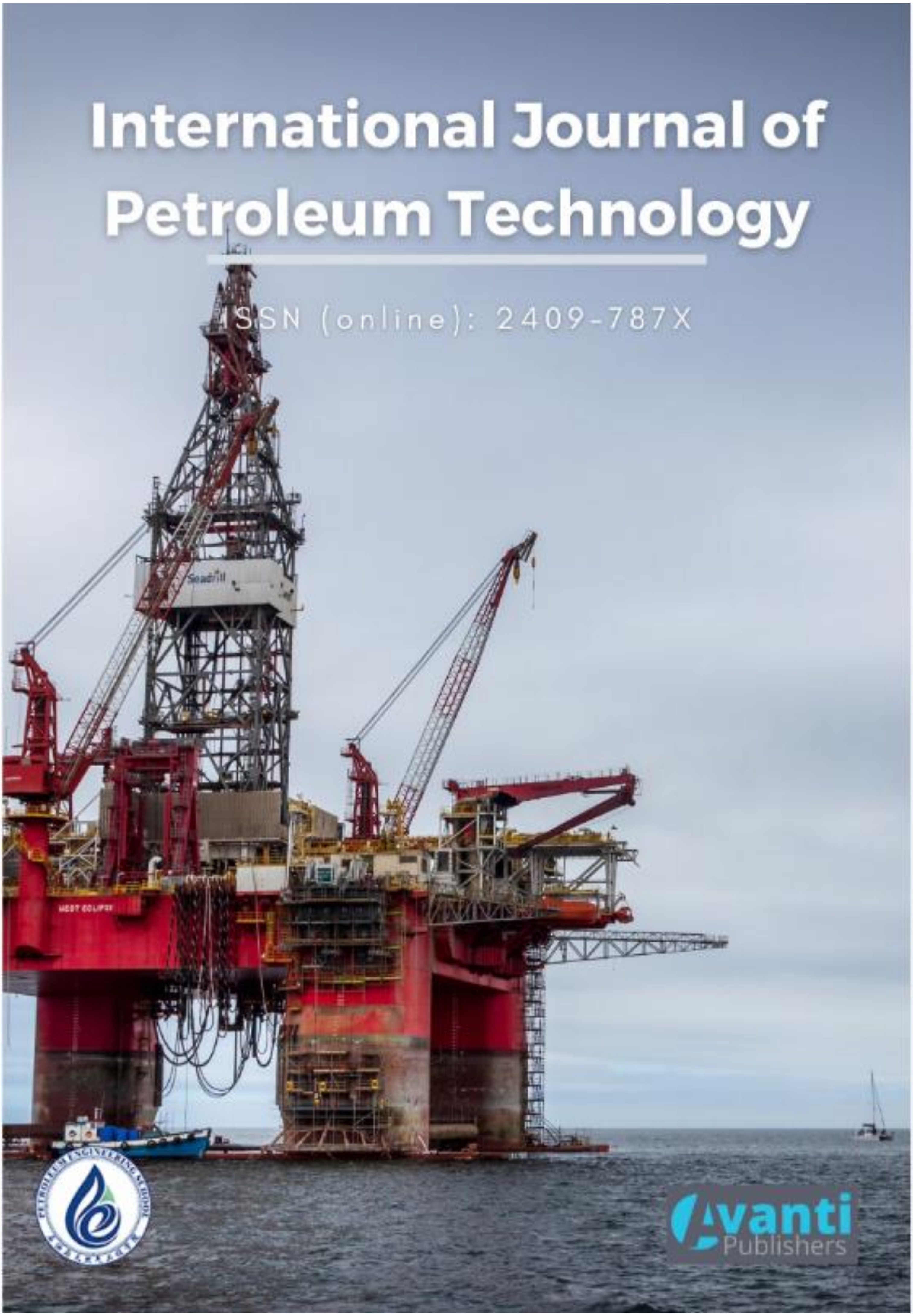

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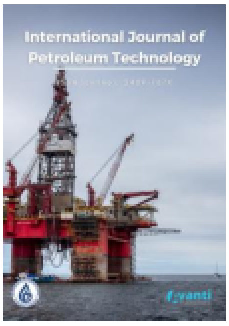

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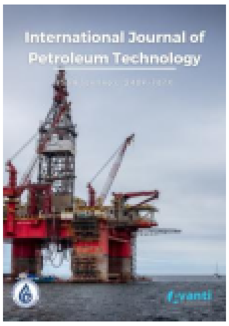

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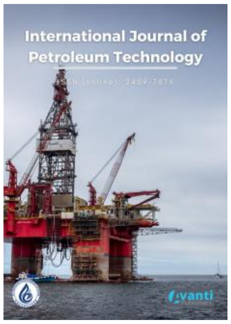

Matrix Acidizing Optimization for Screened Sandstone Formation at High-Rate Gas Well of Deepwater GWK-8

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ABSTRACT

Deepwater GWK-8 is a gas well in deep sea with 1500 meters water depth and a deviated well with a sandstone formation that has good permeability, potentially high-rate gas well, high reservoir pressures, and large reservoir size. This well is expected to immediately ramp up production at optimal productivity through Floating Production Storage and Offloading (FPSO) in Makassar Strait. For a gas well at deep-water exploration must be commercially viable, it needs to achieve optimal production rate. Gas production initially was not meet the expectations, so it needed to be optimized by one of stimulation method that suitable for this well is matrix acidizing. Sandstone formation is screened by Shape Memory Polymer (SMP) sand control system and matrix acidizing is carried out to optimize the deliverability of gas well by dissolving formation impurities and normalize damage in the wellbore. Methodology of this study begins with collecting data on reservoir data, formation lithology, completion, and well-testing. The optimization of matrix acidizing process is based on initial well-testing results where skin (s) of pre-acidizing is 46 with a permeability (k) is 51.4 mD. The matrix acidizing process uses mud acid (HCl-HF) for upper zone of deepwater GWK-8 that has been installed Shape Memory Polymer (SMP) sand control at the pay zone area. Based on well-testing of post-matrix acidizing, successfully proven in reducing the skin number (s) from 46 to 10, increasing permeability (k) from 51.4 mD to 120 mD, and increasing productivity from 30 MMSCFD to 44 MMSCFD.

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1. Introduction

The main purpose of matrix acidizing in sandstones is to dissolve impurities of formation and normalize damage at near wellbore area which is relatively high skin factor (s) by dissolving particles and pore throat blockages (clay, feldspar, and quartz) that restrict the flow of hydrocarbons in the pore of formation. Matrix acidizing applied to normalize damage (lowering skin factor) and increasing permeability around wellbore [1–3]. Formation damage indicated by high skin factors, porosity blockage and decreased permeability may occur during drilling, completion, and long period of production processes. Sandstone is an unconsolidated formation that may easily breakthrough due to higher gas rate. To achieve optimal gas rate, filtration with a sand control system is mandatory required. For this specific case, application of new technology for sand control which is Shape Memory Polymer (SMP) is highly recommended [4, 5].

The installation of Shape Memory Polymer (SMP) as Well Completion, which is an alternative technology for open hole gravel packs has the same side effect for damaging wellbore due to pressure or high viscous material entering the formation [6]. Studies have been conducted on similar well for sandstone formations strengthen by open hole gravel pack (OHGP) have average productivity increment up to 40% for several gas wells in Cambay Bay the coast of India [7] Based on calculation of gas well deliverability with Inflow Performance Relationship – IPR [8], pre-matrix acidizing productivity of deepwater GWK-8 is below expectation. The application of Shape Memory Polymer (SMP) sand control at wellbore is required to increase the strength of wellbore for the purpose of achieve an optimal gas rate [9] which has a pore throat diameter 50 microns that prevent any sand break out. Wellbore with Shape Memory Polymer (SMP) sand control system is going to be normalized by matrix acidizing to dissolved wellbore impurities and damage to achieve optimum skin (s), porosity (Φ), permeability (k), and deliverability (Q).

Recommended combination of Matrix acidizing by hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1% will be applied for deepwater GWK-8 gas well. However, there are potential side effect problems that may occur during acidizing, especially the advanced reaction of hydrofluoric acid (HF) when dissolving clays, feldspar and quartz that produce aluminum and silica fluoride as well as precipitate gels that possibly blocked the pore throat of sandstone formation. To minimize this risk, there is pre-flush stage with Ammonium chloride (NH_4Cl) for preliminary conditioning prior to main acid [10]. In matrix acidizing process, it is necessary to pay attention to maximum allowable bottomhole pressure (BHP) when pumping acid should not exceed the fracturing pressure of formation.

Matrix acidizing at sandstone formation strengthen by Shape Memory Polymer (SMP) the new technology of sand control system will improve production deliverability in significant numbers [4, 5, 9]. The improvement of production deliverability proven by accurate well-testing; post-matrix acidizing skin (s), permeability (k), and Inflow Performance Relationship (IPR) are improved significantly. This achievement is required for highly cost deep-water operation in deepwater GWK-8 well.

2. Methodology

The methodology of this research begins with collecting data on reservoir data, lithology, completion, well-testing, and acid composition for matrix acidizing. Reservoir data include porosity (Φ), net pay of reservoir (h), permeability (k), reservoir pressure, reservoir temperature and skin (s). Lithology data include the percentage of quartz, feldspar, mica, siderite, dolomite, etc. Completion data includes well schematic, well properties, and Shape Memory Polymer (SMP) properties. Well-testing data includes bottomhole pressure, bottomhole temperature, pressure of each flow test data, and gas rate data. Acidizing matrix data includes volume, composition, well pressure when pumping acid as well as fracturing pressure.

Success of matrix acidizing process was carried out from the previous studies that have been valid for similar process; implementation of matrix acidizing in sandstone formations filtered by latest game changer technology Shape Memory Polymer (SMP) sand control system. The analysis starts from overview of deep-water GWK-8 well; well data; study of scientific fields, discussion of wellbore conditions, discussion of sand control process, discussion of matrix acidizing process, discussion of phenomena, reactions of acid to formations, and analysis of matrix acidizing challenges that may occur. Finally, proof of success was carried out by well-test interpretation analysis for skin (s) and permeability (k) determinations also determination of gas well productivity, in this case inflow performance relationship (IPR) pre and post acidizing.

3. Results and Discussion

Deepwater GWK-8 is a gas well in the deep sea 1500 meters water depth. The wells cluster are connected through subsea pipeline to Floating Production Storage and Offloading (FPSO). The operating cost for deep-water project is high cost due to latest technology application such as semisubmersible drilling rig, service companies, floating storage (FPSO) and tanker. Therefore, each well at deep-water cluster is expected to have optimal productivity. Fig. **1** show the exploration and production process in the deep-water cluster.

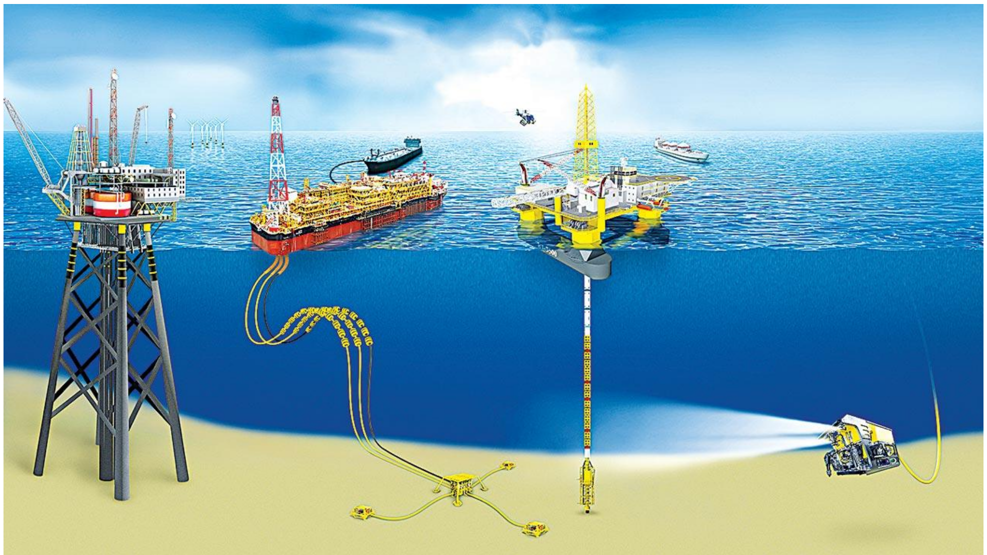


Figure 1: Exploration and production process in the deep-water cluster.

The reservoir properties of deepwater GWK-8 well are shown at Table **1**, for analysis and calculations are based on results of exploration phase that analyzed by valid and measurable lab tests. In addition to reservoir data, there is also lithological data of formations from the results of core analysis obtained from exploration process at coring stage, shown at Table **2**.

Table 1: **Reservoir properties of deepwater GWK-8 well.**

Parameters	Value
Average Permeability (k), mD	48
Pay Zone (h), m	19
Porosity (Φ), fraction	0.21
Rock Compressibility ($c_{f,}$), Psi^{-1}	$3.6x10^{-6}$
Fracture Pressure (P_{ff}), Psia	4545
Bottomhole Temperature (BHT), ^{o}C	55
Formation Pressure (P_f), Psia	3867.34
Well Radius (r_w), Inch	4.25
Interval, m	2707 - 2726
Gas Gravity (SG)	0.62

Matrix acidizing application with combination hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1% is recommended for Sandstone formation that consists of quartz, feldspar, high clay-silt, and permeability 20 - 100 mD [1, 6]. Matrix acidizing combination expected to dissolve clays, fine grains and particles in pore space, pore throat and pore wall. Silts and clays are the component minerals that have fast reaction to hydrofluoric acid (HF) that potentially create precipitation formation. Hydrochloric acid (HCl) with higher ratio HCl : HF is the way to retard and prevent by-product formations which is precipitation that caused pore-throat blockage and decreasing permeability. There is illustration of matrix (quartz, feldspar, chert, and mica), pore-lining clays (illite), pore cavity filling clays (kaolinite), and secondary cement materials (carbonate and quartz) as shown in Fig. **2**.

Table 2: Formation lithology of deepwater GWK-8 well.

Minerals	Value
Quartz, %	49 - 60
Mica, %	1 - 3
Feldspar, %	1 - 6
Smectite, %	1.4 - 2.3
Glauconite, %	1
Chlorite, %	7 - 10
Siderite, %	7 - 20
Fe-Dolomite, %	0-7

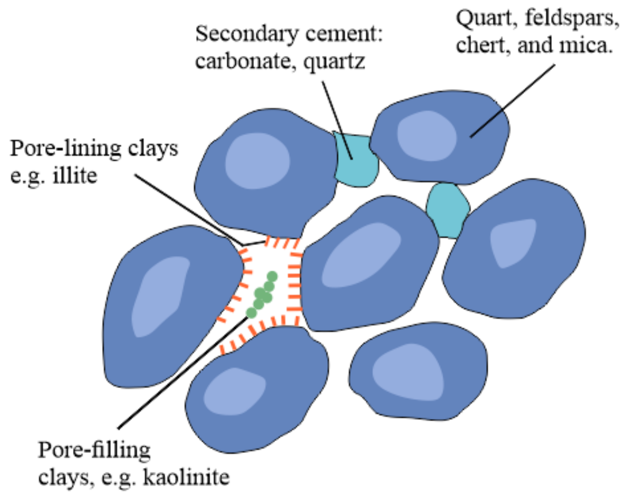


Figure 2: Illustration of minerals and impurities at sandstone formations.

In purpose of achieve optimal productivity of gas well, un-consolidated sandstone formations need to be strengthened by sand control system. There are two available sand control technologies: conventional open hole gravel pack (OHGP) and Shape Memory Polymer (SMP). For deep-water projects, time savings with optimal results are mandatory target that must be achieved so the selected sand control system is latest technology Shape Memory Polymer (SMP). This is a new game changer technology for sand control on open holes which is an alternative of conventional Open Hole Gravel Pack (OHGP), as shown in Fig. **3**.

Shape Memory Polymer (SMP) consists of engineered polymer material that formed on a retainer cartridge attached on a modular perforated base pipe that installed at end of production liner shoe to target zone of wellbore. Material of Shape Memory Polymer (SMP) is polymer that has glass transition property which when run to wellbore at compacted state condition, after being installed on open hole (wellbore) will expand to fill gap and conform irregular wellbore by activation fluid soaking. On this case using activation fluid of 120 barrels. Acetyl

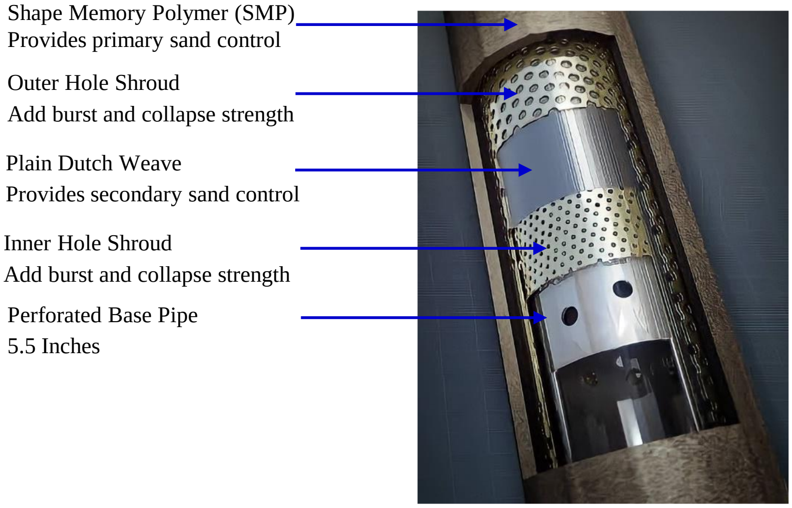


Figure 3: Desain of Shape Memory Polymer (SMP) on perforated base pipe.

Acetone with 3% concentration soaked to the wellbore. Shape Memory Polymer (SMP) that expanded to fill gap and conform to wellbore space has good porosity and pore-throat of 44 - 50 microns in diameter that able to filtrate and bind the sandstone to be strongly consolidated. However, this process requires normalization of wellbore damage by matrix acidizing to achieve optimal gas well productivity. Fig. **4** show the Shape Memory Polymer (SMP) pre and post activation that fill up wellbore gap. The advantages of this new technology compared to conventional are as follows:

- Excellent filtration and sand holding capabilities equivalent to Open Hole Gravel Pack (OHGP).
- Average pore throat size of 44 - 50 microns.
- More efficient installation by minimizing footprints on offshore rigs, minimizing logistics and without gravel pumping process.
- Engineer efficiency for installation process.
- Reducing the risk and hazard of HSE (Health Safety and Environment).
- Eventually, installation duration is shorter and more cost efficient which is the main target of deep-water operation project.

Figure 4: Shape Memory Polymer (SMP) pre and post activation that fill up wellbore gap.

Deepwater GWK-8 has an open hole diameter of 8.5 inches and compacted outer diameter of Shape Memory Polymer (SMP) of 7.25 inches. The polymer material capable to conform, fill up gap, filter and hold up to open hole size 9.5 inches. Eventually, the expanding polymer is hardened with average pore throat diameter 48 microns. The average size of pore throat diameter in Shape Memory Polymer (SMP) is confirmed based on lab testing. However, there is a possibility of wellbore or formation near wellbore damage on the interface area due to expansion of polymer that pressed the wellbore while expanding.

Area near wellbore that damage during installation of Shape Memory Polymer (SMP) will be normalized by the most suitable stimulation process for this case is matrix acidizing. Matrix acidizing, combination of hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1% is expected to dissolve and normalized damages at wellbore, polymer interfaces and especially part around the flow tunnel. The damage of wellbore commonly indicated by higher skin factor (s), lower permeability (k) and lower gas rate production (Q). Fig. **5**, show the wellbore damage during pre-matrix acidizing and post-matrix acidizing.

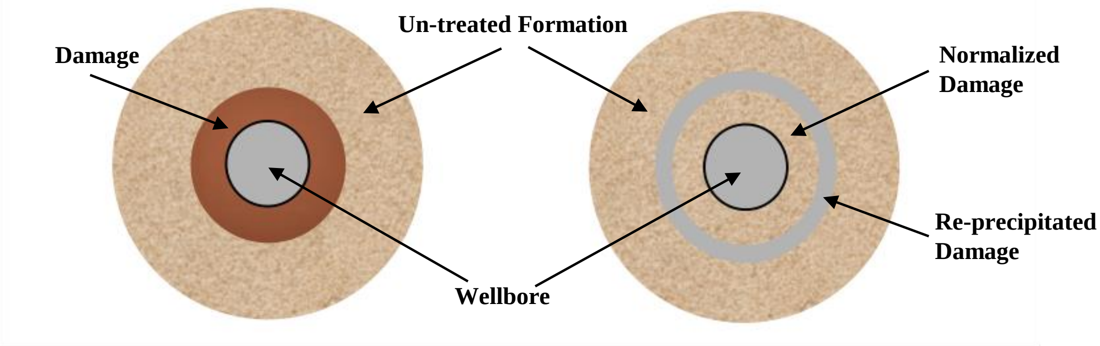


Figure 5: Wellbore damage during pre-matrix acidizing and post-matrix acidizing.

Critical parameters during matrix acidizing execution that need to be concerned; maximum bottomhole pressure (BHP) during pumping for entire stages starting from pre-flush, main acid, and over-flush. The fracturing pressure of formation is 4545 Psia, so during pumping process must be maintain at 3900-4000 Psi to avoid fracking phenomena at wellbore. The principle of matrix acidizing is dissolving any wellbore damage to normalize formation condition whereas hydraulic fracturing is fracking and creating wormhole channel. The pumping rate during whole process is 4 BPM (Barrels Per Minute) for whole operation stages. The stages of matrix acidizing process are pre-flush, main acid, and over flush.

3.1. Pre-Fush

Pre-flush uses 10 barrels of sweet water with 5% Ammonium Chloride (NH_4Cl) as initial conditioning of formation before the main acid treatment. In this case to prevent precipitate formation of silicates (Na_2SiF_6, K_2SiF_6) and fluorides (CaF_2) [11]. The pre-flush execution is pumping fluid to formation at 4 BPM (Barrels Per Minute) and maintained bottomhole pressure at 3900 - 4000 Psia below fracturing pressure 4545 Psia. The purpose of pre-flush are as follows:

- Initial conditioning of formation in order to ensure main acidizing reaction is effective.
- Eliminate impurities of the organic and inorganic crust.
- Ensuring that hydrocarbons are perfectly displaced to prevent emulsions.
- Displace cations materials that lead to precipitate formation.

3.2. Main Acid

Main Acid uses 50 barrels of combined hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1%. The mixture of HCl-HF or commonly called mud acid in matrix acidizing is intended to dissolve Impurities of clay, feldspar, and quartz materials. This Main Acid is pumped with the same parameters as the previous stage (pre-flush) and is carried out continuously without any delay between stages.

3.3. Over Flush

The over-flush uses 30 barrels base oil with 0.78 of SG. The purpose of this step is to push the acid further into the formation until tertiary reaction occurred and clean formation from residual mud acid. The process is the same as previous stage and simultaneous without any delay between stages. After over-flush, clean-up phase must be carried out after 30 minutes soaking process is achieved in the purpose of prevent unnecessary reaction that may create by-products.

The minerals from sandstone are divided into two categories based on the reactivity rate to be dissolved against mud acid: slow reactions and fast reactions. Quartz tends to react slower which Feldspar is faster and Clays are the fastest one [12]. Fig. **6** show types of reactions that occur during the sandstone formation is exposed with mud acid.

When sandstone formation is treated with mud acid (HCl-HF), there are three groups of reactions that occur as described by Al-Harthy, 2008 [13]. The primary reaction occurs close to the wellbore whose reaction will produce aluminum formations of fluoride and silica fluoride. In this reaction, the mineral will dissolve quickly and no form of precipitate. Furthermore, secondary reaction occurs where the result (product) of the primary reaction reacts into silica gel (slow reaction) which is produce precipitate. This precipitate needs to be avoided because it can create blockage in the pore throat. Furthermore, there will be a tertiary reaction, the more silica gel will be formed. HF is main one that reacts with formation of rocks. HCl is added to the mixture to reduce and slow down HF consumption and maintain acidic conditions surrounding which aims to prevent formation of precipitate from HF reactions [13].

When sandstone formation is treated with hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1%, there is a possibility of forming several types of precipitate from minerals [11]. The formation of this precipitate if not properly calculated will be detrimental, at this case it will clog the formation and cause lower porosity and permeability. The following are some of precipitates that may occur, i.e:

- Formation of potassium precipitate and sodium silicate.
- Formation of calcium precipitate fluoride.
- Formation of hydrated silica.

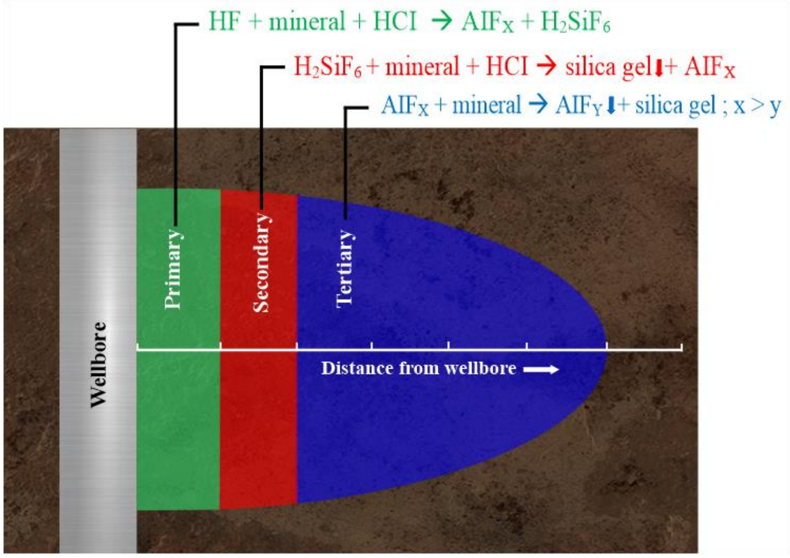


Figure 6: Primary, secondary, and tertiary reactions of mud acid in wellbore formations.

Mud acid reacts with wellbore formations to dissolve different minerals. In addition, it will dissolve most of clays so that pore throat will be larger and of course increase permeability. The most important are carbonate reactions with HCL-HF and HF reactions with quartz, feldspar, kaolinite, and other types of silicate. For example, the reaction below:

- Reaction of Acid and Quartz

$$4HF + SiO_2 \longrightarrow \uparrow SiF_4 + 2H_2O$$

$$SiF_4 + 2HF \longrightarrow H_2SiF_6$$

The first reaction is produced Silicon tetra fluoride (SiF_4) which partially releases as soluble gas and part of it will continue react with acid create fluorosilicic acid (H_2SiF_6). H_2O will flow easily through pore throat that getting bigger because there is more dissolved part. This reaction occurs at 2 - 3 feet distance from wellbore.

- Reaction of Acid and Sodium Feldspar (Albite)

$$NaAlSi_3O_8 + 14HF + 2H^+ \longrightarrow Na + AlF_2^+ + 3SiF_4 + 8H_2O$$

- Reaction of Acid and Potassium Feldspar (Orthoclase)

$$KAlSi_3O_8 + 14HF + 2HF^+ \longrightarrow K^+ + AlF_2^+ + 3SiF_4 + 8H_2O$$

- Reaction of Acid and Kaolinite

$$Al_4Si_4O_{10}(OH)_8 + 24HF^+ \longrightarrow 4AlF_2^+ + 4SiF_4 + 18H_2O$$

- Reaction of Acid and Montmorillonite

$$Al_4Si_8O_{20}(OH)_4 + 40HF + 4H^+ \longrightarrow 4AlF_2^+ + 8SiF_4 + 24H_2O$$

Any stage of acid reaction when dissolving damage at formations will enlarge pores. However, it is necessary to be aware that each reaction will produce by-product as precipitate which is mishandling will create blockage and restriction at pore throat of sandstone formation. From the sight of reaction distance from wellbore, there are three types of reactions: primary, secondary, and tertiary. The chemical reaction of acids to each clays (i.e illite, kaolinite), carbonates and minerals (i.e Al, Si) has their own processes. The primary reaction of mud acid toward sandstone formations reviewed against Al and Si minerals is as follows;

$$HF + \text{mineral (Al, Si)} + H^+ \longrightarrow AlF_x + H_2SiF_6 + H_2O^+$$

Hydrofluoric acid (HF) meets minerals in this case Aluminium (Al), Silicon (Si) and Hydrogen (H) will produce Aluminium Fluoride, Fluorosilicic acid (H_2SiF_6) and Water. Fluorosilicic acid (H_2SiF_6) and remaining acid will react again in farther areas from wellbore, secondary reaction:

$$H_2SiF_6^+ + \text{mineral (Al, Si)} + H^+ \longrightarrow AlF_x + \text{silica gel}$$

Fluorosilicic acid (H_2SiF_6) meets minerals and acid residues in the zone further away from wellbore produces aluminium fluoride and silica gel. In farther part of wellbore as shown in Fig. **6**, Aluminum Fluoride with minerals and residual acids that have not been spent will be a tertiary reaction:

$$AlF_x + \text{mineral (Al, Si)} + H^+ \longrightarrow AlF_y + \text{silica gel; } x > y$$

The reaction occurs until remnants of HCl are finished, this reaction is not significant at temperatures below 90 ^oC where bottomhole temperature (BHT) of deepwater GWK-8 well is 55 ^oC. As reaction continues, there will be precipitate of Aluminum Fluoride complex so selection of HCL-HF must be deliberately considered. Recommended combination of hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1% [10]. This combination of mud acid is commonly used for matrix acidizing in standard conditions with bottomhole temperature (BHT) below 90 ^oC.

This Aluminum Fluoride precipitate from reaction HF with clays and feldspar is an undesirable problem because it will reduce porosity and permeability. This phenomenon is minimized by preliminary conditioning using

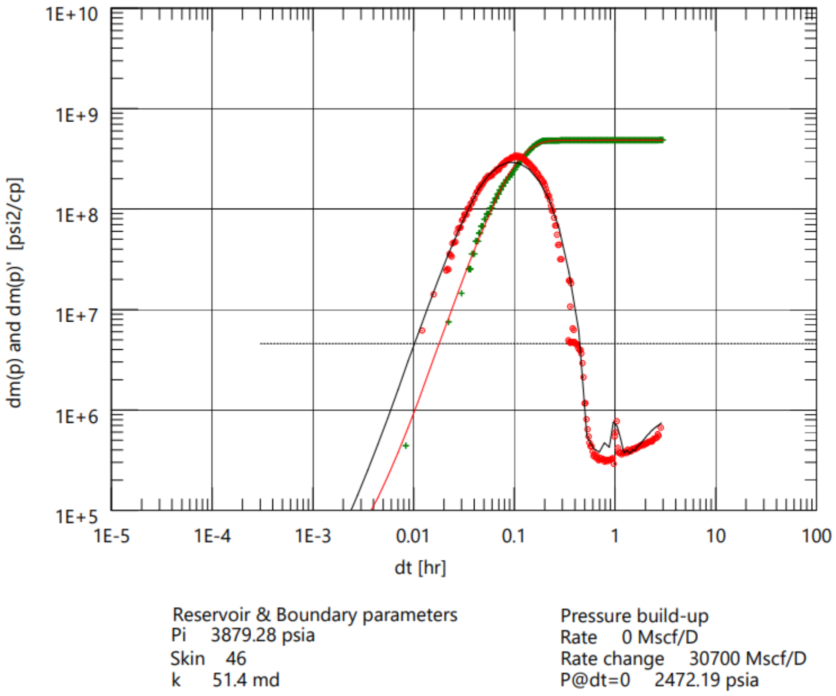
Ammonium Chloride (NH_4Cl) at pre-flush stage. Pre-flush will displace brine containing K, Na or Ca ions so it does not mix with HF which will cause a precipitate formation reaction. Also, to dissolve material (calcium carbonate) to minimize formation of calcium fluoride precipitate.

The expectation of matrix acidizing is damage normalization which is indicated by decreasing of skin number (s), increasing permeability (k) and increasing well productivity in this case is gas rate. This happens because pore throat blockage has dissolved and by-product (precipitate formation) reaction has been minimized by several precaution, for example pre-flush, over flush and soaking time for 30 minutes also immediately flowback by opening the well to well-testing facility. From the results of the Well-testing operation, obtained data and parameters:

- Bottomhole pressure (BHP) and Bottomhole temperature (BHT) at various choke sizes.
- Gas flow rates at various choke sizes.
- Liquid flow rates at various choke sizes.
- Properties of hydrocarbons.
- Watercut or water content against condensate.

Well-test interpretation analysis from well-testing and reservoir parameter for pre-matrix acidizing shown in Fig. **7**. Damage is indicated by higher skin number (s) 46 and lower permeability (k) 51.4 mD. While, from the calculation results by well-test interpretation using the well-testing and reservoir parameter for post-matrix acidizing shown in Fig. **8**. Damage has been normalized by decreasing skin (s) to 10 and increasing permeability (k) to 120 mD.

Well-testing Operation proven that gas production rate pre-matrix acidizing was 30 MMSCFD and post-matrix acidizing was 44 MMSCFD, there was significant increment in gas production rate by 30%. The productivity or deliverability of gas well calculated by Inflow Performance Relationship (IPR) shown by Fig. **9**. Based on Inflow Performance Relationship (IPR) Fig. **9**, it is shows that the deliverability of the well deepwater GWK-8 pre and post matrix acidizing has increased significantly. This is pretty much by the book as calculations and literacy studies of



Reservoir & Boundary parameters
Pi 3879.28 psia
Skin 46
k 51.4 md

Pressure build-up
Rate 0 Mscf/D
Rate change 30700 Mscf/D
P@dt=0 2472.19 psia

Figure 7: Determination of skin (s) and permeability (k) pre-matrix acidizing.

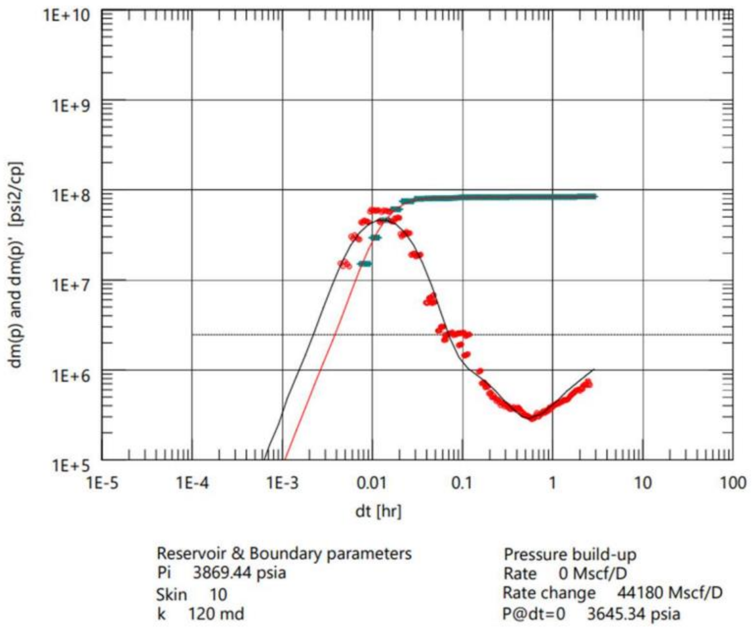


Figure 8: Determination of skin (s) and permeability (k) post-matrix acidizing.

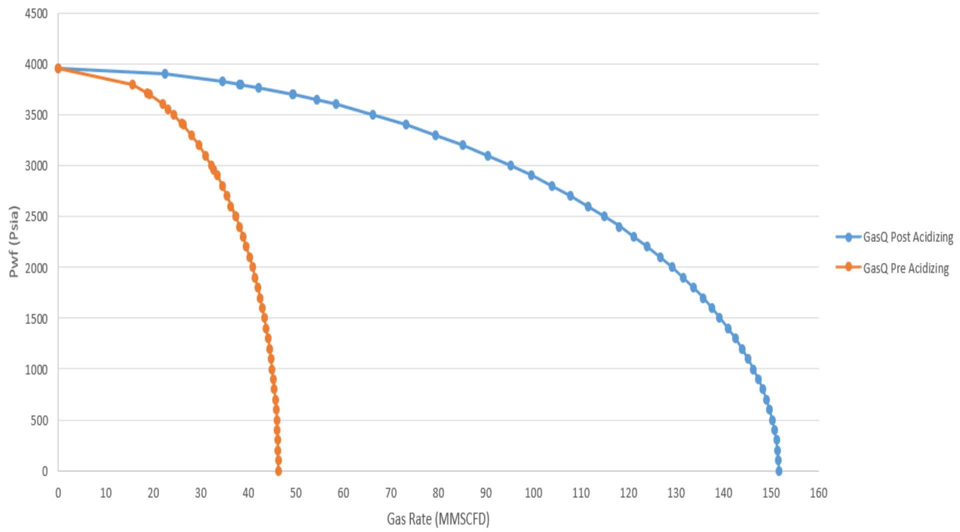


Figure 9: IPR pre-matrix acidizing and post-matrix acidizing at well deepwater GWK-8.

previous successful story in term of selection of combination hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1%. Pre-matrix acidizing has an Absolute Open Flow (AOF) value of 46 MMSCFD while in post-matrix acidizing has an Absolute Open Flow (AOF) of 150 MMSCFD, which is significantly increase of gas deliverability. The increment of productivity well deepwater GWK-8 is result of the acid dissolving impurities and blockage in the pore throat of the formation rock for hydrocarbon flowing pathway. The wellbore area two (2) feet to three (3) feet and Shape Memory Polymer (SMP) section are the main damage normalization target of matrix acidizing. Other factors that play in important role of the successful result of this project are the job execution procedure including pumping rate, maximum bottomhole pressure (BHP), pre-flush with Ammonium Chloride (NH_4Cl), over-flush and soaking for 30 minutes then immediately cleaned up or flowback to well-testing facility.

4. Conclusion

Based on the results of analysis and discussion that has been thoroughly executed, the conclusions can withdraw as follows:

1. In deep-water gas well exploration and production such as deepwater GWK-8 which is high cost of operation, gas production optimization is mandatory. Shape Memory Polymer (SMP) sand control system is new technology to filtered and strengthen sandstone formations to prevent sandstone breakthrough in order to achieve optimal productivity. This technology is an alternative solution for conventional Gravel Packs.
2. Combination hydrochloric acid (HCl) of 9% and hydrofluoric acid (HF) of 1% is successfully proven for sandstone formation with permeability 20 - 100 mD, high clays-silts, quartz, and feldspar. This combination will increase permeability by dissolving clays, quarts, feldspar and other minerals to enlarge the pore throat. This mud acid is effective for normalizing damage due to drilling, completion and production processes. The result is proven that matrix acidizing normalizes damage for shape memory polymer (SMP) sand control system installation.
3. Concern and precaution for by-products (precipitate) formation is the key because precipitate become blockages in the pores of wellbore formation. To minimize the occurrence of precipitate, application of higher ratio of HCl : HF for main acid and Ammonium Chloride (NH_4Cl) as pre-treatment.
4. Proven by accurate and comprehensive welltesting operation that significant increment of gas productivity. The gas production rate pre-matrix acidizing is 30 MMSCFD and post-matrix acidizing is increased up to 44 MMSCFD. Proven in reducing the skin number (s) from 46 to 10, increasing permeability (k) from 51.4 mD to 120 mD, and increasing productivity from 30 MMSCFD to 44 MMSCFD. This matrix acidizing optimization campaign project is play in important role for future development projects at similar gas well.

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