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Parametric Wormhole Studies on Matrix Acidizing Carbonate Reservoir

Teodoro Marcos Mota, Prof. Dr. Ir. Sudjati Rachmat, DEA
Lecturer of the School of Petroleum Studies, Lecturer of Petroleum Engineering
Dili Institute of Technology, Timor-Leste, Institut Teknology Bandung (ITB), Indonesia
Email: teodoro.marcosmota@yahoo.com , sudjati@tm.itb.ac.id

ABSTRACT

Matrix stimulation is one of the key intervention treatments that is performed to increase well productivity in carbonate formation reservoirs. Stimulation using matrix acidizing can cause a wormhole around the well so that it can increase the permeability around the wellbore which results in decrease of skin values. Wormholes are channels that resemble natural fractures that have very large permeability. Wormhole is the formation of branched holes in formation as a result of acidizing treatment. Skin is a barrier factor that affects the rate of production. Skin is an area of formation that is damaged. Skin formed around the wellbore. If it's positive value mean the area near wellbore is damaged and negative value if the area was improved or stimulated. In this research, by knowing the value of acid volume, permeability ratio (k/ks), porosity of the original formation, fractal dimension and acid injection rate, calculations were performed using the equivalent hydraulic radius concept and making a plot to see the effect on skin factor and productivity index (PI). The indicator of the success of implementing acidizing stimulation can be seen from the decrease in skin factor, increases in well productivity (productivity index ratio) and increased production rates.

Keywords: Well stimulation, matrix acidizing, skin, wormhole, fractal, equivalent hydraulic radius.

1. Introduction

One of the problems in oil and gas production wells is that the wells have very low production rates. This can be caused by low formation permeability and formation damage which causes the skin factor in wells to be positive and large. Formation damage refers to a region of decrease in permeability wells resulting in reduced performance of the wells, which can occur during drilling, cementing, workover operation, production, or even during acidizing and chemical treatment, followed by plugging of pore throats (McLeod, 1984; McLoad, 1989; Kankaria et al., 2017; Mou et al., 2019). Therefore, things that can be done is by stimulation of wells, either by using matrix acidizing or by hydraulic fracturing in order to increase well deliverability (Mahmoud et al., 2014). The purpose of performing well stimulation is to improve formation permeability (Li et al., 2019). Fracture and matrix acidizing are the two key techniques used in well stimulation (Pandey et al., 2018; Ali and Nasr-El-Din., 2019).

Matrix acidizing is a remedial well stimulation that done to overcome formation damage near wellbore or improve the permeability in order to enhance production (Huang et al., 2000; Rae and Lullo, 2003; Bulgakova et al., 2011; Gomma et al., 2015; Nasr-El-Din, et al., 2015; Rabie et al., 2015; Akanni, et al., 2017; Al-Othman et al, 2017; Wei et al., 2017; Alrashidi et al., 2018; Fan et al, 2018; Livescu et al., 2018; Li et al, 2019; Mou et al., 2019; Schwalbert et al., 2019). Matrix acidizing for carbonate reservoirs, Hydrochloric acid (HCL) is injected bellow the formation fracture pressure and used small amount of acid (Pandey et al., 2018; Ali and Nasr-El-Din, 2019). While in acid fracturing, the volume of acid injected is relatively large. The acid is always injected at a high rate and pressure or above the fracture pressure of the formation (Hung et al., 1989).

Matrix acidizing is a method of injecting acid into a reservoir under its fracture pressure so that the reaction can spread radially (Kankaria et al., 2017). The efficiency of this process depends on the type of acid used, injection conditions, medium structure, fluid to solid mass transfer, and others (Li et al., 2015). Matrix acidizing is one of the stimulation methods commonly used mainly in carbonate reservoirs. This matrix acidizing method is considered one of the most effective stimulation methods in terms of cost because its stimulation technique is simple and has high success rate (Burton et al., 2018). The result of this stimulation is an increase in permeability around the well due to a wormhole, a channel that resembles a natural fracture that has a very large permeability (Nasr-El-Din et al., 2015). This research aims to study the matrix acidizing of carbonate reservoirs and to see the effect of various factors such as the volume of acid, permeability ratio (k/ks), porosity of the original formation, fractal dimensions, injection rate and it's impact on skin factor and productivity index (PI).

2. Literature Review

2.1. Wormhole

A comprehensive study on wormhole has been conducted to improve the understanding of matrix acidizing in carbonate reservoirs (Burton et al., 2018). Wormhole is reactive acid injected into the formation to dissolve

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

carbonate rock and creates highly permeable channels (Fan et al., 2018; Cheng et al., 2019).

The wormhole-propagation mechanism has been studied using experiments by many researchers (Hoefner and Fogler., 1988; Pichler et al., 1992; Wang et al., 1993; Daccord et al., 1993a, b; Buijse., 2000). Typical wormhole patterns comprise face dissolution, conical shape, dominant wormhole, ramified wormhole, and uniform dissolution. Researchers found that there exists an optimal injection rate generating dominant wormholes. Below the optimal injection rate, face-dissolutions pattern or conical-shaped wormholes are created whereas ramified or uniform dissolution patterns are generated above the optimal one (Mou et al., 2019).

Matrix acidizing process is characterized by wormhole efficiency (Cheng et al., 2019). Figure 2.1 shows the wormhole patterns under different injection rate (McDuff et al., 2010). When injection rate is low, a compact dissolution patterns is observed, in which acid dissolves a large amount of rock near the core sample inlet. When injection rate is intermediate, a dominant wormhole pattern is created. When the injection rate is high, ramified wormhole is generated. For a given volume of acid injection there is an optimal injection rate under which the deepest wormhole penetration can be achieved (Wang et al., 1993; Cheng et al., 2019).

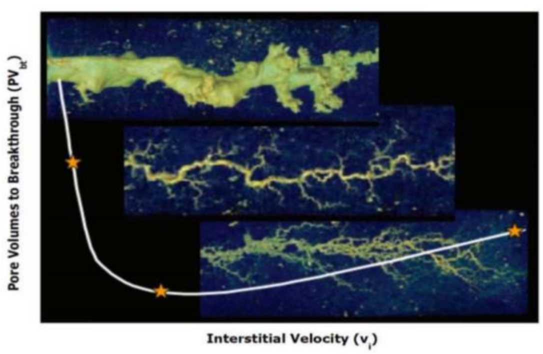

Figure 2.1. Dissolution patterns at different interstitial velocity (McDuff et al., 2010)

2.2. Acidizing

Acidizing was one of the earliest methods developed for increasing well productivity. The technique was first used in 1895, with patents issued in 1896. The patents describes a technique in which HCL is injected into a limestone formation, where it reacts to create channels within the rock (Al-Othman et al, 2017). Acid stimulation treatments are widely recognized as the primary technique to enhance production and increase injectivity in oil and gas field (Aldakkan et al., 2018). The success of such treatments relies heavily on the proper selection of the recipe and job design based on thorough investigation of the rock mineralogy, acid-rock reaction mechanism, diversion technologies and damage source (Muecke, 1982).

The goal of acid stimulation is to improve the near-wellbore permeability by propagating dissolution channels called wormholes beyond the drilling-damaged zone and into the original formation (Seagraves et al., 2018). In wormholes there is a very high increase in permeability that will connect the reservoir with the borehole thus increasing the rate of production (Rabie and Nasr-El-Din, 2015).

2.3. Matrix Acidizing

Matrix acidizing has been extensively used as an effective stimulation method to facilitate the development of carbonate reservoir due to the formation of high-permeability channels (Fan et al., 2018). In matrix acidizing in carbonate reservoirs, when acid is injected in to the formation, wormholes (highly conductive flow channels) or different dissolution patterns may form, depending on the properties of the rock and the acid system, as well as the injection rate (Seagraves et al., 2018; Schwalbert et al., 2019). The relationship between these dissolution patterns and the acidizing results has been studied before (Daccord et al., 1989; Fredd and Fogler., 1996; Fredd et al., 1997; McDuff et al., 2010).

Matrix acidizing may be implemented as a remedial method to minimize resultant skin (Aldakkan et al., 2018). Matrix carbonate acidizing is commonly conduced with HCL in concentration between 15-20 wt% (Aldakkan et al., 2018; Pandey et al., 2018). Carbonate reservoir, including limestones, chalks, and dolomites, are stimulated with simple acid systems, such as HCL while sandstone reservoirs are treated with more complex acid systems containing HF or HF/HCL mixtures (Burton et al., 2018). HCL is the commonly utilized fluid in acidizing treatments in carbonates (Aldakkan et al., 2018). Petroleum engineers usually use HCL solutions as acidizing fluids, but reservoir, fluids and compaction conditions may dictate the use of organic acids, chelating agents, or emulsified acids (Ali and Nasr-El-Din., 2019). HCL is the most commonly used acid in matrix acidizing of carbonates due to its cost effectiveness, availability, and soluble reaction products (Muecke, 1982; Kankaria et al., 2017).

Williams et al. (1979) describe the chemical stoichiometries reaction of HCL with limestone, dolomite and siderite are illustrated in equation 1-3:

a) Calcite: $2HCl + CaCO_3 \longrightarrow CaCl_2 + H_2O + CO_2$ (1)

b) Dolomite: $4HCl + CaMg(CO_3)2 \longrightarrow CaCl_2 + MgCl_2 + 2H_2O + 2CO_2$ (2)

c) Siderite: $2HCl + FeCO_3 \longrightarrow FeCl_2 + CO_2 + H_2O$ (3)

HCL is cheap, it has a high rock dissolving power and the reaction products are usually soluble. HCL-carbonate

Vol.1, Issue.1, pp.11-27, 2020
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reaction is also fast, especially at the higher temperatures encountered down hole (Buijse et al., 2003). The rapid reaction of HCL with carbonate rocks results in the formation of wormholes, which is the primary purpose of matrix acidizing in carbonates (Aldakkan et al., 2018). The effective penetrations of HCL can range from 1-5 ft (Aldakkan et al., 2018).

Figure 2.2 shows the wormhole profile created by the acid dissolution of limestone (Hoefner and Fogler, 1987). Table 1 summarizes the recommended acid package per treatment type (Guo et al., 2007).

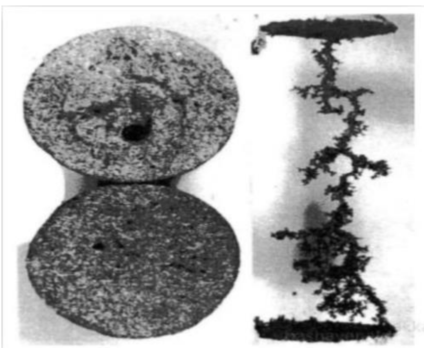

Figure 2.2. Wormhole profile created by acid dissolution in limestone cores (Hoefner and Fogler, 1987).

Table 1. Recommended acid package per carbonate acidizing treatment type (Guo et al., 2007).

Treatment Type	Damaged Perforations	Deep Wellbore Damage
Acid	5% Acetic Acid	15%HCl
	9% Formic Acid	28% HCl
	10% Acetic Acid	Emulsified Acid
	15% HCl	

Stimulation with matrix acidizing using HCL has high success rate and enhance production rate on carbonate reservoirs (Burton et al., 2018). As an example, some wells in the northern Buzurgan oil field before acidizing treatment only produced 1139 bbl/d, but after acidizing treatment cleared the scale, lowering the skin factor to -2.8 thereby increasing production at the well reaching 1571 bbl/d (Gao et al., 2019). Furthermore, there are more literature survey carried over more 500 wells in Middle Eastern, North Sea, Caspian, Southeast Asian, and North American fields show that high-rate matrix acidizing techniques can be used to effectively stimulated carbonate reservoirs (Burton et al., 2018). Field-post stimulation pressure buildup and production test data for carbonate matrix acidizing presented by Furui et al., (2012a) show that skin factors collected from separate groups of Middle Eastern Limestone and North Sea chalk wells both have P50/median skin values in the -3.5 to -4.0 range. Additional public data (Singh, 1985; Bartko et al., 1997; Chambers et al., 1997; MaGee et al., 1997; Aslam and Al Salat, 1998; Bazin et al., 1999; Gong and El-Rabaa, 1999; Sannier et al., 1999; Al-Dhalan and Nasr-El-Din, 2000; Fredd and Miller, 2000; Sharaf et al., 2000; Al-Dhafeeri et al., 2002; Thomas and Nasr-El-Din, 2003; Bitanov, 2005; Albuquerque et al., 2006; Abou-Sayed et al., 2007; Arangth et al., 2008; Haldar et al., 2008; Rachmawati et al., 2008; Thabet et al., 2009; Foglio and Wtorek, 2010; Ussenbayeva et al., 2012; Van Domelen et al., 2012; Jardim Neto, A.T. et al., 2013; Clancey et al., 2014; Cui et al., 2014; Folomeev et al., 2014; Kayumov et al., 2014; Issa et al., 2015) and additional ConocoPhillips data has been added to the original dataset to provide the plot showing in figure 2.3. As shown, P50/median skin values from the larger, combined data sets are in the same -3.5 to -4.0 range as reported previously (Burton et al., 2018).

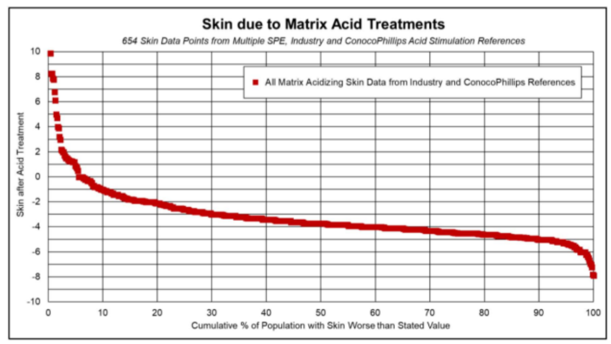

Figure 2.3. Industry skin data for matrix acidized carbonate wells (Burton et al., 2018).

The data set compiled for figure 2.3 covers a wide range of carbonate rock types with reservoir permeabilities ranging from less than 0.1 md to over 1000 md as shown in figure 2.4.

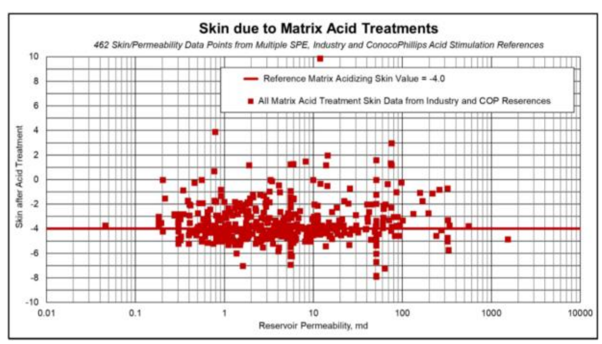

Figure 2.4. Industry skin data for matrix acidized carbonate wells vs reservoir permeability (Burton et al., 2018).

Review of the information in Figure 2.3 and 2.4 indicates that carbonate matrix acidizing results are roughly

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

similar over a wide range of well types, rock types, and reservoir permeabilities (Burton et al., 2018).

2.4. Skin Factor

Skin factor is a numerical factor that is used to measure formation damage and to model the additional pressure drop created due to skin (Elshahawi et al., 2001; Yildiz, 2006; Byrne and McPhee, 2012; Mohamed et al., 2014; Patel and Singh, 2016; Al-Othman et al., 2017; Schwalbert et al., 2019). Skin can be defined as the additional pressure drop in the near wellbore area that result from the drilling, completion and production practices used (Van Everdingen, 1953).

A positive skin factor is obtained when the near wellbore region has permeability lower than the native formation permeability (formation damage), while negative skin factor means the permeability of the near wellbore region has been increased (stimulation) (Byrne and McPhee, 2012; Mohamed et al., 2014; Patel et al., 2016; Shirley et al., 2017; Burton et al., 2018; Schwalbert et al., 2019). The skin factor obtained has a direct impact on the productivity of the well (Shirley et al., 2017). The degree to which the skin factor will impact the overall productivity/injectivity essentially depends on the wellbore geometry relative to the reservoirs (Shirley et al., 2017). Skin cause decrease in production wells, so skin also consider as an economic problem. Therefore, reducing the skin factor can also improve the productivity index and recovery rate for the well which further improves the project's net present value (Shirley et al., 2017; Burton et al., 2018; Gao et al., 2019).

Hawkins (1956), presented the following model to calculate the skin factor using the permeability and radius of the skin zone:

$$s = \left(\frac{k}{ks} - 1\right) x \ln \left(\frac{rs}{rw}\right) \tag{4}$$

Muscat, show the comparison of fluid productivity of damaged and undamaged wells with uniform permeability (Williams et al., 1979), as follows:

$$\frac{J_s}{J_o} = \frac{F_k \, \log\left(re/rw\right)}{\log\left(rs/rw\right) + F_k \, \log\left(re/rs\right)} \tag{5}$$

2.5. Planing Procedure Matrix Acidizing in Carbonate Reservoirs

Successful acid stimulation depends on three important treatment parameters which are fluid volume, injection flow rate, and fluid type (Van Domelen et al., 2011). Williams et al. (1979) describe matrix acidizing planing procedure in carbonate reservoirs are as follows:

Step 1: determine the fracture gradient for the well. The best data is obtained from the shut-in pressure measured during or immediately after fracture treatment. If no recent data can be obtained, the fracture gradient can be estimated with the approach relationship as given in the following equation:

$$gf = \alpha + (go - \alpha)\, x\, (Pr/D) \tag{6}$$

Step 2: estimate the maximum possible injection rate without fracturing with the equation:

$$qi_{\max} = \frac{4{,}917\, 10^{-6}\, k\, h\left(gf\;\; D - P_r\right)}{\mu \ln\left(re/rw\right)} \tag{7}$$

Step 3: estimate the maximum surface pressure without friction for fluids that can be injected without fracturing the formation by the equation:

$$Pmax = (gf - gha)\; x\; D \tag{8}$$

Step 4: determine the volume and type of acid being injected.

2.6. Fractals and Fractal Dimension

Fractal is the dissolution patterns of acid injected into carbonate formations. Fractals are shapes that grow proportionally to a fractal dimension (Frick et al., 1994). The fractal dimension is constant for each fractal object, regardless of the scale at which it is observed (Frick et al., 1994).

To determine the fractal dimension (df) we need to know the number of units (N) within a certain radius (R), it can also be written:

$$N(R) \approx R^{df} \tag{9}$$

For a 2D cluster of fractals, the constant varies between one and two (example 1.46) (Frick et al., 1994). From equation 9 above, we can determine the fractal dimension of a fractal object by calculating the slope plot between ln N (R) and ln R.

$$d_f = \lim_{R \to \infty} \frac{\ln N(R)}{\ln R} \tag{10}$$

where N (R) is the number of units growing within a certain radius (R).

2.7. Equivalent Hydraulic Radius

Equivalent hydraulic radius (r_{eq}) is introduced that represents the radius of a zone of neglible pressure drop (Frick et al., 1994). The following describes the various zones:

Zone 1. Nearest to the well: the wormhole creates new permeability, considered to be independent of the permeability of the previously damaged zone. The channels

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

are wide and the pressure drop can be ignored, so the pressure is constant within the wormholes.
Zone 2. Transition zone: the flow is divided between wormhole and porous medium. Ignoring this transition zone leads to equivalent hydraulic radius.

Zone 3. Zone outside the stimulation area: this zone is a porous media outside the stimulated area where the pressure varies radially according to Darcy's law. The wormhole radius will be replaced by the equivalent hydraulic radius which is a function of the fractal dimension (Frick et al., 1994).

The relationship between fractal dimensions and the radius of the observation area can be written as follows:

$$r_{eq} = \left(r_w^{\ df} + \frac{V_{acid}}{L_{inj}} N_{ac} N_{Pe}^{\ -1/3} \frac{b}{\pi\phi} \frac{df}{2} \right)^{1/df} \tag{11}$$

2.8. Calculation of the Post-Treatment Skin Effect

According to Muskat's formulation for two zones, a model was presented to explain the effect of post treatment skin for three zones with different permeability values (Frick et al., 1994).

a) For a stimulated zone, ($r_w \le r \le r_{eq}$), p = constant.
b) For a still damaged zone, (($r_{eq} \le r \le rs$), Darcy's Law.
c) For the original formation zone, ($r_s \le r \le re$), Darcy's Law

For the case of three zones, the post treatment skin effect can be determined by the equation:

$$s = \frac{k}{k_s} \ln \frac{r_s}{r_{eq}} - \ln \frac{r_s}{r_w} \quad , r_{eq} \le r_s \tag{12}$$

In the case of two zones, if the wormhole radius is greater than the damage radius the equation is as follows:

1. The stimulated zone, (($r_w \le r \le r_{eq}$), p = constant.
2. Original formation zone, ($r_{eq} \le r \le re$), Darcy's Law.

The post-treatment skin effect equation can be written as follows:

$$s = -\ln\left({r_{eq}}/{r_w} \right) , r_s \le r_{eq} \tag{13}$$

Figure 2.5 is used to calculate the skin factor before and after matrix acidizing, which shows a partition of the near-wellbore region into several zones with different radius and permeability (Bekibayev et al., 2015).

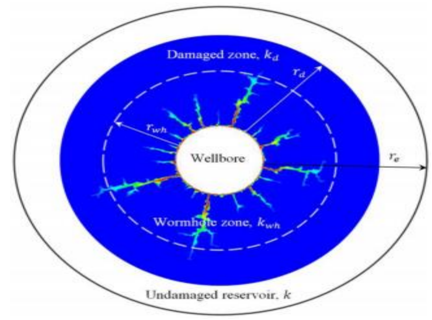

Figure 2.5. Schematic illustration of the near-wellbore zone with a variety of areas (Bekibayev et al., 2015).

3. Research Methods

The analysis and calculations carried out by this research are using well, reservoir and stimulation data by assuming the stimulation is carried out along the thickness of the vertical well formation. The data used in this research is shown in table 2 (appendix). With the flow of research to be carried out can be seen in figure 3.1 (appendix).

4. Results

4.1. Impact of Acid Volume and Permeability Ratio on Post Treatment Skin Effect

Figure 4.1 is the result of the plot of the merging ratio permeability value. This graph clearly shows that adding acid volume to different permeability ratio will decrease different skin values, especially with large permeability ratio, it will decrease skin factor to negative. This is because the acid injected into the reservoir will flow in areas of large permeability and form a conductive channel in the rock thus giving a reduction in the skin factor (Byrne and McPhee, 2012; Mohamed et al., 2014; Patel et al., 2016; Shirley et al., 2017; Kankaria et al., 2017; Burton et al., 2018; Schwalbert et al., 2019). The results figure 4.1 show the initial skin value of 8.85, 30.98, 64.18, after adding 1300 gal of acid volume to the permeability ratio (k/ks) of 5 md, 15 md, 30 md gave the skin a decrease of -2.43, -2.88, and - 3.55. The results table 3 (appendix) explain the acid volume value, the hydraulic equivalent radius value and the value of skin reduction at different permeability ratio.

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

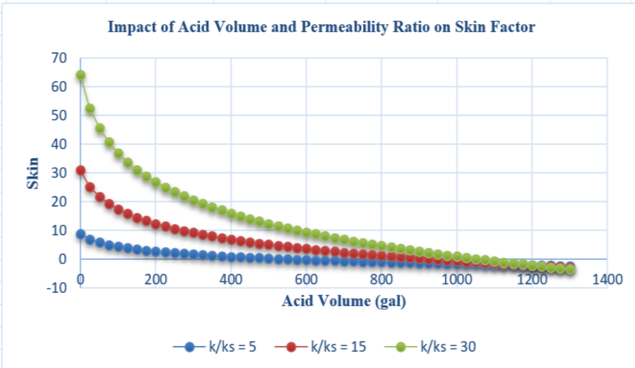

Figure 4.1. Impact of acid volume and permeability ratio (k/ks) 5 md, 15 md and 30 md on the post treatment skin effect.

4.2. Impact of Acid Volume and Porosity on Post Treatment Skin Effect

The graph below is the plot result of combining porosity values. From this graph by adding acid volume to different porosity values will result in decrease of skin factor. Figure 4.2 show an initial skin value of 8.85, after adding 1300 gal of acid volume to porosity 0.15, 0.20, 0.25 giving a decrease in skin to -3.36, -2.30, and -1.50. The results table 4 (appendix) explain the acid volume value, the hydraulic equivalent radius value and the skin reduction value at the different of the original formations porosity.

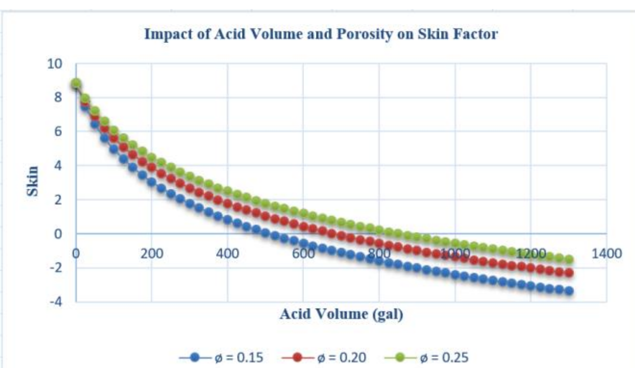

Figure 4.2. Effect of acid volume and porosity (ϕ) 0.15, 0.20, 0.25 on the post treatment skin effect.

4.3. Impact of Acid Volume and Fractal Dimension on Post Treatment Skin Effect

The graph below is a plot result of combining fractal dimension values. The smaller of fractal dimension value formed will have a better effect on decrease skin factor. This is because the small fractal dimension value has a long and branched wormhole shape, so it is able to penetrate the damage zone (Daccord et al., 1989; Fredd and Fogler., 1996; Fredd et al., 1997; McDuff et al., 2010; Seagraves et al., 2018; Schwalbert et al., 2019. The results figure 4.3 show that the initial skin value is 8.85, after adding 1300 gal of acid volume to the fractal dimensions 1.3, 1.75, 2 has a better effect on reducing the skin to -3.36, -2.43, -2.04. The results table 5 (appendix) explain the acid volume value, the equivalent hydraulic radius value and the skin reduction value at different fractal dimensions.

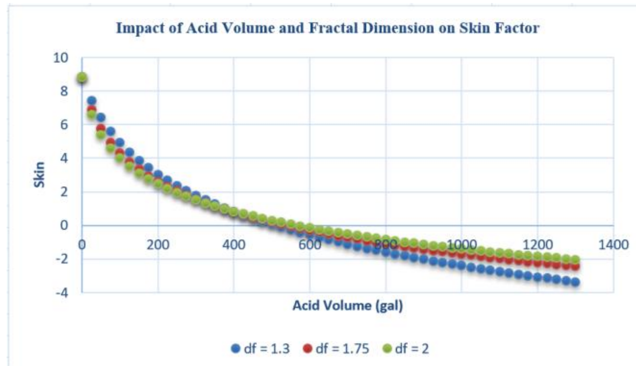

Figure 4.3. Impact of acid volume and fractal dimension values (df) 1.3, 1.75, 2 on the post treatment skin effect.

4.4. Impact of Acid Injection Rate on Post Treatment Skin Effect

The graph below shows the effect of acid injection rate on skin factors and stimulation performance. The results figure 4.4 show the initial skin value of 8.85, after adding 1300 gal of acid volume with an injection rate of 1 BPM, 3 BPM and 5 BPM giving skin decreases to -3.36, -2.02 and -1.41. The results of this analysis show that the optimal acid injection rate for matrix acidizing is 1 BPM because it gives a significant decrease in skin value -3.36. This is because at a small injection rate the volume of acid injected into the rock surface will form a wider, dominant and branched wormhole that will improve the damage zone and influence the skin factor (Wang et al., 1993; Cheng et al., 2019; Mou et al., 2019). Table 6 explain the effect of injection rate on skin factors on stimulation results.

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

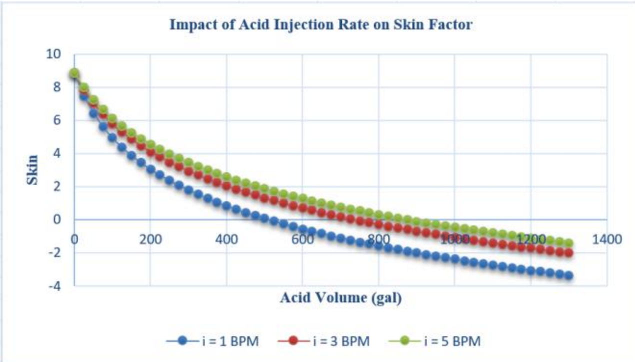

Figure 4.4. Impact of acid injection rate 1 BPM, 3 BPM, 5 BPM on the post treatment skin effect.

Table 6. Impact of injection rate on stimulation results.

Injection rate, bpm	Skin, pre-treatment	Skin, post-treatment
1	8.85	-3.36
3	8.85	-2.02
5	8.85	-1.41

4.5. Impact of Permeability Ratio on Productivity Index Ratio

The graph below is the result plot of the combined value of permeability ratio. From the plot results figure 4.5 show that adding an acid volume to a large permeability ratio will provide a significant increase in the productivity index ratio (PI ratio). Smaller value of permeability ratio will have a small effect on increasing the PI ratio. This is because the small permeability ratio has a small gap or space to pass fluid from productive formation into the wellbore and vice versa. The results of the research in figure 4.5 show after addition of 1300 gal acid volume to the permeability ratio (k/ks) of 5 md, 15 md, 30 md gives an increase in PI ratio of 3.16, 8.11, 17.58. The results of study in table 7 explain the effect of k/ks on the PI ratio in stimulation results.

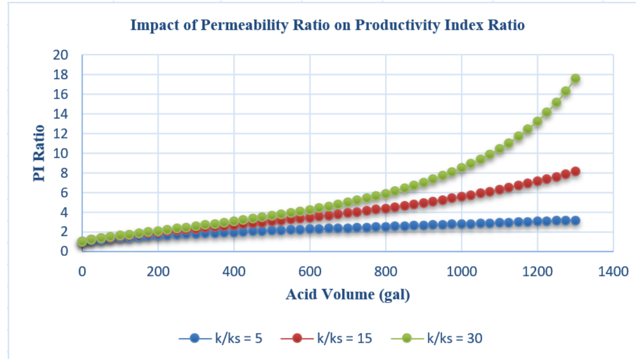

Figure 4.5. Impact of permeability ratio (k/ks) 5 md, 15 md, 30 md on PI ratio.

Table 7. Effects of permeability ratio on stimulation results.

Permeability ratio, md	PI ratio, pre-treatment	PI ratio, post-treatment
5	1	3.16
15	1	8.11
30	1	17.58

5. Conclusions and Recommendations

5.1. Conclusions

The following conclusions can be drawn from this work:

1. The results of the research show that adding acid volume to different permeability ratio (k/ks) will give a significant reduction in skin factor. Results of the study showed the initial skin pre-treatment was 8.85, 30.98, 64.18, after treatment with 1300 gal acid volume in the k/ks 5 md, 15 md, 30 md gave a decrease in skin factor -2.43, -2.88, and -3.55.

2. The results show that after treatment with the addition of acid volume at different porosity values, it will give a different skin factor reduction. The results showed initial skin factor before treatment was 8.85, after treatment with the addition of 1300 gal acid volume to the porosity of the original formation 0.15, 0.20, 0.25 gave a decrease in the skin factor -3.36, -2.30, and -1.50.

3. Research show that the smaller of fractal dimension value formed would have a better effect on the decrease in skin factors. Results of study showed an initial skin factor of 8.85, after acidizing with the addition of 1300 gal acid volume in the fractal dimensions 1.3, 1.75, 2 had a better effect on decreasing the skin factor to -3.36, -2.43, -2.04.

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

4. From the results of the study showed that effect of injection rate is very important on the performance of the stimulation. The results of the analysis show that an initial skin factor of 8.85, after acidizing with an additional volume of 1300 gal of acid with an injection rate of 1 BPM, 3 BPM, 5 BPM gave a decrease in the skin factor -3.36, -2.02 and -1.41.

5. Results showed high permeability ratio and small fractal dimension, resulting in a good increase in productivity index (PI) and significant decrease in skin factor (S < -3.55). From the results of the analysis of the study showed initial value of the productivity index ratio (PI ratio) is 1, after treatment with acid volume of 1300 gal on permeability ratio (k/ks) 5, 15, 30 had impact on increasing the PI ratio 3.16, 8.11, and 17.58.

5.2. Recommendations

1. Need to know in advance the source and degree of formation damage, rock type when designing stimulation with matrix acidizing which includes selection of the proper type of acid, techniques and appropriate implementation in the field in order to reduce formation damage, low skin factor, enhance permeability formation and improving productivity of wells.

2. It is best to do drilling with underbalanced drilling and underbalanced completion methods to prevent formation damage due to lost circulation in the fracture zone.

3. It is better before acidizing, needs to evaluated in advance the cause of decreased in production rate, in term of production facilities, sub-surface condition; insufficient driving energy, decreased reserves and/or low permeability, so that it will facilitate the process of stimulation, safe, less toxic, environmental friendly, and cost effective in designing acidizing treatment.

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Nomenclature

α	= constant, range between 0,33-0,50
b	= constant Daccord, 1.7 x 10^4 m^{df-2}
C_{acid}	= acid concentration, mol/L^3, mol/ft^3
df	= fractal dimension, dimensionless
D	= diffusion constant, 10^{-5} ft^2/sec
D	= well depth, ft
F_k	= original permeability of formation to skin permeability, md
gf	= fracture gradient, psi/ft
gha	= acid hidrostatics gradient, psi/ft
go	= overburden gradient, psi/ft
h	= formation thickness, L, ft
i	= injection rate, L^3/t, ft^3/sec, bbl/min
J_s	= PI of damaged well, L^4t/m, STB/D-psi
J_o	= PI of stimulated well, L^4t/m, STB/D-psi
k	= permeability of improved (stimulated) zone, L^2, md
k_s	= permeability of damaged zone (skin), L^2, md
k/k_s	= permeability ratio, L^2, md
L_{inj}	= length of stimulated interval, L, ft
μ	= acid viscosity, cp
M_{min}	= molecular weight of dissolvable mineral, lbm/mol
$N(R)$	= many units at a radius
N_{ac}	= acid capacity number, dimensionless
N_{Pe}	= Peclet number, dimensionless
ϕ	= porosity
p_{max}	= maximum fluid pressure, psi/ft
Pr	= reservoir pressure, psi
qi_{max}	= maximum injection rate, bbl/ft
re	= drainage radius, L, ft
r_{eq}	= equivalent hydraulics radius, ft
r_s	= radial penetration of damage, L, ft
r_w	= wellbore radius, L, ft
r_{WH}	= wormhole radius, L, ft
s	= skin factor, dimensionless
V_{acid}	= acid volume, gal, ft^3

Greek

γ	= stoichiometric constant, dimensionless
ρ_{Min}	= density of dissolved mineral, m/L^3, lbm/ft^3

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Vol.1, Issue.1, pp.11-27, 2020
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Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

Appendix

Tabel 2. Well, Reservoir, and Stimulation Data for Case Study

Parameter	Unit	Case
Drainage radius (r_e)	ft	1450
Wellbore radius (r_w)	ft	0.328 (7 7/8" well)
Radial penetration of damage (r_s)	ft	3
Formation thicness (h)	ft	45
Permeability ratio (k/ks)	md	5, 15, 30
Porosity (ϕ)	%	0.15, 0.20, 0.25
Injection rate (i)	bbl/min	1, 3, 5
Acid concentration (C_{acid})	%	10
Density of dissolved mineral (p_{min}/M_{min})	ft^3/mol	5916 x 10^{-4}
Diffusion constant (D)	cm2/sec	10^{-5}
y *(dolomite)*		4
Fractal dimension (df)		1.3, 1.75, 2
b (m^{df-2})		1.25 x 10^4
Acid volume (V*acid*)	gal	1300

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

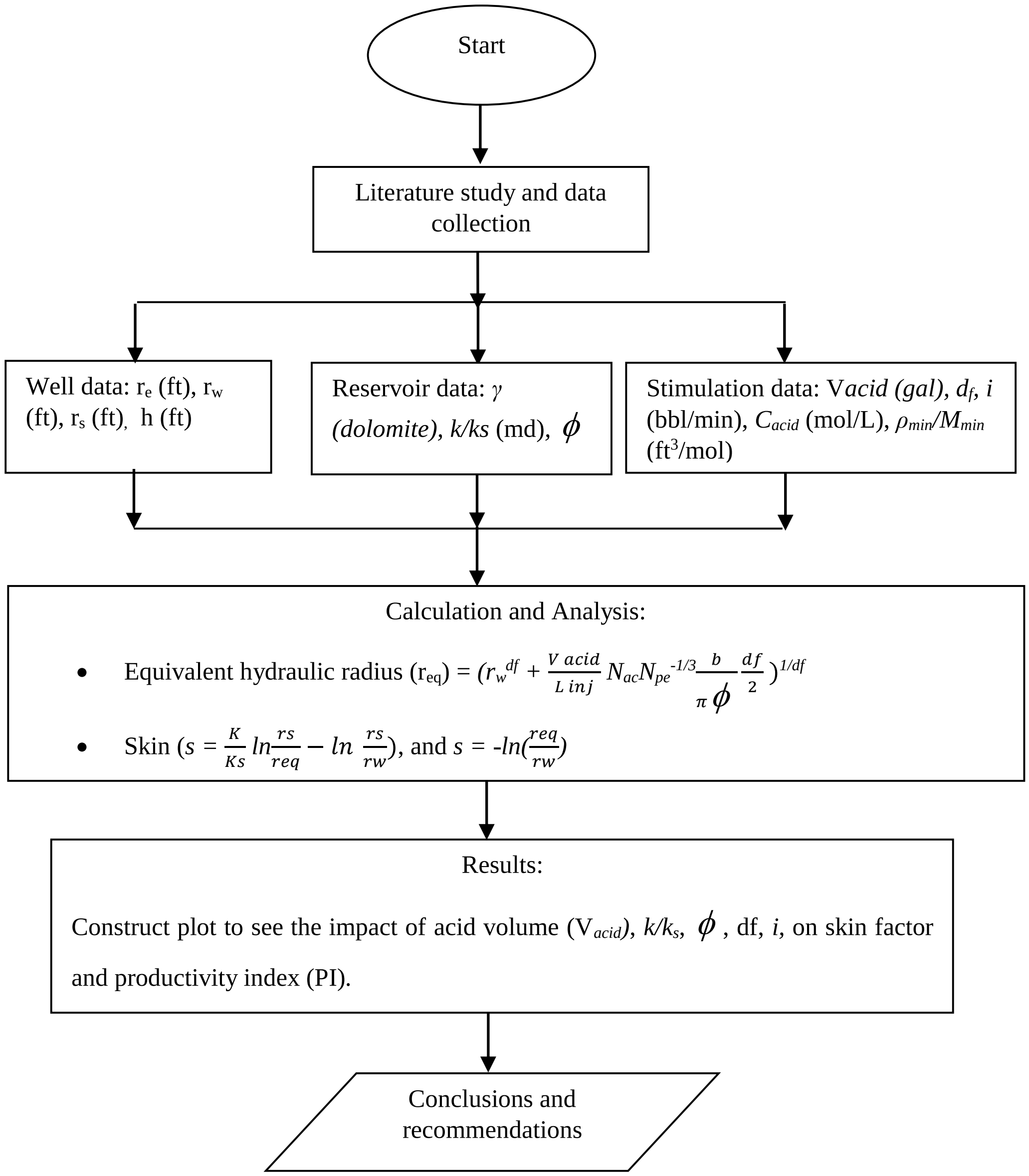

Figure 3.1. Research flow

Timor-Leste Journal of Engineering and Science

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

Table 3. Study results of the calculation of equivalent hydraulic radius (r_{eq}) and calculation of post-treatment skin effects with different permeability ratio values.

V acid (gal)	V acid (cuft)	r_{eq}	k/ks = 5 s	k/ks = 15 s	k/ks = 30 s
0	0	0.328	8.853415837	30.98695	64.18726
50	6.68403	0.61012568	5.750159034	21.67718	45.567
100	13.36806	0.815767329	4.29783799	17.32022	36.8537
150	20.05209	0.988098539	3.339571734	14.44542	31.1042
200	26.73612	1.14030133	2.623244723	12.29644	26.8062
250	33.42015	1.278571247	2.050991276	10.5796	23.3727
300	40.10418	1.406425744	1.574449719	9.15005	20.5134
350	46.78821	1.526095608	1.166144566	7.92514	18.0636
400	53.47224	1.63910371	0.808959612	6.85358	15.9205
450	60.15627	1.746545994	0.491506885	5.90122	14.0158
500	66.8403	1.849243166	0.205825205	5.04418	12.3017
550	73.52433	1.947829239	-0.053870223	4.26509	10.7435
600	80.20836	2.042806405	-0.291915271	3.55096	9.31527
650	86.89239	2.134580706	-0.511643699	2.89177	7.99690
700	93.57642	2.22348614	-0.715674004	2.27968	6.77272
750	100.26045	2.309801491	-0.906100447	1.708406	5.63016
800	106.94448	2.393762397	-1.08462428	1.17283	4.55902
850	113.62851	2.475570218	-1.252646319	0.66876	3.55089
900	120.31254	2.555398681	-1.411333771	0.19270	2.598767
950	126.99657	2.633398949	-1.561669455	-0.25830	1.69675
1000	133.6806	2.709703548	-1.704488701	-0.68675	0.83983
1050	140.36463	2.784429458	-1.840507465	-1.09481	0.02372
1100	147.04866	2.857680566	-1.970344041	-1.48432	-0.75529
1150	153.73269	2.929549649	-2.094536054	-1.85690	-1.50044
1200	160.41672	3.000119975	-2.213553913	-2.21395	-2.21455
1250	167.10075	3.069466629	-2.327811567	-2.55672	-2.90009
1300	173.78478	3.137657602	-2.437675191	-2.88631	-3.55928

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

Table 4. Study results of the calculation of the equivalent hydraulic radius (r_{eq}) and the calculation of post-treatment skin effects with different porosity values.

		ø = 0.15		**ø = 0.20**		**ø = 0.25**	
V acid (gal)	**V acid (cuft)**	r_{eq}	**s**	**req**	**s**	**req**	**s**
0	0	0.328	8.85341	0.328	8.85341	0.328	8.853416
50	6.68403	0.53368	6.41945	0.48487	6.89902	0.45487	7.218374
100	13.36806	0.71737	4.94051	0.62755	5.60933	0.571784	6.074674
150	20.05209	0.8877	3.87496	0.76101	4.64520	0.68187	5.194262
200	26.73612	1.0487	3.04147	0.88776	3.87496	0.78684	4.478319
250	33.42015	1.2027	2.35683	1.00927	3.23353	0.88776	3.874961
300	40.10418	1.3509	1.77584	1.12654	2.6839	0.98534	3.353544
350	46.78821	1.4943	1.27120	1.24024	2.20315	1.08009	2.89445
400	53.47224	1.6337	0.82517	1.35090	1.77584	1.17241	2.484358
450	60.15627	1.7697	0.42552	1.45889	1.39129	1.26260	2.113809
500	66.8403	1.90262	0.06352	1.56454	1.04172	1.35090	1.775844
550	73.52433	2.0327	-0.26731	1.66809	0.7212	1.43749	1.465192
600	80.20836	2.16047	-0.57193	1.76974	0.42552	1.52255	1.177767
650	86.89239	2.2859	-0.85419	1.86967	0.15088	1.60620	0.910336
700	93.57642	2.4093	-1.11714	1.96802	-0.10544	1.68856	0.660298
750	100.26045	2.53094	-1.36326	2.0649	-0.34576	1.76974	0.425526
800	106.94448	2.65078	-1.59457	2.16047	-0.57193	1.84982	0.204265
850	113.62851	2.76901	-1.81275	2.25477	-0.7855	1.92886	-0.00496
900	120.31254	2.88575	-2.0192	2.34790	-0.98791	2.00695	-0.20338
950	126.99657	3.0010	-2.21517	2.43994	-1.18016	2.08413	-0.39207
1000	133.6806	3.11511	-2.4016	2.53094	-1.36326	2.16047	-0.57194
1050	140.36463	3.22790	-2.57945	2.62098	-1.53803	2.23601	-0.74376
1100	147.04866	3.33951	-2.74941	2.71009	-1.7052	2.3107	-0.90824
1150	153.73269	3.45001	-2.91219	2.7983	-1.86542	2.38484	-1.06597
1200	160.41672	3.55947	-3.06835	2.8857	-2.0192	2.45822	-1.21749
1250	167.10075	3.66792	-3.21842	2.97238	-2.16711	2.53094	-1.36326
1300	173.78478	3.77542	-3.36285	3.05826	-2.3095	2.60304	-1.50371

Vol.1, Issue.1, pp.11-27, 2020
Available online at: https://www.tljes.org/index.php/tljes/issue/archive

Table 5. Study results of the calculation of the equivalent hydraulic radius (r_{eq}) and calculation of post-treatment skin effects with different fractal dimension values.

		df = 1.3		df = 1.75		df = 2	
V acid (gal)	**V acid (cuft)**	r_{eq}	**s**	r_{eq}	**s**	r_{eq}	**s**
0	0	0.328	8.853416	0.328	8.85341	0.328	8.8534
50	6.68403	0.53368	6.419451	0.61012	5.75015	0.6530	5.4101
100	13.36806	0.71737	4.940516	0.81576	4.2978	0.8633	4.0143
150	20.05209	0.88776	3.874961	0.98809	3.3395	1.0316	3.1239
200	26.73612	1.04879	3.041475	1.14030	2.6232	1.17608	2.4687
250	33.42015	1.20270	2.356834	1.27857	2.05099	1.3046	1.9500
300	40.10418	1.35090	1.775844	1.40642	1.57444	1.4216	1.5207
350	46.78821	1.49436	1.271209	1.52609	1.16614	1.5296	1.1544
400	53.47224	1.63379	0.825171	1.6391	0.80895	1.6305	0.8350
450	60.15627	1.76974	0.425526	1.74654	0.49150	1.7255	0.55186
500	66.8403	1.90262	0.063527	1.8492	0.20582	1.8156	0.2975
550	73.52433	2.03277	-0.26731	1.9478	-0.05387	1.9014	0.0666
600	80.20836	2.16047	-0.57194	2.04280	-0.29191	1.9835	-0.1446
650	86.89239	2.28594	-0.85419	2.13458	-0.51164	2.0623	-0.3394
700	93.57642	2.40938	-1.11714	2.2234	-0.71567	2.1382	-0.5202
750	100.26045	2.53094	-1.36326	2.3098	-0.90610	2.2115	-0.6888
800	106.94448	2.65078	-1.59457	2.39376	-1.0846	2.2825	-0.8467
850	113.62851	2.76901	-1.81276	2.47557	-1.25264	2.3513	-0.9952
900	120.31254	2.8857	-2.01923	2.55539	-1.41133	2.4182	-1.1354
950	126.99657	3.0010	-2.21518	2.6333	-1.56166	2.4832	-1.2681
1000	133.6806	3.11511	-2.40163	2.70970	-1.70448	2.54666	-1.3942
1050	140.36463	3.22790	-2.57945	2.78442	-1.84050	2.60852	-1.5142
1100	147.04866	3.33951	-2.74942	2.85768	-1.9703	2.66895	-1.6287
1150	153.73269	3.45001	-2.91219	2.9295	-2.09453	2.72804	-1.7382
1200	160.41672	3.55947	-3.06835	3.00011	-2.2135	2.7858	-1.8431
1250	167.10075	3.66792	-3.21842	3.06946	-2.3278	2.8425	-1.9437
1300	173.78478	3.775422	-3.36285	3.13765	-2.4376	2.89808	-2.0405