SELECTION OF SUITABLE CHEMICALS FOR ACID MATRIX STIMULATION: A MALAYSIA BROWN FIELD SCENARIO

SUZANNA JUYANTY BINTI MOHD JEFFRY

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Petroleum Engineering

Faculty of Chemical and Energy Engineering
Universiti Teknologi Malaysia

JUNE 2018

“In loving memory of my dad”

ACKNOWLEDGEMENT

Firstly, I would like to express my sincere appreciation to my supervisor, Associate Professor Issham Ismail, for his advice, encouragement, guidance, patience and friendship. His knowledge and expertise had significantly helped me throughout the whole completion of the Final Year Project.

In addition, special recognition to PETRONAS for the support in this project. Special thanks also to Universiti Teknologi Malaysia especially Department of Petroleum Engineering for providing the priceless knowledge.

Finally, I would like to express my profound gratitude to my mum, husband and children for their endless support and continuous encouragement throughout my studies and producing this thesis. The accomplishment of this project would not have been possible without them. Thank you..

ABSTRACT

Matrix acidizing in sandstone reservoirs requires a series of chemicals to dissolve the plugging materials around the near wellbore. The selection of suitable chemicals is important because it is one of the key factors to acidizing success due to the complex mineralogy of sandstone reservoirs and limited studies that have been done to compare between the chemicals selection from the industry guidelines with success rate from historical field execution especially in Malaysia oil fields. In view of the current low oil price and increasing treatment cost, the selection of the chemicals is important to maximize the oil gain. Hence, this project was embarked to develop a database of the historical acid matrix stimulation chemicals used in a Malaysia brown field and recommend the suitable acid matrix stimulation chemicals for future applications. The chemicals selection can be enhanced by using the combination of historical experience, recommendations from industry guidelines, and simulation results to provide assurance in achieving economic oil gain for future matrix stimulation candidates. There were five main steps to achieve the objectives, namely historical analysis of previous acid stimulation jobs, chemicals selection using industry guidelines, nodal analysis on current well performance using Prosper software, acid placement analysis using Stimpro software to quantify skin reduction for each case, and finally the gain quantification using Prosper software. From the project, database has been established to review the chemicals that have been applied in the selected Malaysia brown field. The oil gain formula has been identified as the success rate indicator. The comparison on skin reduction and oil gain between the three chemicals shortlisted from historical analysis and industry guidelines has been conducted using Prosper and Stimpro software which has enabled the selection of the most suitable chemicals. The most suitable chemicals were selected based on the highest average oil gain.

ABSTRAK

Pengasidan matriks terhadap reservoir batu pasir memerlukan rangkaian bahan kimia untuk melarutkan bahan pemalam di sekeliling dasar lubang. Pemilihan bahan kimia yang sesuai adalah penting kerana perkara itu ialah satu daripada faktor penentu kepada kejayaan pengasidan, berikutan mineral rencam yang terdapat pada reservoir batu pasir dan kajian yang terhad terhadap pemilihan bahan kimia daripada garis panduan industri dan kadar kejayaan daripada pengasidan yang dilakukan di medan minyak Malaysia. Memandangkan harga terkini minyak yang rendah dan kos rawatan yang terus meningkat, pemilihan bahan kimia yang sesuai adalah penting untuk memaksimumkan gandaan minyak. Oleh itu, projek ini bertujuan untuk membangunkan satu pangkalan data tentang bahan kimia yang digunakan dalam pengasidan matriks terhadap medan matang di Malaysia dan mencadangkan bahan kimia yang sesuai untuk pengaplikasian pada masa hadapan. Pemilihan bahan kimia boleh dimantapkan menerusi gabungan pengalaman lalu, cadangan daripada garis panduan industri, dan hasil penyelakuan. Sepintas lalu, terdapat lima langkah utama untuk mencapai objektif, iaitu penganalisisan kerja perangsangan asid yang lalu, pemilihan bahan kimia menggunakan garis panduan industri, penganalisisan nodal terhadap prestasi terkini telaga menggunakan perisian Prosper, penganalisisan terhadap pelarasan asid menggunakan perisian Stimpro bagi mengira pengurangan kulit bagi setiap kes, dan pengiraan tentang gandaan minyak menggunakan perisian Prosper. Pangkalan data yang terhasil digunakan untuk mengkaji semula prestasi bahan kimia yang diaplikasikan terhadap medan minyak matang terpilih di Malaysia. Rumusan gandaan minyak telah dikenal pasti sebagai penunjuk kadar kejayaan. Perbandingan tentang pengurangan kulit dan gandaan minyak bagi ketiga-tiga bahan kimia yang disenarai pendek, hasil daripada analisis dan garis panduan industri, telah dilaksana menggunakan perisian Prosper dan perisian Stimpro bagi memilih bahan kimia yang paling sesuai. Bahan kimia yang paling sesuai dipilih berdasarkan purata gandaan tertinggi minyak.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABF	-	Ammonium bifluoride
AF	-	Ammonium fluoride
AOF	-	Absolute open flow
CTU	-	Coiled tubing unit
EDTA	-	Ethylenediaminetetraacetic acid
EMG	-	Equivalent mud gradient
ESP	-	Electrical submersible pump
HCl	-	Hydrochloric acid
HEDTA	-	Hydroxyethylenediaminetriacetic acid
HEIDA	-	Hydroxyethyliminodiacetic acid
HF	-	Hydrofluoric acid
IPR	-	Inflow performance relationship
MASTP	-	Maximum allowable surface treating pressure
PI	-	Productivity Index
PV	-	Pore volume
SEM	-	Scanning Electron Microscope
VLP	-	Vertical lift performance
XRD	-	X-Ray Diffraction

APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Well stimulation is a technique which can be used to improve the flow of oil or gas from a reservoir by dissolving the plugging materials or creating new pathways around the near wellbore (Economides and Nolte, 2000; Crowe *et al.,* 1992; Schechter, 1992). The most commonly applied stimulation techniques are acidizing and hydraulic fracturing (Nitters *et al.,* 2016). In Malaysia, acidizing is the most common well stimulation method because majority of the reservoirs have moderate to very good permeability and the need to conduct acid stimulation arises when the initial rates of the wells is below expectation or when the productivity of the reservoir drops significantly.

Historically, the first acid treatment on oil well was conducted in 1895 with the use of concentrated hydrochloric acid (HCl) to stimulate producing carbonate formations in Lima, Ohio (Portier *et al.,* 2007). The first sandstone acidizing treatment using mixture of HCl and hydrofluoric acid (HF) was accomplished by Halliburton in 1933 near Archer City, Texas (Kalfayan, 2008). Unfortunately, the first attempt was very discouraging and had caused sand production into the wellbore. Dowell introduced ‘mud acid’ in 1939 which contained a mixture of 12% HCl – 3% HF. The chemical had been applied in the Gulf Coast area and had successfully removed damage around the wellbore (Portier *et al.,* 2007). This acid mixture is still relevant and currently known as ‘regular strength’ mud acid.

Numerous matrix acidizing treatments of sandstone formations have been conducted since the mid-1960s. In the 1970s and 1980s, developments of ‘novel’ sandstone acidizing systems had aimed to provide benefits such as retarding HF spending, stabilizing fine particles, and preventing excessive acid reaction. In the 1980s and 1990s, developments in sandstone acidizing had focused on treatment execution. Fluid chemistry has stepped to the forefront in the recent years whereby old systems are further improved to enhance chemical performance (Portier *et al.,* 2007). The recent advancements are aimed to expand acid stimulation applications for high temperature (Al-Harthy *et al.,* 2009; Aboud *et al.,* 2007) and unconventional reservoirs (Houseworth *et al.,* 2016).

The number of well stimulation activities (such as acid matrix stimulation and fracturing jobs) in the recent years has doubled compared to the number of treatments performed throughout the 1990s. In 1994, 79% of the stimulation jobs were acid treatments which used only 20% of the money spent for well stimulation (Shafiq and Mahmud, 2017). This is because they are low cost and low volume operation compared to hydraulic fracturing treatments. Operators around the world have reported about 40% to 50% of their wells have significant formation damage, but only 1% to 2% of their wells are treated every year due to the rising cost of acid stimulation jobs. Hence, only promising wells are selected to be stimulated to give additional value.

The failure rate of acid jobs was 32% (Shafiq and Mahmud, 2017). Some other companies reported failure in the range from 25 to 30% of the treatments (Nitters *et al.,* 2000). The reported causes of failure are due to the poor candidate selection, lack of mineralogical information, improper chemical selection (main acid, additives, strength and volume), improper fluid placement (lack of diversion strategies) and shutting-in acid treatment for too long which caused secondary and tertiary reactions in the reservoirs (Kalfayan, 2008; Rae and Di Lullo, 2002).

There are six steps towards successful sandstone acidizing. The steps can properly select candidates and dictate whether acid removable skin is present, determine appropriate fluids treatment (acid types, concentration, and treatment volumes), establish a proper additives program, determine treatment placement method, ensure proper treatment execution (and quality control), and evaluate the treatment (Kalfayan, 2008).

The reduction of permeability around the wellbore is usually termed as formation damage which is caused by fines migration, completion, and stimulation fluids (Al-Harbi *et al.,* 2013). The formation damage can be expressed via the introduction of skin factor where positive skin shows the occurrence of damage to the reservoir. Hence, the most vital aim of sandstone matrix acidizing is to dissolve or remove the siliceous particles (i.e., clay, feldspar, and quartz) that reduce permeability around the wellbore and consequently restrict the flow of hydrocarbons into the wellbore. After the discovery of HF acid in 1935, it was widely applied on sandstone formation to remove the near wellbore damage due to drilling and production (Shafiq and Mahmud, 2017). This can be achieved via the injection of hydrofluoric acid (HF) or its precursors (Kalfayan, 2008). There are several acids which are based on HF acid that has been widely used to stimulate sandstone formations. In fact, mud acid with different HCl-HF ratios has been used in sandstone acidizing applications with various success rates (Al-Harbi *et al.,* 2013).

The sandstone formation contains various amounts of quartz, clays (such as kaolinite or illite), alkaline aluminosilicates (such as feldspars and zeolites), carbonates (calcite, dolomite, and ankerite), and iron-based minerals (hematite and pyrite) (Hu *et al.,* 2017; Nasr-El-Din *et al.,* 2007). Hence, sandstone matrix acidizing usually requires the use of a carefully designed sequence of stages to manage the complex reactions between hydrofluoric acid (HF) and siliceous minerals in the formation. There are three main steps involved in conventional sandstone matrix treatment: preflush, main acid stage, and postflush. In the main acid stage, mixtures of mud acid have been widely employed in the field (Smith and Hendrickson, 1965; Williams *et al.,* 1979; Economides and Nolte, 2000). In mud acid, the role of hydrofluoric acid (HF) is to dissolve aluminosilicates and silica while hydrochloric acid (HCl) helps to keep reaction products soluble in spent acid. Spent acid is referred to the acid that has been reacted to the silicaeous particles or acid removable particles upon contact with the formation (Economides and Nolte, 2000).

The chemicals are pumped in sequence, each with its own purposes to manage the primary, secondary, and tertiary reactions in the sandstone formations. The precipitation from reactions which produce potassium silicates, sodium silicates, calcium fluoride, and hydrated silica precipitates may lead to formation damage and reduction in permeability and effective porosity (Smith and Hendrickson, 1965).

Over the years of industry experience, various chemical formulations have been developed to suit the wide range of reservoir conditions and field applications. Numerous guidelines have been developed from field experience and laboratory data (Ali *et al.,* 2016; Economides and Nolte 2000). The guidelines were a traditional approach to avoid problems with the precipitation of spent acid when no previous experience exists in acidizing a particular formation. Although they provided a useful reference, acid formulations should be optimized on the basis of a detailed formation evaluation (Ebrahim *et al.,* 2013; Portier *et al.,* 2007). As such, the recommended acid formulations are not final as each sandstone formation has its own complex mineralogy, temperature, and permeability which require detailed analysis to determine the best chemical to be used for acid stimulation.

When actual field experience is present, the historical stimulation recipes need to be evaluated with proper success indicators. Furthermore, simulators (such as Prosper and Stimpro) can be used to further evaluate the suitable chemical concentration, establish pumping schedule, and finally evaluate the expected improvement in well performance for future candidate wells. In actual field conditions, it is also important to establish the chemical formulation for acid stimulation treatments to ensure subsequent treatments are executed using the most suitable recipe towards improving the success rate.

This research work focuses on the selection of acid stimulation chemicals using data from a Malaysia oil field. It is an offshore brown field with 150 ft water depth. The field was discovered in 1960s. Subsequent exploration wells had justified the field development which led to the first oil in 1970s. The sandstone reservoirs in the field are described as multi-stacked and thin layered, where the major hydrocarbon accumulations are located from 2000 to 5000 ft. The reservoirs are proven to have moderate to strong water drive characteristics. All wells within the major reservoirs were completed with internal gravel pack as the main sand control mechanism. The wells are producing under gas lift.

Majority of the wells in the field suffer formation damage due to fines migration. The problem is seen to be prominent as water breaks through and the well production shows water cut increases. In some of the wells, gross production drops and water cut increases which indicate fines migration continues to affect the well productivity. Based on inflow and outflow performance analysis, the gas lift performance was found to be at optimum condition and wells are producing at maximum choke size. This concludes that the drop in the wells production is due to the skin build-up caused by formation damage.

The first acid stimulation was conducted as early as 1980s. The wells were treated with various chemical formulations throughout the early life until the recent stimulation campaigns. Some wells were stimulated during initial completion stage and acid stimulation treatments were repeated when production decline was observed. Since the brown field has experienced acid stimulation using various chemical applications, this research work is to verify the acid stimulation chemicals selection using various available data in the field; such as the analysis of actual results from field application, analysis of mineralogy data, and simulation using acid placement software.

1.2 Problem Statement

Improper chemical selection is one of the factors that reduces the success rate of sandstone acidizing treatments (Kalfayan, 2008). This is due to the lack of understanding in formation mineralogy (Hanafy and Nasr-El-Din, 2018; Economides and Nolte, 2000). Furthermore, the chemical selection for matrix acidizing in sandstone formation is challenging due to the complex mineralogy of the reservoirs. Each different type of minerals has different elements, structures, surface area and sensitivity to acids (Abdelmoneim, 2014; Portier *et al.,* 2007). In fact, the mineral components of the reservoirs throughout a field can vary greatly from one layer to another layer due to the differences in lithology. In addition, the permeability of sandstone reservoirs derived from logs or cores throughout a field usually shows varied trends due to reservoir heterogeneity (Chavez, 2007).

Although acid selection guidelines have been established based on sandstone acidizing chemistry and industry practices, they were derived from limited research studies (Shafiq and Mahmud, 2017). Furthermore, limited studies have been done to compare the chemical selection from the industry guidelines with the success rate from historical field execution especially in Malaysia oil fields (Chavez, 2007).

Misapplied stimulation treatments are ineffective and costly, often creating more problems than they solve. In view of the current low oil price and increasing treatment cost, the selection of the best treatment chemical is important to maximize the treatment gain (Ugbenyen, 2010; Kartoatmodjo *et al.,* 2007).

1.3 Hypotheses

The hypotheses on the selection of acid treatment chemicals in a matrix stimulation design process encompass the following elements:

(1) Acidizing can improve oil and gas production via removal of skin near wellbore (Rabbani *et al.,* 2018; Ali *et al.,* 2016; Gomaa *et al.,* 2013, da Motta *et al.,* 1992).

(2) Engineers should know the composition of the formation to achieve a successful acidizing treatment. The most effective preflush, HCl-HF acid mixture, and postflush treatment chemicals are selected based on the formation mineral component, permeability and temperature (Hanafy and Nasr-El-Din, 2018; Hassan, *et al.*, 2018; Reinoso *et al.,* 2016; Portier *et al.,* 2007).

(3) Although industry guidelines provide general recommendations, detailed analysis of formation evaluation and historical field experience are required to select the

final acid formulation (Hibbeler and Garcia, 2003; Economides and Nolte, 2000; Davies *et al.,* 1992; Nitters and Hagelaars, 1990).

(4) Acid stimulation fluid selection depends on the type of damage, lithology, mineralogy, and well types. It is also based on field and laboratory experience and can be determined from a relevant numerical simulator (Hanafy and Nasr-El-Din, 2018; Perthuis *et al.,* 1989).

(5) Mixtures of HCl and HF are used in sandstone matrix acidizing because they can dissolve feldspars and clays at temperatures below 200°F (Al Salmi *et al.*, 2018; Hong and Mahmud, 2017; Nitters *et al.,* 2016; Kalfayan, 2008).

(6) The highest productivity improvement can be economically achieved by utilizing the suitable hydrofluoric acid (HF) concentration (Abdelmoneim and Nasr-El-Din, 2015; Shafiq and Shuker, 2013; Samsuri *et al.,* 1998).

1.4 Objectives

The objectives of the project are listed as follow:

(1) To develop a database of the historical acid matrix stimulation chemicals used in a Malaysia brown field.

(2) To recommend the suitable acid matrix stimulation chemicals for future applications.

1.5 Research Scope

The scope of the project are listed as follow:

(1) Identifying all historical acid matrix stimulation chemicals that have been applied in a selected Malaysia brown field (during preflush, main flush, and postflush stages), its chemical concentration, additives, diversion technique, deployment method and pumping strategy.

(2) Establishing the success rate of the chemicals by using oil gain as success indicator.

(3) Evaluating the acid matrix stimulation chemicals recommended by the industry guidelines using the relevant data from the field and comparing the guideline recommendations with the historical field performance.

(4) Selecting the acid matrix stimulation chemicals (preflush, main flush, and postflush stages), its chemical concentration, additives and fluid diversion technique by using relevant simulators (such as Prosper and Stimpro).

1.6 Significance of Study

The project was aimed to select the best acid matrix stimulation chemicals by comparing the actual results from historical field application, analysis of field-wide mineralogy data and simulation using acid placement software. The chemicals selected from this project shall be used as reference for nearby fields or other fields with similar reservoir characteristics.

The research methods and steps to select the acid stimulation chemicals can be adapted to other fields that have experienced stimulation jobs before. For fields with limited experience, the methods implemented to model acid stimulation treatment using simulators can also be used to select the best chemicals formulation and come-up with the treatment pumping schedule.

There were a number of published papers on actual acidizing experience in other regions but none can be found for Malaysia field. In fact, there were no field-wide study on the chemicals being used thoughout the years of treating the wells. Hence, this project was aimed highlight how the different chemicals contributed to the success rates of the acidizing treatments. The uniqueness of this project is that it combined the actual experience in the selected Malaysia brown field, industry guidelines and simulation analysis to provide the best chemical formulation that can be applied in the future.

Furthermore, implementing the best chemicals that is suited for the field can improve the effectiveness of matrix acidizing which also improve well productivity. In the economic perspective, evaluating the best treatment formulation shall provide the assurance on the success of future acid stimulation activities while maximizing the gain from the treatment.

1.7 Chapter Summary

This chapter explains the importance of acid stimulation as one of the production enhancement activities that was carried out to improve well productivity. Sandstone reservoirs usually consist of various complex minerals that make up the formation. When the mineralogical compositions were not well understood, it was often led to the improper chemical selection which affected the success rate of matrix treatments. Although there are various guidelines available in the industry, the recommended acid formulations were not absolute because each sandstone formation around the world has its own complex mineralogy, temperature, and permeability which require detailed analysis to determine the best treatment chemicals to be used. There were limited studies done to compare the chemical selection from the industry guidelines and success rate from actual field execution especially in Malaysia oil fields. For brown fields with historical stimulation activities, it is beneficial to conduct detailed analysis to establish the success rates of the chemicals that have been applied. Subsequently, the most suitable chemical recipe shall be selected via the use of simulators to improve the treatment design. Two objectives and four scopes were outlined to realize the research work by studying the best acid stimulation chemical formulation for a selected Malaysia brown field scenario. By having the analysis, the understanding of the chemical performance in the field can be improved. The research methods and analysis also can be adapted by other brown fields. The uniqueness of this project is that it combined the actual experience in the selected Malaysia brown field, industry guidelines and simulation analysis to provide the best chemical formulation that can be applied in the future. Furthermore, evaluating the best treatment formulation shall provide the assurance on the success of future acid stimulation activities while maximizing the gain from the treatment.

REFERENCES

Abdelmoneim, S. S. and Nasr-El-Din, H. A. (2015). Determining the Optimum HF Concentration for Stimulation of High Temperature Sandstone Formations. Paper SPE 174203 presented at the *SPE European Formation Damage Conference and Exhibition,* Budapest, Hungary, 3 – 5 June.

Abdelmoniem, S. S. (2014). *A New Approach to Designing the Optimum Acid Treatment for Sandstone Reservoirs.* Master of Science. Texas A&M University.

Abdullah, K. S. (2016). *Acidizing in Oil Wells, a Sister-Technology to Hydraulic Fracturing: Risks, Chemicals and Regulations.* Doctorate in Environmental Science and Engineering. University of California, Los Angeles.

Aboud, R. S., Smith, K. L., Forero Pachon, L. and Kalfayan, L. J. (2007). Effective Matrix Acidizing in High-Temperature Environments. Paper SPE 109818 presented at the *SPE Annual Technical Conference and Exhibition*, Anaheim, California, 11 – 14 November.

Afolabi, A. F., Opusunju, A. U., Jaspers, H. F., Onyekwere, C., Onyekwere, C. O., and Davalos, J. C. (2008). Increasing Production in a Brownfield with Heavy Crude and Fine Problems by Application of New HF-Acid System: Case Histories. Paper SPE 112558 presented at the *SPE International Symposium and Exhibition on Formation Damage Control*, Lafayette, Louisiana, 13 – 15 February.

Al Ayesh, A. H., Salazar, R., Farajzadeh, R., Vincent-Bonnieu, S. and Rossen, W. R. (2017). Foam Diversion in Heterogeneous Reservoirs: Effect of Permeability and Injection Method*. SPE Journal.* Volume 22 (Issue 5). 1402-1415.

Al Salmi, A., Al-Yaaribi, A. and Al-Ruzeiqi, S. (2018). Successful Acidizing on an HF Acid Sensitive Formation using a Protective Ion-Complexing Agent. Paper SPE 189360 presented at the *SPE/IADC Middle East Drilling Technology Conference and Exhibition,* Abu Dhabi, UAE, 29 – 31 January.

Al-Araimi, N. and Jin, L. (2006). A High Success Rate Acid Stimulation Campaign – A Case History. Paper SPE 101038 presented at the *2006 SPE Asia Pacific Oil and Gas Conference and Exhibition*, Adelaide, Australia, 11 – 13 September.

Al-Dahlan, M. N., Nasr-El-Din, H. A. and Al-Qahtani, A. A. (2001). Evaluation of Retarded HF Acid Systems. Paper SPE 65032 presented at the *SPE International Symposium on Oilfield Chemistry*, Houston, Texas, 13 – 16 February.

Al-Harbi, B. G., Al-Dahlan, M. N., Al-Khaldi, M. H., Al-Harith, A. M. and Abadi, A. K. (2013). Evaluation of Organic-Hydrofluoric Acid Mixtures for Sandstone Acidizing. Paper IPTC 16967 presented at the *International Petroleum Technology Conference*, Beijing, China, 26 – 28 March.

Al-Harthy, S., Bustos, O. A., Fuller, M. J., Hamzah, N. E., Ismail, M. and Parapat, A. (2009). Options for High Temperature Well Stimulation. *Oilfield Review.* Volume 20 (Issue 4), 52-62.

Alhetari, N. (2017). Formation Damage in Oil and Natural Gas Reservoirs. *Technical Report.* Istanbul Technical University.

Ali, S. A., Kalfayan, L. and Montgomery, C. (2016). *Acid Stimulation.* Richardson, Texas, USA: Society of Petroleum Engineers.

Almubarak, T., Ng, J. H. and Nasr-El-Din, H. (2017). Chelating Agents in Productivity Enhancement: A Review. Paper SPE 185097 presented at *the SPE Oklahoma City Oil and Gas Symposium*, Oklahoma City, Oklahoma, 27 – 31 March.

Arifin, A. (2017). *Improvising Candidate Selection Screening Workflow for Matrix Acidizing.* Master of Petroleum Engineering. Universiti Teknologi Malaysia.

Behrmann, L., Brooks, J. E., Farrant, S., Fayard, A., Venkitaraman, A., Brown, A., Michel, C., Noordermeer, A., Smith, P. and Underdown, D. (2000). Perforating Practices That Optimize Productivity. *Oilfield Review.* Volume 12 (Issue 1), 52-74.

Bruhn, D., Peksa, A., Ilangovan, N., Deon, F. and Nick, H. M. (2016). *A Workflow for Laboratory and Numerical Analysis of Matrix Acidizing in Geothermal Wells.* Kasals Energiebron. Netherlands.

Chavez, M. R. (2007). *Evaluation and Optimisation of Matrix Acidizing in OMV Fields.* Master of Petroleum Engineering. Mining University of Leoben.

Civan, F. (2006). *Formation Damage Mechanisms.* Mewbourne School of Petroleum and Geological Engineering. The University of Oklahoma, USA.

Civan, F. (2016). *Reservoir Formation Damage. Fundamentals, Modeling, Assessment and Mitigation.* (Third Edition). Oxford, UK: Elsevier

Cosad, C. (1992). Choosing a Perforation Strategy. *Oilfield Review*. Volume 4 (Issue 4), 54-69.

Coulter, G. R. and Jennings, A. R. (1997). A Contemporary Approach To Matrix Acidizing. Paper SPE 56279 presented at the *SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, 5 – 8 October.

Crowe, C., Masmonteil, J., Touboul, E. and Thomas, R. (1992). Trends in Matrix Acidizing. *Oil Field Review.* Volume 4 (Issue 4). 24-40.

Crows, C.W. and Minor, S.S. (1982). Acid Corrosion Inhibitor Adsorption and Its Effect on Matrix Stimulation Results. Paper 10650 presented at the *SPE Formation Damage Control Symposium,* Lafayette, Louisiana, 24 – 25 March.

Cunningham, W. C. and Smith, D. K. (1968). Effect of Salt Cement Filtrate on Subsurface Formations. *Journal of Petroleum Technology.* Volume 20 (Issue 3). 259–264.

Da Motta, E. P., Plavnik, B. and Schechter, R. S. (1992). Optimizing Sandstone Acidization. *SPE Reservoir Engineering.* Volume 7 (Issue 1). 149-153.

Ebrahim, A. S., Garrouch, A. A. and Lababidi, H. M. S. (2013). Automating Sandstone Acidizing Using a Rule-based System. *Journal of Petroleum Exploration and Production Technology.* Volume 4 (Issue 4). 381-396.

Economides, M. J. and Nolte, K. G. (2000). *Reservoir Stimulation.* (Third Edition). Baffins Lane, Chichester: John Wiley & Sons.

Economides, M. J., Hill, A. D., Ehlig-Economides, C. and Zhu, D. (2012). *Petroleum Production Systems*. (Second Edition). Upper Saddle River, N. J.: Prentice Hall.

Farkha, S. A., Khoshnaw, F. A. and Jaf, P. T. (2017). Formation Damage Removal Through Acidizing of an Oil Well After Drilling and Completion. *European Scientific Journal.* Volume 13 (Issue 9). 154-167.

Finšgar, M. and Jackson, J. (2000). Application of Corrosion Inhibitors for Steels in Acidic Media for the Oil and Gas Industry: A Review. *Journal of Corrosion Science.* Volume 86. 17-41.

Fogler, H. S., Lund, K. and McCune, C. C. (1975) Acidization III – The Kinetics of the Dissolution of Sodium and Potassium Feldspar in HF/HCl Mixtures. *Chemicals Engineering Science.* Volume 30. 1325-1332.

Ghalambor, A. and Economides, M. J. (2000). Formation Damage Abatement: A Quarter-Century Perspective. Paper SPE 77304 presented at the *SPE International Symposium on Formation Damage Control*, Lafayette, Louisiana, 23–24 February.

Ghalambor, A. and Economides, M. J. (2002). Formation Damage Abatement: A Quarter-Century Perspective. *SPE Journal.* Volume 7 (Issue 1). 4–13.

Gidley, J. L. (1971). Stimulation of Sandstone Formations with the Acid-Mutual Solvent Method. *Journal of Petroleum Technology.* Volume 23 (Issue 5). 571-579.

Gidley, J.L. (1985). Acidizing Sandstone Formations: A Detailed Examination of Recent Experience. Paper SPE 14164 presented at the *SPE Annual Technical Conference and Exhibition*, Las Vegas, Nevada, 22 – 25 September.

Gomaa, A. M., Cutler, J., Qi Q., Boles, J. and Wang, Xiaolan (2013). An Effective Single Stage Acid System for Sandstone Reservoirs. Paper SPE 165147 presented at the *SPE European Formation Damage Conference and Exhibition*, Noordwijk, the Netherlands, 5 – 7 June.

Guo, B., Liu, X. and Tan, X. (2017). *Petroleum Production Engineering.* (Second Edition). Cambridge, United States: Gulf Professional Publishing.

Hanafy, A. M. and Nasr-El-Din, H. A. (2018). A New Method to Assess Stimulation of Sandstone Cores Damaged by Fines Migration. Paper SPE 190123 presented at the *SPE Western Regional Meeting,* Garden Grove, California, 22 – 27 April.

Hassan, M. H., Rusman, L., Chandrakant, A. A., Haslan, M. H., Moktar, N. S. Abdussalam, K. (2017). An Innovative Approach for Stimulation Treatment in Clastic Reservoir Quadruples Net Oil Production. Paper SPE 189195 presented at the *SPE Symposium: Production Enhancement and Cost Optimisation*, Kualan Lumpur, Malaysia, 7 – 8 November.

Hibbeler, J. and Garcia, T. (2003). An Integrated Long-Term Solution for Migratory Fines Damage. Paper SPE 81017 presented at the *SPE Latin American and Caribbean Petroleum Engineering Conference,* Port-of-Spain, Trinidad, West Indies, 27 – 30 April.

Hill, A. D., Sepehrnoori, K. and Wu, P. Y. (1994) Design of the HCl Preflush in Sandstone Acidizing. *Journal of SPE Production & Facilities.* Volume 9 (Issue 2). 115-120.

Hodge, M., Augustine, B. G., Burton, B. C., Sanders, R. W. and Atkinson Stomp, D. (1997). Evaluation and Selection of Drill-In-Fluid Candidates to Minimize Formation Damage. *SPE Drilling & Completion.* Volume 12 (Issue 3). 174-179.

Hong, L. V. and Mahmud, H. B. (2017). A Comparative Study of Different Acids used for Sandstone Acid Stimulation: A Literature Review. *IOP Conference Series: Materials Science and Engineering*. Volume 217.

Houseworth, J., Long, J., Birkholzer, J. and Jordan, P. (2016). *Advanced Well Stimulation Technologies in California.* An Independent Review of Scientific and Technical Information. California Council on Science and Technology, California.

Hu, X., Hu, S., Jin, F. and Huang, S. (2017). *Physics of Petroleum Reservoirs*. (Second Edition). Berlin, Germany: Springer.

Ismail, A. S. I. and Ismail, I. (2011). The Effect Of Matrix Acidizing on The Compressive Strength of Sandstone Formation. *Journal Technology (Science and Engineering).* Volume 56 (Issue 1). 175–191

Kalfayan, L. (2008). *Production Enhancement with Acid Stimulation.* Tulsa, Oklahoma: PennWell.

Kalfayan, L. J. and Martin, A. N. (2009). The Art and Practice of Acid Placement and Diversion: History, Present State and Future. Paper SPE 124141 presented at the *SPE Annual Technical Conference and Exhibition*, New Orleans, Louisiana, 4 – 7 October.

Kalfayan, L. J. and Metcalf, A. S. (2000). Successful Sandstone Acid Design Case Histories: Exceptions to Conventional Wisdom. Paper SPE 63178 presented at the *SPE Annual Technical Conference and Exhibition*, Dallas, Texas, 1 – 4 October.

Kartoatmodjo, G., Caretta, F., Flew, S. and Jadid, M. (2007). Risk-based Candidate Selection Workflow Improve Acid Stimulation Success Ratio in Mature Field. Paper SPE 109278 presented at the *SPE Asia Pacific Oil and Gas Conference and Exhibition*, Jakarta, Indonesia, 30 October – 1 November.

Khilar, K. C. and Fogler, H. S. (1983). Water Sensitivity of Sandstones. *Society of Petroleum Engineers Journal.* Volume 23 (Issue 1). 55–64.

Kume, N., Van Melsen, R., Erhahon, L. and Abiodun, A. F. (1999). New HF Acid System Improves Sandstone Matrix Acidizing Success Ratio By 400% Over Conventional Mud Acid System in Niger Delta Basin. Paper SPE 56527 presented at the *SPE Annual Technical Conference and Exhibition*, Houston, Texas, 3 – 6 October.

Li, N., Zeng, F., Li, J., Zhang, Q., Feng, Y. and Liu, P. (2016). Kinetic Mechanics of the Reactions between HCl/HF Acid Mixtures and Sandstone Minerals. *Journal of Natural Gas Science and Engineering.* Volume 34. 792-802.

Mahmoud M. A., Nasr-El-Din H. A., De Wolf C. and Alex A. (2011). Sandstone Acidizing Using a New Class of Chelating Agents. Paper SPE 139815 presented at the *SPE International Symposium on Oilfield Chemistry*, The Woodlands, Texas, 11 – 13 April.

McLeod, H. O., Ledlow, L. B. and Till, M. V. (1983). The Planning, Execution and Evaluation of Acid Treatments in Sandstone Formations. Paper SPE 11931 presented at the *SPE Annual Technical Conference and Exhibition*, San Francisco, California, 5 – 8 October.

McLeod, H.O. (1986). *Matrix Acidizing to Improve Well Performance.* Short Course Manual. Richardson, Texas: SPE.

McLeod, H.O. Jr. (1984). Matrix Acidizing. *Journal of Petroleum Technology*. Volume 36 (Issue 12). 2055–2069.

Nasr-El-Din, H. A., Al-Anazi, M., Al-Zahrani, A., Samuel, M. and Kelkar, S. K. (2007). Investigation of a Single Stage Sandstone Acidizing Fluid for High-Temperature Formations. Paper SPE 107636 presented at the *European Formation Damage Conference*, Scheveningen, the Netherlands, 30 May – 1 June.

Neasham, J. W. (1977). The Morphology of Dispersed Clay In Sandstone Reservoirs And Its Effect On Sandstone Shaliness, Pore Space And Fluid Flow Properties. Paper SPE 6858 presented at the *SPE Annual Fall Technical Conference and Exhibition*, Denver, Colorado, 9 – 12 October.

Nitters, G., Pittens, B. and Buik, N. (2016). *Well Stimulation Techniques for Geothermal Projects in Sedimentary Basins.* Dutch Geothermal Research Agenda (Kennisagenda Aardwarmte), the Netherlands.

Nitters, G., Roodhart, L., Jongma, H., Yeager, V., Buijse, M., Fulton, D. and Jantz, E. (2000). Structured Approach to Advanced Candidate Selection and Treatment Design of Stimulation Treatments. Paper SPE 63179 presented at the *SPE Annual Technical Conference and Exhibition,* Dallas, Texas, 1 – 4 October.

Nwaochei, F., Hackney, D., Olufemi, B., Carrillo, I. and Obembe, A. (2014). Acid Stimulation in Agbami Deepwater – The Innovative Success Story. Paper SPE 172365 presented at the *SPE Nigeria Annual International Conference and Exhibition*, Lagos, Nigeria, 5 – 7 August.

Oluwagbenga, O. O., Oseh, J. O., Oguamah, I. A., Ogungbemi, O. S. and Adeyi, A. A. (2015). Evaluation of Formation Damage and Assessment of Well Productivity of Oredo Field, Edo State, Nigeria. *American Journal of Engineering Research (AJER).* Volume 4 (Issue 3). 1-10.

Paccaloni, G. and Tambini, M. (1993) Advances in Matrix Stimulation Technology. *Journal of Petroleum Technology*. Volume 45 (Issue 03). 256-263.

Paccaloni, G., Tambini, M. and Galoppini, M. (1988). Key Factors for Enhanced Results of Matrix Stimulation Treatments. Paper SPE 17154 presented at the *SPE Formation Damage Control Symposium*, Bakersfield, California, 8 – 9 February.

Permadi, A. K., Naser, M. A. N., Mucharam, L., Rachmat, S. and Kishita, A. (2012). *Formation Damage and Permeability Impairment Associated with Chemical and Thermal Treatments: Future Challenges in EOR Applications.* The Contribution of Geosciences to Human Security. (Chapter 7, 103-126). Germany: Logos Verlag.

Perthuis, H. and Thomas, R. (1991). *Fluid Selection Guide for Matrix Treatments.* (Third Edition). Tulsa, Oklahoma: Dowell Schlumberger.

Perthuis, H., Touboul, E. and Piot, B. (1989). Acid Reactions and Damage Removal in Sandstones: A Model for Selecting the Acid Formulation. Paper SPE 18469 presented at the *SPE International Symposium on Oilfield Chemistry*, Houston, Texas, 8-10 February.

Piro, G., Barberis Canonico, L., Galbariggi, G., Bertero, L. and Carniani, C. (1996). Experimental Study on Asphaltene Adsorption onto Formation Rock: An Approach to Asphaltene Formation Damage Prevention. *SPE Production & Facilities*. Volume 11 (Issue 3). 156-160.

Portier, S., Andre, L. and Vuataz, F. (2007). Review on Chemical Stimulation Techniques in Oil Industry and Applications to Geothermal Systems. *Technical Report.* Deep Heat Mining Association, Switzerland.

Poyyara, R., Patnana, V. and Alam, M. (2014). Optimization of Acid Treatments by Assessing Diversion Strategies in Carbonate and Sandstone Formations. *International Journal of Chemical, Nuclear, Metallurgical and Materials Engineering*. Volume 8 (Issue 9). 879-884.

Rabbani, E., Davarpanah, A. and Memariani, M. (2018). An Experimental Study of Acidizing Operation Performances on the Wellbore Productivity Index Enhancement. *Journal of Petroleum Exploration and Production Technology.* https://doi.org/10.1007/s13202-018-0441-8.

Rae, P. and Di Lullo, G. (2002). Achieving 100 Percent Success in Acid Stimulation of Sandstone Reservoirs. Paper SPE 77808 presented at the *SPE Asia Pacific Oil and Gas Conference and Exhibition,* Melbourne, Australia, 8 – 10 October.

Rae, P. and Di Lullo, G. (2003). Matrix Acid Stimulation - A Review of the State-Of-The-Art. Paper SPE 82260 presented at the *SPE European Formation Damage Conference*, The Hague, Netherlands, 13 – 14 May.

Reinoso, W., Torres, F., Aldana, M., Campo, P., Alvarez, E and Erika, T. (2016). Removing Formation Damage From Fines Migration in the Putumayo Basin in Colombia: Challenges, Results, Lessons Learned, and New Opportunities after More Than 100 Sandstone Acidizing Treatments. Paper SPE 178996 presented at the *SPE International Conference and Exhibition on Formation Damage Control*, Lafayette, Louisiana, 24 – 26 February.

Rylance, M., & Hoq, A. (2017). Opportunity in Adversity: A Paradigm Shift in Chemical Stimulation. Paper SPE 187931 presented at the *SPE Russian Petroleum Technology Conference,* Moscow, Russia, 16 – 18 October.

Saavedra, N., Solano, R., Gidley, J., Reyes, C. A., Rodriguez, P., Kondo, F. and Hernandez, J. (1998). Well Screening for Matrix Stimulation Treatments. *CT&F - Ciencia, Tecnología y Futuro*. Volume 1 (Issue 4). 5-19.

Samsuri, A, Amawoty, S. A., Shukor, N. A. (1998). Optimum Acid System for Trengganu Offshore Gas Well Acidizing Process. Paper presented at the *Malaysian Science & Technology Congress*, Johor Bahru, Malaysia, 30 – 31 October.

Sarkar, A. K. and Sharma, M. M. (1990). Fines Migration in Two-Phase Flow. *Journal of Petroleum Technology.* Volume 42 (Issue 5). 646-652.

Schechter, R. S. (1992). *Oil Well Stimulation*. Englewood Cliffs, N. J.: Prentice Hall.

Senters, C. W., Leonard, R. S., Ramos, C. R., Wood, T. M. and Woodroof R. A. (2017). Diversion – Be Careful What You Ask For. Paper SPE 187045 presented at the *SPE Annual Technical Conference and Exhibition,* San Antonio, Texas, 9 – 11 October.

Shafiq, M. U. and Mahmud, H. B. (2017). Sandstone Matrix Acidizing Knowledge and Future Development. *Journal of Petroleum Exploration and Production Technology.* Volume 7 (Issue 4). 1-12.

Shafiq, M. U. and Mahmud, H. K. B. (2016). An Effective Acid Combination for Enhanced Properties and Corrosion Control of Acidizing Sandstone Formation. *IOP Conference Series: Materials Science and Engineering.* Volume 121.

Shafiq, M. U. and Shuker, M. T. (2013). Finding Suitable Acid for Acidizing of Low Permeable Sandstone Formation: A Research. Paper SPE 169641 presented at the *SPE/PAPG Annual Technical Conference*, Islamabad, Pakistan, 26 – 27 November.

Shafiq, M. U., Kyaw, A. and Shuker, M. T. (2013). A Comprehensive Research to Find Suitable Acid for Sandstone Acidizing. *Advanced Material Research*. Volume 787. 274–280.

Shafiq, M. U., Mahmud, H. K. B. and Hamid, M. A. (2015). Comparison of Buffer Effect of Different Acids During Sandstone Acidizing. *IOP Conference Series: Materials Science and Engineering.* Volume 78.

Shah, S., Singh, S. K., Bahuguna, V. K. and Rajendra, K. W. (2017). Successful Matrix Acidization using Organic Acid System for Sandstone Reservoir of Western Onshore Fields of India: A Case Study. Paper SPE 185393 presented at the *SPE Oil and Gain India Conference and Exhibition,* Mumbai, India, 4 – 6 April.

Shuchart, C. E and Gdanski, R. D. (1996). Improved Success in Acid Stimulations with a New Organic-HF System. Paper SPE 36907 presented at the *European Petroleum Conference*, Milan, Italy, 22 – 24 October.

Smith C. F. and Hendrickson A. R. (1965). Hydrofluoric Acid Stimulation of Sandstone Reservoirs. *Journal of Petroleum Technology.* Volume 17 (Issue 2). 215-222.

Smith, C.F., Crowe, C.W. and Nolan, T.J. III (1969). Secondary Deposition of Iron Compounds Following Acidizing Treatments. *Journal of Petroleum Technology.* Volume 21 (Issue 9). 1121–1129.

Sopngwi, J. S., Gauthreaux, A., Kiburz, D. E., Kashib, T., Reyes, E. A., Beuterbaugh, A., Smith, A. L. and Smith, S. K. (2014). Successful Application of a Differentiated Chelant-Based Hydrofluoric Acid for the Removal of Aluminosilicates, Fines and Scale in Offshore Reservoirs of the Gulf of Mexico. Paper SPE 168171 presented at the *SPE International Symposium and Exhibition on Formation Damage Control*, Lafayette, Louisiana, 26 – 28 February.

Thomas, R.L., Nasr-El-Din, H. A., Mehta, S., Hilab, V. and Lynn, J. D. (2002). The Impact of HCl to HF ratio on Hydrated Silica Formation during the Acidizing of a High Temperature Sandstone Gas Reservoir in Saudi Arabia. Paper SPE 77370 presented at the *SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, 29 September-2 October.

Ugbenyen, B. O. (2010). *An Approach to Stimulation Candidate Selection and Optimization.* Master of Petroleum Engineering. African University of Science and Technology, Abuja.

Vaidya, R. N. and Fogler, H. S. (1990). Formation Damage due to Colloidally Induced Fines Migration. *Colloids and Surfaces*. Volume 50. 215-229.

Van Domelen, M. S. (2017). A Practical Guide to Modern Diversion Technology. Paper SPE 185120 presented at the *SPE Oklahoma City Oil and Gas Symposium*, Oklahoma City, Oklahoma, 27 – 31 March.

Walsh, M.P., Lake, L.W. and Schechter, R.S. (1982). A Description of Chemical Precipitation Mechanisms and Their Role in Formation Damage during Stimulation by Hydrofluoric Acid. *Journal of Petroleum Technology*. Volume 34 (Issue 9). 2097–2112.

Weimer, R. J. and Tillman, R. W. (1982). Sandstone Reservoirs. Paper SPE 10009 presented at the *International Petroleum Exhibition and Technical Symposium*, Beijing, China, 17 – 24 March.

Williams, B. B., Gidley, J. L. and Schechter, R. S. (1979). Acidizing Fundamentals. *SPE Monograph Volume 6.*

Xiao, J., Jianghong, W. and Xin, S. (2017). Fines Migration: Problems and Treatments. *Oil and Gas Research.* Volume 3 (Issue 1). 1-4.

You, Z. and Bedrikovetsky, P. (2018). Well Productivity Impairment due to Fines Migration. Paper SPE 189532 presented at the *SPE International Conference and Exhibition on Formation Damage Control,* Lafayette, Louisiana, 7 – 9 February.

Zaman, M. A., Alam, M. M. and Abdul Matin, M. (2013). Performance of Different Acids on Sandstone Formations. *Journal of Engineering Science and Technology Review.* Volume 6 (Issue 3). 25-29.