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Experimental Design Study of Hydraulic Fracturing Application in Water Dominated Geothermal Field Numerical Simulator, Improvement and Comparison of Parameters and Experimental Designs

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ABSTRACT

Geothermal wells that have existing heat and fluids but are lack of permeability usually end up being not commercial, this problem could be solved by implementing hydraulic fracturing stimulation that has been a huge success in the oil and gas industry. Hydraulic fracturing is a stimulation method used to increase the performance of a well by creating artificial fractures which will increase near-wellbore permeability, overcome formation damage and connect natural fractures that already exist in the reservoir. This study is a development from a previous study with additional tested parameter and two experimental designs (full factorial and Plackett-Burman) to study the uncertainty parameters of hydraulic fracturing stimulation in a water dominated reservoir for the outcome of mass rate, by using existing published CMG STARS numerical model of Wairakei geothermal field. The simulation results from each experimental design scenarios are then followed by a statistical analysis using MiniTab software and a Monte Carlo simulation for a probabilistic result. The result concluded that fracture half-length appears to be the most significant parameter and the most probable mass rate output after hydraulic fracturing implementation or P10 from the Monte Carlo Simulation is estimated to be around 115 kg/s which is 1.6 times the base case for both designs. While the P50 and P90 for full factorial design are 346 kg/s and 752 kg/s and for Plackett-Burman 317 kg/s and 519 kg/s respectively. Compared to previous study, the additional parameter ends up being the least significant parameter to the mass rate output, therefore no significant impact. Furthermore, unlike the use of full factorial design, Plackett-Burman experimental design produces an unsatisfactory result when used in this study.

1. INTRODUCTION

Geothermal wells can be categorized as a productive and commercial well when it has existing heat, geothermal fluids and good permeability. Statistical study (Sanyal, et al., 2014), based on 215 geothermal wells from 80 sites in Indonesia shows that 38 percent of drilled geothermal wells generate well productivity less than two megawatt which is considered relatively not commercial as shown in Figure 1**Error! Reference source not found.**. Wells which are considered not commercial are usually ended up turning into injection wells, observation wells or abandoned wells. Sanyal, et al (2014) also concluded that most of the remaining commercial successful wells only generate well productivity of 3 to 5 MW, which is considered low, as shown in Figure 2. Unsuccessful and low productivity wells could occur due to several causes such as formation damage, completion effects or lack of connectivity to main fluid conduits (Flores, et al., 2005). Furthermore, it can economically affect the utilization of a geothermal project.

The utilization of Indonesian geothermal energy could be improved by drilling new wells or improving uncommercial wells that already exists. Since drilling a new well is high in cost and very difficult in regard to legal permits administration, improving existing unsuccessful and low productivity wells seems to be a good option one of which is by hydraulic fracturing stimulation. Adapting stimulation treatment from the petroleum industry, hydraulic fracturing which has been developed since 1947 in the United States of America, started to be implemented in the geothermal industry in the 1970s. Since then, hydraulic fracturing has been used in geothermal formations as a means to stimulate both production and injection wells (Naceur & Economides, 1998). Hydraulic fracturing is a stimulation method that is used to increase the performance of a well by increasing the productivity index or the injectivity index. It creates artificial fractures which will increase near-wellbore permeability, overcome formation damage and connect natural fractures that already exist in the reservoir. Almost all producing geothermal reservoirs are naturally fractured, and a well may not always produce when a fracture is not met because of the low matrix permeability; therefore, hydraulic fracturing is being attempted (Naceur & Economides, 1998).

Attempts of implementing such method in geothermal fields has been conducted over the years in several fields such as East Mesa and Baca Field in the United States, Baca Field in Mexico, Salak Mountain and Wayang Windu in Indoesia, Soultz-Sous-Foretz in France and Landau in Germany (Asri & Rachmat, 2016). However, there are several challenges and issues towards this action, geothermal reservoir generally has some existing fracture permeability, so it is difficult to build up the pressures required for true hydraulic fracturing. It has also been difficult to find proper proppants which could maintain strength and property at a very high temperatures that is found in geothermal reservoirs. Another issue is that geothermal wells is usually completed with an open hole hanging liner at the very bottom which made it another challenge to concentrate pressure at a specific depth to fracture the formation.

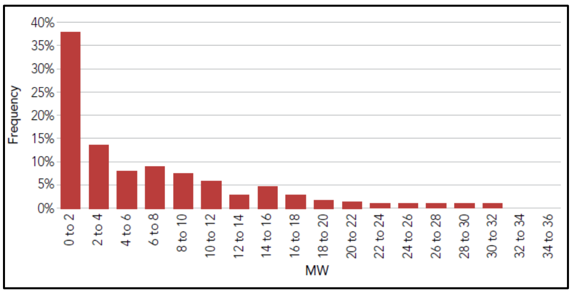


Figure 1: Histogram of Indonesia's well capacity (Sanyal, et al., 2014)

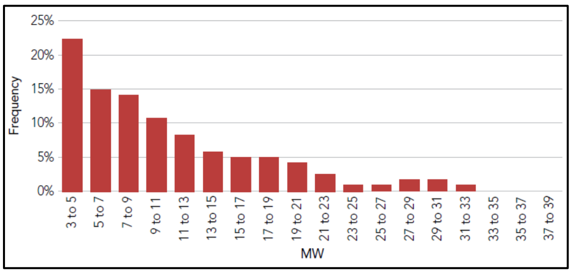


Figure 2: Histogram of Indonesia's commercial well capacity (Sanyal, et al., 2014)

Since the means of hydraulic fracturing is to increase the performance of the well, it is essential to predict the improvement of mass rate after hydraulic fracturing stimulation. Therefore, in this study, mass rate production after hydraulic fracturing stimulation in water dominated geothermal field is predicted using probabilistic Monte Carlo simulation. The probabilistic method is chosen to generate a range of results, different from the single value resulted from the deterministic method, which will lower the possibility of error. Previous studies in geothermal sectors has also uses this probabilistic Monte Carlo approach (Hidayat, et al., 2017), (Ahmad, et al., 2017), (Quinao & Zarrouk, 2014).

Experimental design is a scientific approach that is usually used to analyzed how an input affects the response or the desire output by changing inputs and also comprehend the existing process. This method has been used by several previous studies especially for resource assessment in geothermal fields (Ashat, 2018) (Quinao & Zarrouk, 2018). In this study, experimental design is applied to generate the proxy polynomial used in Monte Carlo probabilistic simulation and to study the significances of the uncertainty input parameters of hydraulic fracturing stimulation which is taken from the previous study by Reinicke (2011), and Hofmann, et al. (2012). This study uses the same numerical model and steps from the previous study by Judawisastra (2018) with the improvement of adding parameter and using a different type of experimental design.

2. OBJECTIVE

The objectives of this study are:

1. Executing a mass rate prediction of 30 years of production after hydraulic fracturing stimulation in various hydraulic fracturing scenarios.
2. Generating a proxy polynomial equation to describe mass rate production one year after hydraulic fracturing stimulation by using full factorial and Plackett-Burman experimental design.
3. Analyzing the input parameter significances regarding geothermal field hydraulic fracturing.
4. Estimating the increase of mass rate production after hydraulic fracturing stimulation estimation using probabilistic Monte Carlo simulation.
5. Analysing the effect of adding a parameter into the study.
6. Comparing the full factorial and Plackett-Burman experimental design use for hydraulic fracturing in water dominated geothermal field analysis.

However, this study has also a few limitations as follows:

1. The numerical model which is being used in this study has not been calibrated with the recent field production history real data, hence only uses existing natural state numerical model generated from the previous study.
2. The hydraulic fracturing parameters that are being tested in this study is limited to four parameters, which are fracture half-length, fracture width, fracture permeability and penetration.

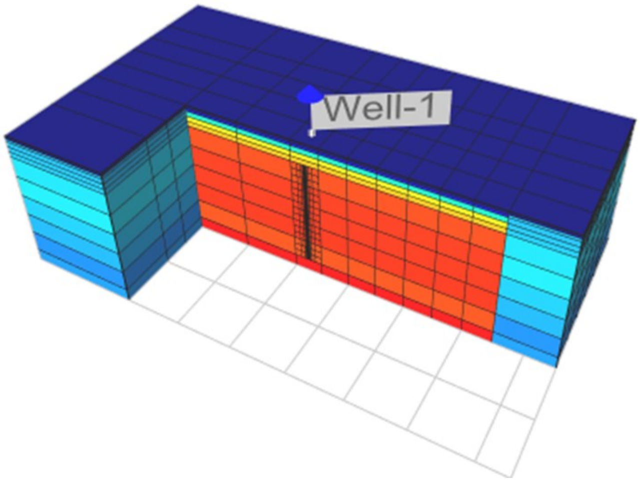
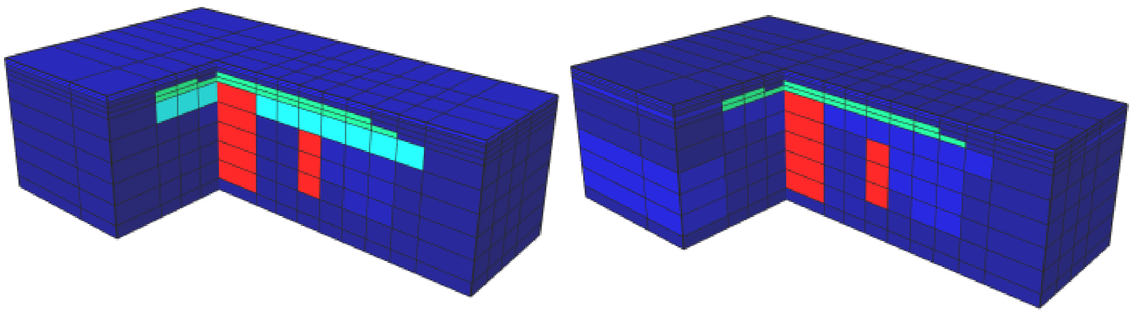


Figure 3: Numerical model visualization after hydraulic fracturing (Judawisastra, 2018)

3. METHODOLOGY

The numerical model used by this study is a model of Wairakei geothermal field, New Zealand developed by a previous study (Lukmana, 2017) and the procedure from previous study (Judawisastra, et al., 2018) is adopted to conduct the hydraulic fracturing simulation using CMG STARS simulator. The visualization example of the numerical model used in this study after hydraulic fracturing can be seen in Figure 3 and the permeability distribution can be seen in Figure 4 and Figure 5.



(a) (b)

Figure 4: Numerical model permeability distribution visualization I and J direction (a) and K direction (b) (Lukmana, 2017) Modified by Judawisastra, 2019.

No	Color	Permeability I and J	Permeability K
1		0.01-1 mD	0.01-1mD
2		1- 50 mD	1-10 mD
3		500-800 mD	50 mD
4		400 mD	-
5		1000 mD	100 mD

Figure 5: Numerical Model Permeability Distribution table (Lukmana, 2017) Modified by Judawisastra, 2019.

Methodology flowchart of this study is presented in Figure 6. First, the parameters to be tested are selected followed by determining the maximum minimum value for each parameter and generating the matrix combination scenario of the experimental design used. Next, numerical models are generated based on the matrix scenario and parameter value. Thirty years of production simulation for a single well is then run for each of the numerical models. Results are then analyzed using MiniTab software to obtain the proxy polynomial equation and other statistical data. The last step is to run the Monte Carlo probabilistic simulation based on the obtained proxy polynomial equation to obtain the most probable mass rate. The output of statistical analysis and Monte Carlo simulations from both experimental designs are then compared and analyzed. Meanwhile, the previous study is compared to the output of full factorial design.

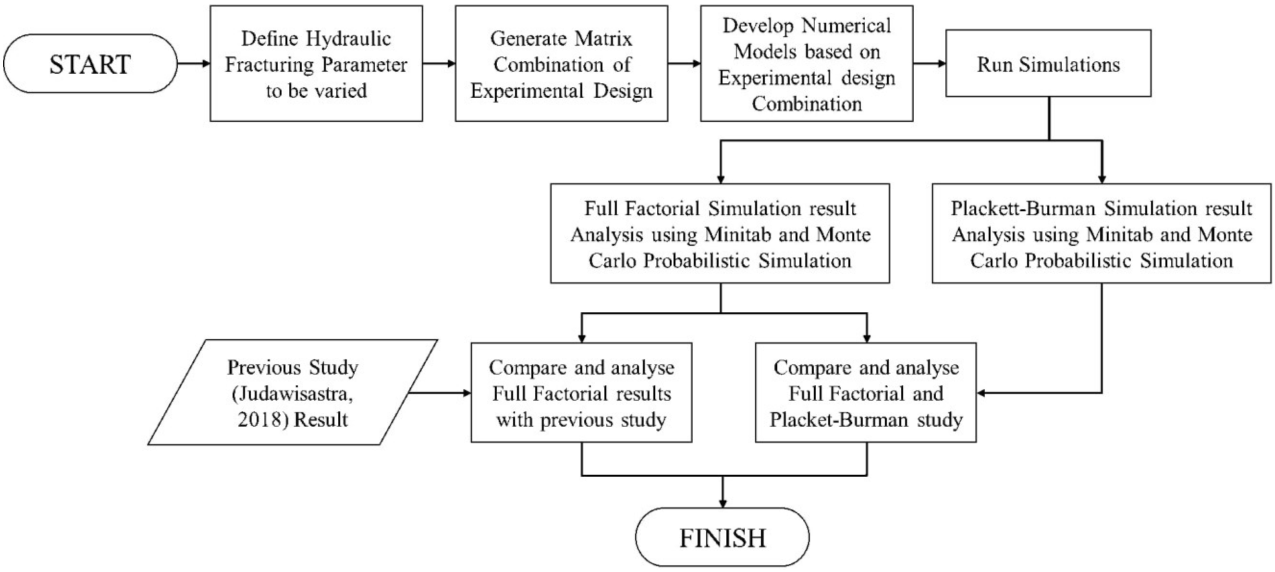


Figure 6: Methodology workflow

4. EXPERIMENTAL DESIGN

Full factorial design and a Plackett-Burman design are used in this study by means to compare both results for the study of hydraulic fracturing in the geothermal field. For both designs, four parameters are investigated at two levels (max [+1] and min [-1]) to identify the significant parameters which affect fluid production after the hydraulic fracturing treatment is conducted. These four parameters are fracture half-length (x_f), fracture width (w), fracture permeability (k_f) and penetration (p). Fracture half-length describes how far does 1 wing length of the fracture go throughout the reservoir. Fracture width describes how wide the fracture open in the reservoir, fracture permeability illustrates the capability of the fracture to allow fluids pass through. The last parameter, penetration describes the length of the liner where hydraulic fracturing is conducted to form the fractures or can also describes how many feed zones are being hydraulically fractured.

The maximum and minimum value of the first 3 parameters, which are fracture permeability, fracture width and fracture half-length that is being tested in this study is based on Reinicke (2011), and Hofmann, et al. (2012) which was also used in the previous study (Judawisastra, et al., 2018). Whereas, penetration parameter values are based on the numerical model being used. The minimum value of penetration parameter is 1 layer of reservoir numerical model which describes 1 feed zone, because it is the least number layer of reservoir that could be chosen. Meanwhile, the maximum value of penetration is 3 layers which indicated multiple feed zones, considering that the full penetration of hydraulic fracturing treatment could only be conducted in the feed zones which are in the range of the liner depth. The liner length itself is assumed to be no more than half-length of the whole well. The minimum and maximum value of the four parameters are presented in Figure 7.

Parameter		Min (-1)	Max (+1)
A	Fracture Half-Length (x_f)	5 m	250 m
B	Fracture Width (w)	1 mm	25 mm
C	Fracture Permeability (k_f)	10 D	1000 D
D	Penetration (p)	1 layer	3 layers

Figure 7: Experimental design parameters value.

By using MiniTab software, a two-level full factorial design with 4 parameters generated 16 different scenarios while a two-level Plackett-Burman design of 4 parameters generated 12 scenarios. The parameters conditions for scenarios from both full factorial design and Plackett-Burman design, which is generated using MiniTab software is shown in Figure 8. The blue highlighted rows indicate the scenarios that are not used for Plackett-Burman design. As indicated by the number of scenarios, using Plackett-Burman design produce less numerical models to be built, where in this case 4 scenarios less. This is only a simple example of difference; more parameters and more complex experimental design will result a significant difference in numbers of scenarios between the two design which also means much less simulation run time for Plackett-Burman design compared to the full factorial design. It must be noted that the range of parameter values that are being used will directly limit the results within the values identified. Therefore, an expert's judgment should ideally be used in order to guide the parameter values.

Scenario	x_f	w	k_f	p
1	-1	-1	-1	-1
2	-1	-1	-1	1
3	-1	-1	1	-1
4	-1	-1	1	1
5	-1	1	-1	-1
6	-1	1	-1	1
7	-1	1	1	-1
8	-1	1	1	1
9	1	-1	-1	-1
10	1	-1	-1	1
11	1	-1	1	-1
12	1	-1	1	1
13	1	1	-1	-1
14	1	1	-1	1
15	1	1	1	-1
16	1	1	1	1

Figure 8: Two-level experimental design scenarios.

Next, numerical models are built based on the experimental design scenario and the minimum and maximum value of the parameters. The simulation is conducted to generate a fluid production profile for 30 years of production at 50 bar constant bottom hole pressure production.

5. RESULT AND DISCUSSION

5.1 Mass Rate Prediction of 16 Scenarios

From the executed simulation, mass rate production for each of the 16 scenarios is collected. As predicted, mass rate production throughout the 30 years of production keeps declining for all the scenarios due to non-injection scenario applied to this simulation. Furthermore expected, all the scenarios deliver various mass rate data, which are always larger than the mass rate from the base case where no hydraulic fracturing treatments are applied. Hence, the results suggest that the hydraulic fracturing treatment method to the numerical model fulfill the purpose of the hydraulic fracturing stimulation to increase the mass rate production of the well under the same condition.

Scenario	x_f	w	k_f	p	Years Mass Rate (Kg/s)					Fold of Increase
					1	5	10	20	30	
Base Case					71.8	49.3	40.9	34.6	32.2	1.0
Scenario 1	-1	-1	-1	-1	104.7	61.0	48.4	40.2	37.3	1.4
Scenario 2	-1	-1	-1	1	164.4	95.9	76.1	63.2	58.7	2.2
Scenario 3	-1	-1	1	-1	160.3	82.7	66.8	57.3	54.0	2.2
Scenario 4	-1	-1	1	1	253.1	130.1	105.1	90.1	84.9	3.5
Scenario 5	-1	1	-1	-1	153.4	74.5	58.7	49.4	46.2	2.1
Scenario 6	-1	1	-1	1	240.3	116.9	92.2	77.6	72.7	3.3
Scenario 7	-1	1	1	-1	319.4	181.7	145.1	121.1	112.4	4.4
Scenario 8	-1	1	1	1	503.6	285.8	228.2	190.4	176.7	7.0
Scenario 9	1	-1	-1	-1	106.5	83.5	76.5	70.7	67.5	1.4
Scenario 10	1	-1	-1	1	167.3	131.3	120.3	111.2	106.2	2.3
Scenario 11	1	-1	1	-1	808.6	558.4	484.5	424.2	394.5	11.2
Scenario 12	1	-1	1	1	1,275.6	878.8	762.2	667.3	620.6	17.7
Scenario 13	1	1	-1	-1	408.6	281.1	242.0	210.5	195.5	5.6
Scenario 14	1	1	-1	1	641.2	441.9	380.5	331.1	307.5	8.9
Scenario 15	1	1	1	-1	3,509.2	2,695.4	2,407.0	2,126.1	1,961.6	48.9
Scenario 16	1	1	1	1	5,528.2	4,239.8	3,786.1	3,344.0	3,085.0	77.0

Figure 9: Mass rate and fold of increase result for the base case and experimental design scenarios

Figure 9 presents the mass rate production for 1 year, 5 years, 10 years, 20 years and 30 years after the hydraulic fracturing stimulation treatment of the base case and the 16 scenarios. This table also presents each condition of the parameters in each scenario. It also features another variable, which is Fold of Increase, a measure of mass rate increase percentage 1 year after stimulation compared to the base case first-year mass rate. Scenario 1 is conducted with all necessary parameter in their minimum value, while scenario 16 is conducted with all necessary parameter in their maximum value. The former results the smallest value of mass rate while latter scenario 16 generate the highest value of mass rate. Henceforth, it can be said that all parameters should probably have a positive effect on the output of mass rate.

The graph of 16 scenarios mass rate production through 30 years of simulation is presented in Figure 10. It is prominent to say that scenario 15 and 16 show a significantly higher result compared to the other scenarios. This result is estimated to be the effect of parameter A, B, C to have higher positive response to the output of mass rate. In contrast, parameter D is estimated to have the least effect on the mass rate output.

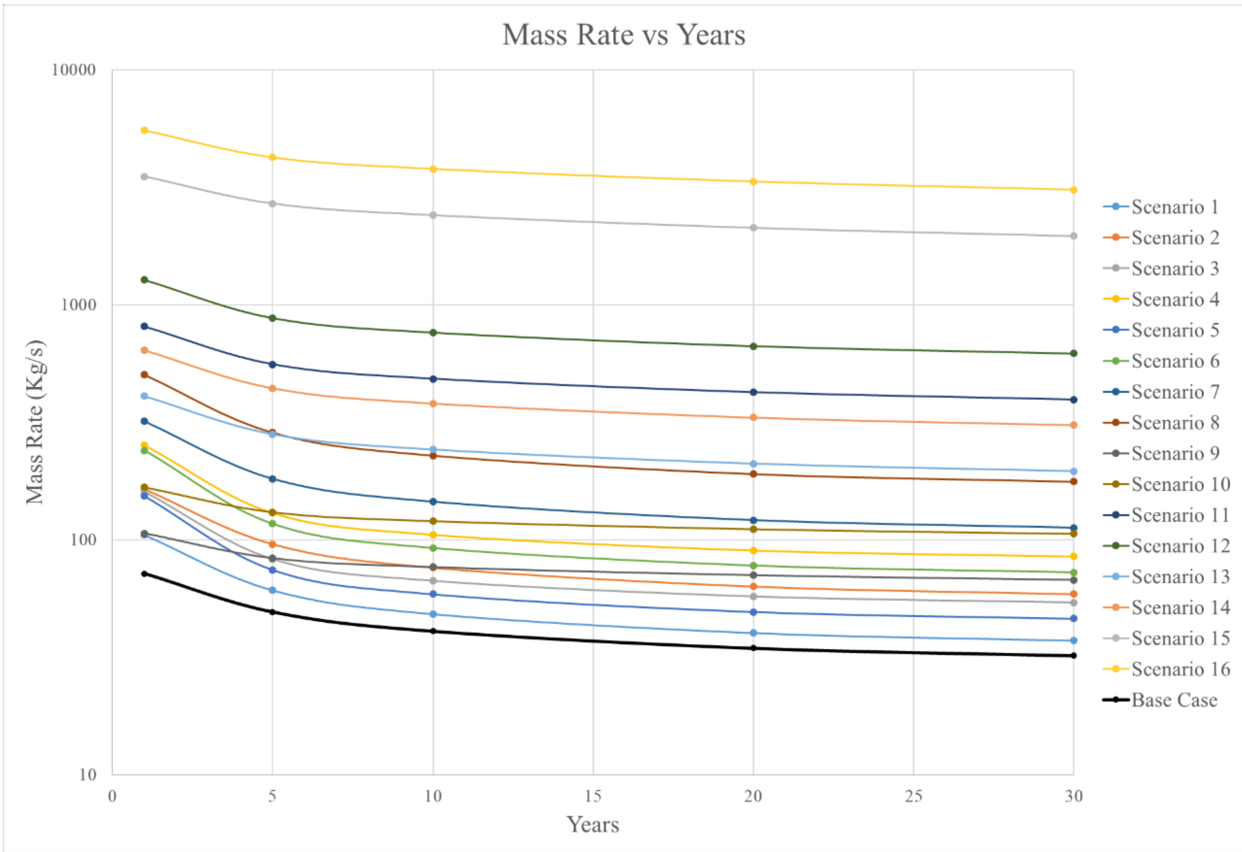


Figure 10:Base case and experimental design scenarios mass rate production over 30 years

5.2 Comparation

5.2.1 Proxy Polynomial Equation

Mass rate production resulted from the conducted simulation in the first year after hydraulic fracturing treatment is analyzed using MiniTab software in order to generate a proxy polynomial equation, as follows.

$$\text{Mass rate} = 459.7 + 382.6x_f + 281.7\,w + 351.5k_f + 101.1\,p + 263.4x_f w + 321.6x_f k_f + 86.48x_f p + 241.0wk_f + 61.41wp + 79.54k_f p + 221.8x_f wk_f + 59.91x_f wp + 70.30x_f k_f p + 54.92wk_f p + 48.08x_f wk_f p \quad (1)$$

The proxy polynomial (Equation 1) resulted from the full factorial design of 16 scenarios generates a complex equation with a 100% coefficient of determination (R^2). This occurs due to the full factorial design equation consider all the parameter and also the interaction between them, which results in a two-way, three-way and four-way interactions variable.

$$\text{Mass rate} = 162.9 + 117x_f + 114.9\,w + 114.9k_f + 101.5x_f w + 101.5x_f k_f + 86.43wk_f + 86.64x_f wk_f \quad (2)$$

Previous study (Judawisastra et al, 2018) generates the proxy polynomial equation only from 3 parameters, as presented in equation 2. Compared to equation 1, it is still quite complex due to the use of full factorial design that consider all the interaction between parameters but simpler because of the use of less parameter. Eight scenarios are used in the previous study are which indicate less simulation running time. However, by adding the penetration parameter, a more comprehensive understanding of the whole stimulation parameters can be achieved

$$\text{Mass rate} = 438 + 262x_f + 137\,w + 210k_f \text{ - } 89\,p \quad (3)$$

On the other hand, the Plackett-Burman experimental design of four parameters, which consists of 12 scenarios generates a polynomial equation, as shown in Equation 3. Equation 3 is generally modest compared to equation 1, as it only considers the effect of the main parameters, excluding the interactions that happened between the parameters. However, an odd condition is found in Equation 3 where parameter D shows a negative coefficient value, even though a increase of value in parameter D suggests that it has a positive effect in response to the output of mass rate as shown in Figure 9. Another issue in this equation is that the coefficient of determination (R^2) for this equation is only 52,57%, which is significantly smaller in contrast with Equation 1. It can be concluded that even though Plackett-Burman experimental design reduce simulations running time, it results poor proxy polynomial equation.

5.2.2 Significance Analysis

By using MiniTab software, other means of descriptive statistical data are also generated in order to do further analysis. Figure 11 presents the Pareto chart full factorial design of three parameters (Judawisastra et al, 2018), full factorial design of four parameters and Plackett-Burman design of four parameters, which ranks the linear effects of all the parameters in response to the mass rate by decreasing order. Judawisastra et al (2018) concluded that fracture half-length had the highest effect on mass rate output followed by fracture permeability and fracture width. However, none of the three parameters being used in the study is consider significant.

Figure 11 (b) shows that parameter A which is fracture half-length, is categorized as a significant parameter for it is the only parameter that passes the reference line which means it has the highest effect on the response of mass rate similar to previous study (Judawisastra et al, 2018). Furthermore, excluding the interaction of parameters, the order of parameters effects to the mass rate output are also alike followed by the additional parameter of penetration as the least significant. Furthermore, pareto chart generated from Plackett-Burman design presented in Figure 11 (c) also suggests that parameter A which is fracture half-length as the most significant parameters among all of the parameters and the same order of the parameter effects to mass rate.

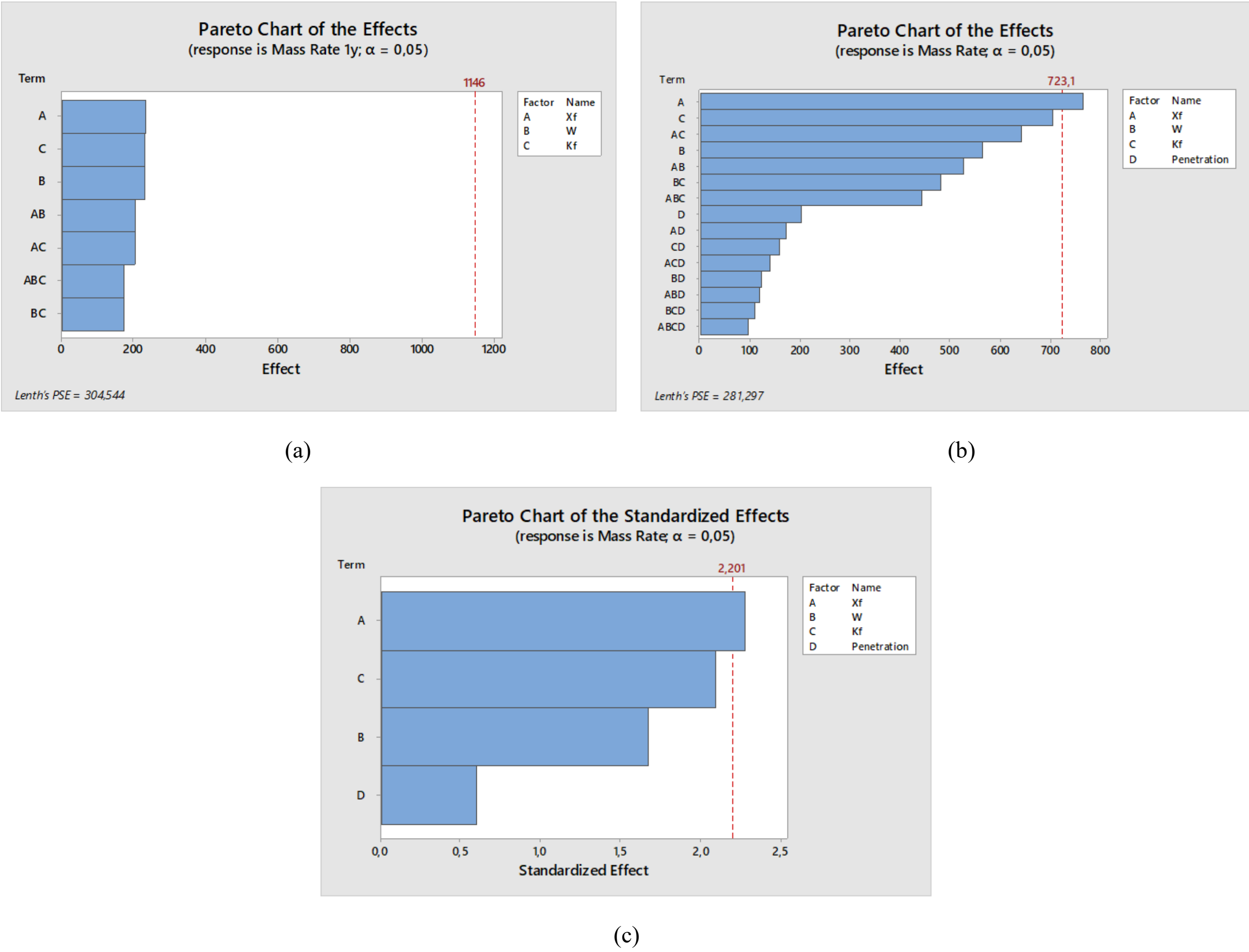
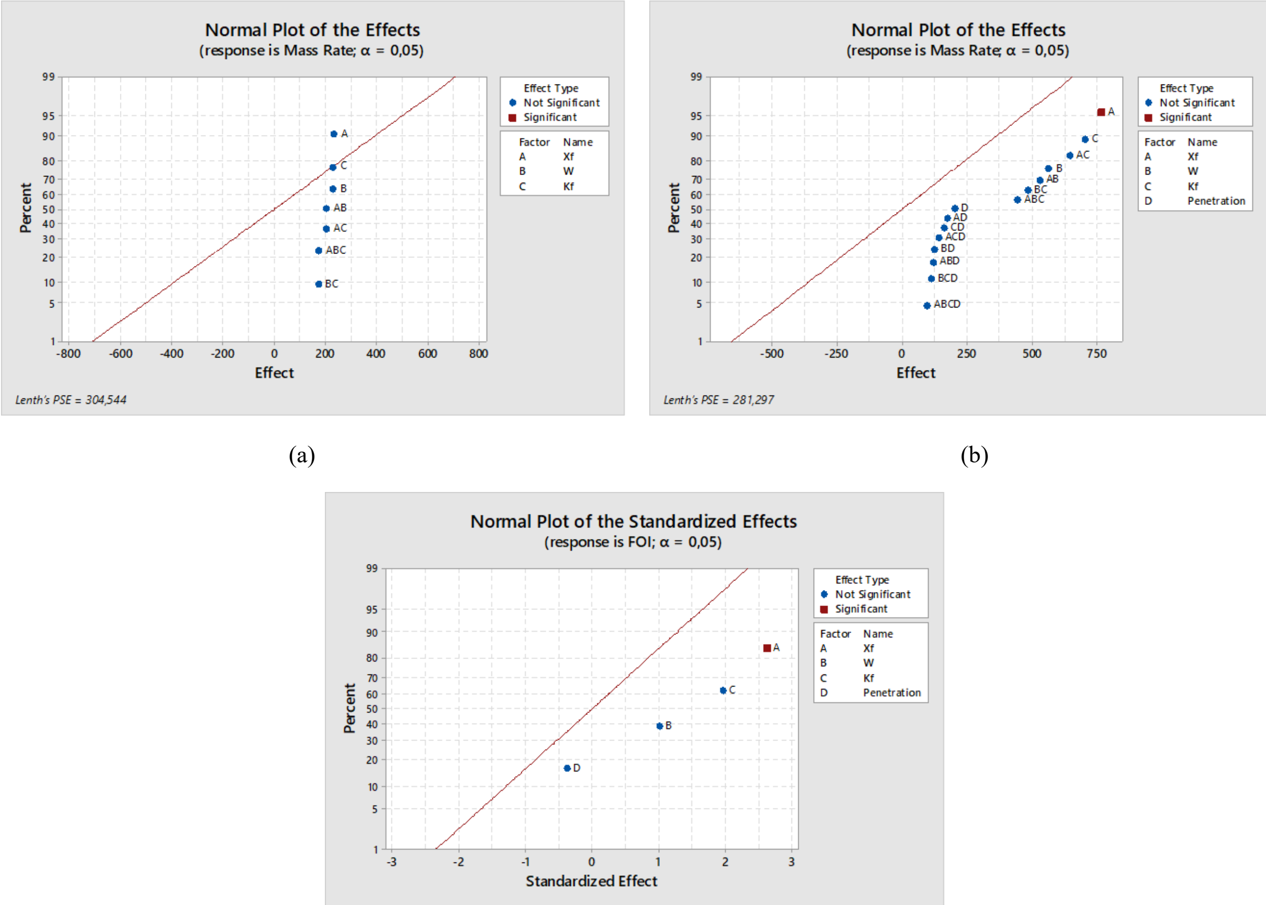


Figure 11. Pareto chart result (a) Judawisastra, et al (2018), (b) Full factorial design, (c) Plackett-Burman design.

In the intention of comparation to previous study, the Normal Plot of the Effects is also generated as presented in Figure 12. Identical to the pareto chart, all the normal plot confirms that the three different condition suggested parameter A which is fracture half-length has the most effects to output of mass rate with both experimental designs that uses four parameters consider it as a significant parameter. Additionally, it can also be concluded that the both conditions that uses full factorial designs come up with all the parameters being in the positive side of response to the output of mass rate. Meanwhile, in Figure 12 (c) it can be seen that the use of Plackett-Burman design resulted parameter D which is penetration as a negative response to mass rate. Positive response means that when the value of the parameter stated increases it affects the output by also increasing it while negative response vice versa. This validated the condition of equation 3 where Parameter D value is negative in the proxy polynomial equation generated from the Plackett-Burman design. This occurs due to Plackett-Burman design did not consider scenario 16 in to the analysis and creation of proxy polynomial equation as can be seen in Figure 8. Scenario 16 is where all the parameters are in their highest value and as stated before, scenario 15 and 16 had a significant difference in the result of productivity increase compared to other scenarios as presented in Figure 10. Therefore, those two scenarios are essential for the analysis of hydraulic fracturing stimulation analysis and the absence of it bring tremendous impact to the outcome as showed in the outcome of Plackett-Burman design.



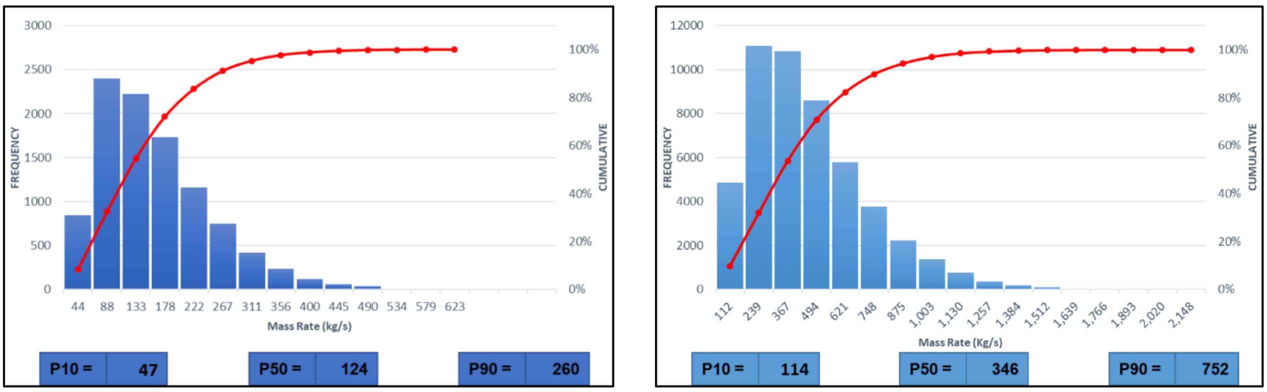
(a) (b)

(c)

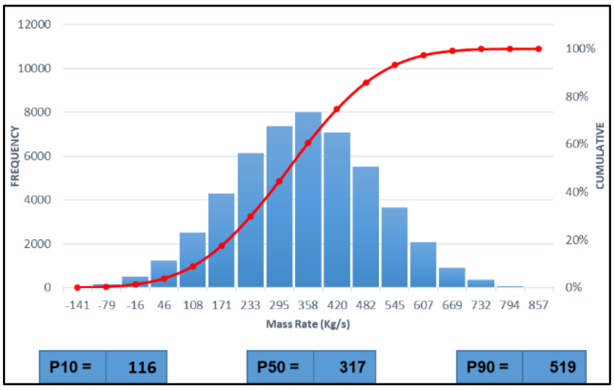
Figure 12. Normal plot of the effect (a) Judawisastra, et al (2018), (b) Full factorial design, (c) Plackett-Burman design.

5.2.3 Monte Carlo Simulation

From the proxy polynomial equation generated before from the full factorial design and Plackett-Burman design, Monte Carlo probabilistic simulation is conducted using 50,000 iterations of randomly sampled value within the range of maximum (+1) and minimum (-1) value for each of all parameter. The result of Monte Carlo simulation for the full factorial design is shown as graph in Figure 13 (b), which suggests that hydraulic fracturing stimulation in Wairakei geothermal field is able to increase mass rate production to P10 = 114 Kg/s (1,58 times base case), P50 = 346 Kg/s (4,81 times base case) and P90 = 752 Kg/s (10,46 times base case). It can also be seen from the graph that the distribution of the probabilistic mass rate tends to create a positive skewness where the mass rate will probably have a value under the average data. This positive skewness is identical to previous study as shown in Figure 13 (a) which suggested that the use of full factorial in the study of hydraulic fracturing stimulation tends to generate a positive skewness for Monte Carlo result.



(a) (b)



(c)

Figure 13. Monte Carlo simulation (a) Judawisastra, et al (2018), (b) Full factorial design, (c) Plackett-Burman design.

Furthermore, the Monte Carlo probabilistic graph generated from the proxy polynomial equation from Plackett-Burman design is presented in Figure 13 (c). As shown in the graph, a normal distribution of data is generated with a probable mass rate production after hydraulic fracturing stimulation of P10 = 116 Kg/s (1,58 times base case), P50 = 317 Kg/s (4,41 times base case) and P90 = 519 Kg/s (7,22 times base case). Compared to the full factorial design, the value of P10 and P50 generated from Monte Carlo simulation for the Plackett-Burman are quite similar, while the value of P90 between Plackett-Burman and full factorial design results a very different value, 519 Kg/s to 752 Kg/s. As explained before, this happens due to the absence of a specific scenario in which all of the values of the parameters are in their maximum value in Plackett-Burman design analysis. This again strengthens the analysis that the value produced from scenario 16, which shows a very significant difference compared to the other applied scenarios gave a significant impact on the generated equation and the further analysis. Therefore, it is essential to keep the maximum scenario in the analysis of hydraulic fracturing stimulation production increase prediction using experimental design.

6. CONCLUSION

From the results and the analysis of the study that has been performed, it can be concluded that:

1. A prediction of 30 years of mass rate production after hydraulic fracturing stimulation in Wairakei geothermal has been successfully generated.
2. The proxy polynomial equation that describes mass rate production 1 year after hydraulic fracturing stimulation in Wairakei geothermal field using both full factorial and Plackett-Burman design is generated based on specific parameters which are fracture half-length, fracture width and fracture permeability and penetration.
3. Fracture half-length appears to be the most significant parameter affecting the output of mass rate production compared to fracture width, fracture permeability and penetration
4. Hydraulic fracturing stimulation could successfully increase the mass rate by 1.58 times higher than the base case for full factorial design and 1.61 times higher than the base case for Plackett-Burman design, obtained from the most pessimistic Monte Carlo probabilistic simulation results (P10).
5. Additional parameter penetration turns out to has the least effect to mass rate output.
6. For the analysis of hydraulic fracturing analysis, it is more recommended to use full factorial design compared to the Plackett-Burman design. Even though Placket-Burman design gave the same result for significance analysis, the proxy polynomial equation had a far smaller coefficient of determination (R^2) and generated a significant difference in the value of P90 in the Monte Carlo probabilistic simulation.

7. RECOMMENDATION

Several recommendations for further study to improve this study and improve the accuracy of the result are given as follows:

1. Validation of the numerical model being used by the recent field production history actual data.
2. The numerical model used in this study should be improved to a more complex model with more refined grids, a dual-porosity system and a model that consider existing fault and geological structure of the field.
3. The addition of a various number of wells and scenarios is also suggested to be compared and analysed.
4. Other hydraulic fracturing parameters is suggested to be used regarding the experiment design to comprehend all the effect of parameters on the study.
5. For the experimental analysis, it is suggested to test not only operating parameters but also reservoir parameters together with the operating to parameters to gain a more comprehensive understanding and obtaining a more precise equation and significance analysis output.
6. Another experimental design is suggested to be used as means of comparison.
7. Other output response should be generated, such as temperature, enthalpy and electricity power.

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