HYBRID TREATMENT OF ULTRASOUND AND ULTRAVIOLET RADIATION TO MITIGATE MICROBIAL CORROSION ON API 5L X70 CARBON STEEL

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DEDICATION

This thesis is especially dedicated to,

My beloved family members: Hamidah Bte Abu Samah, Zaiton Mohamed, Anis Farzana Azmiluddin, Aisyah Inara, Arif Firdaus, Syed Hamzah Bin Syed Abd. Rahman, Azmiluddin Bakar, Syed Hamizan, and Sharifah Shazwani and other relatives,

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ABSTRACT

The destructive effects of microbial corrosion of carbon steel in pipes have been widely found in soil and water environment. Numerous studies have proven the ability of ultraviolet (UV) radiation as an alternative technique to substitute hazardous chemical biocides in disinfecting microbes for pipelines system. Unfortunately, the radiation efficiency is hindered due to the presence of suspended particles in the environment. Moreover, the UV treated microbes would undergo photo-reactivation which allows the damaged deoxyribonucleic acid (DNA) to be repaired or rejuvenated. In order to counter these drawbacks, a recent study recommended that combining UV radiation with ultrasound (US) technology can led to its irreversible damage inflicted to the microbe’s cell wall. However, information on the efficiency of the integrated treatment between US and UV and the influences of its variables on corrosion process is scarce and limited, thus restricting any efforts to explore the potential application of UV combined with US as an alternative for chemical biocide replacement. Present study aimed to investigate the optimal performance of integrated treatment using US with UV technology in controlling microbial corrosion caused by sulfate reducing bacteria (SRB) strain. The investigation utilized one pure SRB strain known as *Desulfovibrio vulgaris* (ATCC 7757) and focused on static treatment condition. Four experimental stages were involved in order to attain the research objectives and aim. The metal loss of API 5L X70 carbon steel coupon was recorded systematically, then the corrosion rate of steel coupon in untreated and treated environment was determined using weight loss technique. The corrosion rate of steel coupon in biotic sample was found approximately 34% higher than abiotic sample. A total of 438 steel coupons were used throughout research duration. Based on screening design, the findings have successfully identified the most influential variables of the hybrid treatment which are US exposure time, UV exposure time, distance of UV lamps to sample, amplitude of US, and volume of sample. In addition, interactions between the variables were also considered when performing the hybrid treatment. Subsequently, one microbial corrosion mitigation empirical model was derived sequential to the hybrid treatment using response surface method (RSM) with correlation coefficient (R^2) of 72%. Regardless of the moderate value of R^2, since it has statistically significant predictors, it is still possible to draw important conclusions about how changes in the predictor values are associated with changes in the response value. Results also have confirmed that the hybrid treatment outperformed individual UV and US treatment based on the reduction of corrosion rate by approximately 50%. On the other hand, the simultaneous (US+UV) reactor set-up performed effectively with corrosion rate 0.0108 mm/year as compared to 0.0174 mm/year by non-simultaneous (US-UV) reactor set-up. These corrosion values are much lower than the control sample and non-hybrid treated sample. Valuable findings from present research shows promising future for non-physical corrosion treatment since this can serve as an impetus for the transfer of the integrated technology from its infancy level to the real-world practice of corrosion mitigation in the oil and gas industry.

ABSTRAK

Kesan kakisan mikrob terhadap saluran paip keluli karbon banyak digunakan di persekitaran tanah dan air. Banyak kajian telah membuktikan kemampuan radiasi ultraviolet (UV) sebagai teknik alternatif untuk menggantikan biosid kimia berbahaya dalam usaha membasmi mikrob di dalam sistem saluran paip. Namun begitu, kehadiran zarah terampai di persekitaran menghalang kecekapan radiasi membasmi mikrob. Selain itu, bakteria yang telah dirawat menggunakan UV mempunyai kebolehan untuk memperbaiki asid deoksiribonukleik (DNA) yang rosak menerusi proses pengaktifan semula foto. Untuk mengatasi kekurangan radiasi UV, kajian terkini mengesyorkan untuk menggabungkan radiasi UV dengan teknologi ultrabunyi (US) kerana kerosakan pada dinding sel mikrob yang dihasilkan oleh US tidak dapat dipulihkan. Namun begitu, maklumat mengenai kecekapan rawatan gabungan diantara US dan UV serta pengaruh pemboleh ubahnya terhadap proses kakisan sukar ditemui dan terhad, sekaligus menyekat sebarang usaha untuk meneroka potensi gabungan US dan UV sebagai kaedah rawtan alternatif untuk menggantikan penggunaan biosid. Kajian ini bertujuan untuk mengkaji prestasi optimal kaedah rawatan gabungan teknologi US dan UV bagi proses pembasmian dan mengawal kakisan mikrob yang disebabkan oleh bakteria penurun sulfat (SRB). Siasatan menggunakan sejenis SRB yang dikenali sebagai *Desulfovibrio vulgaris* (ATCC 7757) dan kajian dilaksankan menerusi kondisi rawatan yang statik. Kajian ini terdapat empat peringkat eksperimen bagi mencapai objektif penyelidikan. Sebanyak 438 kupon keluli digunapakai dan kehilangan logam API 5L X70 dicatatkan sepanjang tempoh kajian. Kadar kakisan kupon keluli di persekitaran yang tidak dirawat dan dirawat ditentukan dengan menggunakan teknik kehilangan berat logam. Kadar kakisan kupon keluli sampel biotik adalah 34% lebih tinggi berbanding sampel abiotik. Berdasarkan rekabentuk penyaringan, kajian berjaya mengenal pasti pemboleh ubah utama yang paling berpengaruh bagi rawatan hibrid iaitu masa pendedahan terhadap US dan UV, jarak lampu UV ke sampel, amplitud US, dan jumlah isipadu sampel yang dirawat. Disamping itu, interaksi antara pemboleh ubah juga dikaji sewaktu melakukan rawatan hibrid. Satu model empirikal mitigasi kakisan mikrob dihasilkan menggunakan kaedah permukaan tindakbalas (RSM) dengan pekali korelasi (R^2) 72%. Walaupun nilai R^2 yang sederhana, masih terdapat pemboleh ubah yang signifikan secara statistik. Justeru, terdapat kesimpulan penting tentang cara perubahan dalam nilai pemboleh ubah dapat dikaitkan dengan perubahan dalam nilai tindak balas. Keputusan kajian berdasarkan kadar kehilangan logam juga menunjukkan bahawa prestasi rawatan hibrid (0.0528 mm/tahun) lebih baik berbanding kaedah UV (0.1005 mm/tahun) dan US (0.1061 mm/tahun). Selain itu, reaktor serentak (US+UV) berfungsi lebih effektif jika dibandingkan dengan reaktor bukan serentak (US-UV) kerana kadar kakisan yang direkodkan masing-masing adalah 0.0108 mm/tahun dan 0.0174 mm/tahun. Penemuan maklumat penting daripada penyelidikan ini memperlihatkan bahawa rawatan kakisan bukan fizikal mempunyai potensi yang amat baik dimasa hadapan. Dapatan kajian semasa sesuai dijadikan sebagai rujukan dan batu lonjatan bagi kajian seterusnya agar teknologi hibrid ini dapat direalisasikan penggunaannya oleh pihak industri minyak dan gas.

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LIST OF ABBREVIATIONS

ATCC	-	American Type Culture Collection
APB	-	Acid-Producing Bacteria
BBD	-	Box–Behnken design
CCD	-	Central composite design
CMIC	-	Chemical Microbially Influenced Corrosion
CR	-	Corrosion rate
DNA	-	Deoxyribonucleic Acid
EMIC	-	Electric Microbially Influenced Corrosion
EPS	-	Extracellular Polymeric Substances
FESEM	-	Field emission scanning electron microscope
GTD	-	Glutaraldehyde
GDS	-	Glow Discharge Spectrometer
H_2S	-	Hydrogen sulphide
HAZ	-	Heat-Affected Zone
HCL	-	Hydrochloric acid
FeS	-	Iron Sulfide
IB	-	Iron bacteria
MIC	-	Microbiologically Influenced Corrosion
MoB	-	Manganese Oxidizing Bacteria
RNA	-	Ribonucleic Acid
SRB	-	Sulfate Reducing Bacteria
SCC	-	Stress-Corrosion Cracking (SCC),
SoB	-	Sulfur-Oxidizing Bacteria
Si-C	-	Silicon carbide
THPS	-	Tetrakis hydroxymethyl phosphonium sulfate
US	-	Ultrasound
UV	-	Ultraviolet
USD	-	United State Dollar

LIST OF SYMBOLS

α	-	Axial points
k	-	Corrosion rate constant in mm/year
°C	-	Degree Celcius
D	-	Density of metal coupon
W_f	-	Final weight of coupon
g	-	Gram
W_i	-	Initial weight of coupon
$	-	Money
N	-	Number of cells counted
%	-	Percentage
P	-	Proportion of chambers counted
t	-	Time exposure
Va	-	Volume of squares counted
V_1	-	Volume of original sample
V_2	-	Volume of diluted sample
w	-	Weight loss of coupon

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CHAPTER 1

INTRODUCTION

1.1 Overview

Even though carbon steel pipe materials with high strength grade such as X70 have been introduced, corrosion still persists and dominates the statistics as the major cause of pipeline failure. Of the many corrosion mechanisms, previous investigation results have concluded that the pipe is most likely to suffer severe internal or external corrosion damage due to microbial corrosion (Abdullah et al., 2014; Afizza et al., 2016; Narenkumar et al., 2017). This implies that the increase in corrosion rate is due to the presence of bacterial activities, for example the presence of sulfate reducing bacteria (SRB), which accelerates the rate of anodic and/or cathodic reactions (Muthukumar, 2014). It is a huge challenge to mitigate this delicate phenomenon, in view of the fact that it cannot be simply eliminated altogether from the deteriorating infrastructure. Unstable economic conditions has forced many oil and gas companies to either stop or slow down their physical operations, which has impacted production in both upstream and downstream operations. Although the oil prices will not be negative forever, the oil and gas industry will never be the same. Various approaches could be done by the companies to stay relevant in the market, for example through the reduction or replacing the application of expensive and hazardous chemical inhibitor and biocides in combating microbial corrosion by investing in greener technology such as ultrasound (US) and ultraviolet (UV) equipment.

According to Rosa et al. (2016) and da Silva et al. (2019), the former method is very costly and hazardous to the assets, environment and personnel. The latter method is much simpler to operate, requires low cost and is environmentally friendly. Therefore, there is no doubt it is time for energy companies to revisit business resilience plans to figure out ways to make profit by reducing and possibly eliminating the overhead costs permanently. Researches done by Rasol et al. (2014)

and Bakar et al. (2017) have proven the importance and capability of US and UV as the alternative technologies for combating microbial corrosion due to SRB. Therefore, this issue requires detailed investigation related to US and UV technologies so that alternative strategies, which promotes greater economy and are more effective for controlling microbial corrosion by SRB in order to maintain the reliability and integrity of the expensive assets, can be made into reality in the near future.

1.2 Problem Background

Economic conditions around the world today are unstable and seriously affected by geopolitical issues, which has resulted a plunge in oil prices and caused a huge drop in cash flow and revenues of the oil-producing companies and countries. According to Ajami (2020) recently during the economic crisis in 2020, the oil price has dropped dramatically as low as $20 USD per barrel. This has caused a profound change in the financial landscape; as the oil price swings, operators are struggling to maintain uptime and production and pressured with stringent regulations. Current price of oil is so low that it has forced some companies to apply retrenchment of existing operations including maintenance cost by postponing non-essential maintenance and manpower downsizing and even forced some companies out of business. However, it is wise to bear in mind that the damages stated are only the beginning and the worst is yet to come. For example, as one of the oil producing countries, Malaysia owns more than 2500 kms of buried pipelines. Othman (2015) reported that these carbon steel pipelines faced various types of corrosion problems including microbial corrosion due to the presence of SRB. Recently, the initiative of researchers to study the effectiveness of natural resources as green biocide to eradicate internal corrosion caused by bacteria in order to replace the usage of expensive (Bautista et al., 2016) and hazardous (Li et al., 2016) chemical biocide has been actively done. In addition, prolonged exposure of the same chemical biocide onto bacteria will promote resistance of microbes and inevitably cause dosage escalation thus resulting in increased costs (Acosta-Díaz et al., 2011 and Li et al., 2016).

Numerous natural resources have been studied as a green biocide to replace the usage of chemical biocide to inhibit the SRB growth and reduced microbial corrosion impact onto steel structure; among them are capsicum frutescens (Oguzie et al., 2013), neem extract (Bhola et al., 2014), lemongrass (De Souza et al., 2017), acanthus montanus leaves extract (Ibisi and Onyekwere, 2017) and garlic extracts (Md Zain, Salleh and Abdullah, 2018: da Silva, et al., 2019). Unfortunately, these green biocides have shortcomings as the green biocides have limitations of their production volume on large industrial scales (Khan et al., 2015). In addition, researchers have pointed out that there was a significant variation in chemical compositions of plant extract of the same species when it was collected from different parts of the world (Ahmed et al., 2016). Xhanari et al. (2017) also stated that the manufacture of green biocide requires high costs because the process of extracting the plant requires a complicated and difficult procedure. Nowadays, industrial sector has drastically revolutionised their inspection methodology by implementing new technologies with less human intervention. The employment of artificial intelligence and automation system will enable totally new designs and concepts of the operation. Thus, proactive action should be taken by the researchers with the cooperation of energy companies to explore new ways of working including processing, production and maintenance management in order to provide more effective and safer method. Hence, high cost related problems involving production and maintenance (e.g.: injection of expensive biocides) of oil and gas assets (e.g.: carbon steel pipelines) could be overcome and stay relevant in the market while making profit over time.

Many past researchers have proven the capability of green technology such as US or UV as non-physical inhibitor (NPI) to eradicate bacteria and controlling microbial corrosion impact in various environments including the use for wastewater (Kollu and Örmeci, 2015), carbon steel pipeline system (Bakar et al., 2017) and food processing (Amabilis-Sosa et al., 2018) treatment. The application of US or UV technology as NPI possesses substantial advantages over conventional technique. Technically, both US and UV technologies required low operational cost, easy and fast operational system, effective and categorized as an environmentally friendly disinfection method. Unfortunately, when US and UV technologies are applied individually, they have their own shortcomings as the US requires high energy consumption and bacteria that have been radiated to UV can rejuvenate through the process of photo reactivation (Naddeo et al., 2014: Bakar et al., 2017). Therefore, there are researchers who suggested combining US with UV technology to overcome each other's weaknesses (Naddeo et al., 2014: Ali, 2016a). The application of combining both technologies is scarcely found for mitigating SRB activities and the existing hybrid method is not suitable to be applied directly for oil and gas system due to different environmental condition and insufficient information related to the interaction between the treatment technologies properties. Hence, due to the lack of such important information, the optimization of this integrated technique is not feasible and available for application. For that reason, the performance, effectiveness and suitable treatment set-up of US irradiation combined with UV radiation treatment towards mitigating microbial corrosion attack due to SRB onto carbon steel API 5L X70 should be further investigated and evaluated. It could be such a great alternative technology and economical as compared to the usage of expensive and hazardous chemical biocides in maintaining the reliability and integrity of the expensive assets such as the pipeline system.

1.3 Problem Statement

Although previous studies have proven US and UV capable of eradicating various bacteria found in the environment such as SRB (Ali, 2016a; Zhou et al., 2017b and Annisha et al., 2019), the use of these technology in combination to eradicate microbial corrosion in expesnive assests (e.g.: crude oil pipeline or tank) is extremely scarce and not well explored. Hence, a more in-depth study to develop a deeper understanding of the impact, interaction and characterization of the efficiency of US-UV combined technology (later indicated as hybrid treatment) to eradicate microbial corrosion especially due to SRB in expensive assets is crucial to be investigated. As reported by Kang et al. (1999) and Ismail (2016), the carbon steel API 5L pipeline is often and widely used by local pipeline designers due to its strength and superior quality. In addition, the techniques to optimize the hybrid treatment for microbial corrosion (i.e.; SRB) mitigation related to different sequence of operational variables and hybrid treatment set-up stays solitary, remained unsolved and not fully understood since past researches performed by Ali et al. (2016b) and Abu Bakar (2016) were done under fixed treatment conditions.

As the research on hybrid treatment between US and UV were unsettled, additional concerns regarding the hybrid were raised such as; How effective is a combination of US and UV on anaerobic type of microbe such as SRB? What is the suitable and optimum condition for US and UV operation in combined mode to inactivate SRB while controlling microbial corrosion effect upon carbon steel structure? Which operating variables are more significant or important when it comes to hybrid treatment for mitigating SRB, US time exposure, US amplitude, UV time exposure, volume of sample, UV lamp distance to sample or the intensity of UV lamp? What type of hybrid treatment set up is the best to eradicate SRB? Since the proposed treatment is hybrid in nature, these uncertainties must be responded with measurable confirmations to optimize the capacity and capability of US and UV technology for microbial corrosion (e.g.: SRB) mitigation. Statistical evidence and numerical modeling related to hybrid operational variables towards bacteria such as SRB survivability and their impact onto the carbon steel is incredibly inadequate.

In addition, unawareness in regard to this matter from the industry players (i.e.: oil and gas sector) will jeopardize public safety, integrity and reliability of the assets. The time has come for the industries to take proactive steps by immediately implementing more effective working methods and start investing and using new technologies such as hybrid treatment to address the problems of using expensive and hazardous biocide. Therefore, detailed investigation on the optimal performance of hybrid treatment is vital in order to solve the unestablished information related to its behaviour and performance for mitigating microbial corrosion occurrence upon carbon steel structure (e.g.: pipeline system). Without comprehensive study and reliable information, there is no guarantee on how this hybrid treatment method can be optimized, applied and lead to commercialization in the near future. Present research will provide statistical evidence to display the performance of hybrid treatment to disinfect SRB quantitatively and mitigating/controlling microbial corrosion phenomenon in closed environment. The information is greatly required so that the proposed hybrid treatment can be materialised as a viable full-scale technology to mitigate microbiological induced corrosion as experienced by oil and gas assets.

1.4 Research Aims and Objectives

The aim of this research is to investigate the optimal performance of hybrid treatment, which is a combination of US irradiation and UV radiation to inactivate SRB strain of *Desulfovibrio vulgaris subsp. desulfuricans* (strain number of ATCC® 7757) and its impact upon corrosion progress on API 5L X70 carbon steel coupon. In order to achieve the mentioned research aims, this study embarks on the following objectives:

1. To identify the performance and impact of hybrid treatment using fixed operating parameters to disinfect sulfate reducing bacteria while controlling microbial corrosion effect upon API 5L X70 carbon steel.

2. To identify the significant operating variables of hybrid treatment for disinfecting sulfate reducing bacteria while controlling microbial corrosion upon API 5L X70 carbon steel.

3. To analyze the relationship of ultrasound (US) and ultraviolet (UV) operating variables in combined mode and its effect upon metal loss value of API 5L X70 carbon steel through the application of response surface method.

4. To evaluate the appropriate hybrid treatment set-up for disinfecting sulfate reducing bacteria in controlling microbial corrosion impact upon API 5L carbon steel coupon through a simultaneous (US+UV) and non-simultaneous (US-UV) treatment set up.

1.5 Research Scope

Present research work was performed in order to investigate the performance of hybrid treatment to eradicate SRB and slow down the microbial corrosion impact upon API 5L X70 carbon steel. Current stage of research is conducted in a miniature scale and the main idea or context is to use hybrid treatment as a treatment method that complements existing method (i.e.: chemical biocide) for the purpose of eradicating and controlling microbial corrosion inside the pipeline systems. Present research focuses on studies involving treatment methods using ultrasound (US) technology as a pre-treatment to ultraviolet (UV) and does not cover biocides effectiveness. For example, in the context of oil and gas systems, present research recommends the hybrid set-up to be installed in the storage of chemical or separation tank since it is not feasible to be installed inside the pipeline due to the intervention of product flow. This is to ensure the water retrieved from the reservoir are being treated first before entering the main, gathering or/and distribution pipelines systems. Hence, this method could reduce the problem of microbial contaminations and microbial corrosion caused by bacteria such as SRB inside the pipeline systems.

In addition, the implementation of hybrid treatment also has high potential and the capability to reduce the frequency of application of the hazardous and expensive biocide into the system. This study does not include microorganism's deoxyribonucleic acid (DNA) identification, since manufactured and known SRB species called *Desulfovibrio vulgaris* (formerly known as *Desulfovibrio desulfuricans subsp. Desulfuricans*) were used throughout the study. The SRB with designated code number ATCC 7757 is obtained from American Type Culture Collection (ATCC) and the optimum environment for ATCC 7757 to actively grow and proliferate throughout current study were set at 8.5 and 37°C for pH and temperature, respectively, as reported by Ali (2016a). Since most of the bacteria such as SRB were found in seawater and not exactly in crude oil, the present study only used modified Baar's media (ATCC 1249^{TM}) in order to replicate the environment of artificial seawater for the ATCC 7757 SRB to grow in and treated. Present study is limited to physical recognition of SRB activity through observation in changes of the medium color, presence of rotten egg smell and through microscopic observation for biofilm formation onto the carbon steel coupon by using high technology equipment called Field Emission Scanning Electron Microscope (FESEM).

The impact of microbial corrosion onto API 5L X70 carbon steel coupon upon untreated and treated environment was studied after 28 days of incubation. In addition, the carbon steel coupon used is assumed to be continuously exposed to the corrosive environment. As this study is still at its initial stage, the hybrid treatment was conducted mainly in a static mode throughout the study and does not involve any flow condition. In the present study, there are six operating variables considered for conducting hybrid treatment such as the influences of US and UV exposure time, amplitude of US, number of UV lamps, distance of UV lamp to sample and volume of treated sample. Hybrid reactor consists of US probe with fixed frequency of 24 kHz (200 watts) and UV lamp with wavelength of 254 nm (14 watts). Graphical and statistical analysis software (Minitab 16 and Design expert 7) were utilized in order to extend better understanding of the findings and to evaluate the optimal performance of hybrid treatment to inactivate SRB while controlling microbial corrosion impact onto API 5L X70 carbon steel coupon. Cost analysis to run the hybrid treatment is not included in the study as a comparison to the actual cost of biocide injection since the proposed hybrid treatment is not a full-scale reactor.

1.6 Significance of Research

Demand for oil and gas requires expensive and reliable system (e.g.: pipeline) to sustain and function safely and efficiently for a period of many years. This research findings will provide deep understanding on the effect and provide reliable information related to hybrid treatment performance to complement the existing approach on the extermination of SRB and its impact on the metal loss of API 5L X70 carbon steel. In addition, the optimum variables related to US and UV technology can then be identified numerically and statistically validated. The proposed mathematical model can predict the response of metal loss after the sample undergoes hybrid treatment. Even though current research is still at miniature scale, once present research manages to identify the effectiveness of hybrid treatment against microbial corrosion, this will facilitate more in-depth studies to replace hazardous and expensive biocide as a whole in the future, especially in oil and gas systems. Therefore, the development of strategic maintenance scheme, mitigation scheme and financial estimation could be eased and properly designed. Reliable data/information and strong evidence related to hybrid treatment performance and its impact need to be established to ensure that hybrid treatment can be the most economical alternative technology for mitigating microbial corrosion phenomenon and together, it can possibly curtail the microbial corrosion impact caused by microorganisms (e.g.: SRB). Hence, current research findings may initiate significant efforts to take advantage of US with UV technology as a realistic technique for microbial corrosion mitigation rather than applying it just as visionary innovation at a pilot scale.

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LIST OF PUBLICATIONS

1. Muhammad Khairool Fahmy Bin Mohd Ali, Norhazilan Bin Md. Noor, Astuty Binti Amrin, Nordin Bin Yahaya, ,Shamila Azman, and Akrima Abu Bakar. 'An Overview Of "Green" Techniques To Control Microbiologically Influenced Corrosion', 7th International Graduate Conference on Engineering, Science and Humanities (IGCESH 2018), 13-15 August 2018, Convention Hall, Faculty of Built and Surveying, UTM, Skudai Johor Bahru. . **– Conference**

2. Ali M.K.F.M, Norhazilan M.N., Yahaya N., Bakar A.A, A. Abdullah, Mohammad Amar Bin Masuri, Ismail M. "Application Of Ultraviolet Radiation To Control Microbiologically Influenced Corrosion: A Case Study On Soil Sample From Mangrove Forest". Journal of Engineering Science And Technology, Vol 11;12 (2016), pp. 1695-1704 **(SCOPUS)**

3. Muhammad Khairool Fahmy, Norhazilan Md. Noor, Nordin Yahaya, Akrima Abu Bakar & Mardhiah Ismail, "Corrosion of X-70 Carbon Steel Pipeline Subject to Sulfate Reducing Bacteria", ARPN Journal of Engineering and Applied Sciences, 11(21): (2016), 12643-12652. **(SCOPUS)**

4. Ali M.K.F.M., Bakar A.A., Norhazilan M.N., Yahaya N., Ismail M.& A.S. Rashid L.,"Hybrid Soliwave Technique for Mitigating Sulfate Reducing Bacteria in Controlling Biocorrosion: A Case Study on Crude Oil Sample", Environmental Technology, 38(19): (2017), 2427–2439. **(SCI – Q3:1.75)**

5. A. Abu Bakar, M.K.F. Mohd Ali, N. Md Noor, N. Yahaya, M. Ismail, and A. Abdullah, 'Bio Corrosion Of Carbon Steel By Sulfate Reducing Bacteria Consortium In Oil & Gas Pipelines', Journal of Mechanical Engineering & Science, Vol 11 (2): (2017), pp. 2592-2600. **(SCOPUS)**

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7. Ali M.K.F.M, Ismail M., Yahaya N., Bakar A.A., Libriati Z. & Norhazilan M.N., “Effects of Low Frequency Ultrasound Treatment in Mitigating Sulfate Reducing Bacteria”, International Journal of Water Resources Engineering International Journal of Water Resources Engineering, 4(2), (2018); pp. 1-6 **(Invited Paper)**

8. Muhammad Khairool Fahmy Mohd Ali, Mardhiah Ismail, Akrima Abu Bakar, Norhazilan Md. Noorr, Nordin Yahaya, Libriati Zardasti & Abdul Rahman Md. Sam “Influence Of Environmental Parameters On Microbiologically Influenced Corrosion Subject To Different Bacteria Strains”, Sains Malaysiana, 49(3), (2020): 671-682. **(SCI - Q4:0.643)**