and Yuan, J. (2014). Influence of Produced Water with High Salinity and Corrosion Inhibitors on the Corrosion of Water Injection Pipe in Tuha Oil Field. *Engineering Failure Analysis*. 45 225-233. (http://www.sciencedirect.com/science/article/pii/S1350630714001940) Assessed April, 2015.

Ma, K.-T., Ferng, Y.-M. and Ma, Y.-P. (1998). Numerically Investigating the Influence of Local Flow Behaviors on Flow-Accelerated Corrosion Using Two-Fluid Equations. *Nuclear technology*. 123(1), 90-102.

Mamat, M. F. and Hamzah, E. (2014). Corrosion Behavior of Low Carbon Steel Welded Joint in Nacl Solution. *Advanced Materials Research*. 173-177. (http://www.scientific.net/AMR.845.173) Assessed March, 2012.

Marchal, J. and Crochet, M. (1987). A New Mixed Finite Element for Calculating Viscoelastic Flow. *Journal of Non-Newtonian Fluid Mechanics*. 26(1), 77-114. (http://www.sciencedirect.com/science/article/pii/0377025787850486) Assessed January, 2013

Markwalder, T.-M., Grolimund, P., Seiler, R. W., Roth, F. and Aaslid, R. (1984). Dependency of Blood Flow Velocity in the Middle Cerebral Artery on End-Tidal Carbon Dioxide Partial Pressure—a Transcranial Ultrasound Doppler Study. *Journal of Cerebral Blood Flow and Metabolism*. 4(3), 368-372.

Mazumder, Q. H. (2012). Cfd Analysis of Single and Multiphase Flow Characteristics in Elbow.

Mccafferty, E. (2010). *Introduction to Corrosion Science*. Springer Science & Business Media.

Mcnamara, C. G., Davidson, E. S. and Schenk, S. (1993). A Comparison of the Motor-Activating Effects of Acute and Chronic Exposure to Amphetamine and Methylphenidate. *Pharmacology Biochemistry and Behavior.* 45(3), 729-732. (http://www.sciencedirect.com/science/article/pii/009130579390532X) Assessed March, 2014

Metzger, L. and Kind, M. (2015). On the Transient Flow Characteristics in Confined Impinging Jet Mixers-Cfd Simulation and Experimental Validation. *Chemical Engineering Science.* 133 91-105. (http://www.sciencedirect. com/science/ article/pii/S0009250914007751)

Mitchell, J. E. and Hanratty, T. J. (1966). A Study of Turbulence at a Wall Using an Electrochemical Wall Shear-Stress Meter. *Journal of Fluid Mechanics.* 26(01), 199-221 Assessed May, 2015.

Mitsunobu, A. and Cheng, K. (1971). Boundary Vorticity Method for Laminar Forced Convection Heat Transfer in Curved Pipes. *International Journal of Heat and Mass Transfer.* 14(10), 1659-1675.(http://www.science direct. com/science/article/pii/0017931071900755) Assessed March, 2014

Mohanarangam, K., Tian, Z. and Tu, J. (2008). Numerical Simulation of Turbulent Gas–Particle Flow in a 90 Bend: Eulerian–Eulerian Approach. *Computers & ChemicalnEngineering.* 32(3), 561-571. (http://www. science direct. com/ science/article/pii/S0098135407000932) Assessed February, 2015

Mohd Fairusham, G. and Mohd Fadzil, A. R. (2012). Cfd Prediction of Heat and Fluid Flow through U-Bends Using High Reynolds-Number Evm and Dsm Models. (http://www.sciencedirect.com/science/article/pii/S18777058130019 63) Assessed February, 2015

Moussiere, S., Roubaud, A., Boutin, O., Guichardon, P., Fournel, B. and Joussot-Dubien, C. (2012). 2d and 3d Cfd Modelling of a Reactive Turbulent Flow in a Double Shell Supercritical Water Oxidation Reactor. *The Journal of Supercritical luids* .6525-31. (http://www.sciencedirect .com/science/article /pii/S089684461200068X) Assessed February, 2014

Munson, B. R., Young, D. F. and Okiishi, T. H. (1990). Fundamentals of Fluid Mechanics. *New York.* 3 4. John Wiley & Sons, Inc.

Nakatani, T., Kuriyama, S., Tominaga, K., Tsujimoto, T., Mitoro, A., Yamazaki, M., Tsujinoue, H., Yoshiji, H., Nagao, S. and Fukui, H. (2000). Assessment of

Efficiency and Safety of Adenovirus Mediated Gene Transfer into Normal andDamaged Murine Livers.*Gut.*47(4),563-570.

Nesic, S., Postlethwaite, J. and Olsen, S. (1996). An Electrochemical Model for Prediction of Corrosion of Mild Steel in Aqueous Carbon Dioxide Solutions. *Corrosion.* 52(4), 280-294. (http://www.corrosion journal.org)

Neville, A. and Mcdougall, B. (2001). Erosion–and Cavitation–Corrosion of Titanium and Its Alloys. *Wear.* 250(1), 726-735. (http://www.science direct.com/science/article/pii/S0043164801007098) Assessed February, 2015

Njobuenwu, D., Fairweather, M. and Yao, J. (2013). Coupled Rans–Lpt Modelling of Dilute, Particle-Laden Flow in a Duct with a 90 Bend. *International journal of multiphase flow.* 50 71-88. (http://www.sciencedirect.com/science/article /pii/S0301932212001590) Assessed January, 2015

Njobuenwu, D. O. and Fairweather, M. (2012). Modelling of Pipe Bend Erosion by Dilute Particle Suspensions. *Computers & Chemical Engineering.* 42 235-247. (http://www.sciencedirect.com/science/article/pii/S009813541200049X) Assessed May, 2015

Odziemkowski, M. (2009). Spectroscopic Studies and Reactions of Corrosion Products at Surfaces and Electrodes. *Spectrosc. Prop. Inorg. Organomet. Compd.* 40 385-450.

Oldfield, J. W. (1988). *Electrochemical Theory of Galvanic Corrosion. Galvanic Corrosion.* ASTM International.http://www.astm.org/Digital_Library /stp/ pages/STP26188S.htm

Ozalp, C., Pinarbasi, A. and Sahin, B. (2010). Experimental Measurement of Flow Past Cavities of Different Shapes. *Experimental Thermal and Fluid Science.* 34(5),505-515. (http://www.sciencedirect.com/science/article/pii/S08941777 09001939) Assessed February, 2015

Pak, B., Cho, Y. I. and Choi, S. U. (1991). Turbulent Hydrodynamic Behavior of a Drag-Reducing Viscoelastic Fluid in a Sudden-Expansion Pipe. *Journal of Non-Newtonian Fluid Mechanics.* 39(3), 353-373. (http://www.sciencedirect. com/science/article/pii/037702579180022C) Assessed July, 2015

Palumbo, G., King, P., Aust, K., Erb, U. and Lichtenberger, P. (1991). Grain Boundary Design and Control for Intergranular Stress-Corrosion Resistance. *Scripta Metallurgica et Materialia.* 25(8), 1775-1780. (http://www.science direct.com/science/article/pii/0956716X9190303I) Assessed February, 2015

Parthasarathy, H., Dzombak, D. A. and Karamalidis, A. K. (2015). Alkali and Alkaline Earth Metal Chloride Solutions Influence Sulfide Mineral Dissolution. *Chemical Geology*. 412 26-33. (http://www.sciencedirect.com/ science/article) Assessed February, 2016

Patankar, S. V., Pratap, V. and Spalding, D. (1975). Prediction of Turbulent Flow in Curved Pipes. *Journal of Fluid Mechanics*. 67(03), 583-595.

Petroski, H. and Achenbach, J. (1978). Computation of the Weight Function from a Stress Intensity Factor. *Engineering Fracture Mechanics*. 10(2), 257-266. (http://www.sciencedirect.com/science/article/pii/0013794478900097)

Pietralik, J. M. (2012). The Role of Flow in Flow-Accelerated Corrosion under Nuclear Power Plant Conditions. *EJ. Adv. Maint*. 4(2), 63-78.

Poulson, B. (2014). Predicting and Preventing Flow Accelerated Corrosion in Nuclear Power Plant. *International Journal of Nuclear Energy*. 2014. (http://www.hindawi.com/journals/ijne/2014/423295/abs/,http://dx) Assessed April, 2015

Poulson, B. (1991). Measuring and Modelling Mass Transfer at Bends in Annular Two Phase Flow. *Chemical Engineering Science*. 46(4), 1069-1082. (http://www.sciencedirect.com/science/article/pii/000925099185100C) Assessed February, 2012

Poulson, B. and Robinson, R. (1988). The Local Enhancement of Mass Transfer at 180° Bends. *International Journal of Heat and Mass Transfer*. 31(6), 1289-1297. (http://www.sciencedirect.com/science/article/pii/0017931088900713) Assessed December, 2014

Quek, T. Y., Wang, C.-H. and Ray, M. B. (2005). Dilute Gas-Solid Flows in Horizontal and Vertical Bends. *Industrial & Engineering Chemistry Research*. 44(7), 2301-2315. (http://pubs.acs.org/doi/abs/10.1021/ie040123i)

Rajahram, S., Harvey, T. and Wood, R. (2011). Electrochemical Investigation of Erosion–Corrosion Using a Slurry Pot Erosion Tester. *Tribology International*. 44(3), 232-240. (http://www.sciencedirect.com/science/article/ pii/S0301679X10002513) Assessed June, 2015

Ramachandran, V. S. and Beaudoin, J. J. (2000). *Handbook of Analytical Techniques in Concrete Science and Technology: Principles, Techniques and Applications*. *(*Elsevier.https://books.google.com.my/books?hl=en&lr=&id= LnnQV4G180oC&oi=fnd&pg=PP1&dq=Hand)

Rani, H., Divya, T., Sahaya, R., Kain, V. and Barua, D. (2014). Cfd Study of Flow Accelerated Corrosion in 3d Elbows. *Annals of Nuclear Energy*. 69 344-351. (http://www.sciencedirect.com/science/article/pii/S0306454914000498) Assessed February, 2015

Rao, K. (2012). *Companion Guide to the Asme Boiler and Pressure Vessel Code, Volume 1*. ASME PRESS. (http://ebooks.asmedigitalcollection.asme.org/book.aspx?bookid=223) Assessed June, 20135

Revie, R. W. (2008). *Corrosion and Corrosion Control*. John Wiley & Sons.

Revie, R. W. and Uhlig, H. H. (2011). *Uhlig's Corrosion Handbook*. John Wiley & Sons.

Rhie, C. and Chow, W. (1983). Numerical Study of the Turbulent Flow Past an Airfoil with Trailing Edge Separation. *AIAA journal*. 21(11), 1525-1532. doi: 10.2514/3.8284. (http://arc.aiaa.org/doi/abs/10.2514/3.8284) Assessed February, 2015

Robertson, A., Li, H. and Mackenzie, D. (2005). Plastic Collapse of Pipe Bends under Combined Internal Pressure and in-Plane Bending. *International Journal of Pressure Vessels and Piping*. 82(5), 407-416. (http://www.sciencedirect.com/science/article/pii/S0308016104002340) Assessed January, 2012

Röhrig, R., Jakirlić, S. and Tropea, C. (2015). Comparative Computational Study of Turbulent Flow in a 90 Pipe Elbow. *International Journal of Heat and Fluid Flow*. 55 120-131. (http://www.sciencedirect.com/science/article/pii/S0142727X15000934) Assessed February, 2015

Rütten, F., Schröder, W. and Meinke, M. (2005). Large-Eddy Simulation of Low Frequency Oscillations of the Dean Vortices in Turbulent Pipe Bend Flows. *Physics of Fluids (1994-present)*. 17(3), 035107. (http://scitation.aip.org/content/aip/journal/pof2/17/3/10.1063/1.1852573 Assessed February, 2015

Sakakibara, J. and Machida, N. (2012). Measurement of Turbulent Flow Upstream and Downstream of a Circular Pipe Bend. *Physics of Fluids (1994-present)*. 24(4), 041702. http://scitation.aip.org/content/aip/journal/pof2/24/4/10.1063/1.4704196) Assessed May, 2015

Sambit, S. (2014). *Simulation and Flow Analysis through a Straight Pipe. (http://ethesis.nitrkl.ac.in/5977/)* Assessed February, 2015

Santamarina, A., Weydahl, E., Siegel Jr, J. M. and Moore Jr, J. E. (1998). Computational Analysis of Flow in a Curved Tube Model of the Coronary Arteries: Effects of Time-Varying Curvature. *Annals of Biomedical Engineering.* 26(6), 944-954. (http://link.springer.com/article/10.1114/1.113 #page-1)

Schefski, C., Pietralik, J., Dyke, T. and Lewis, M. (1995). Flow-Accelerated Corrosion in Nuclear Power Plants: Application of Checworks™ at Darlington. *CANDU.* 19 149.

Schmidtchen, F. P. and Berger, M. (1997). Artificial Organic Host Molecules for Anions. *Chemical Reviews.* 97(5), 1609-1646. (http://pubs.acs. org Assessed March, 2013

Shalaby, M. A. and Younan, M. Y. (1998). Nonlinear Analysis and Plastic Deformation of Pipe Elbows Subjected to in-Plane Bending. *International Journal of Pressure Vessels and Piping.* 75(8), 603-611. (http://www.sciencedirect.com/science/article/pii/S0308016198000593) Assessed February, 2014

Shames, I. H. and Shames, I. H. (1982). *Mechanics of Fluids.* McGraw-Hill New York and Nelson Thomas ltd, 27 Bath road, Cheltenham, Gl537th United Kingdom. ISSBN 0-7487-4043-0 Assessed August, 2015.

Shi, F., Zhang, L., Yang, J., Lu, M., Ding, J. and Li, H. (2016). Polymorphous Fes Corrosion Products of Pipeline Steel under Highly Sour Conditions. *Corrosion Science.* 102 103-113. (http://www.sciencedirect.com/science/ article/pii/S0010938X15300986) Assessed February, 2015

Shi, X., Lei, T., Zhang, F. and Yan, Y. (2015). Velocity Measurement of Water Flow within Gravel Layer with Electrolyte Tracer Method under Virtual Boundary Condition. *Journal of Hydrology.* 527 387-393. (http://www.sciencedirect. com/science/article/pii/S0022169415003571) Assessed Juene, 2015

Shih, T.-H., Liou, W. W., Shabbir, A., Yang, Z. and Zhu, J. (1995). A New K-ϵ Eddy Viscosity Model for High Reynolds Number Turbulent Flows. *Computers & Fluids.* 24(3), 227-238. (http://www.sciencedirect.com/science/article/pii/004 579309400032T) Assessed January, 2012

Son, S., Kihm, K. and Han, J.-C. (2002). Piv Flow Measurements for Heat Transfer Characterization in Two-Pass Square Channels with Smooth and 90 Ribbed Walls. *International Journal of Heat and Mass Transfer.* 45(24), 4809-4822.

(http://www.sciencedirect.com/science/article/pii/S0017931002001928) Assessed February, 2015

Song, G., Johannesson, B., Hapugoda, S. and Stjohn, D. (2004). Galvanic Corrosion of Magnesium Alloy Az91d in Contact with an Aluminium Alloy, Steel and Zinc. *Corrosion Science.* 46(4), 955-977. (http://www.sciencedirect.com/science/article/pii/S0010938X03001902) Assessed February, 2015

Spedding, P. and Benard, E. (2007). Gas–Liquid Two Phase Flow through a Vertical 90 Elbow Bend. *Experimental Thermal and Fluid Science.* 31(7), 761-769. (http://www.sciencedirect.com/science/article/pii/S0894177706001324) Assessed April, 2013

Spedding, P., Bénard, E. and Crawford, N. (2008). Fluid Flow through a Vertical to Horizontal 90 Elbow Bend Iii Three Phase Flow. *Experimental Thermal and Fluid Science.* 32(3), 827-843. (http://www.sciencedirect.com/science/article/pii/S0894177707001392) Assessed February, 2012

Sprague, P., Patrick, M., Wragg, A. and Coney, M. (1985). Mass Transfer and Erosion Corrosion in Pipe Bends. *Proceedings of the 8. European congress on corrosion. Vol. 1.*

Standard, A. (2004a). Standard Practice for Laboratory Immersion Corrosion Testing of Metals. *American Society for Testing and Materials G31-72. (http://www.corrosionjournal.org/doi/abs/10.5006/1.3315961?journalCode=corr)*

Standard, A. (2004b). Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens. *American Society for Testing and Materials G1-03.* (*http://www.sciencedirect.com/science/article/pii/S175058361000174X)*

Sudo, K., Sumida, M. and Hibara, H. (1998). Experimental Investigation on Turbulent Flow in a Circular-Sectioned 90-Degree Bend. *Experiments in Fluids.*25(1), 42-49. (http://link.springer.com/article/10.1007/s003480050206#page-1)

Sun, K., Lu, L. and Jiang, H. (2011). A Computational Investigation of Particle Distribution and Deposition in a 90° Bend Incorporating a Particle–Wall Model. *Building and Environment.* 46(6), 1251-1262. (http://www.sciencedirect.com/science/article/pii/S0360132310003586) Assessed February, 2014

Sun, K., Lu, L. and Jiang, H. (2012). A Numerical Study of Bend-Induced Particle Deposition in and Behind Duct Bends. *Building and Environment.* 52 77-87.

(http://www.sciencedirect.com/science/article/pii/S0360132311004252) Assessed June, 2013

Tavakkolizadeh, M. and Saadatmanesh, H. (2001). Galvanic Corrosion of Carbon and Steel in Aggressive Environments. *Journal of Composites for Construction.* 5(3), 200-210.

Tavares, S., Pardal, J., Mainier, F., Da Igreja, H., Barbosa, E., Rodrigues, C., Barbosa, C. and Pardal, J. (2015). Investigation of the Failure in a Pipe of Produced Water from an Oil Separator Due to Internal Localized Corrosion. *Engineering Failure Analysis. (http://www.sciencedirect.com/science/article /pii/S1350630715301011)*

Tawancy, H., Al-Hadhrami, L. M. and Al-Yousef, F. (2013). Analysis of Corroded Elbow Section of Carbon Steel Piping System of an Oil–Gas Separator Vessel. *Case Studies in Engineering Failure Analysis.* 1(1), 6-14. (http://www.sciencedirect.com/science/article/pii/S2213290212000041)

Tay, B. L. and Thorpe, R. B. (2014). Hydrodynamic Forces Acting on Pipe Bends in Gas–Liquid Slug Flow. *Chemical Engineering Research and Design.* 92(5), 812-825. (http://www.sciencedirect.com/science/article/pii/S0263876213003419)

Thangam, S. and Speziale, C. (1987). Non-Newtonian Secondary Flows in Ducts of Rectangular Cross-Section. *Acta mechanica.* 68(3-4), 121-138. (http://link. springer.com/article/10.1007/BF01190878#page-1)

Tijsseling, A. (1996). Fluid-Structure Interaction in Liquid-Filled Pipe Systems: A Review. *Journal of Fluids and Structures.* 10(2), 109-146. (http://www. sciencedirect.com/science/article/pii/S0889974696900092) Assessed February, 2015

Tominaga, A. and Nagao, M. (2000). Secondary Flow Structures in Bends of Narrow Open Channels with Various Cross Sections. *Proc., 4th Int. Conf. on Hydro-Science and Engineering.*

Tropea, C., Yarin, A. L. and Foss, J. F. (2007). *Springer Handbook of Experimental Fluid Mechanics.* Springer Science & Business Media.

Uzoh, C. E. 2000. Electroetch and Chemical Mechanical Polishing Equipment. Google Patents. (https://www.google.com/patents/US6066030)

Versteeg, H. K. and Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics: The Finite Volume Method.* Pearson Education.

Virdung, T. and Rasmuson, A. (2007). Hydrodynamic Properties of a Turbulent Confined Solid–Liquid Jet Evaluated Using Piv and Cfd. *Chemical Engineering Science.* 62(21), 5963-5978. (http://www.sciencedirect.com/science/article/pii/S0009250907004708) Assessed August, 2014

Visscher, J., Andersson, H., Barri, M., Didelle, H., Viboud, S., Sous, D. and Sommeria, J. (2010). A New Set-up for Piv Measurements in Rapidly Rotating Turbulent Duct Flows. (http://www.sciencedirect.com/science/article/pii/S095559861000107X) Assessed February, 2015

Visscher, J., Andersson, H. I., Barri, M., Didelle, H., Viboud, S., Sous, D. and Sommeria, J. (2011). A New Set-up for Piv Measurements in Rotating Turbulent Duct Flows. *Flow Measurement and Instrumentation.* 22(1), 71-80. Available from: 2010-10-04 Created: 2010-10-04 Last updated: 2010-10-04

Wallis, G. (1991). The Averaged Bernoulli Equation and Macroscopic Equations of Motion for the Potential Flow of a Two-Phase Dispersion. *International journal of multiphase flow.* 17(6), 683-695. (http://www.sciencedirect.com/science/article/pii/030193229190050D) Assessed January, 2015

Wang, L., Cuthbertson, A. J., Pender, G. and Cao, Z. (2015). Experimental Investigations of Graded Sediment Transport under Unsteady Flow Hydrographs. *International Journal of Sediment Research.* 30(4), 306-320. (http://www.sciencedirect.com/science/article/pii/S1001627915000189) Assessed February, 2015

Wang, Y., Zheng, Y., Ke, W., Sun, W., Hou, W., Chang, X. and Wang, J. (2011). Slurry Erosion–Corrosion Behaviour of High-Velocity Oxy-Fuel (Hvof) Sprayed Fe-Based Amorphous Metallic Coatings for Marine Pump in Sand-Containing Nacl Solutions. *Corrosion Science.* 53(10), 3177-3185. (http://www.sciencedirect.com/science/article/pii/S0010938X11002939) Assessed May, 2014

Wood, J. (2008). A Review of Literature for the Structural Assessment of Mitred Bends. *International Journal of Pressure Vessels and Piping.* 85(5), 275-294. (http://www.sciencedirect.com/science/article/pii/S0308016107001639)

Wood, R., Jones, T., Miles, N. and Ganeshalingam, J. (2001). Upstream Swirl-Induction for Reduction of Erosion Damage from Slurries in Pipeline Bends. *Wear.* 250(1), 770-778. (http://www.sciencedirect.com/science/article/pii/S0043164801007153) Assessed February, 2015

Wusatowski, Z. (2013). *Fundamentals of Rolling.* Elsevier.

Xia, Y., Wang, C., Luo, H., Christon, M. and Bakosi, J. (2016). Assessment of a Hybrid Finite Element and Finite Volume Code for Turbulent Incompressible Flows. *Journal of Computational Physics.* 307 653-669. (http://www.sciencedirect.com/science/article/pii/S0021999115008414) Assessed April, 2016

Xiong, R. (2007). *Single- and Two-Phase Pressure-Driven Flow Transport Dynamics in Micro-Channels.*

Xiong, R. and Chung, J. N. (2008). Effects of Miter Bend on Pressure Drop and Flow Structure in Micro-Fluidic Channels. *International Journal of Heat and Mass Transfer.* 51(11), 2914-2924. (http://www.sciencedirect.com/science/article /pii/S0017931007005935) Assessed February, 2015

Yan, B., Gu, H. and Yu, L. (2012a). Cfd Analysis of the Loss Coefficient for a 90° Bend in Rolling Motion. *Progress in Nuclear Energy.* 56 1-6. (http://www.sciencedirect.com/science/article/pii/S0149197011002393) Assessed May, 2014

Yan, W. C., Luo, Z. H., Lu, Y. H. and Chen, X. D. (2012b). A Cfd-Pbm-Pmlm Integrated Model for the Gas–Solid Flow Fields in Fluidized Bed Polymerization Reactors. *AIChE Journal.* 58(6), 1717-1732.

Yan, X., Liu, S., Long, W., Huang, J., Zhang, L. and Chen, Y. (2013). The Effect of Homogenization Treatment on Microstructure and Properties of Znal15 Solder. *Materials & Design.* 45 440-445.

Yang, W. and Kuan, B. (2006). Experimental Investigation of Dilute Turbulent Particulate Flow inside a Curved 90 Bend. *Chemical Engineering Science.* 61(11), 3593-3601. (http://www.sciencedirect.com/science/article/pii/ S0009250906000467) Assessed February, 2015

Yoo, J., Ogle, K. and Volovitch, P. (2014). The Effect of Synthetic Zinc Corrosion Products on Corrosion of Electrogalvanized Steel: I. Cathodic Reactivity under Zinc Corrosion Products. *Corrosion Science.* 81 11-20. (http://www.sciencedirect.com/science/article/pii/S0010938X13005271) Assessed July, 2015

Yuki, K., Hasegawa, S., Sato, T., Hashizume, H., Aizawa, K. and Yamano, H. (2011). Matched Refractive-Index Piv Visualization of Complex Flow Structure in a Three-Dimentionally Connected Dual Elbow. *Nuclear*

Engineering and Design. 241(11), 4544-4550. (http://www.sciencedirect.com/science/article/pii/S0029549311000720) Assessed August, 2013

Zeng, L., Zhang, G. and Guo, X. (2014a). Erosion–Corrosion at Different Locations of X65 Carbon Steel Elbow. *Corrosion Science.* 85 318-330. (http://www.sciencedirect.com/science/article/pii/S0010938X14002169) Assessed February, 2015

Zeng, Y., Liu, J. and Huang, W. (2014b). A Statistical Model for Accessing Wall Thinning Rate Due to Flow Accelerated Corrosion Based on Inspection Data in Nuclear Power Plants. *2014 22nd International Conference on Nuclear Engineering.*

Zhang, G., Zeng, L., Huang, H. and Guo, X. (2013). A Study of Flow Accelerated Corrosion at Elbow of Carbon Steel Pipeline by Array Electrode and Computational Fluid Dynamics Simulation. *Corrosion Science.* 77 334-341. (http://www.sciencedirect.com/science/article/pii/S0010938X13003892) Assessed March, 2016

Zheng, D. and Che, D. (2006). Experimental Study on Hydrodynamic Characteristics of Upward Gas–Liquid Slug Flow. *International journal of multiphase flow.* 32(10),1191-1218.(http://www.sciencedirect.com/science/article/pii/S0301932206000966) Assessed November, 2014

Zhu, X., Lu, X. and Ling, X. (2013). A Novel Method to Determine the Flow Accelerated Corrosion Rate in the Elbow. *Materials and Corrosion.* 64(6), 486-492.doi: 10.1002/maco.201106345 Assessed February, 2015