ISSN 2712-8008
Volume / Том 22 №2 2022
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622+553.982.2
Article / Статья


# On the question of hydraulic flow units use in terrigenous deposits taking into account facies (on the example of the Sof'inskoye field in the Perm Krai)

**Ekaterina I. Efremova, Ivan S. Putilov**

PermNIPIneft branch of LUKOIL-Engineering LLC in Perm (3a Permskaya st., Perm, 614015, Russian Federation)

# К вопросу о применении гидравлических единиц потока в терригенных отложениях с учетом фаций (на примере Софьинского месторождения Пермского края)

**Е.И. Ефремова, И.С. Путилов**

Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми (Россия, 614015, г. Пермь, ул. Пермская, 3а)

Received / Получена: 24.02.2022. Accepted / Принята: 31.05.2022. Published / Опубликована: 21.12.2022

*Keywords:*
oil and gas potential, field, oil, permeability, porosity, hydraulic flow units, flow zone indicator, terrigenous reservoir, facies, correlation coefficient, reservoir properties, core, sedimentation environments, reservoir class, Visean terrigenous oil and gas complex.

Within the Perm Krai, most of the hydrocarbon reserves are associated with terrigenous deposits of the Visean stage, which are characterized by high lithological heterogeneity, variability of reservoir properties, which are associated with different geological conditions of sedimentation, as a result of which the overall dependence of such petrophysical parameters, as porosity ($K_{por}$) and permeability ($K_{perm}$), is characterized by a fairly high dispersion. The use of one common dependence $K_{por} = f(K_{perm})$ for the entire area can lead to significant errors in the calculation of permeability.
In foreign literature, the solution to this problem is most often covered through the method of "hydraulic flow units", this technique was considered by domestic authors for the last decade.
Reconstruction of the conditions for the productive layer formation with the further use of the method of hydraulic flow units will increase the efficiency in creating hydrodynamic models of deposits, as well as study in more detail changes in the porosity and reservoir properties of reservoir rocks over the area and predict zones with improved reservoir properties.
The hydraulic flow unit is defined as "a representative unit volume of rock within which the geological and petrophysical properties that affect fluid flow are mutually consistent and predictably distinct from those of other rocks".
On the example of the Sof'inskoye oil field in the Perm Krai, the porosity and permeability properties of reservoir rocks ($K_{por}$, $K_{perm}$) were analyzed using core data.
The calculation of the flow zone indicator (FZI) and the allocation of hydraulic units (HU) were carried out within the productive deposits of the Visean terrigenous complex. To isolate the HU groups, a graph of the accumulated frequencies of the FZI values was plotted. Within each HU group, mean FZI, porosity and permeability values were determined. A matrix of the occurrence of the FZI depending on the facies setting was constructed, and an analysis of the FZI was carried out depending on the granulometric composition of the rock.
Based on the results of the studies, the authors of the works found that the calculation of permeability using the petrophysical dependences $K_{por} = f(K_{perm})$, based on the release of HU, made it possible to predict zones with the highest reservoir properties, which further increased the efficiency of drilling production wells.

*Ключевые слова:*
нефтегазоносность, месторождение, нефть, проницаемость, пористость, гидравлические единицы потока, индикатор гидравлической единицы, терригенный коллектор, фация, коэффициент корреляции, фильтрационно-емкостные свойства, керн, обстановки осадконакопления, класс коллектора, визейский терригенный нефтегазоносный комплекс.

В пределах Пермского края большая часть запасов углеводородного сырья приурочена к терригенным отложениям визейского яруса, которые, в свою очередь, характеризуются высокой литологической неоднородностью, изменчивостью фильтрационно-емкостных свойств, что связано с различными геологическими условиями осадконакопления, в результате чего общая зависимость таких петрофизических параметров, как пористость ($K_п$) и проницаемость ($K_{пр}$), характеризуется достаточно высокой дисперсией. Использование для всей площади одной общей зависимости $K_п = f(K_{пр})$, может привести к значительным погрешностям в расчете проницаемости.
В зарубежной литературе наиболее часто освещено решение данной проблемы через метод «гидравлических единиц потока», отечественными авторами данная методика стала рассматриваться последнее десятилетие.
Реконструкция условий формирования продуктивных пластов с дальнейшим использованием метода гидравлических единиц потока позволит повысить эффективность при создании гидродинамических моделей месторождений, а также более детально изучить изменения фильтрационно-емкостных свойств пород-коллекторов по площади и спрогнозировать зоны с улучшенными коллекторскими свойствами.
Гидравлическая единица потока определяется «как представительный элементарный объем породы, внутри которого геологические и петрофизические свойства, влияющие на течение жидкости, взаимно согласованы и предсказуемо отличны от свойств других пород».
На примере Софьинского нефтяного месторождения Пермского края проанализированы фильтрационно-емкостные свойства пород-коллекторов ($K_п$, $K_{пр}$) по керновым данным.
Расчет индикатора гидравлической единицы (FZI) и выделение гидравлических единиц (HU) проводились в пределах продуктивных отложений визейского терригенного комплекса. Для выделения групп HU строился график накопленных частот значений FZI. В пределах каждой группы HU определялись средние значений FZI, пористости и проницаемости. Построена матрица встречаемости параметра FZI в зависимости от фациальной обстановки, проведен анализ параметра FZI в зависимости от гранулометрического состава породы.
По результатам проведенных исследований, авторы работ установили, что—расчет проницаемости с использованием петрофизических зависимостей $K_п = f(K_{пр})$, основанных на выделении HU, позволяет спрогнозировать зоны с наиболее высокими фильтрационно-емкостными свойствами, что в дальнейшем повышает эффективность бурения эксплуатационных скважин.

© **Ekaterina I. Efremova** – Head of the Division for Estimation of the Reserves of the Northern group fields of the Volga-Ural region (e-mail: EfremovaEI1986@yandex.ru, tel.: +007 (919) 717 80 00). The contact person for correspondence.
© **Ivan S. Putilov** – (Author ID in Scopus: 25723777700) – Doctor of Engineering, Deputy Director of the Branch for Scientific Work in the Field of Geology (tel.: +007 (342) 233 64 58, e-mail: Ivan.Putilov@pnn.lukoil.com).

© **Ефремова Екатерина Игоревна** – начальник отдела подсчета запасов Северной группы месторождений Волго-Уральского региона (e-mail: EfremovaEI1986@yandex.ru, тел. +007 (919) 717 80 00). Контактное лицо для переписки.
© **Путилов Иван Сергеевич** – доктор технических наук, Заместитель директора Филиала по научной работе в области геологии (e-mail: Ivan.Putilov@pnn.lukoil.com, тел.: +007 (342) 233 64 58).

Please cite this article in English as:
Efremova E.I., Putilov I.S. On the question of hydraulic flow units use in terrigenous deposits taking into account facies (on the example of the Sof'inskoye field in the Perm Krai). *Perm Journal of Petroleum and Mining Engineering*, 2022, vol.22, no.2, pp.52-57. DOI: 10.15593/2712-8008/2022.2.1

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Ефремова Е.И., Путилов И.С. К вопросу о применении гидравлических единиц потока в терригенных отложениях с учетом фаций (на примре Софьинского месторождения Пермского края) // Недропользование. – 2022. – Т.22, №2. – С.52–57. DOI: 10.15593/2712-8008/2022.2.1

## Introduction

At the Sof'inskoye field, within the Visean terrigenous oil and gas complex, four productive layers have been identified: Tl2-a, Tl2-b, Bb1 and Bb2.

A total of twenty one wells were drilled with core sampling at the field. The total footage with core sampling amounted to 2914.1 m, with a core recovery of 1943.5 m, or 66.7 %. In nine wells, the length of cored interval was 891.7 m with a recovery of 880 m, or 98.7 %.

Based on previously conducted lithological-facial analysis for terrigenous deposits of the Visean stage [1–19], the following facies complexes were identified at the Sof'inskoye field:

1. Delta channel (DC).
2. Bay-lagoon coastal zone (BLC).
3. Bars and other coastal cumulative formations (B).

## Materials and methods

Table 1 shows the statistical characteristics of porosity and permeability parameters for each identified facies.

Terrigenous rocks of the delta channel (DC) facies are predominantly represented by samples with porosity ranging from 17.5 to 22.5 % (91 % of the sample). The permeability coefficient of this facies in most samples is from 100 to 500 mD (54 % of the sample).

The facies of the bay-lagoon coastal zone (BLC) is represented mainly by rocks with a porosity of 10–15 % (63 % of the sample) and more than 15 % (34 %). The permeability coefficient for reservoir rocks of this facies mainly ranges from 100 to 500 mD (43 % of the sample), while 23 % of samples show permeability greater than 500 mD). Low-permeability rocks make up 36 % of the sample (10–100 mD) and in 21 % of samples the permeability is less than 10 mD.

The coastal cumulative complex facies, bars (B), mainly include rocks with a porosity of more than 15 % (70 % of the sample), 15 % of samples with a porosity of 10–15 %. Permeability is mainly from 10 to 100 mD (58 % of the sample), 12 % are samples with a permeability of 100–500 mD (Table 1).

## Results of calculations and analysis

To determine the statistical significance of the mean values in the samples, the Student's *t*-criterion was calculated with formula (1):

$$t = \frac{M_1 - M_2}{\sqrt{m_1^2 + m_2^2}}, \qquad (1)$$

where $M_1$ – arithmetic mean of the first sample, $M_2$ – arithmetic mean of the second sample, $m_1$ – average error of the first arithmetic mean, $m_2$ – average error of the second arithmetic mean.

The calculations showed that there are statistically significant differences between the mean values of the porosity and permeability coefficients of the delta channel and bar facies. However, there are no statistically significant differences in parameters between the bar facies and the bay-lagoon coastal facies, indicating that the deposits within these facies are similar in filtration and storage properties.

Based on the available core data on porosity ($K_{por}$) and permeability ($K_{perm}$), a correlation field was constructed (Fig. 1); with the correlation coefficient ($r$) is 0.66. The diagram also shows that the sequence of facies changes, however there is an uncertainty zone where the data points characterizing different facies settings converge into a single area.

Due to the significant variability in values when establishing the relationship between porosity and permeability coefficients, as well as the errors present in permeability calculations, international practices have proposed the use of the hydraulic flow units method for predicting permeability [5–14]. This method correlates petrophysical and geological parameters, allowing for more accurate forecasts in subsurface studies.

The method is based on identifying groups of reservoir rocks (Hydraulic Flow Units) on the accumulated frequency graph of the flow zone indicator (FZI – Flow Zone Indicator) parameter by highlighting linear segments that correspond to groups of hydraulic units (HU) with similar FZI values [5, 20-22].

The identification of flow hydraulic units is based on the calculation of the FZI parameter, mm, using porosity and permeability (2):

$$\text{FZI} = \frac{0{,}0314\sqrt{\dfrac{K_{pr}}{K_p}}}{\dfrac{K_p}{1-K_p}}. \qquad (2)$$

The use of Hydraulic Units (HU) implies that there are a limited number of reservoir rock types, each characterized by an individual mean FZI value, while the variation in FZI values is attributed to random experimental errors [4, 5, 22].

Based on the fact that the FZI parameter links geological parameters, sedimentation conditions, and reservoir properties [17, 23–32], the relationship was studied in clay-rich rocks with grain sizes of less than 0.01 mm in diameter and their ability to function as reservoirs, as well as their FZI parameters. It is known that the higher the clay fraction content in the rock, the greater the specific surface area and the higher the amount of residual bound water, and therefore the FZI values should be lower. Conversely, less clayey, well-sorted sands are characterized by a lower specific surface area and a higher FZI parameter.

The conducted analysis established that with an increase in the clay fraction content in the rock, the amount of bound water increases, which is revealed by a direct linear correlation between the parameter of relative clay content (η) and the coefficient of residual water saturation ($K_{ws}$) (Fig. 2, *a*),

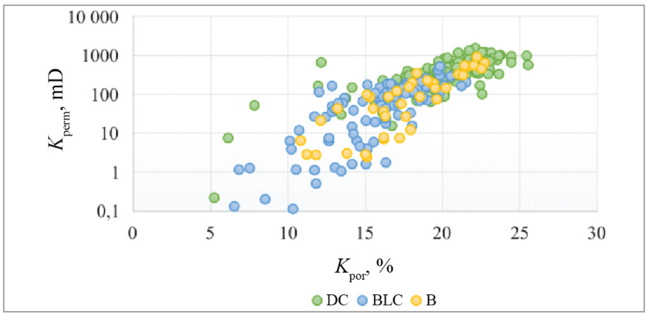


Fig. 1. Correlation field of $K_p$ and $K_{pr}$ for terrigenous deposits of the delta channel (DC) facies, the bay-lagoon coastal zone (BLC), and bars (B)

Table 1

Main statistical characteristics of facies

| Para meter | Delta channel | $t_{calc} > t_{theor}$ / $p$ | Bars | $t_{calc} > t_{theor}$ / $p$ | Bay-lagoon coastal zone |
|---|---|---|---|---|---|
| $K_{por}$, % | 19.3 ± 3.8<br>3.4–25.5 | 4.21 > 1.97<br>0.05 | 16.1 ± 4.8<br>4.2–22.7 | 0.44 < 1.97<br>0.05 | 15.7 ± 3.1<br>6.5–21.5 |
| $K_{perm}$, % | 433.2 ± 339.5<br>0.23-1590.7 | 6.15 > 1.97<br>0.05 | 160.4 ± 217.1<br>0.1-940.4 | 1.74 < 1.97<br>0.05 | 100.2 ± 97.9<br>0.12–541.4 |

Note: in the numerator – the mean value and standard deviation, in the denominator – the minimum and maximum values of the $K_{por}$, $K_{perm}$ parameters; $t_{calc}$ – the value of the calculated Student's *t*-criterion; $t_{theor}$ – the theoretical value of the Student's *t*-criterion; $p$ – the level of statistical significance.

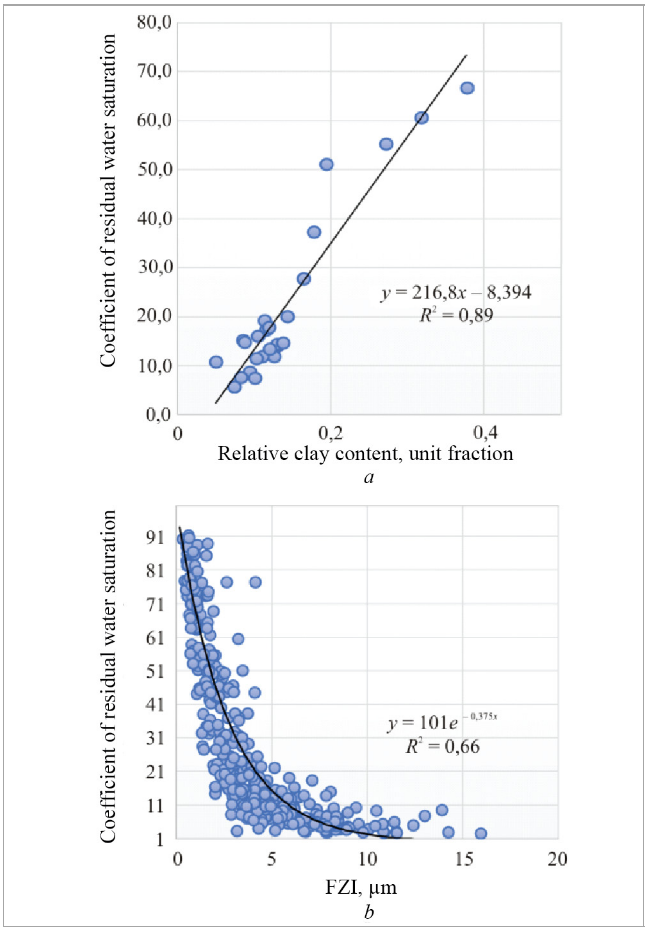


Fig. 2. Graphs of dependencies: *a* – coefficient of residual water saturation ($K_{ws}$) and relative clay content of rocks (η); *b* – FZI parameter and coefficient of residual water saturation

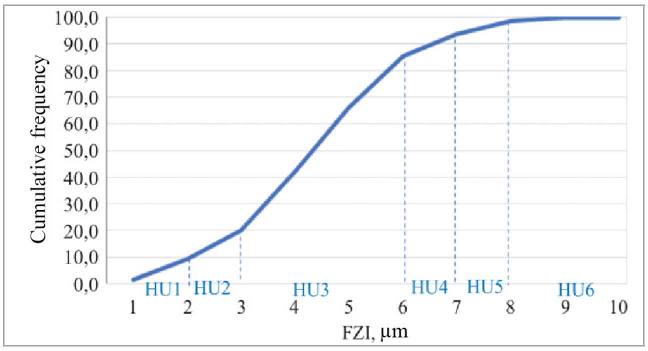


Fig. 3. FZI cumulative frequency graph for the delta channel facies

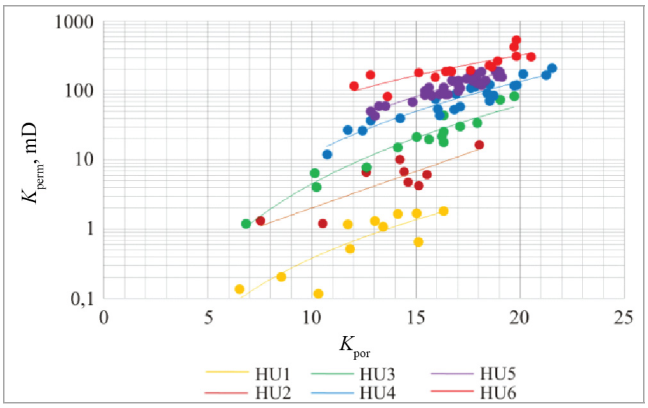


Fig. 4. Dependency of $K_{perm}$ on $K_{por}$ for facies of the bay-lagoon coastal zone

Table 2

Characteristics of hydraulic flow units

| Facies | HU | FZI average, μm | $t_{calc} > t_{theor}$* / $p$ |
|---|---|---|---|
| Delta channel (DC) | 1 | 1.37 | 7.22 > 2.22 / 0.05 |
| | 2 | 2.70 | 17.29 > 1.99 / 0.05 |
| | 3 | 4.76 | 15.81 > 1.98 / 0.05 |
| | 4 | 6.42 | 9.77 > 2.03 / 0.05 |
| | 5 | 7.41 | 6.08 > 2.11 / 0.05 |
| | 6 | 8.80 | |
| Bay-lagoon coastal (BLC) | 1 | 0.56 | 6.75 > 2.10 / 0.05 |
| | 2 | 1.27 | 6.31 > 2.07 / 0.05 |
| | 3 | 2.08 | 10.33 > 2.03 / 0.05 |
| | 4 | 3.27 | 9.49 > 2.00 / 0.05 |
| | 5 | 4.1 | 6.16 > 2.01 / 0.05 |
| | 6 | 5.60 | |
| Bars (B) | 1 | 0.21 | 7.05 > 2.11 / 0.05 |
| | 2 | 1.54 | 8.06 > 2.08 / 0.05 |
| | 3 | 3.35 | 7.03 > 2.11 / 0.05 |
| | 4 | 4.48 | 6.05 > 2.13 / 0.05 |
| | 5 | 6.04 | |

Table 3

Table of forecast equations $K_{perm}$ = f ($K_{por}$), with and without taking into account the allocated HU

| Facies | HU | Equation taking into account FZI | *R* (correlation coefficient) | *N* (number of samples) |
|---|---|---|---|---|
| Delta channel (DC) | 1 | - | - | - |
| | 2 | y= 3.1947e0.1669x | 0.86 | 10 |
| | 3 | y= 1.3574e0.2649x | 0.74 | 74 |
| | 4 | y= 11.859e0.1878x | 0.96 | 25 |
| | 5 | y= 17.452e0.1829x | 0.95 | 14 |
| | 6 | y= 10.535e0.2217x | 0.94 | 8 |
| | y= 1.7657e0.261x (generalized dependence for delta channels facies) | | 0.61 | 133 |
| Bay-lagoon coastal (BLC) | 1 | y= 0.0179e0.2933x | 0.81 | 11 |
| | 2 | y= 0.1788e0.2427x | 0.77 | 9 |
| | 3 | y= 0.1941e0.3034x | 0.80 | 15 |
| | 4 | y= 1.7189e0.2204x | 0.89 | 22 |
| | 5 | y= 3.5957e0.2072x | 0.89 | 33 |
| | 6 | y= 17.15e0.1486x | 0.77 | 16 |
| | y= 0.0396e0.4387x (generalized dependence for the bay-lagoon coastal facies) | | 0.64 | 106 |
| Bars (B) | 1 | y= 0.0029x0.6871 | 0.58 | 4 |
| | 2 | y= 0.0657e0.3245x | 0.64 | 15 |
| | 3 | y= 1.8866e0.2182x | 0.94 | 7 |
| | 4 | y= 3.5274e0.2149x | 0.94 | 11 |
| | 5 | y= 18.33e0.1612x | 0.69 | 6 |
| | y= 0.0015e0.5908x (generalized dependence for bar facies) | | 0.67 | 43 |

with a determination coefficient ($R^2$) of 0.89. Accordingly, there is an inverse nonlinear relationship between the FZI parameter and the coefficient of residual water saturation, with a determination coefficient of 0.66 (Fig. 2, *b*) [33].

Thus, the FZI parameter allows grouping rocks with similar pore space characteristics, the difference of which is determined by sedimentation conditions.

To identify HU groups, a graph of accumulated frequencies of FZI parameters was constructed [12, 15, 17, 34–40] and straight-line sections were identified on the graph, which corresponded to the HU reservoirs groups (Fig. 3).

Next, for each HU group, the average parameters of the formation reservoir properties (FRP) were determined (Table 2). Table 2 shows that the FZI parameter depends on the facies environments; in the delta channel facies, it reaches its maximum. Using Student's *t*-criterion, a comparison of the obtained samples within the facies was carried out, which showed the presence of statistically significant differences between the identified HU groups.

For each HU group, identified with FZI, the forecast equations $K_{perm} = f(K_{por})$, were constructed, presented in table 3.

The closest relationship was obtained between the porosity and permeability coefficients when separating the HU groups within the facies, the correlation coefficients vary in the range from 0.58 to 0.96 [29, 40].

The ratio of porosity and permeability coefficients in this case is considered as a set of dependencies for each HU group with its own petrophysical properties (Fig. 4), which indicates the possibility of determining a more accurate permeability coefficient using dependencies obtained with FZI [12, 26, 27].

## Conclusion

Concerning the results of the research, it has been established that there is a relationship between the FZI parameter and the petrophysical properties of rocks, which are determined by conditions of sedimentation. Using the FZI parameter and the division of rocks into hydraulic units allows for a detailed consideration of the the reservoir geological heterogeneity.

A single dependence based on core data for 'porosity – permeability' can lead to significant errors when determining permeability from geophysical logging data, which is subsequently used in the hydrodynamic model of the field. The analysis of the correlation dependencies for 'porosity – permeability', with the HU identification in the facies, has shown a sufficiently close relationship between the coefficients of porosity and permeability. Therefore, to increase the reliability in determining the formation reservoir properties, it is recommended to use the $K_{perm} = f(K_{por})$ dependencies, constructed with HU groups.

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Funding: The study had no sponsorship support.
Conflict of interest. The authors declare no conflict of interest.
The authors' contribution is equal.