The use of well completion efficiency in the assessment of formation damage in initial well completion and workover operations

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Abstract

The calculation of well completion efficiency is very important in comparing pre/post workover or re-entry completion efficiencies of wells to enable the quantification and ranking of the success of workover operations. However, the quantification of the success of an operation could be misleading if comparisons are wrongly placed on wells or fields basis by different operators. In this work, comparative analysis of pre and post well completion efficiencies for different completions types are evaluated for wells in different fields using averaging techniques. According with this, the aim is to quantify the success rate of workover operations. The average completion efficiencies were calculated using the arithmetic mean for wells in different reservoirs and fields having the same completion type. The analysis of the results from the workover operation showed that some operations were successful while others are not and no field had all operations completely successful. Those that were adjudged successful are fields were enhanced production due to the operations was able to offset low productions from failed operations. However, it was observed in some fields that there was complete failure in the operations as all post-operation productions are lower than the pre-operation productions. The operations where failure occurred are due to loss of completion fluids into the formations, resulting to formation damage. Hence, chemical consolidation treatments must be handled with caution as they seem to be more susceptible to damage than other completion types.

Keywords

Well completion efficiency; Formation damage; completion fluid; Workover; Re-entry; Productivity index; Completion types; Chemically consolidated wells

Introduction

The Well Completion Efficiency (WCE) is a dimensionless parameter that gives an indication of a well's productivity. The WCE is the ratio of the initial well productivity index to the ideal well productivity index. It is usually calculated throughout the life of a well. However, the initial (first) well completion efficiency for a newly completed well or immediately after a workover operation is very important as it is used as a baseline completion efficiency for planning and assessing the degree of impairment for future completions and as well as a planning tool for new completions. It also helps in comparing pre/post workover or re-entry completion efficiencies of the wells to enable the quantification and ranking of the success of workover operations. The following sections gives background literature of well completion efficiency and about how it is calculated using well and reservoir parameters in order to quantify the success rate of workover operations.

The efficiency of a well completion depends on a number of factors among which are the reservoir pressure, completion fluids and handling, drilling, completion practises, sand exclusion methods etc. Well completion efficiency also depends on the type of well. Horizontal wells have been generally found to have higher completion efficiency than the conventional vertical or deviated wells. The ability to defer gas and water production is also a measure of completion efficiency. In economic sense, well completion efficiency is measured on how soon the capital investment is recovered following the additional productions arising from workover operations. In other words, completion efficiency is inversely proportional to the pay-out time.

Taking cognisance of the economics, PI goes further to consider the overall reservoir management. The productivity index is a critical parameter and one of the most important parameters to characterise well performance and reservoir property in the oil and gas production process and management [1,2].

Regardless of the type of formation and the type of wellbore, the index is defined as the amount or volume of reservoir fluids that can be produced daily by one PSI pressure drop at the sand face [1]. Simply put, it could be defined as the ratio of the oil production rate to the drawdown. Some key parameters that significantly influence productivity index include: the reservoir permeability, reservoir fluid properties as well as the geometry of the drainage area. Productivity index does not remain constant but changes with pressure decline, alteration of the reservoir permeability, deviation from homogeneous fluid and rock deformation [2]. Productivity index reduction is a recognized phenomenon in oil and gas production that is monitored until production becomes uneconomic. Monitoring of productivity could be real time or intermittently at different periods of production. One recent method of well completion efficiency monitoring is using the PI microseismic monitoring tool that extracts microseismic data which when combined with engineering data gives insights into the effectiveness of a treatment thereby saving costs [3]. Productivity index decrease may be caused by several factors arising from reservoir, completion, and operational issues. The reservoir-related factors include compaction, fines migration, pressure support and multi-phase fluid flow. The completion-related issues arise from frac-pack geometry and stress-sensitivity of proppant conductivity. Understanding the interactions of the different parameters controlling the PI behaviour and the resultant well performance is paramount for maximizing the ultimate recovery and net present value (NPV) [4].

Well productivity is one of the major concerns in oil field development, and provides the means for oil field development strategy. Sometimes, well performance and productivity is measured in terms of productivity index [5]. Even with the most powerful methods and hardware available, the calculation of the productivity index is not always an easy task as several factors directly influence its determination. The productivity index for a well produced under constant pressure condition is different, although very close, from the productivity index of a well produced with constant rate [6]. The lower the quantity of crude oil produced per unit change in pressure drawdown, the higher is the reservoir energy required by the well to flow. In this regard, therefore, the productivity index should be maintained as high as possible by timely interventions through stimulations.

The well productivity index should be evaluated after initial completion as well as after every well intervention activity. This will help in assessing the degree of damage or improvement on the well. For situations where the ideal PI of the well is affected, the dimensionless productivity index of the well should be a better option for post job evaluation. In addition, for wells producing from the same reservoir, specific productivity index, which is PI per foot, should be used in evaluating the well performance relative to other wells draining the same reservoir.

It was showed that increasing water-cut increases PI of the well [7]. Therefore, since productivity index is the basis for measuring the completion efficiency, its increase due to water breakthrough does not necessarily mean increase in oil production. On this note, it is important to recognise the possible causes of change in PI while comparing well performance. The basic sediment & water (BS&W) associated with the PI of wells should be used in assessing well performance.

Evaluating the completion efficiency could also be carried out using the concept of cluster completion efficiency where the percentage of clusters that receive effective stimulation for a given interval is estimated [8]. Higher completion efficiency in this method implies the presence of greater number of highly conductive transverse fractures whereas a poor completion implies the existence of gaps in the fracture network [8]. With unconventional resources playing key roles in the global supply of oil and gas, more ways of analysing completion efficiency have emerged. Some of these methods include the advanced modified heterogeneity index (MHI) which measures the impact of well-to-well interaction and restimulation performance improvements [9] and the use of geochemistry and reservoir stimulation to investigate the vertical and lateral communications between intervals [10].

Another method of evaluating the performance of a well after an intervention is the use of average well completion efficiency. The average well completion efficiency can be evaluated on well specific bases or by the sand completion type. In the absence of the well specific completion efficiency, the average completion efficiency for the sand control type should be used. Average well completion efficiencies for different sand completion types were presented by Onyeizugbe [11].

The average dimensionless PI can also be used as a cut-off in the selection of stimulation candidates. With more detailed investigation, intervals with below-average dimensionless PI for a particular reservoir and sand control type will require stimulation to improve their dimensionless PI's. Therefore, this work uses the concept of the average well completion to evaluate the performance of wells after a workover operation.

Material and method

The success of a job can be measured by determining the success factor (SF) defined as the ratio of the dimensionless PI of the well prior to execution of the job to the post job dimensionless PI.

$$SF = PID_{(post\ job)}/PID_{(before\ job)} \quad (1)$$

where: SF is the success factor categorised as SF < 1 failure; SF = 1 No improvement; SF > 1 Success; PID = Dimensionless productivity index.

Estimation of technical potential using average dimensionless PI

The minimum improvement in dimensionless PI ($PID_{(min)}$) expected after a well re-entry is defined as follows:

$$PID_{(min)} = \text{Average completion efficiency} - PID_{(before\ job)} \quad (2)$$

and the minimum expected post re-entry PI and technical potential are

$$PI = PID_{(min)} \cdot PI_i \quad (3)$$

where: $PID_{(min)}$ = Average PID (CE) and PI_i is the ideal productivity index.

$$q = PID_{(min)} \cdot \text{Average drawdown} \quad (4)$$

where q is the technical potential. Note that average drawdown is a function of sand control type [7].

Methods of determining average well completion efficiency

Various methods exist for calculating the average completion efficiency. These include the arithmetic, weighted average and frequency histogram plot methods. The weighted average is important in comparing wells in the same reservoir, reservoirs in a field, etc. It is important during analysis to use combination of these methods to allow comparison.

The arithmetic average involves finding the simple average for a given data set. It does not consider conditions behind the source of data. This method is used where there is no strong basis for comparing the values. The arithmetic average is calculated by the expression:

$$\text{Average}_{\text{arithmetic}} = \frac{\sum_{i=1}^{n} CE}{n} \tag{5}$$

where n is the total number of wells in the same interval and of the same completion type.

Although well completion efficiency is dimensionless, PI is a strong function of permeability, which on the other hand is a property of the reservoir that is susceptible to reduction due to damage. Thus, within the same reservoir, completion efficiency values are representative of the intervals from which they are obtained. Since all the intervals do not have uniform thickness, weighted averages are calculated using perforation interval (the zone open to flow) as a weighting factor. If all the wells were of uniform perforation interval, arithmetic average will be the same as weighted average. The weighted average can be expressed as:

$$\text{Average}_{\text{weighted}} = \frac{\sum_{i=1}^{n} CE \times h_p}{\sum_{i=1}^{n} h_p} \tag{6}$$

where h_p is the perforation thickness of the wells.

For reservoirs in a field, average net pay sand thickness (NOS) is used as a weighting factor. Another method is the use of the frequency distribution plot. In this method, the median value is taken to be the representative dimensionless PI for the field. However, there is a 50% chance that the dimensionless PI could be above or below the median value.

Evaluation of well completion/well re-entry

The completion efficiency can be used to evaluate the success rates of well completions or re-entries. Average completion efficiency is used to categorize the completion types. It is also important in evaluating the sensitivity of well productivity to water cut. If the completion efficiency (PID measured after the job) is greater than that measured before the job, then the job is successful. The reverse holds for unsuccessful jobs. This was used in evaluating the effect of changing from one completion type to another. The well specific completion efficiency was used and the results are discussed below. However, for situations where the well specific CE is not known, the average completion efficiency by Onyeizugbe [7] applies. Note, the duration of sustainability and the ability to recoup the cost of the workover or re-entry operation must be investigated to adjudge the overall success of the operation.

Procedure for calculating productivity index (PI) and well completion efficiency (WCE)

1. Calculate the PI ideal and PI actual for all the reservoir intervals to be monitored for pre and post workover and/or re-entry operations using the following equations:

For PI ideal:

$$PI_i = \frac{q_o}{P_r - P_{wf}} = \frac{7.08 \times 10^{-3} k_o h}{\mu_o B_o \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75\right]} \quad (7)$$

For PI actual:

$$PI_a = \frac{q_o}{P_r - P_{wf}} = \frac{7.08 \times 10^{-3} k_o h}{\mu_o B_o \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s_t\right]} \quad (8)$$

where q_o is the oil flow rate, P_r is the reservoir pressure, P_{wf} is the bottom-hole flowing pressure, k_0 is the effective oil permeability, h is the reservoir thickness, r_e and r_{wf} are the reservoir and wellbore radius. μ_o is the oil viscosity, B_o is the oil formation volume factor, s_t is the total skin.

2. Calculate the well specific well completion efficiency (WCE) for each interval at the onset of production:

$$CE = PID = \frac{PI_a}{PI_i} \quad (9)$$

3. Estimate the dimensionless PI (PID) for each interval before the workover operation using equation (9).
4. Calculate the post re-entry PID using equation (9).
5. Calculate the $PID_{(min)}$ using equation 2 and the minimum expected post re-entry PI using equation (3).
6. Estimate the technical potential, q using equation (4).
7. Determine the success factor, SF for each operation using equation (1).

In Figure 1 is represented a flow chart showing step by step guide on how to calculate the pre and post completion efficiencies for workover operations, and also how to investigate if an operation is successful or not.

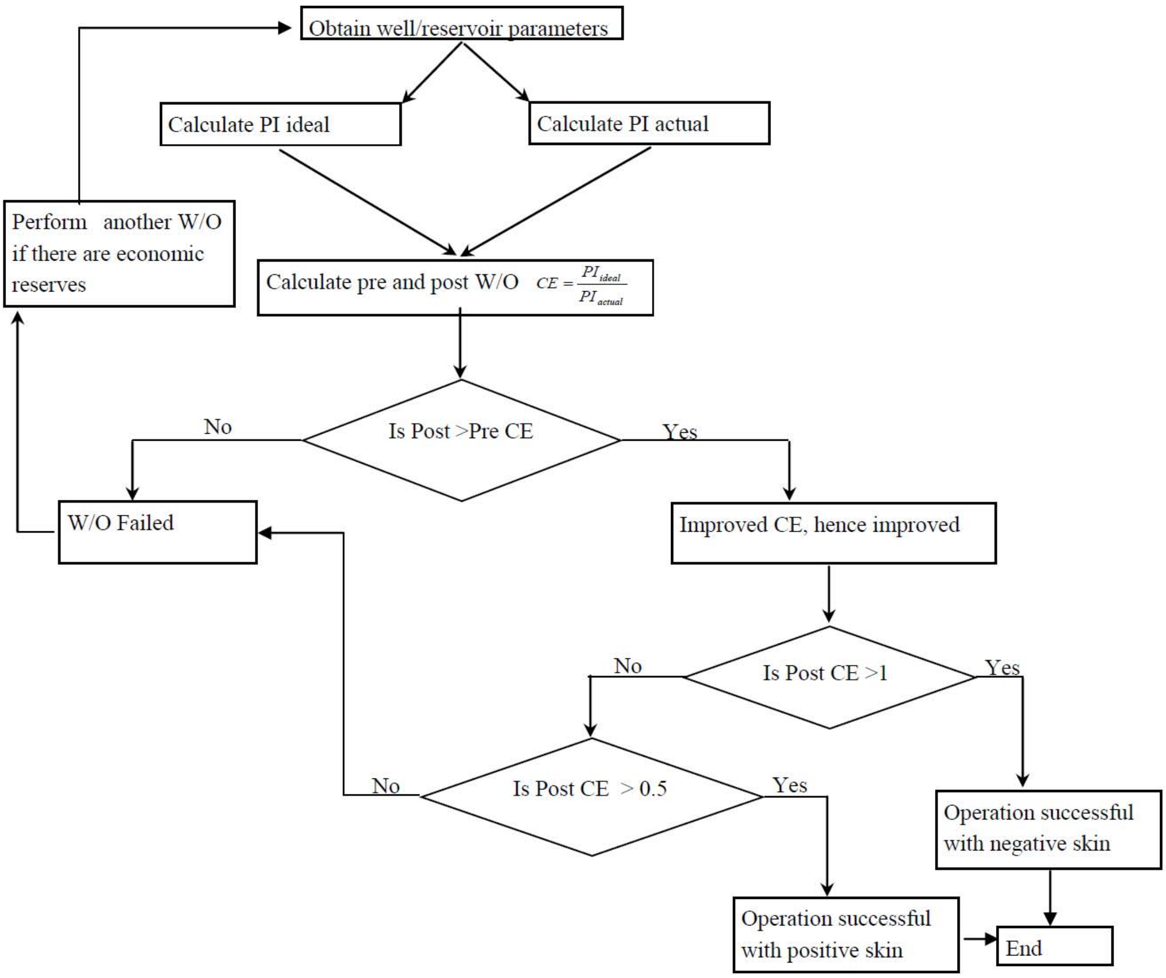

***Figure 1**. Algorithm of the method described in the paper*

Results and discussion

In order to evaluate the success rate, the post workover operations were evaluated using a common baseline which serves as a control since different sand completion types have different effects on the well performance. This baseline constitutes intervals which had no change in the sand control type in place. They include such re-entries like repair of another interval (perhaps in dually completed well) or surface casing repair without changing the completion status of the existing intervals. The results of post workover CE analysis for various re-entries are given below:

Table 1 shows the average completion efficiencies for different completion types calculated from 46 wells in different fields. The wells comprise of 4 wells that serve as control, 14 SCONed wells that were originally internally gravel packed, 10 internally gravel packed wells that were originally completed as SCON, 9 SCONed wells that were reconsolidated and 9 wells that were subjected to true tubing (TT) stimulation respectively. The average completion efficiency presented in Table 1 was calculated using the arithmetic mean because the data spanned across wells in different reservoirs and fields. Therefore, it was not easy to find suitable weighting factor.

Table 1. Average CE for different completion types

Completion type	**Average CE**
ALL	0.48
EGP (external gravel pack)	0.66
IGP (internal gravel pack)	0.40
SCON (is perforated (untreated))	0.57
PERF (chemical sand consolidation)	0.48

CE = completion efficiency

a) Intervals that was untouched during workover re-entry

Figure 3 shows the dimensionless PI from wells which serve as the baseline for the evaluations.

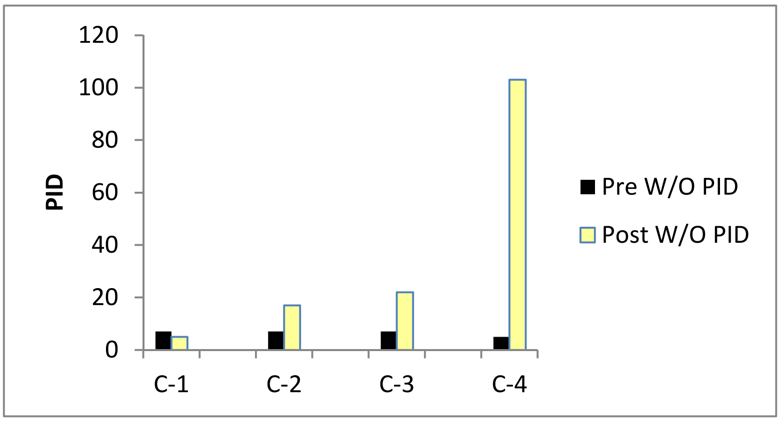

***Figure 2**. PI_D of intervals that was untouched during workover repair*

They are wells whose intervals were not altered during the workover operations. Investigation on the effect of workover on completion efficiency, for untouched intervals as shown in Figure 3, showed that after the workover operations, the CE generally remained high as expected since no activity was carried out in the intervals except in C-1 which shows a reduction in PID after the re-entry operation. This could be attributed to loss of workover fluids into well C-1 while carrying out a workover operation on a different section of the well.

b) SCONned/Internal gravel packed intervals

Investigation by Okorie and Ajienka [6] on the effect of changing the sand control type from chemical sand consolidation to internal gravel pack shows that chemically sand consolidated intervals have higher CE than initially internal gravel packed wells. However, the evaluation of some workovers done in mid 90's in the Niger Delta show that chemically consolidated intervals has:

1. Lower PID on intervals that were originally internally gravel packed but SCONned during workover re-entry (Figure 3) except in D-2 and D-3 which has higher PID after the re-entry. On a field wide basis, the operation can be adjudged to be a failure since the post-PID for most wells shows a significant reduction in the PID from the pre-PID which implies that the success factor is less than 1 and the additional production from the wells with successful operations may not be able to recoup the overall cost of the workover operation.

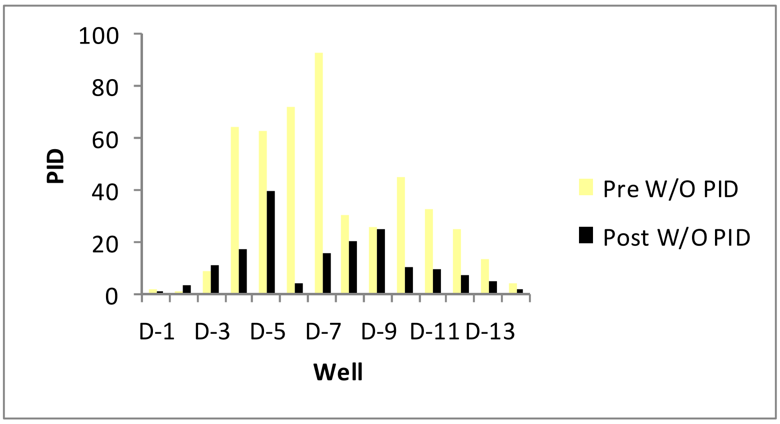

Figure 3. *PI$_D$ of internally gravel packed intervals but chemically consolidated during the workover/re-entry*

2. Higher PID on intervals that were originally SCONned but internally gravel packed after the workover re-entry (Figure 4) except in well A-1 where the re-entry PID is higher than the initial PID from SCON.

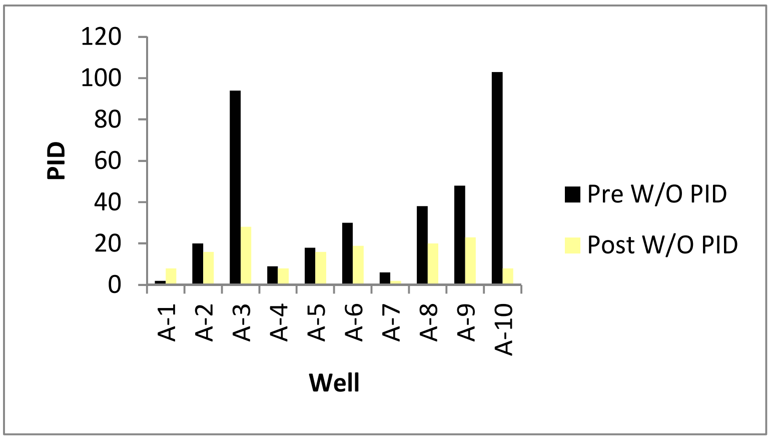

Figure 4. *PI$_D$ of SCONed intervals but were internally gravel packed during the workover re-entry*

This could be attributed to the height of the perforation interval of well A-1 since studies [7] have shown that SCON is less successful at large perforation intervals. Again, this operation is a failure as the technical potential in each re-entry operative reduced drastically and the success factor (SF) for all the wells except that of A-1 is less than one.

The failure from these two operations could be due to impairment arising from losses of workover fluids into the formations, cement squeezes, re-perforation, wrong judgement on intervals for workover operations etc. The degree of impairment experienced during workover operation due to fluid losses, re-perforation, cement squeezes and others, are potential causes of production decline [12,13].

c) Reconsolidated intervals

Chemically consolidated intervals that were reconsolidated during the workover operation show no consistent trend. Whereas there was significant improvement in post PID after the workover operations in wells B-1, B-2, B-3, B-7, and B-8, re-entry operations in wells B-5, B-6 and B-9 were unsuccessful and no change was observed in well B-4. The observed differences could be attributed to how good the wells were cleaned or the extent of impairment during a workover as shown in Figure 5. Unless the successful operations observed in wells B-1, B-2, B-3, B-7, and B-8 is able to offset the cost of the operations in the entire field, the entire operations in field B can be adjudged a failure.

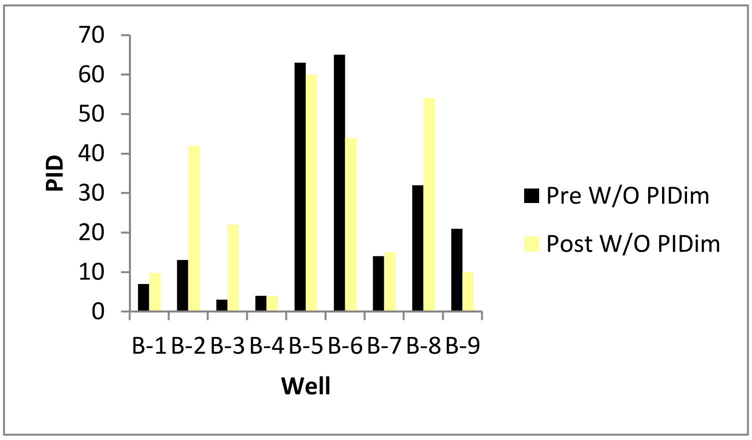

Figure 5. *PI_D of intervals re-consolidated during workover repair*

d) Stimulated intervals

Stimulation is the process of improving permeability. Stimulation operations can only remove skin due to damage arising from fines migration, cement squeeze, etc. Examples of typical stimulation operations are hydraulic fracturing and acidization. Figure 6 shows the dimensionless productivity indices of stimulated intervals for field S. The post-stimulation operations across the field shows a significant improvement in the production except in wells S-3 and S-4 where the post job PI is less than the pre-job PI.

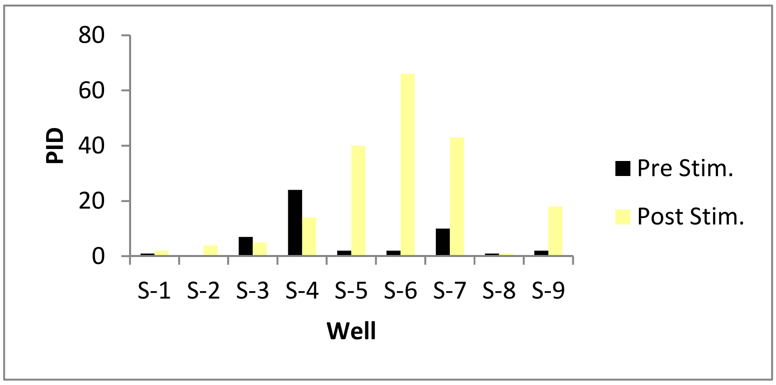

Figure 6. *PI_D before and after TT stimulation*

Generally, for a large database, the weighted average dimensionless PI is less or equal to the arithmetic average dimensionless PI. Thus, the weighted average method is preferred in determining intervals that perform below the average value. Since all the intervals do not have uniform thickness or perforation interval, weighted averages are more realistic in comparing performances. The arithmetic average dimensionless PI is only a good quick estimate of the average trend.

To identify the average dimensionless PI of producers in a reservoir, similar sand exclusion types should be compared. Similarly, using the field-wide average to identify below-average producers sometimes can be erroneous. Therefore, most comparisons should be made on well or reservoir specific basis.

Conclusions

1. Majority of the intervals have improved dimensionless PI after workover particularly for the stimulated and reconsolidated intervals. Most of the intervals with unimproved dimensionless PI are gravel packed or damaged during workover. The impairment is believed to be due to poor washing of gravel packed intervals prior to gravel packing and loss of workover fluids into such zones.
2. SCON completions are less susceptible to formation damage.
3. Water breakthrough in production has a decreasing effect on dimensionless PI. This is due to increases in PI's. This may be misleading in assessing impact of workover re-

entries to the well productivity and as a result should be closely monitored.

4. Comparison of dimensionless PI's of dissimilar sand exclusion types and producers from different reservoirs should be discouraged if it is to be used to identify intervals performing below average.
5. Weighted average dimensionless PI is more realistic to arithmetic average. For the completions in the same reservoir, the perforation interval, (hp) should be used as a weighting factor while for field-wide average dimensionless PI determination; average NOS should be used as weighting factor.
6. Average dimensionless PI is an important parameter for well diagnosis. It enables the evaluation of the minimum improvement expected from a well re-entry effort and thus estimate post re-entry technical potential. It also enables the identification of intervals performing below average in a reservoir to analyse possible causes of impairment and recommend remedial action.
7. For the fields evaluated, average dimensionless PI's are reported on reservoir basis to identify intervals below average dimensionless PI. Average dimensionless PIs are also reported for different sand exclusion types to give an idea of what dimensionless PI value to expect for an initial completion or well re-entry.
8. The statistical method of determining the median (50%) dimensionless PI from frequency histogram/distribution is very useful for determining field wide or OPCO average dimensionless PI determination where a large database will be available (frequency distribution or OPCO methods was not used in these cases investigated).
9. The untreated (open hole completions) seems to have the worst dimensionless PI possibly because, in the majority of cases, no back-flush /washing is carried out. This emphasizes the need to clean-up oil wells after workover as is the case with gas wells.

Recommendations

1. To calculate average dimensionless PI, use data from similar sand control types in the same reservoir.
2. Weighted averages are preferred to arithmetic averages which are only useful for quick-look estimates. For producers on the same reservoir, use perforation interval as

weighting factor. For the sands or field wide average dimensionless PI, use average NOS as weighting factor.

3. Frequency histogram/distribution or Regression methods can also be used to evaluate the data but could only be useful with large data base and for field wide analysis or OPCO dimensionless PI analysis. In these cases investigated, the data base is not too large to deploy either frequency distribution or regression method.
4. The Regression Method can be useful in a large data set. By plotting actual versus ideal PI, different dimensionless PI lines and intervals that fall in between these lines can be indicated.
5. The weighted average and frequency histogram plot methods are recommended for field-wide average determination.
6. Identify below-average dimensionless PI intervals for analysis of sources of impairments such as completion fluid type, practices etc. Identify opportunities for stimulation campaign.
7. Post workover clean-up is necessary to improve dimensionless PIs.

Nomenclature

CE = completion efficiency
EGP = external gravel pack
IGP = internal gravel pack
PE = performance efficiency
PERF = perforated (untreated)
PIa = actual productivity index
PID = dimensionless productivity index
PIi = ideal productivity index
SCON = sand consolidation
SF = success factor

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