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Flow Thermodynamic Interpretation of Chemical EOR Methods

I. Lakatos[1] and G. Szentes[2]

[1] Miskolci Egyetem, Alkalmazott Földtudományi kutató Intézet, szentes@afki.hu
[2] Miskolci Egyetem, Alkalmazott Földtudományi kutató Intézet, lakatos@afki.hu

Abstract

As reported by the BP statistical review published in 2022, the total world oil production was roughly 4.23 Gt last year. Although the hectic change of recovery factor is significant, the role of advanced oil recovery technology forms a continuous effort due to the fact that basically primary methods characterized by only by average world-wide recovery factor between 35-40 %. Namely, substantial efforts have to be made using secondary and even EOR methods with the aim at increasing the recovery factor. Despite great number of concepts, procedures, theories, etc. are used to attain the final goals, but the numerous books, papers, presentations (more than 200,000 hits in OnePetro data bank) the thermodynamic approach is completely neglected in the cited topics. Unfortunately, all the efforts are based on evaluation of *intensive* physical and chemical data (temperature, pressure, interfacial tension, etc.), meanwhile the extensive parameters are completely neglected. Thus, surveying the published and applied important parameters, focused only on phenomenological description of processes and interactions formed the basis of classification and comparability, and hence, the possible production technologies, which fits the best to an oilfield, or reservoir.

1 Introduction

Despite urgent need to utilize natural hydrocarbons, controversial attitude towards EOR methods characterizes the industry and the society. The operators are particularly keeping distance from routine application of chemical IOR/EOR methods and this fact cannot not be justified by hectic the oil and gas price. Therefore, it is an urgent need to reevaluate the methods elucidating their mechanism more deeply under formation conditions, using new approaches and principles, searching new materials and facilities, developing more adequate mathematical, up-scaling technique and even financial analysis. From theoretical point of view, one of the progressive options might be the thermodynamic interpretation and classification of IOR/EOR methods. It should be mentioned, however that that this approach is generally absent in reservoir engineering theories and practice. Namely, these valuable books offer basic aspects of thermodynamic principles of reservoirs like phase behavior, equilibrium, interactions, etc., energetical description of fluid flow is completely neglected in different chapters. Thus, the activation energy of viscous flow is a brand new approach and my open new vistas in EOR evaluation of different methods and technologies.

2 Thermodynamic interpretation

As reported by the BP statistical review the total world oil production in 2021 was roughly 4.2 Gt. Despite the change of recovery factor is significant even today, the role of advanced oil recovery technology forms a continuous efforts due to the fact that the primary methods are characterized by low production rate. As shown in Fig. 1, the average world-wide recovery factor is usually between 30-35%, viz. substantial efforts have been made using secondary and even EOR methods. Despite great number of concepts, procedures, theories, etc. are used to attain the final goals, but the numerous books, papers, presentations (more than 200,000 hits in OnePetro data bank) the thermodynamic approach is completely neglected. Unfortunately, all the efforts are based on evaluation of intensive physical and chemical data (temperature, pressure, interfacial tension, etc.), meanwhile the extensive parameters are completely neglected (see references [1-3]). Thus, surveying the published and applied important parameters, focused only on phenomenological description of processes and interactions formed the basis of classification and comparability, and hence, the possible production technologies, which fits the best to an oilfield, or reservoir.

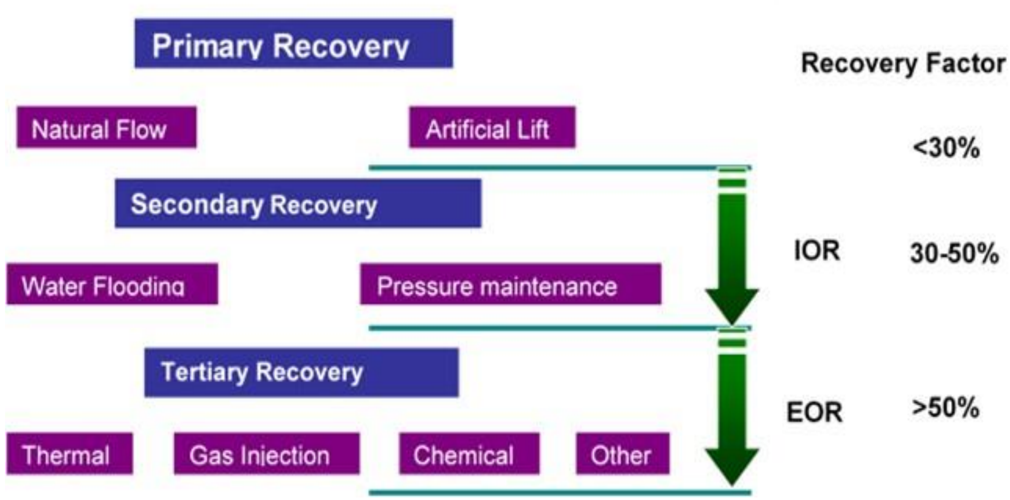


Fig 1: Classification of recovery technologies at different stage of production

Advantages of the present engineering techniques using intensive parameters:

- Explanation of processes is tangible
- Easy to set up functions and models
- Direct communication between theory and practice
- No need of new paradigms, etc.

Disadvantages of the present engineering techniques:

- The different physical and chemical factors influencing the displacement phenomena don't form a common and additive parameter, which can be used as a universal parameter characterizing the displacement process, and among others, the recovery efficiency.
- Theoretically, it is reasonable and advantageous if the IOR/EOR method to be applied results in a substantial decrease in the thermodynamic threshold potential (activation energy) ruling the flow process, and hence determining the recovery efficiency

Trap of the IOR/EOR technology: some IOR/EOR methods do not decrease, but rather increase the thermodynamic threshold potential. Consequently, they may represent both thermodynamically both convergent and divergent solutions even though these methods might be beneficial from engineering point of view.

Thermodynamic calculation of flow activation energy is simple and is based on well-known dependency of viscosity on temperature. Thus, the intensive property can be transformed to extensive property (ΔEv):

$$\eta = A_v e^{\Delta E_v / RT}$$

If the entropy change is negligible (Ree-Eyring hypothesis) the De Guzman (Arrhenius) equation can be described as

$$\eta = \frac{hN_a}{V_M} e^{\Delta G_v / RT}$$

where ΔG is the Gibbs energy of viscous flow. The viscosity often depends on shear rate as well as non-Newtonian fluid character

$$\eta = \frac{\eta_0}{\left[1+\left(\tau_r \gamma\right)^2\right]^m}$$

Obviously, the activation energy of viscus flow of non-Newtonian fluids, formally will reflect the dependency of viscosity on shear rate. That statements is well proved by diagram shown in Fig. 2 for a polymer solution often used in chemical EOR technology. Theoretical consequences of thermodynamic calculation is that the activation energy of viscous flow of both Newtonian and non-Newtonian fluids may differ orders of magnitude (Fig. 3) and the absolute value significantly differs from viscosity. However, one should keep in mind that the former one is intensive and the last one is extensive state constant.

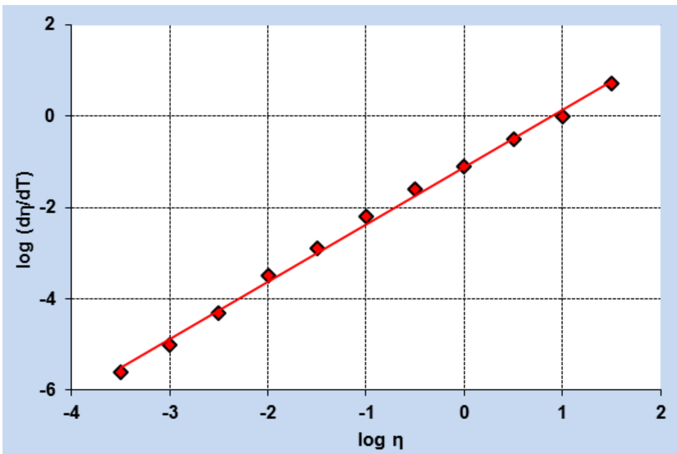


Fig. 2: Activation energy of viscous flow as a function of logarithmic viscosity

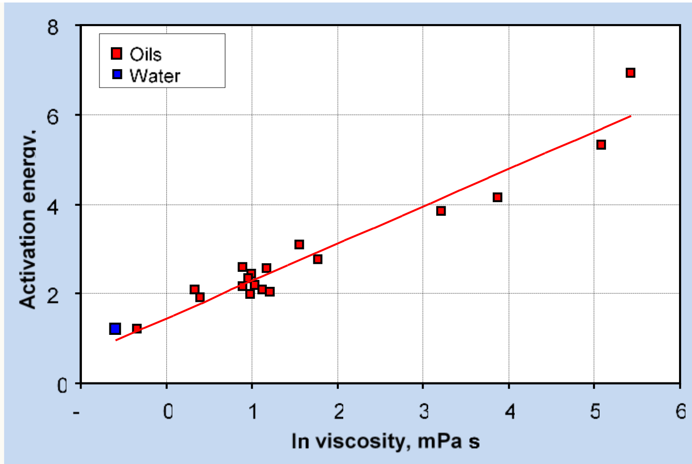


Fig. 3: Activation energy of viscous flow as a function of logarithmic viscosity

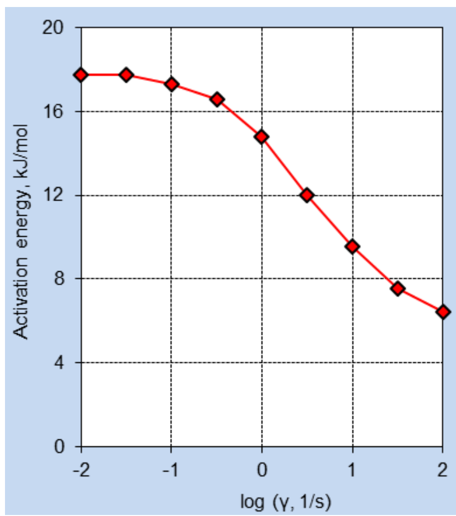
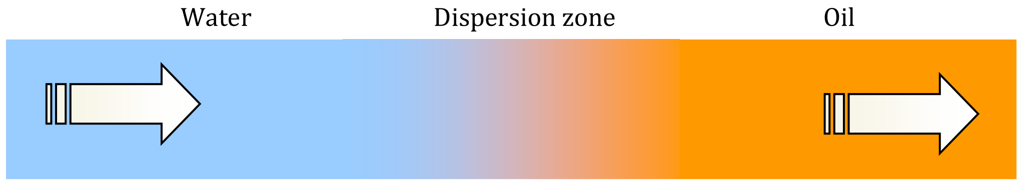


Fig. 4: Effect of shear rate on activation energy

Divergent Methods	Mixed Methods	Convergent Methods
Polymer Gel Emulsion Foam	Tenside Alkaline Microemulsion	Gas injection (CO_2, CH, inert) Thermal methods (Steam, hot water Combustion Methods

Fig. 5: Classification of EOR methods using flow thermodynamic approach



ΔE_v^w ΔE_s^{wo} ΔE_v^o

$$\Delta E_t = \Delta E_v + \Delta E_s = (\Delta E_v^w + \Delta E_v^o) + \Delta E_s^{wo}$$

Fig.6: Additivity of activation energy of different flow regime

Representative example of EOR application

The unique advantage of flow hydrodynamic concept will be presented below. The EOR application was performed in the Algyő field aim at increasing the recovery factor in a gas field after intensive waterflooding. The basic concept of lean gas flooding was to enhance vaporization of light hydrocarbon from the residual oil saturation and later removal of liquid hydrocarbon from the recovered gas/hydrocarbon mixture. Truly, the lightest cut was a gain from economic point of view, however, the residual fluid in the reservoir become so viscous that probably its recovery could become impossible in the future (Fig. 7.). However, today we may say the little gain – big loss. As a summary, we may conclude that using thermodynamic evaluation, even a positive preliminary finding may prove finally negative.

Advantages:

Light hydrocarbons present in residual oil saturation after water flooding evaporates into the gas phase which can be removed from the produced gaseous gas mixture by condensation. The project was qualified as a **very successful technology**.

Disadvantages:

The hydrocarbon residue remaining in the reservoir after gas injection has extreme viscosity, which needs extremely high activation energy to recover. Since such an EOR method is not existing today, the oil saturation will not be able to recover, viz. it is lost forever. Little gain and big lost! From thermodynamical point of view, the project is **not a successful technology!**

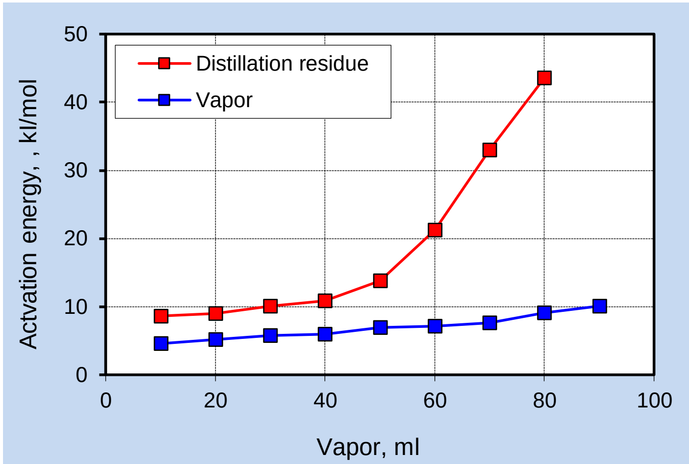


Fig 7: Hydrodynamic evaluation of lean gas injection EOR

Mechanism of mobility (profile) control in multilayered systems

The profile (mobility) control in multilayered reservoir systems being the basis of volumetric sweep efficiency is apparently under rheology (viscosity) control, however the theoretical interpretation should be the equivalent activation energy of viscous flow to get better understanding of piston-like displacement!

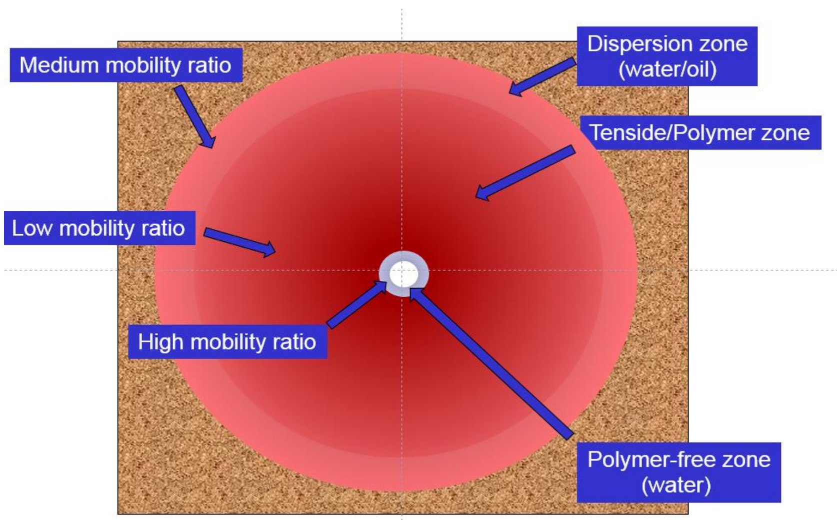


Fig 8: Mobility control in 2D interpretation (surfactant/polymer flooding in Hungary)

The project has been started at the field 10 years ago using two injection wells and several thousand m3 surfactant/polymer solution has been injected into the wells. At the beginning similar volumetric rate was applied at wells. However, within a short time the injectivity of one well (well-1) dropped rapidly reaching the maximum safety injection pressure (see Figs 9 and 10). In contrast, the good injectivity remained the same as it was at the beginning. Based on these field experiences, the behavior of Well-2 was accepted as good, and Well-1 was qualified as irregular and often should have been controlled its injectivity. From thermodynamic point of view just the opposite situation is correct. The continuous injection rate in case of Well-2 definitely can be attributed to cross flow, viz. the injected treating fluid was flowing not into the target layer. As a result, the lost and expensive surfactant polymer solution jeopardized not only technical expectation but caused significant economic losses.

Namely, in sample above the constant well head pressure, despite injecting several hundred m3 treating surfactant/polymer solution definitely indicate cross-flow in multilayered reservoir system, viz. Well 1 is a closed, Well 2 is operating in an open thermodynamic system.

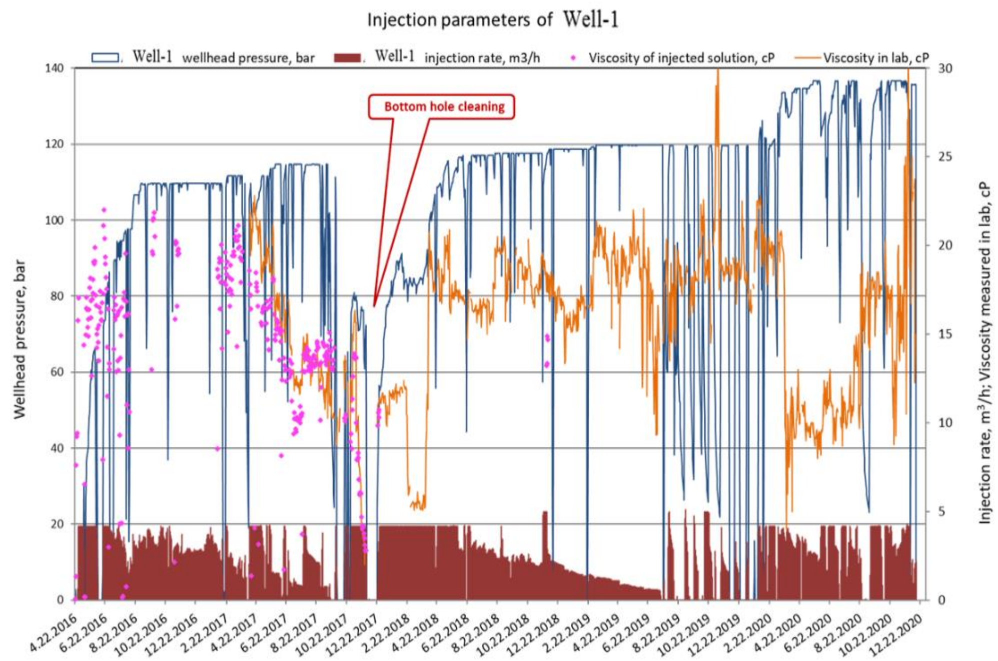


Fig. 9: Injection parameters characterizing Well-1

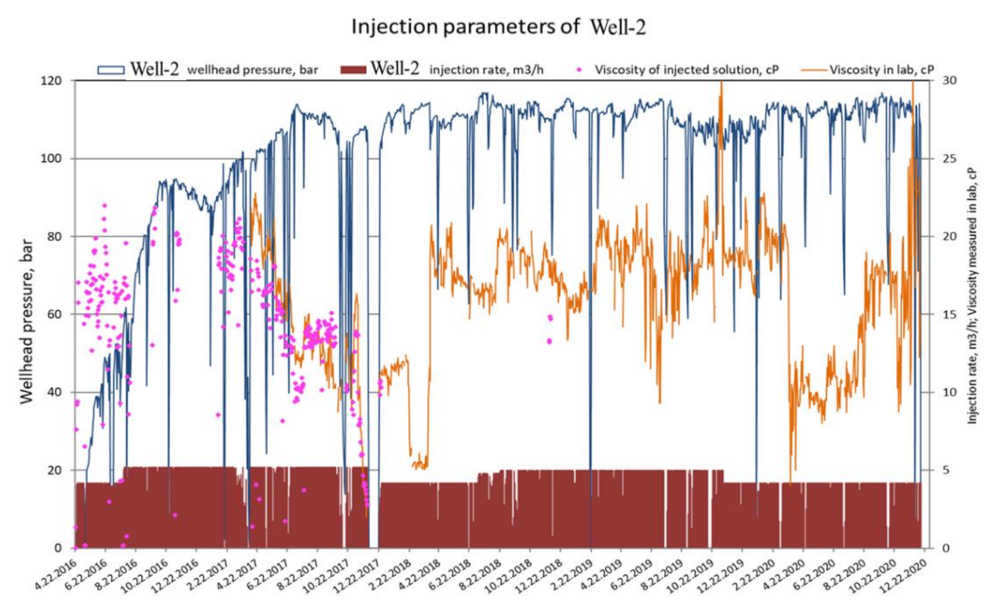


Fig. 10: Injection parameters characterizing Well-2

3 Conclusions

The flow thermodynamic interpretation of viscous flow of EOR technologies may open new vistas in theoretical and practical reservoir engineering. Resolving controversial views will help to decide what is **good** and what is **wrong**. The new approach will also result improved recovery efficiency economizing the utilization of the explored hydrocarbon resources.

4 Acknowledgement

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