

Causes of solvent slug decrease during oil displacement processes under miscible conditions, with a review of simulation aspects of such processes

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REVIEW

The paper briefly describes the effects of diffusion and dispersion and other effects present during the oil displacement processes with miscible fluids, i.e. solvents. Recovery of oil is significantly improved during the application of such processes, but at the same time accompanied with decrease or even total loss of solvent slug. When designing such processes, particular attention should be paid to determine optimum slug size that is in direct contact with reservoir fluids, and where the mentioned effects have to be taken into consideration. Thereby the application of reservoir simulation, as a prediction method for calculation of incremental recovery, can be useful if sufficient high-quality data, such as laboratory core analyses, slim-tube tests and/or pilot tests performed on representative parts of the reservoir, are available for a particular simulation project, and the review of that is given in the final part of the text.

Key words: diffusion, dispersion, enhanced oil recovery, phase behaviour, solvent slug

INTRODUCTION

The enhanced oil recovery processes (EOR processes), which include displacement with miscible fluids, are based on different, and often combined mechanisms of functioning, for instance such as the application of chemicals with different action effects, decrease of mobility ratio between the displacing and displaced fluids (M), use of thermal energy, optimisation of reservoir pressure and displacement rate, etc.^{2,13} The basic operating principle of such processes is enhanced recovery obtained through a change of chemical properties (for example, by changing the pH value) and/or physical properties at the contact between displaced fluids (different types of oil) and displacing fluids (surfactants, micro-emulsions, alkali, solvents, carbon dioxide, etc.).^{2,6} In line with that, by changing reservoir pressure and temperature additional effects are obtained that change physical and chemical properties of displacing and displaced fluids, and more intense mutual effects at the contact between them are achieved. The purpose of enhanced recovery, as the very name suggests, is additional recovery of oil, in most cases unrecoverable by conventional secondary processes,⁸ such as flooding,^{3,15,23} which remained in a reservoir after their application. The paper mostly focuses on diffusion and dispersion effects, which are present only during oil displacement under miscible conditions, and also describes some other effects present during such and other processes applied to enhance oil recovery.

The efficiency of oil displacement under miscible conditions is based on annulment of interfacial tension between the displacing and displaced fluids, where at the

contact between the fluids comes to diffusion and dispersion effects.^{6,14,15,19} These methods under laboratory conditions achieve displacement efficiency even up to 100 %. The fluids are brought to p , T conditions when mixing occurs in all concentrations without the creation of dividing surface between them, i.e. there is only one phase. Under such conditions a mixing zone, i.e. slug, which is by composition their mixture, is formed between the oil and displacing fluid. According to the manner of slug forming we distinguish between three main types of EOR processes under miscible conditions, i.e. high-pressure injection of lean (dry) gas, injection of enriched gas and injection of solvents.²

During displacement of oil by lean gas, middle hydrocarbon components of displaced oil vaporize under high pressure into displacing gas. In that manner a slug of enriched gas is formed in the reservoir between the injected gas and oil, which mixes both with oil and gas. Fulfilment of mixing requirements necessitates proper conditions of pressure and temperature and at that temperature the pressure which is not lower than minimum miscibility pressure (MMP), as well as oil composition which contains a sufficient concentration of middle hydrocarbon components, from C_2 to C_6 .

Injection of enriched gas is applied in reservoirs with heavier oils. Enriched gas contains middle components, from C_2 to C_6 , which oil absorbs from it, and it results in creation of miscible zone between the fluids. The secondary displacing fluid, which follows the enriched gas slug in much larger quantities, is lean gas that can be followed by water. The main difference between this and previously mentioned process is that displacement by

lean gas results in the formation of mixing zone so that middle components, C_2 - C_6 , are mostly transferred from oil to gas, while in displacement by enriched gas middle components are mostly transferred from gas into oil, i.e. vice versa.

Injection of solvent, which is a subject of more detailed consideration in further text, is a process similar to injection of enriched gas. That method is applied in displacement of heavy oils under conditions of lower reservoir pressures. Solvents are usually injected in limited quantities as slugs followed by other displacing fluids. It is due to high cost of the solvent, which, if used in greater quantities, would render the displacing process unprofitable. Displacing fluids, that follow after the solvent plug are most often lean gas (usually methane) or carbon dioxide. These fluids are considerably cheaper and can be injected in much larger quantities.

Solvent injection processes are further classified according to the type of injected solvents, which include liquefied natural (petroleum) gas (LNG or LPG), alcohol and carbon dioxide.^{14,15}

Liquefied natural gas is injected into an oil reservoir as a primary slug, which is further displaced through the reservoir by lean gas and/or water as a secondary displacing fluid (slug). During displacement of liquefied petroleum gas with lean gas, adequately high pressure must be maintained in the reservoir so that the two fluids are kept under miscibility conditions. If the primary slug of liquefied petroleum gas is directly displaced with water as a secondary slug, then after the primary slug high quantities of it remain in the reservoir, since the system 'liquefied petroleum gas - water' is not miscible. It results in premature direct contact between oil and water and total absence of miscible conditions, turning the process into conventional flooding. In order to avoid the problem, some authors suggest using lean gas as displacing slug immediately after liquefied petroleum gas, and water could follow only after considerably larger quantities of lean gas.²

The process of oil displacement by butyl or propyl alcohol slug is similar to the previously described process, but with much more favourable mobility ratio.^{14,15} The slug is displaced with water, with which it is miscible. Disadvantages of this process are the high cost of alcohol and its even faster loss in the reservoir compared to liquefied petroleum gas process.

The principle of enhanced oil recovery through injection of carbon dioxide slug is also similar to the previously described methods of liquefied natural gas

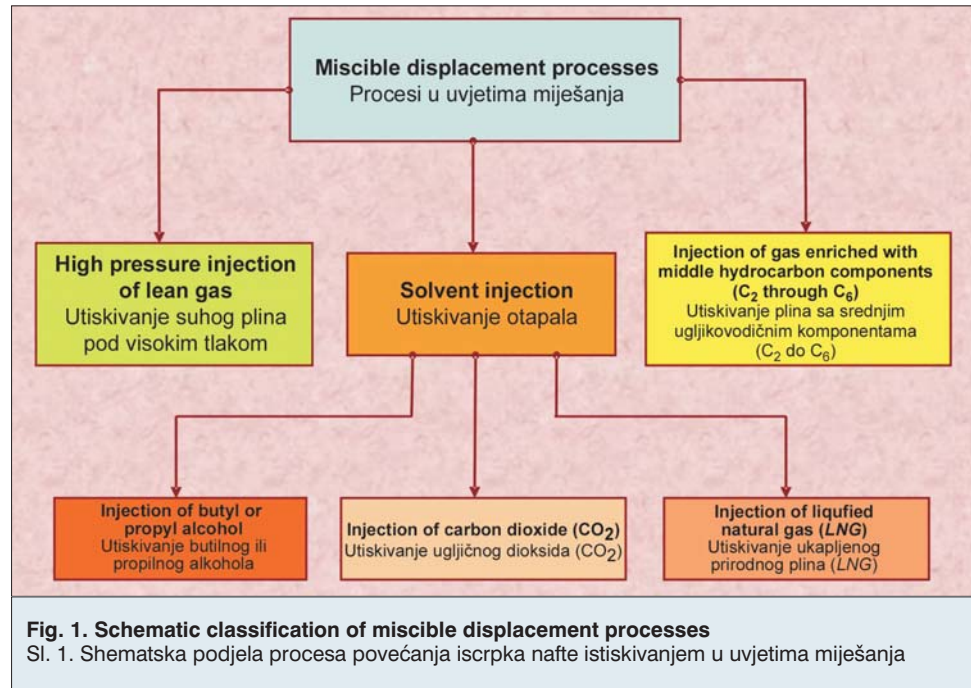


Fig. 1. Schematic classification of miscible displacement processes
Sl. 1. Shematska podjela procesa povećanja iscrpka nafte istiskivanjem u uvjetima miješanja

and alcohol injection. Carbon dioxide, as the injection medium, has very wide applications in the world. If at reservoir temperature the reservoir pressure exceeds the minimum miscibility pressure, mixing occurs both with oil before and with water after the slug, resulting in a series of positive effects established during laboratory analyses, which have considerable impact on enhancement of ultimate recovery.^{14,15}

In short, what additional recovery of oil will be fulfilled during displacement by solvent depends on the type of reservoir rock, type of displaced oil, selection and quantity of solvent, selection and quantity of fluid used to displace the solvent slug, temperature and pressure in the reservoir and the speed of the displacing process. In Figure 1 are schematically represented previously described processes.

1. CAUSES OF SOLVENT SLUG DECREASE

When designing the size of solvent slug necessary for oil displacement, we must primarily take into consideration the main physical and chemical phenomena present during the oil displacement under miscible conditions, such as phase behaviour and accompanying diffusion and dispersion effects. The computation of solvent quantity to be injected is of utmost importance due to its high cost. The solvent slug, located between oil and displacing fluid, at a given reservoir conditions must be miscible with both fluids. The problem lies in fast spreading of solvent slug through the reservoir, and when designing the slug size we must determine its optimum quantity sufficient to maintain 100 % concentration between mixture of oil and solvent before and mixture of solvent and displacing fluid after the slug during the entire project. Above mentioned mixtures must have a concentration above critical one (MME)⁶, where critical concentration and other additional terms related to the

subject are explained in continuation, in sub-sections 1.1 - 1.6. In these processes can be present the following causes, primarily of solvent losses,^{14,15} and generally inefficiencies in application of such processes:

- too fast mixing through processes of diffusion and dispersion with reservoir fluids before the slug and displacing fluids after the slug (for example, with lean gas as displacing fluid),
- slug spreading due to unfavourable network of wells: allocation of injection and production wells with irregular pattern is often used in practice due to unfavourable terrain configuration, shape and heterogeneity of the reservoir, as well as the rationality of using existing producing wells for injection which in the meantime have become flooded, but have a good, although not optimal, position for injection,
- solvent loss in highly permeable layers, i.e. in reservoirs with considerable heterogeneity (definition of heterogeneity and ways in which it is expressed are explained in further text),
- unfavourable viscosity ratios between oil and solvent, and between solvent and displacing fluid (unfavourable mobility ratios),
- saturation of oil reservoir with gas: due to existence of different phases, displacement process does not proceed under miscible conditions because of forming of increasing gas slug between the oil and displacing solvent,
- collector type: some reservoir rocks are characterized with such porosity in which a part of oil even under miscible conditions is not recoverable,⁶ and
- velocity of displacement: if in a part or whole reservoir miscible conditions have not been achieved, residual oil saturation will increase, i.e. oil recovery will decrease, with reduction of displacement rate (presence of Jamin's effect,^{6,14} briefly explained in

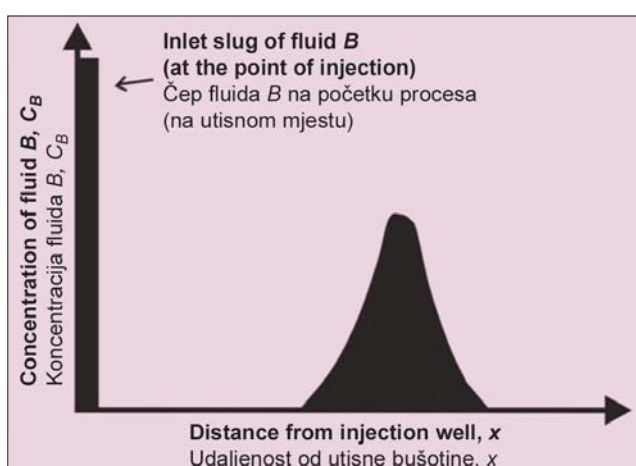


Fig. 2. Idealized concentration slug profile of fluid B (solvent) during miscible displacement of fluid A (oil)⁶

Sl. 2. Idealizirani profil koncentracije čepa fluida B (otapala) kod procesa istiskivanja fluida A (nafte) u uvjetima miješanja⁶

further text). However, the impact of displacement rate can be relativized, since at very low displacement rates due to the other effects of reverse action, residual oil saturation can decrease (e.g. at lower displacement rates equilibrium between liquids is more easily established,^{14,15} and in slanted reservoirs with well developed vertical permeability positive mechanism of gravity segregation can appear).

Figure 2 shows an idealized concentration profile in miscible displacement process for solvent slug propagating through the reservoir.

Effects which accompany oil displacement under miscible conditions, as well as certain frequently used terms related to analysis of causes of solvent slug decrease are explained in lower text.

1.1. IMPACT OF PHASE BEHAVIOUR ON DIFFUSION AND DISPERSION

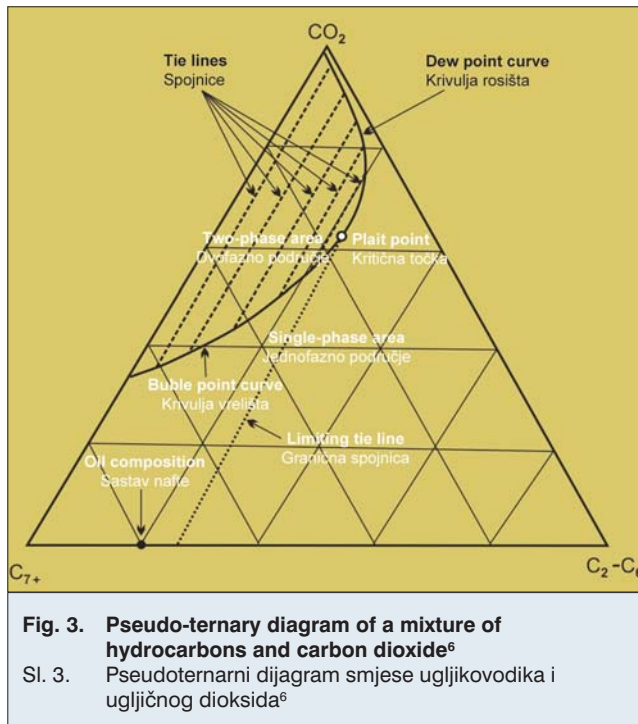
All oil displacement processes under miscible conditions are accompanied with mass transfer at the contact between the present fluids, known as diffusion and dispersion processes.^{6,14,15,19} These processes cause mutual dilution and solution of displacing and displaced fluids, and in that way affect their phase behaviour. Since designing of processes under miscible conditions is related to analyses of phase behaviour of fluids, when effects of diffusion and dispersion intensify, knowledge of such behaviour, as well as knowledge of fluid mixing processes, is necessary.

1.1.1. Phase Behaviour

A good illustration of phase behaviour of the mentioned processes is a pseudo-ternary⁶ diagram. In cases when at certain pressure and temperature we have to show interaction, i.e. phase behaviour, of three components, for example methane (C_1) or carbon dioxide (CO_2), middle pseudo-component (from C_2 to C_6) and heavier (heavy) pseudo-component – reservoir oil (C_{7+}), we often use such mode of presentation.^{14,15} In Figure 3, where an example of such diagram is shown, we can differ between two areas, as follows:

- two-phase area, delineated by phase boundary curve, which includes the dew point curve and in continuation the boiling point curve, where both the gaseous and liquid phases are in equilibrium and are found on the left side of the plait point,
- single-phase area to the right and above the plait point, i.e. to the right and above the dew point curve, with predominating mixture of carbon dioxide (CO_2) and middle hydrocarbon pseudo-component (C_2-C_6), which is common with the single-phase area below the plait point, i.e. below the boiling point curve, with predominating mixture of middle hydrocarbon pseudo-component and reservoir oil (C_{7+}).

The lines connecting two opposite points within the two-phase area, delineated by boiling point and dew point curves are called tie lines^{14,15} and several of them are shown in the Figure. The limiting tie line is a tangent at plait point. On ternary (three-component) diagrams any mixture of two fluids lies on the line between the points which represent their initial compositions.



Displacement processes, which are attempted to keep under miscible conditions, should be performed at a certain pressure, which is not lower than minimum miscibility pressure (*MMP*), and a certain temperature ($p, T = \text{const.}$). Besides, in accordance with previous laboratory analyses, we must know, at least approximately, throughout the entire process the composition of mixtures at the contact between oil (C_{7+}) and primary slug (C_2-C_6), and at the contact between the primary slug (C_2-C_6) and displacing fluid – secondary slug (CO_2 or C_1). In short, according to Fig. 2, compositions of mixtures of displaced and displacing fluids for *FCM* processes should be maintained within the frame of the pseudo-ternary diagram along the lines (lines between points of initial compositions) whose entire length is within the single-phase area, or for *MCM* processes along the lines which at the beginning of the process to a lesser extent intersect the two-phase area.⁶

1.1.2. Molecular and Effective Diffusion

Molecular diffusion occurs when two or more fluids, which are miscible under certain (reservoir) conditions, are in direct contact. The equation which according to simplified model describes diffusion flow through an area can be used to describe molecular diffusion:⁶

$$D_{BA} = \frac{m_{Bx}}{A \cdot \left(\frac{\partial C_B}{\partial x} \right)} \quad (1)$$

From the equation arises that the quantity of diffusion of fluid *B* into fluid *A* is proportional to the concentration gradient $\partial C_B / \partial x$ of fluid *B*. The magnitude of that proportion is called molecular diffusion coefficient, D_{BA} . The negative sign on the right side of the equation means that the diffusion process goes in the direction of concentration decrease of fluid *A*.

Diffusion coefficient, defined according to equation (1), is usually a function of concentration, temperature and chemical composition of mixing fluids. For more precise analyses, dependence on concentration and/or temperature must be included in the diffusion equation. However, assumption on constant value of molecular diffusion coefficient throughout the entire range of concentrations and temperatures during a certain process is often satisfactory in practice.⁶

Equation (1) can be directly applied if the type of porous space of the rock is similar to a bundle of straight capillary tubes, which is mostly not the case in reality. Fluids in the reservoir flow in a tortuous pattern through the pore space. If as a measure of average tortuosity for a particular collector type, i.e. its pore space, we assume a mean slope of 45° with regard to the main direction of the flow, diffusion coefficient can be corrected by means of the following equation:

$$\frac{D_{aBA}}{D_{BA}} = \frac{1}{\sqrt{2}} = 0.707 \quad (2)$$

Diffusion in porous media can be presented as a function of electrical resistivity of the rock. It is based on the analogy between electrical conductivity and mass diffusion in the porous media. It means that the flow path of electric current through the rock is actually analogous to the flow path due to diffusion of fluid *B*. That analogy can be presented by the following equation:

$$\frac{D_{aBA}}{D_{BA}} = \frac{1}{F_R \cdot \phi} \quad (3)$$

Values of factor D_{aBA}/D_{BA} usually range from 0.6 to 0.7, although they can be significantly lower, depending on the type of porous media. Effective diffusion coefficients are obtained by correction of equation (1) with values of factors obtained by means of equations (2) or (3).

By its characteristics, diffusion is a process at molecular level, where mixing of particles occurs due to their random movement at the boundary between the two fluids. Diffusion process, as a mechanism of mixing, is dominant if flow velocities in the porous media are very small.

1.1.3. Longitudinal and Transversal Dispersion

Additional mixing between two different fluids, called dispersion, occurs during flow through porous media, particularly at higher velocities. Increase in mixing intensity occurs due to non-uniform flow of fluids and/or differences in concentrations. Distinction is made between longitudinal and transversal dispersion, depending on direction of dispersion process. Longitudinal dispersion proceeds in the direction of oil displacement, and transverse dispersion is perpendicular to that direction. These two types of dispersion develop at mutually different intensities, which change with regard to time and position in relation to initial conditions. Intensity of mixing depends on interaction of molecular diffusion and dispersion. In the area where diffusion and dispersion are simultaneously present, total dispersion coefficient will be equal to the sum of the two coefficients. If in the same direction is

longitudinal dispersion greater than molecular diffusion, then it is proportional to average flow velocity through porous media. Numerous dispersion studies have indicated that dispersion coefficient is a function of porous media properties, characteristics of displacing/displaced fluids and flow velocity.⁷ Probably the best approach to description of dispersion is based on the introduction of dispersion coefficient as a parameter analogous to molecular diffusion coefficient. The following equation represents a correlation that in many cases can be fairly used for calculation of longitudinal dispersion:⁶

$$\frac{K_l}{D_{BA}} = \frac{1}{F_R \cdot \phi} + 0.5 \cdot \left(\frac{v F_l d_p}{D_{BA}} \right) \text{ for } \frac{v F_l d_p}{D_{BA}} < 50 \quad (4)$$

This equation is dimensionless and can be applied to any group of mutually consistent units. Equation for transversal dispersion is shown in the same form, but with different coefficient of proportionality:

$$\frac{K_t}{D_{BA}} = \frac{1}{F_R \cdot \phi} + 0.0157 \cdot \left(\frac{v F_l d_p}{D_{BA}} \right) \text{ for } \frac{v F_l d_p}{D_{BA}} < 10^4 \quad (5)$$

The mean oil displacement rate by slug, present in equations (4) and (5), is calculated according to the equation:

$$v = \frac{q}{\phi \cdot A} \quad (6)$$

At low flow velocities molecular diffusion is dominant in comparison with dispersion, since it has sufficient time to ensure roughly equal concentration of fluids in all parts of the pore space. At greater flow velocities, due to convective flow, dispersion coefficient is higher than the molecular diffusion coefficient.

1.2. RESERVOIR ROCK HETEROGENEITY

Heterogeneity is a difference in properties between different parts of the reservoir, such as, for example, permeability and porosity. Heterogeneity is divided in three main categories:¹⁴

- change of properties across reservoir surface (areal),
- change of properties across reservoir thickness (layering), and
- cleavage of rocks (different types of porosity within the same collector).

Heterogeneity is most often expressed as a level of porosity change across reservoir thickness, which indicates degree of reservoir layering. The three most often mentioned methods to determine the level of reservoir heterogeneity are as follows:^{6,14,15}

1. Positional approach: the method defines the degree of reservoir heterogeneity by Lorenzo's coefficient, which ranges from 0 to 1. For instance, Lorenzo's coefficient of a perfectly homogeneous reservoirs equals zero.
2. Variation of permeability is a parameter which can serve as a measure of vertical heterogeneity. It is calculated according to the following equation:

$$V = \frac{k_{av} - K_o}{k_{av}} \quad (7)$$

If for a certain reservoir variation of permeability and mobility ratio is known, we can use Dykstra-Parson's diagrams, from which can be read coefficient of vertical displacement efficiency, also known as vertical sweep coefficient.^{6,14}

3. Koval's method for determination of reservoir rock heterogeneity: magnitude of rock heterogeneity determines the oil recovery (%) obtained after injection of 1 p.v. of solvent into the rock sample, where during testing viscosities of oil and solvent are equal.¹⁹

1.3. JAMIN'S EFFECT AND CAPILLARY NUMBER

Knowledge of Jamin's effect is important to understand displacement process in parts of reservoir where miscible conditions are not present, or in the case where entire process is immiscible. Jamin's effect implies the amount of pressure required for displacement of non-wetting fluid through the capillary system of the reservoir.⁶ Analyses of phenomena related to capillarities of different fluids and different pore space geometries are within the scope of investigation of that effect. It also includes knowledge of capillary number, dimensionless group of parameters, which indicates the ratio of viscous versus capillary forces during the flow through porous media.^{6,13,20,22} At higher fluid flow velocities in the reservoir viscous forces become more prominent and capillary number is higher, while at the same time unfavourable Jamin's effect is less pronounced in case when porous media is non-wetting relating to displacing fluid. Capillary number is represented by the following equation:²⁰

$$n_c = \frac{\mu_w U_w}{\sigma_{ow} \phi} \quad (8)$$

The magnitude of capillary number and displacement efficiency, i.e. residual oil saturation, are interdependent. Capillary number ranges from 10^{-8} to 10^{-1} , and the higher the capillary number, the higher the displacement efficiency. Significant increase of displacement efficiency was perceived when capillary number values exceed 10^{-4} , as viscous forces become dominant in comparison with capillary forces. When values exceed 10^{-2} , displacement efficiency coefficient equals one. Regardless of the favourable effect of flow velocity increase in the reservoir, the only efficient way to increase the capillary number in practice (up to the values that allow significant increase of recovery) is reduction of interfacial tension.¹³

1.4. ACCELERATED SOLVENT SLUG DECREASE IN THE FIRST PHASE OF DISPLACEMENT

Mixing of fluids both before the slug with oil and after the slug with displacing gas (and/or water) accompanies the whole process of solvent slug propagation, which results in the formation of two mixing zones. The process of mixing during displacement lasts until the concentration of solvent decreases to the value at which miscible

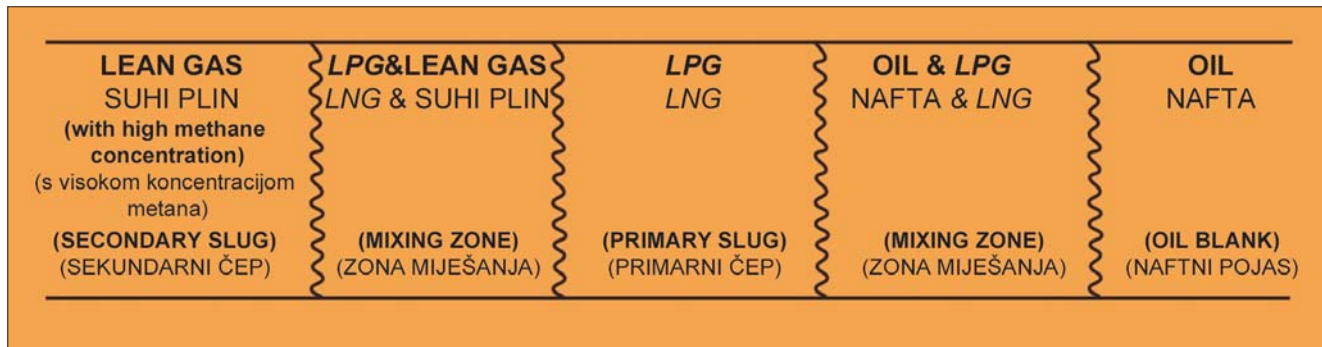


Fig. 4. Schematic presentation of idealized FCM displacement process⁶
Sl. 4. Shematski prikaz idealiziranog FCM procesa istiskivanja⁶

conditions disappear. The mixing process is most intense at the beginning of mixing, until the mixing zones before and after the solvent slug are sufficiently formed to slow down its further decrease. In that manner, it is achieved to maintain sufficiently high concentration of solvent in central part of the slug, ensuring continuation of the process under miscible conditions, and thus additional recovery. Figure 4 is a schematic presentation of idealized FCM displacement process with formed mixing zones, including the injection of slug with a certain volume of solvent, miscible both with oil before the slug and displacing dry gas after the slug.

An additional unfavourable circumstance is that in calculation of slug size must also be taken into consideration the fact that with beginning of displacing fluid injection (CO_2 , C_1 or water), the solvent slug continues to decrease along more and more distant and longer circle around the injection well. That unfavourable trend occurs in the first phase of injection until the displacement fronts of neighbouring injection wells merge into one common front. Among other things, this is solved by well pattern and spacing of injection and production wells, taking into consideration geometry of pore space in reservoir rock.

1.5. CRITICAL CONCENTRATION OF SOLVENT

In analysis of primary solvent slug decrease during displacement, in all three previously described processes we must pay attention to mixtures with critical miscibility enrichment. By that, at certain fixed pressure, higher than minimum miscibility pressure, and at certain temperature, it is implied minimum miscibility enrichment (MME)⁶ in the remaining slug below which miscible conditions disappear and in continuation of displacement process two-phase area is formed.^{6,14,15,19} Related to that, another important parameter of displacement process with solvent slug is rate of its dissolution, i.e. decrease, which is used to design the necessary quantity of solvent, i.e. length of slug to be injected.¹⁹

1.6. WIDTH OF MIXING ZONE

In the processes of displacement with miscible liquids, the width of mixing zone is directly related to the calculation of slug size that has to be injected into the reservoir. If we define the mixing zone as a distance

between positions where dimensionless solvent slug enrichment is 10% and 90%, then we can calculate the width of mixing zone by the following equation:⁶

$$x_{10} - x_{90} = 3.625 \cdot \sqrt{K_r t} \quad (9)$$

A whole series of different parameters exists that affect the efficiency of such processes. For instance, analyses have shown that liquids of lower viscosities have a higher diffusion coefficient and, consequently, greater losses happen at the contact with displacing gas. Width of mixing zone depends as well on mobility ratio, difference of densities between fluids and flow velocity.

The required solvent slug size can be calculated upon the assumption that about 50% of the mixing zones before and after the slug consist of solvent. In displacement of more viscous oils, higher quantity of enriched gas than solvent is necessary. In calculation of slug size, it must be taken into consideration that these are minimum quantities that have to be injected and they should be increased by a certain factor of safety. Reservoir heterogeneity, which has already been discussed in section 1.2, must be particularly stressed since more pronounced heterogeneity requires larger solvent slug.

2. SIMULATION OF RESERVOIR DEVELOPMENT PROCESS BY OIL DISPLACEMENT UNDER MISCIBLE CONDITIONS

Some effects described in previous section, particularly diffusion and dispersion effects, must be, to a certain extent, taken into consideration during calculations required for preparation and design of oil displacement processes under miscible conditions. Several methods exist to calculate volumes of incremental recovery accomplished by such processes, and to calculate quantities of different fluids to be injected into reservoirs for that purpose, which serve to evaluate profitability of such processes. For the same purposes, we can use different physical models suitable for the performance of analogous tests under laboratory conditions, and analytical models, where, to a certain extent, conditions prevailing in the reservoir during such processes can be emulated.

However, different simulation programs (simulators), i.e. mathematical models, have been known for a long time, whose purpose is numerical simulation of oil displacement processes under miscible conditions.^{9,19} The main advantage of this computation method, over the previously mentioned ones, is that complex and realistic conditions prevailing in the reservoir during such processes can be described. By application of simulation programs it can be described multi-phase flow of fluids in two or three dimensions. Behaviour of a larger part or entire hydrocarbon reservoir with a larger number of wells can be simulated, and behaviour of these wells can be as realistically simulated as their actual behaviour. It means that, as in reality, wells can be put on stream, abandoned (shut-down), opened up in different intervals with simultaneous simulation of measured pressures and measured productions of different fluids. Another advantage is that within the reservoir model we can describe spatial heterogeneity of collector rock and test the impact of changes in location of hypothetical wells on production efficiency from certain parts of the reservoir during displacement process. In that manner, when after matching of production history and reservoir pressure a reservoir model is verified, we can locate new wells, for which with some degree of confidence we can predict additional recovery of hydrocarbons. Certainly, only if the model verified in such manner confirms existence of areas within the reservoir with sufficiently high hydrocarbon saturations to justify drilling of new wells and acquirement of incremental recovery.

More than three quarters of all processes in different reservoirs can be simulated by using traditional „black-oil“ mathematical model. However, such model is not satisfactory when we have to simulate the displacement process under miscible conditions for two fluids with considerable differences in properties, displacement of oil by miscible or conditionally miscible fluids, and in case of other special processes.⁹ As to the simulation of displacement processes by miscible fluids, for practical reasons we do not apply the conditionally called 'general' mathematical model, i.e. simulation program which would include all effects potentially or actually present during such processes. Impracticality of simultaneous simulation of all effects involved in such processes implies a long-term simulation, requirement of exceptionally large memory capacity of the computer used for simulation, and extraordinary high price of simulation performed in that manner. Due to such constraints, we apply simulation methods that comprise only chosen effects during such processes. As an example to illustrate it, gainfully can serve variation methods for simulation of miscible displacement of small solvent slugs with included small-scale dispersion effect.¹⁶ Practical implementations have shown that simulation of oil displacement processes under miscible conditions can mostly be reduced to one of the following two categories:¹⁹ use of modified „black-oil“ simulator or compositional simulator. A short description of practical application of each of these numerical simulator types, i.e. simulation programs, is given below.

2.1. MODIFIED „BLACK-OIL“ SIMULATORS

Several methods are mentioned for simulation of processes under miscible conditions by means of modified „black-oil“ mathematical models, but most often they are not applicable to larger projects due to numerical dispersion⁹ which considerably exceeds physical dispersion whose effect should be realistically described by simulation.¹⁹ Among all types of modified „black-oil“ mathematical models, the most suitable for application in larger simulation studies is the Todd and Longstaff model.^{19,21} The authors proposed their model to improve simulation of sweep-out effect and related calculation of oil recovery in displacement processes when conditions for formation of viscous fingering prevail in the reservoir. The model assumes partial mixing in calculation of solvent viscosity (as gaseous phase) and oil viscosity. The authors recommended a modification of relative permeabilities to gas and oil in traditional „black-oil“ models according to the following equations:

$$k_{ro} = \frac{S_o}{S_n} \cdot k_m \quad (10)$$

$$k_{rg} = \frac{S_g}{S_n} \cdot k_m \quad (11)$$

where:

$$S_n = S_o + S_g \quad (12)$$

They also recommended the calculation of effective viscosities for oil and gas according to the following equations:

$$\mu_{oe} = \mu_o^{1-\omega} \cdot \mu_m^\omega \quad (13)$$

$$\mu_{ge} = \mu_g^{1-\omega} \cdot \mu_m^\omega \quad (14)$$

Value of mixing parameter $\omega = 1$ refers to total mixing conditions within one simulation element of the reservoir model and value $\omega = 0$ refers to the conditions when mixing is negligible. When ω has a value less than 1, effective viscosity of solvent component in the given element is lower than effective viscosity of oil component. In that case, solvent will flow from that element at greater velocity than oil, simulating the formation of viscous fingering effect. This simulation method, also known as mixing parameter method,¹⁹ does not take into consideration the structure of viscous fingers. Instead, it is used for approximation of the impact of forming viscous fingers on the value of sweep efficiency and recovery efficiency in reservoir models described with relatively coarse simulation elements. In that manner, through simulation of processes where formation of viscous fingers is a realistic assumption, the mixing parameter ω can be evaluated. This parameter, if by its adjustment we achieve a simulation that realistically describes the behaviour of relevant reservoir, can be used as a measure of mixing magnitude that prevails during displacement process in a given reservoir.

Another constraint in application of modified „black-oil“ simulators for prediction of these processes needs to be mentioned. It is significant effect of mass

transfer between the phases that occurs close to and below miscibility pressure, which is not represented in the simulation at all. The assumption is that solvent and oil will mix at first contact, and multi-contact between different components of gaseous and liquid phase, which occurs under dynamic conditions of mixing, is disregarded. Although it can be satisfactory in many cases, another even more serious constraint is impossibility to simulate satisfactorily the process of displacement in areas where reservoir pressure can fall below minimum miscibility pressure needed for achievement of mixing conditions, but is still high enough to improve displacement efficiency through other effects, such as oil swelling and reduction of viscosity.

Application of modified „black-oil“ mathematical models to simulate processes under miscible conditions requires fast computers with high capacity, larger than in application of conventional „black-oil“ models. They are still much simpler for use and require less computer memory and time than compositional simulators, explained in the following section.

2.2. COMPOSITIONAL SIMULATORS

Compositional simulators or mathematical compositional models are most often used to simulate the behaviour of gas-condensate reservoirs and oil reservoirs containing light, easily volatile oils. Liquid and gaseous phase are represented as multi-component mixtures, which is the main difference in comparison with „black-oil“ simulators, where hydrocarbons are represented as single or two-component systems. Equations describing the flow of individual components usually do not contain term which includes physical dispersion.¹⁹ Balance compositions of multi-component phases, which can exist at the same time within the same block in the simulation grid, are determined either from the so-called „flash“ computation using the correlation with *K*-values of gaseous-liquid ratios of individual components, or through solution of different equations-of-state at balancing condition of equal fugacity for the given component present in each phase.^{9,19,22} In accordance with that, phase properties (densities, viscosities) are calculated either from correlations or through application of equations-of-state. In that manner, the impact of phase behaviour on formation of miscible conditions and displacement efficiency can be taken into consideration when compositional models are used.

In principle, compositional simulation could be useful wherever effects of fluid composition are important. Compositional models have significant advantage over modified „black-oil“ models in case of simulation of miscible processes, or close to such conditions. Many different effects, which occur in the reservoir, can be taken into consideration in compositional simulation of such processes. They include physical mechanisms dependent on composition of fluids, such as, for example, phase behaviour (vaporization and condensation), mixing under dynamic conditions (multi-contact mixing), phase properties depending on their composition, etc. Of particular importance is the fact that effects of composition, which enhance

displacement performance in parts of reservoir that are near but still below miscible conditions, are taken into consideration (oil swelling, change of viscosity and density of fluids).

There are several reasons that, to a certain extent, restrict the application of such simulators. Phase behaviour computation is significantly more difficult for simulation of processes under miscible conditions in comparison with processes also dependent on phase composition, but not under miscible conditions, such as those in gas-condensate reservoirs or in reservoirs containing light oils. The reason for it lies in the fact that processes under miscible conditions proceed at temperatures and pressures which require computation of composition and phase properties near the plait point, where such computations become less precise. The result can be inaccurate computation of fluid composition and inaccurate minimum pressure at which miscible conditions are achieved, which can ultimately lead to inaccurate prediction of displacement efficiency. A particular problem can be simulation instability of such processes. In order to achieve high quality and high reliability reservoir simulation results, in addition to obligatory tests with static PVT cells, it is previously also necessary to perform tests with displacement under laboratory conditions through long slim tubes filled with densely packed sand (known as „slim-tube“ tests), and check by simulator the ability to mimic such laboratory processes under miscible conditions.²⁴ In recent years simulation of laboratory tests of oil displacement by solvent slugs under conditions close to plait point have significantly improved and excellent results have been achieved, even with CO₂ as solvent.^{18,19}

A number of other reasons limit the applicability of current compositional models in simulation of processes under miscible conditions. They include:

- large number of components that may be required for precise computation of complex phase behaviour,
- inaccuracy of computation caused by numerical dispersion,⁹ and
- error in computation caused by inability to simulate precisely enough the formation of viscous fingering.

Efforts to achieve by simulation sufficiently accurate computations require the preparation of reservoir model with larger number of components and even larger number of simulation elements. In that case, duration of simulation can be too long and not worthwhile for precise simulation of such processes.

Attempts to simulate realistically achievement of dynamic mixing conditions in application to large reservoir models with multiple wells, the so-called „full-scale“ models, are a particular problem. Such models include only several simulation elements between the pairs of injection-production wells. If, for instance, average size of elements is 70 m, the mixing effect in simulation can be fulfilled only at distances above 70 m from the injection well, while „slim tube“ tests have shown that mixing conditions are reached at much smaller distances of about 1 to 2 m. Although dynamic mixing conditions in the reservoir can occur at

greater distances than in "slim tube" tests, they are still significantly below 70 m, as shown in this example.

Regardless of all mentioned shortcomings of above mathematical models, simulation approach for computation and obtaining of different predictions of processes under miscible conditions is cost-effective, since in different scientific institutions in the world these shortcomings have been a subject of intense studies^{4,5} and are being solved,^{1,11,12} resulting in preparation of new versions of improved simulators.^{10,17} Besides, more and more sophisticated computer equipment allows the use of larger number of hydrocarbon components and numerous simulation elements, which results in precise description of such processes.

CONCLUSION

All reservoir rock and fluid parameters have to be studied in detail for proper selection of enhanced oil recovery process under miscible conditions. Furthermore, it is essential to carefully plan types, compositions and quantities of injection fluids for project where such process will be carried out. It must be taken into consideration what physical and chemical effects, either favourable or unfavourable, could occur in the reservoir between displaced and displacing fluids during the planned process. Among such effects, the most important are diffusion and dispersion under miscible conditions, and particular attention should be paid to phase behaviour of fluids involved in the considered process. It is also necessary to study the cost-efficiency of application and availability of resources required for implementation of such process.

Because of multiple numerical simulations applied to the same reservoir model, assuming that different enhanced oil recovery processes will be applied, prediction scenarios with different values of incremental oil recovery are obtained, which have to be compared to select the optimal variant. The main goal of simulation, before or during its application in a given project, is to evaluate the risks of total investment or continuation of investment, and to make a right decision on cost-effectiveness of such project. In view of current significantly improved capabilities of personal computers, and current possibilities for far more precise description of hydrocarbon reservoirs by means of high-quality reservoir model prepared using considerably improved sophisticated simulation programs, numerical simulation of such processes can have additional positive role.

LIST OF SYMBOLS AND ABBREVIATIONS:

Nomenclature:

A	surface area of cross-section of reservoir rock sample or surface area across which the diffusion process proceeds, mm ²
A	displaced fluid (Fig. 2)
B	displacing fluid (Fig. 2)
C_B	concentration of fluid B, g/mm ³ or fraction
D_{aBA}	effective diffusion coefficient for fluid B which through diffusion process displaces fluid A, mm ² /s

D_{BA}	molecular diffusion coefficient for fluid B which through diffusion process displaces fluid A, mm ² /s
d_p	average grain diameter, mm
F_I	grain packaging inhomogeneity coefficient, dimensionless
F_R	formation factor – ratio between specific resistance of rock and specific resistance of liquid which saturates the rock ($= R/R'$), dimensionless
k_{av}	mean absolute permeability or absolute permeability with 50% share of data in their total number, 10 ⁻³ μm ²
k_{rg}	relative permeability to gas, fraction
k_{rn}	relative permeability to non-wetting phase in direction of imbibition, fraction
k_{ro}	relative permeability to oil, fraction
k_s	absolute permeability with 84,1 % share of data in their total number, 10 ⁻³ μm ²
K_l	longitudinal dispersion coefficient, mm ² /s
K_t	transversal dispersion coefficient, mm ² /s
m_{Bx}	quantity of fluid B which in direction x by diffusion propagates through surface area A, g/s
M	mobility ratio of fluids, dimensionless
nc	capillary number, dimensionless
p	reservoir pressure, bar
q	flow rate, mm ³ /s
R	specific resistance of porous media saturated by liquid which conducts electricity, Ω·m
R'	specific resistance of liquid which saturates the porous media, Ω·m
S_n	saturation with non-wetting phase, fraction
S_g	gas saturation, fraction
S_o	oil saturation, fraction
t	time, days
T	reservoir temperature, °C
u_w	flow velocity through pore space, m/s, cm/s
v	average (interstitial) velocity of slug displacement, mm/s
V	variation of permeability, dimensionless
x	position along direction of displacement (concentration decrease), m, mm
x_{10}	distance to the position where concentration of solvent slug is 10 %, m
x_{90}	distance to the position where concentration of solvent slug is 90 %, m
f	porosity, fraction
μ_g	gas viscosity, mPa·s
μ_{ge}	effective gas viscosity, mPa·s
μ_m	mixture viscosity, mPa·s
μ_o	oil viscosity, mPa·s
μ_{oe}	effective oil viscosity, mPa·s
μ_w	water viscosity, mPa·s
σ_{ow}	interfacial tension of the oil-water fluid system, dyne/cm or N/m
ω	mixing parameter, dimensionless

Acronyms:

EOR	enhanced oil recovery
FCM	first contact miscibility
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MCM	multiple contact miscibility
MME	minimum miscibility enrichment

MMP	minimum miscibility pressure
PAT	surface active substances (surfactants)
pH	value which shows the concentration of hydrogen ions in a certain solution and also shows acidity or alkalinity of the same
p.v.	pore volume

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