The cost analysis of the separation of produced formation water from the hydrocarbon reservoir using the example of the Upper Miocene sandstone deposits of the Sava Depression

Josip Ivšinović
1 INA-Industry of Oil Plc., Trg G. Szabe 1, 44310 Novska, Croatia, e-mail: Josip.Ivsinovic@ina.hr

Abstract
Formation water is produced during the whole lifetime of a hydrocarbon reservoir alongside the oil and/or gas and it represents the main part of the produced fluid. The produced formation water is separated during the process of dehydration. This paper deals with the formation water separation costs regarding the fields A, B and C which are located in the western part of the Sava Depression. The dehydration process regarding field A is executed in three locations, and in fields B and C, it is executed in one location. The technological system of formation water separation and the geological characteristics of the above-mentioned reservoirs is represented. A statistical analysis regarding the formation water separation costs has been made. The costs have been statistically estimated and a correlation between the costs relevant for the usual formation water separation process has also been made. The purpose of the analysis of the cost of the dehydration process is the optimization of the production system and cost control of the process.

Keywords
Economics formation water, statistical evaluation, cost correlation, Sava Depression

1. Introduction
Formation water is produced during the production from a hydrocarbon reservoir together with oil and/or gas. Globally, oil wells produce about 220 million BWPD (ca. 35 million m³/day) (Tajmir & Reza Ehsani 2016). The ratio between the produced water and oil is 3:1, and the average share of water in the fluids equals 70% (Fakhru’l-Razi et al. 2009). Separation of the formation water is carried out by the dehydration process. The efficiency of formation water separation directly affects the formation water’s quality, and its importance for the injection system has been described in the Western Sava depression water-injection system analysis (Ivšinović 2017). This paper deals with the costs and the formation water separation process and the geological characteristic of the reservoirs in the oil and gas fields A, B and C. These are located in the western part of the Sava Depression. The dehydration process regarding field A is executed at three locations, and in fields B and C, it is executed at one location. The statistical data was gathered between the years 2009 and 2015. This paper describes the formation water separation process and an estimate will be made regarding the formation water separation costs and the correlation between the important variables in the formation water separation process.

2. The Geographic Area of Research and the Basic Geological (Lithostratigraphic) Characteristics of the Area
The oil and gas fields described in this paper are located in the Croatian part of the Pannonian Basin System in the Sava Depression. The geotectonic position of the Sava Depression (blue) within the Pannonian Basin System is shown in Figure 1.

The oil and gas field A is located 55 km south-east from Zagreb, and fields B and C are located approximately 90 km south-east from Zagreb. The general and common geographic locations of the fields in question are shown in Figure 2, (blue), while the observed reservoirs (blue) are shown in Figure 3.

The reservoir rocks of the oil and gas field A are fine to medium grained quartz micaceous sands. On the pre-neogene bottom rock, there lies a transgressive complex of neogenic sediments. Within this sediment complex, the main reservoirs are; the sandstones of Lower Pontian, Kloštar Ivanič Formation, Pannonian, and Ivanič-Grad Formation.

The reservoir rocks of oil and gas field B are poorly to fine grained quartz micaceous sandstones. The reservoir structure (see Figure 4) is brachyanticline with northwest-southeast general orientation. In field B, the reservoirs are formed in Pliocene and Miocene deposits. The total depth of the reservoirs is between 1 000 and 2 000 meters.
The reservoir rocks of oil and gas field C are poorly to middle grained sands and poorly to fine grained quartz micaceous sandstones. The reservoir structure is an elongated anticline with northwest-southeast general orientation. There are two maximums in the central part of the structure. The reservoir rocks are interlayered with marls and sandy marls. Seal rocks are marls that turn into calcitic marls in the deeper reservoirs.

According to Velić et al. 2012, oil and gas fields are divided into: large fields (which produced more than $10^6$ m$^3$ of oil/condensate or more than $10^9$ m$^3$ of gas), medium fields (which produced $10^3$–$10^6$ m$^3$ of oil/condensate or $10^5$–$10^9$ m$^3$ of gas), small fields (which produced $10^2$–$10^5$ m$^3$ of oil, $<10^7$ condensate or $10^3$–$10^8$ m$^3$ of gas) and very small fields (which produced less than $10^4$ m$^3$ of oil or less than $10^7$ m$^3$ of gas). According to the above mentioned classification, the oil and gas fields B and C are medium fields, while the oil and gas field A is classified as a large field.

3. The Dehydration System Technology in the Oil and Gas Fields A, B & C

The dehydration process is performed in separators. These are throughput devices of cylindrical shape (vertical or horizontal). They are used to efficiently separate gas from a liquid phase under a certain pressure and temperature. The retention of the fluids in the processing vessels
causes the formation water to be separated at the bottom of the vessel. The amount of the separated formation water regarding the time of its retention is shown in Figure 5.

The retention time of the produced water in the treatments vessels is from 3 to 30 minutes (Arnold & Stewart, 2008). The technological process of produced water separation in the oil and gas field A is represented in Figure 6.

The formation water is processed at three gathering stations, and the dehydration process is done by using formation water separators and dehydrators. The average value of process parameters in field A are: fluid flow: 2 000 m$^3$/day, pressure: 1.0-1.5 bar and temperature: 35-40 °C. The technological process of produced water separation in the oil and gas fields B and C is represented in Figure 7.

The produced fluids are gathered from five measuring stations at the dispatch station of the oil and gas fields B and C. Fields B and C have a common gathering system, and thus a common dehydration system. Due to this, the common dehydrating system for fields B & C may be viewed as a single technological process. The average value of process parameters in fields B & C are: fluid flow: 800 m$^3$/day, pressure: 1.0-1.5 bar and temperature: 40-45 °C. The formation water separation is performed in the gravity settling vessel and dehydrator.

4. The Formation Water Separation costs in the Oil and Gas Fields A, B & C

The amount of the separated formation water from 2009 to 2015 is shown in Figure 8.
Figure 5 shows an evident increase in the amount of the produced formation water from field A. This is a consequence of the additional optimization of the wells in the analyzed oil and gas field (field A). The optimization of the oil and gas field A was achieved through well workovers. Capital workovers are made on six wells. Capital workover operations in production wells cover operations performed in formations (formation remedial operations), and in the wellbore (equipment repair operations, etc.). The consequence of these capital workovers was an increase of the produced fluids, and the formation water. The oil and gas fields B and C were not optimized. To calculate the overall unit cost, data regarding the energy sources’ price (electric energy and natural gas) is needed. These are shown in Table 1.

The data from Figure 8 and Table 1 was used for the calculation of the unit price of formation water separation according to the methodology of the authors Ivšinović & Dekanić from 2015. The calculated formation water separation costs regarding the fields A, B and C are shown in Table 2.

According to Table 2, the costs with the largest share in the overall costs of formation water separation are: energy (field A: 41.0%, fields B&C: 73.3%), heat exchangers and process vessels maintenance (field A: 32.3%, fields B&C: 10.5%) and chemicals (field A: 21.1%, fields B&C: 11.4%). A statistical evaluation of the above-mentioned data will be made and a correlation between the most important variables will be presented in the following chapters.

5. The Chosen Statistical Methods for the Data Processing

The normal (Gauss) distribution is the most well-known and, in nature, the most common distribution function. It is commonly used in geology and hydrocarbon reservoirs geology (e.g., Malvić & Medunić 2015). The Shapiro and Wilko (S-W) test is the most common
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one for testing the normal distribution of data. This test is based on the correlation of a sample of the “statistical order” which has a normal distribution. The null hypothesis is the normality i.e. the uniformity of data. The Shapiro-Wilko test (W) is calculated according to the relation (e.g., Güner et al. 2009):

\[ W = \frac{\left( \sum a_i y_i \right)^2}{\sum (y_i - m)^2} \]  

Where:
- \( W \) is the test-value,
- \( y_i \) is the data,
- \( m \) stands for the arithmetic mean of data,
- \( a_i \) is the calculated linear regression value for expected values from standard normal “statistical order”.

The Shapiro-Wilko test is a regular tool in the statistical calculation in any statistical computational program so it is important to emphasize that the null hypothesis is not accepted if the p-value is inferior or equal to the threshold of significance (0.05). The sample size for individual costs for Fields A and B & C is seven, for each

### Table 1: The average price of industrial energy sources regarding the period between 2009 and 2015

<table>
<thead>
<tr>
<th>Year</th>
<th>Electrical power (USD/kWh)</th>
<th>Natural gas (USD/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>0.08</td>
<td>0.36</td>
</tr>
<tr>
<td>2010</td>
<td>0.08-0.09</td>
<td>0.53</td>
</tr>
<tr>
<td>2011</td>
<td>0.08</td>
<td>0.59</td>
</tr>
<tr>
<td>2012</td>
<td>0.08-0.09</td>
<td>0.66</td>
</tr>
<tr>
<td>2013</td>
<td>0.09</td>
<td>0.64</td>
</tr>
<tr>
<td>2014</td>
<td>0.08-0.09</td>
<td>0.60</td>
</tr>
<tr>
<td>2015</td>
<td>0.10</td>
<td>0.56</td>
</tr>
</tbody>
</table>

individual cost in Table 2. In order to calculate the interval estimation of expectations and choose the adequate method of correlation, the condition for the calculation is the existence of a normal data distribution. Table 3 shows the test results of formation water separation testing to the existence of normal distribution.

According to the data in Table 3, an interval estimation of expectations with a 0.95 confidence level for t-distribution will be made. The costs with no uniform distribution will be shown with a middle value and the belonging corrected standard deviation.

The interval estimation (IE) is calculated according to the following equation (e.g. Pfaff 2012; Benšić & Suvak 2013):

$$\left\langle \bar{x} - t \frac{s}{\sqrt{n}}, \bar{x} + t \frac{s}{\sqrt{n}} \right\rangle$$  \hspace{1cm} (2)

Where:

- $\bar{x}$ stands for the arithmetic mean,
- $t$- the read value from table for t-distribution,
- $s$- corrected value from table for t-distribution,
- $n$- sample size.

The non-integral estimation is used when it does not exist uniform distribution. The non-integral estimation is calculated according to the following formula:

$$NIE = \bar{x} \pm s$$  \hspace{1cm} (3)

Where:

- NIE stands for non-integral estimation,
- $\bar{x}$ – arithmetic mean,
- $s$ – corrected standard deviation.

The formation water separation costs are estimated in Table 4.

The estimated costs from Table 4 are used in the cost analysis regarding the separation system and a possible optimization and the separation system rationalization. The heat exchangers and process vessels maintenance costs as well as the energy and chemicals costs will correlate with the quantity for the produced formation water, while the energy and chemicals costs will correlate with the heat exchangers and process vessels maintenance costs. To calculate the correlation coefficient, the Pearson and Spearman correlation coefficients will be used. The condition for the application of the Pearson correlation is that the observed samples are normally (uniformly) distributed. The Pearson correlation coefficient is calculated according to the following equation (e.g. Malvić & Medunić 2015; Mukaka 2012):
Table 4: Cost estimates (USD/m³) for the separation of the formation water in oil and gas fields A, B and C

<table>
<thead>
<tr>
<th>Description</th>
<th>Field A</th>
<th>Fields B&amp;C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler room and demulsifiers station maintenance</td>
<td>NIE 0.01 ± 0.01</td>
<td>IE -</td>
</tr>
<tr>
<td>Heat exchangers and process vessels maintenance</td>
<td>- 0.12 ± 0.05</td>
<td>- 0.03 ± 0.17</td>
</tr>
<tr>
<td>Energy</td>
<td>- 0.08 ± 0.02</td>
<td>- 0.50 ± 0.88</td>
</tr>
<tr>
<td>Chemicals</td>
<td>NIE 0.06 ± 0.09</td>
<td>IE -</td>
</tr>
<tr>
<td>Staff costs and amortization</td>
<td>- 0.01 ± 0.04</td>
<td>- 0.02 ± 0.03</td>
</tr>
<tr>
<td>Total cost of the separation of formation water</td>
<td>NIE 0.23 ± 0.49</td>
<td>IE -</td>
</tr>
</tbody>
</table>

Table 5: The correlation between the costs of separated formation water for fields A, B and C

<table>
<thead>
<tr>
<th>Correlation (X vs. Y)</th>
<th>Field A</th>
<th>Fields B&amp;C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler room and demulsifiers station maintenance vs. Quantity of produced formation water</td>
<td>- -0.679</td>
<td>- -0.571</td>
</tr>
<tr>
<td>Heat exchangers and process vessels maintenance vs. Quantity of produced formation water</td>
<td>- -0.821</td>
<td>0.962 -</td>
</tr>
<tr>
<td>Energy vs. Quantity of produced formation water</td>
<td>- -0.429</td>
<td>0.767 -</td>
</tr>
<tr>
<td>Chemicals vs. Quantity of produced formation water</td>
<td>- -0.286</td>
<td>0.077 -</td>
</tr>
<tr>
<td>Chemicals vs. Heat exchangers and process vessels maintenance</td>
<td>- 0.536</td>
<td>0.141 -</td>
</tr>
<tr>
<td>Energy vs. Heat exchangers and process vessels maintenance</td>
<td>- -0.071</td>
<td>0.703 -</td>
</tr>
</tbody>
</table>

According to the results of the existence of normal distribution from Table 3, the correlation coefficients among the formation water separation costs for fields A, B and C variables have been calculated (see Table 5).

The positive correlation between variables showed a linear increase of both variables. Negative correlation between variables shows a linear increase of one variable, while the second variable records a linear decline. There is a correlation field A (-0.821); fields B and C (0.962) between the heat exchangers and process vessels maintenance and the quantity of produced formation water. There is a middle correlation between the remaining variables pairs which comes as a consequence of the unevenness of the investment during the observed period due to the decrease of operational costs caused by the decrease in the price of crude oil on the markets. The non-correlation among the chemicals and energy and the heat exchangers and process vessels maintenance is the consequence of the decrease in the investments in the formation water separation system.

7. Conclusion

The formation water separation costs in the oil-gas field A range from 0.14 USD/ m³ to 0.59 USD/ m³. The average year amount of produced formation water is 478 000 m³. The formation water separation costs in the oil and gas fields B and C range from 0.68 USD/m³ to 1.37 USD/m³ while the average year amount of produced formation water is 152 000 m³. The difference in the unit cost is caused by the difference in the amount of pro-
duced formation water, energy sources, the physical and chemical content of the fluids and the process maintenance. There is a correlation between the heat exchangers and process vessels maintenance and the quantity of produced formation water. There is a middle correlation between the energy and the quantity of produced formation water, and no correlation between the chemicals and the quantity of produced formation water, etc. The consequence of the lack of investment into the separation system is the zero correlation between chemicals and heat exchangers and process vessels maintenance. The lack of uniformity regarding the data is a consequence of the reduction of formation water separation costs. This however is the consequence of the lower price of crude oil on the world market. The formation water separation costs regarding mature oil and gas fields represent a significant share in the overall costs which can, in a certain moment and with a certain combination of technological factors and energy prices, be fundamental for the cost calculation and a business decision regarding the possible continuation of hydrocarbon exploitation in such fields.

8. References

8.1. Publications


Ivšinović, J. (2016): Statistička obrada troškova odvajanja pri dobivene slojne vode iz pješčenjakih ležišta Savske depresije (Statistical analysis of the costs of separating the produced formation water from a sandstone reservoir of Sava Depression), Matematičke metode i nazivlje u geologiji 2016, 69-74. (in Croatian)


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8.2. Unpublished reports

* INA d.d., monthly report on the measurement of the amount of liquid produced by the wells for Production region regarding for the period 2009 to 2015.

** INA d.d., technical documentation 2011, Sector for Field development, Study about oil and gas fields of Sava Depression.
SAŽETAK

Analiza troškova izdvajanja slojne vode iz ležišta ugljikovodika na primjeru gornjomiocenskih ležišta u pješćenjacima Savske depresije


Ključne riječi:
ekonomika slojne vode, statistička procjena, korelacija troškova, Savska depresija

Author contribution:
The author has prepared the whole work.