LECTURE 1
RESERVOIR ENERGY SOURCES AND OIL RESERVES DRIVE MECHANISM

1. Introduction. Subject and content of the discipline, its relation to other disciplines, scientific and practical importance.

Enhanced oil recovery (abbreviated EOR) is the implementation of various techniques for increasing the amount of crude oil that can be extracted from an oil field. Enhanced oil recovery is also called improved oil recovery or tertiary recovery (as opposed to primary and secondary recovery). According to the US Department of Energy, there are three primary techniques for EOR: thermal recovery, gas injection and chemical injection. Sometimes the term quaternary recovery is used to refer to more advanced, speculative, EOR techniques

The effectiveness of oil recovery from oil-bearing formations using modern industrial methods is considered unsatisfactory in all oil producing countries, while the consumption of petroleum products is growing worldwide every year.

Average ultimate oil recovery in different countries and regions is ranging from 25 to 40% and makes, for example, in Latin America and Southeast Asia 24-27%, in Iran 16-17%, in the USA, Canada and Saudi Arabia 33-37%.

Modern geological oil reserves in all known deposits in the world are reaching more than 500 billion t, more than 300 billion t are classified as unrecoverable recourses by mastered modern field methods of development. Remaining oil reserves removal on average of 10-15%, which equals 30-40 billion t may even be reached using enhanced oil recovery methods that are studied at the present time. Therefore, the residual oil reserves in known deposits represent a large source of resources for increasing recoverable reserves and important target for implementation of EOR methods (Figure 1.1).

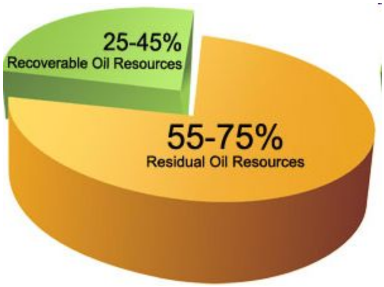

Figure 1.1 - World recoverable and residual oil resources

Interest towards Enhanced Oil Recovery methods is increasing every year all over the world and researches aimed at finding scientific approach for choosing the most effective EOR are developing rapidly.

In order to improve the economic efficiency of oil field development and to reduce direct capital investments the entire period of oil field development is usually divided into three main stages.

At the first stage of oil production (primary production Figure 1.2) the natural energy of an oil field is used as much as possible. This energy is mostly the elastic energy, the energy of the dissolved gas, the energy of the gas cap and the potential energy of gravitational forces.

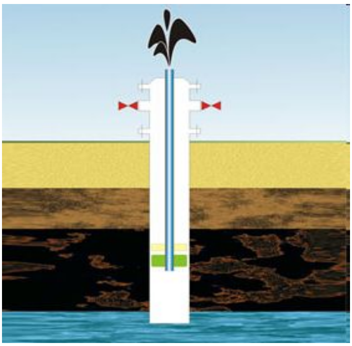

Figure 1.2 – Primary production

At the second stage methods to maintain reservoir pressure by injecting water or gas are implemented. These methods were called methods of secondary production (Figure 1.3).

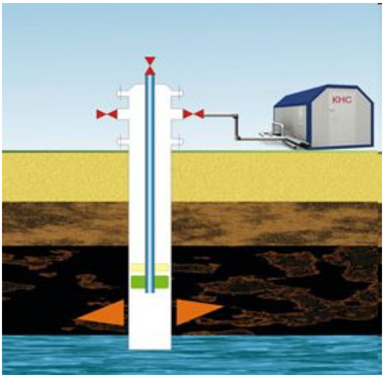

Figure 1.3 – Secondary production

At the third stage enhanced oil recovery (EOR) methods are used to improve the production efficiency. This stage is generally associated with so called tertiary production (Figure 1.4).

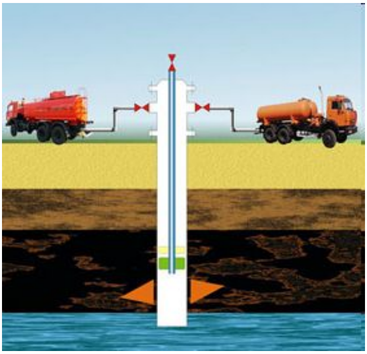

Figure 1.4 – Tertiary production

EOR Classification

1. Thermal EOR
- Steam treatment ;
- In situ combustion (fire flooding);
- Hot water flooding;
- Cyclic steam treatment.

2. Gas EOR
- Air injection;
- Light hydrocarbons injection;
- Carbon dioxide injection;
- Nitrogen, flue and other gases injection.

3. Chemical EOR
- Surfactant flooding (including foam);
- Polymer displacement;
- Alkaline displacement;
- Acid displacement;
- Chemical reagents displacement (including micellar-polymer flood, etc.);
- Microbiological treatment.

4. Hydrodynamic EOR
- Integrated displacement technologies;
- Development of by-passed oil reserves;
- Barrier flooding;
- Non-stationary (cyclical) flooding;
- Accelerated production;
- Stepwise-Thermal flooding.

5. Combined EOR

In most cases combined EOR methods are implemented. These are different combinations of hydrodynamic and thermal, hydrodynamic and physicochemical, thermal and physicochemical and other methods.

6. There are also some locally applied methods which are usually attributed to a special group called **Oil Production Stimulation Methods**. It would not be quite correct to associate these methods with EOR methods since while increasing for some period of time the current oil production (recovery) they do not usually increase the final recovery rate as EOR methods do (Figure 1.5).

The mainly applied Oil Production Intensification methods are as follows:

• Hydraulic fracturing;
• Horizontal wells;
• Electromagnetic treatment;
• Wave treatment;
Acid stimulation.

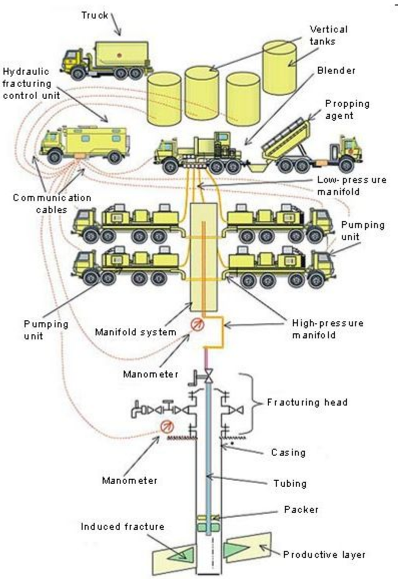

Figure 1.5 - Oil Production Stimulation methods

All these methods of extracting residual oil after flooding can be applied in various modifications. They are accompanied by complex physico-chemical, gas-dynamic, microbiological, gravity-seismic processes, high risk of obtaining suboptimal results and require extensive comprehensive laboratory, analytical and industrial research, prior to their industrial application.

Extracted oil and gas reserves can be increased by properly positioning the wells at the field, taking into account the geological structure of the reservoirs. Good results are obtained when regulating the process of constricting aquifers in order to increase the uniformity of development of various parts of the field. The efficiency of the operation of the field is increased by acting on the bottomhole zone of the wells in order to increase their flow rates and to equalize the profile of the inflow of oil and gas.

For many years of reservoir development practice, many methods and technological techniques have been proposed that allow to increase the extraction of oil and subsoil.

2. Sources and characteristics of reservoir energy

Character of reservoir energy manifestation that forces crude oil out of the reservoir to the bottomhole of the well and depends on natural conditions and stimulation activities, is called ***reservoir drive mechanism***.

The main sources of reservoir energy are:

- Expansion of the reservoir fluids (oil, water and gas)
- Expansion of the reservoir formation
- Expansion of an aquifer if one exists
- Gravitational energy that causes the oil and gas to segregate within the reservoir

The reservoir energy characteristics can be called as reservoir pressure energy; liquid (water, oil), free gas and rocks elasticity; volumes of water and free gas associated with oil deposits; gas-oil ratio; reservoir temperature.

The energy of these types may appear in the deposit together; moreover elasticity energy of oil, water and rocks is always available. For example, in the top part of oil reservoir gas expansion energy plays an active role and in the marginal (peripheral) zone – the elasticity energy and the pressure of formation water. In the oil deposit the production wells, that are located near the outer contour of oil-bearing zone, depending on the oil flow rate, can create a screening effect.

Additional energy can be added into the reservoir during the injection of water, gas, or other displacement agents through the wells. So, manifestation of a certain type of energy can be controlled, and the reservoir energy can be replenished from the surface.

During the process of oil production reservoir energy spent on the overcoming of resistance (internal friction in fluids, friction to wall pore channels, pipes, etc.), gravity (in the lifting of oil to the surface) and capillary (Jamin effect) forces during the oil motion and is manifested in the pressure reduction.

Due to the reservoir energy oil moves along the reservoir to production wells and in some cases can also raise to the surface in the borehole and be transported through the surface pipelines to the gathering facilities.

Oil reservoir drive mechanisms

Reservoir drive mechanism is a manifestation of dominant source of reservoir energy in the process of oil flow to the production wells.

There are six drive mechanisms:

- elastic (volumetric expansion drive), compaction drive,
- water drive,
- dissolved gas (solution gas) drive,
- gas drive,
- gravity drive,
- combined drive.

This division is highly conditional. During the field development, in general, combined drive can be observed.

It should be noted that displacement and starvation drive mechanisms can be distinguished.

Broadly, all commercially productive petroleum reservoirs are divided into either expansion drive, compaction drive, or water drive reservoirs. An expansion- or compaction-drive reservoir is a predominantly sealed reservoir in which the expansion of fluids and rock originally within the reservoir is responsible for petroleum expulsion from the reservoir.

Volumetric expansion drive (Compaction drive)

If pore volume contraction contributes prominently to overall oil expansion while the reservoir is saturated, then the reservoir drive is classified as a ***compaction drive.***

Compaction drive oil reservoirs are supplemented by solution gas drive if the reservoir pressure falls below the bubblepoint pressure; they may or may not be supplemented by a water or gas cap drive.

The condition for elastic drive implementetion - reservoir pressure must exceed bubblepoint pressure. Also bottomhole pressure must be higher than bubblepoint pressure. Oil is in a single-phase state. The influx of oil to the wells is due to elasticity energy (elastic expansion) of oil, connate water and related rocks. In the case of pressure reduction the amount of water and oil increases, pore volume reduces and the corresponding amount of oil flows to the well.

Elastic water drive is a typical for relatively large reservoirs, which are surrounded by fairly large water systems located at considerable distances from oil-bearig boundary.

In compaction drive, the energy for oil production is provided by the collapse of the porous medium skeleton and expansion of the pore fluids when the reservoir pressure drops. The increase in the “grain pressure” or effective stress causes pore “collapse” and “compaction” (consolidation) of the reservoir.

The drive mechanism is common in highly compressible, unconsolidated reservoirs such as those found in California, Venezuela, and the heavy oil deposits of western Canada. Also in high-porosity chalks (e.g., North Sea) (Figure 1.6).

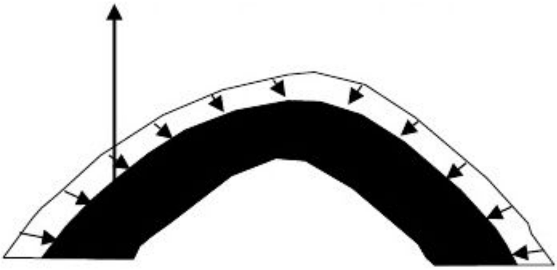

Figure 1.6 – Compaction drive illustration

The Lower Cretaceous Mannville (Clearwater) sands in the Cold Lake district provide an example of compaction drive.

Natural Water Drive Mechanism

The principle of natural water drive is that an aquifer provides the energy for hydrocarbon production. Both water expansion, as a result of pressure reduction, and inflow are involved.

Natural water drive ia associated with high recovery rates; oil from 35-75% OIIP; gas from 60-80% GIIP.

It is not uncommon for flow from the surface to supply the energy for natural water drive.

When a pressure drop occurs, both the oil and water liquid phases expand resulting in production. Additionally, water inflow radially and vertically displaces the oil towards the producers (Figure 1.7).

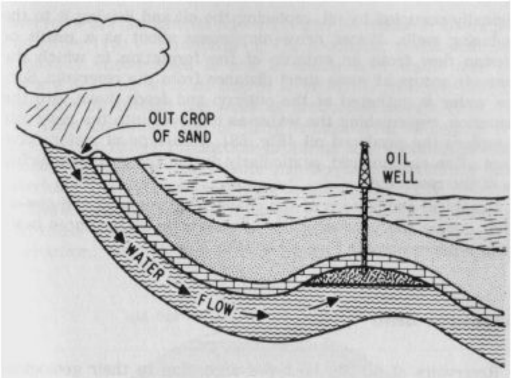

Figure 1.7 – Natural water drive

The selection of this drive contributes to the successful and sufficiently reliable design of the oil production process. The disturbance of equilibrium between the selection of fluid and the flow of water leads to the fact that begins to play the role of energy of other kinds: in the case of increasing water flow - the energy of elasticity; in the case of a decrease in the flow of water (increase in the removal) and a decrease in the pressure below the saturation pressure, the energy of the expansion of free gas released from the oil.

The dynamics of the main parameters of development under water drive is shown in Figure 1.8.

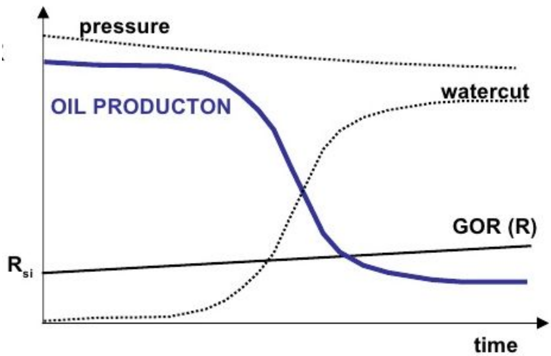

Figure 1.8 – Dynamics of basic parameters of development at water drive

Oil fields that have an active water drive mechanism are developed the most efficiently. It results in achieving high oil yields and the highest economic performance.

Solution gas drive

This drive is caused by expansion energy sourse of the gas dissolved in oil in case of pressure reduction below the bubblepoint pressure P_{bp}.

Solution gas drive occurs in a reservoir which contains no initial gas cap or underlying active aquifer to maintain the pressure and therefore oil is produced by the driving force due to the expansion of oil and connate water, plus any compaction drive. The contribution to drive energy from compaction and connate water is small, so the oil compressibility initially dominates the drive energy. Because the oil compressibility itself is low, pressure drops rapidly as production takes place, until the pressure reaches the bubble point.

Once the bubble point is reached, solution gas starts to become liberated from the oil, and since the liberated gas has a high compressibility, the rate of decline of pressure per unit of production slows down. The dynamics of the main parameters of development at dissolved gas drive is shown in Figure 1.9.

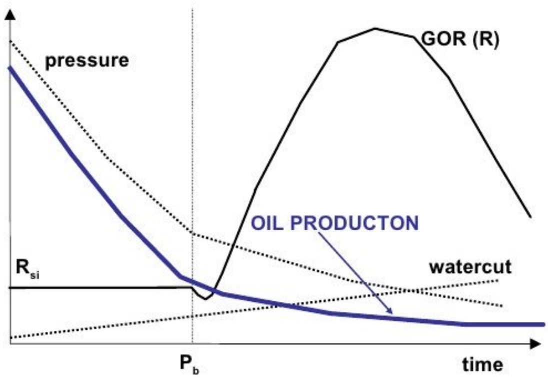

Figure 1.9 - The dynamics of the main parameters of development at dissolved gas drive

This drive is divided into two phases. During the first phase, the cone of depression of each well expands to merge with the cones of other wells or to the natural boundary of the reservoir (oil flow path). In the second phase there is a general decrease in the pressure in the deposit, and on the confluence lines of the cones of depression or at the boundary of the formation. It is characterized by a high rate of reduction of reservoir pressure (oil extraction) and a continuous change of the operating gas factor (the ratio of production gas reduced to standard conditions to the consumption of degassed oil): first increase to the maximum, then decrease. If the deposit is characterized by some excess of the initial reservoir pressure Pin over the bubblepoint pressure Pb, then in the initial period in the case of reducing pressure to a significant pH, it works due to the energy of elasticity or due to the energy of elasticity and head of water. If BHP<Pb, then the gas expansion energy is combined with these energies.

The development of oil fields at the dissolved gas drive is ineffective in view of low oil recovery factor.

<u>Gas drive (gas cap drive)</u>

It is related to the primary manifestation of the compressed free gas of the expansion energy gas cap. Gas cap refers to the accumulation of free gas over an oil reservoir, then the reservoir itself is called oil and gas (or oil and gas condensate). Depending on the change in pressure in the gas cap, there are two types of gas pressure drive: elastic and rigid.

In the case of *an elastic gas-pressure drive*, as a result of a slight decrease in the pressure at the gas-oil contact (GOC), due to the oil extraction, the expansion of free gas volume of the gas cap and the displacement of oil begins. As the oil is extracted from the deposit, the gas pressure decreases.

The rigid gas pressure drive differs from the elastic one in that the pressure in the gas cap remains constant during the extraction of oil. This "pure" mode is only possible if there is a continuous supply of sufficient gas into the gas cap or in case of a significant excess of gas reserves over oil reserves (in volume units under reservoir conditions), when the pressure in the gas cap decreases slightly as oil extraction.

The dynamics of the main parameters of development at gas pressure drive is shown in Figure 1.10.

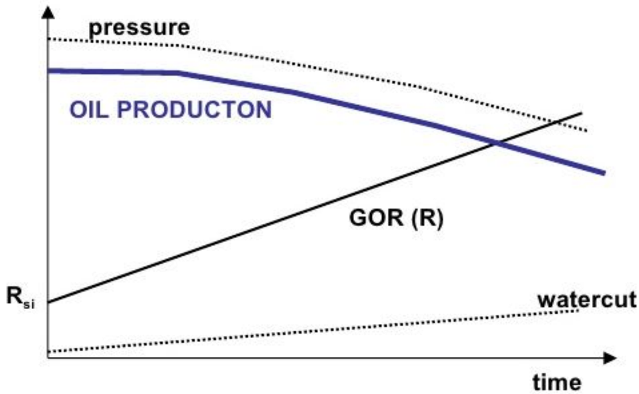

Рисунок 1.10 - The dynamics of the main parameters of development at gas pressure drive

In the case of gas pressure drive, the initial reservoir pressure $P_{initial}$ (at the level of the GOC) is equal to the pressure of bubblepoint pressure Pb. Therefore, when a pressure depression is created, dissolved gas is released and oil moves through the formation due to its expansion energy. Part of the gas segregates into elevated areas and replenishes the gas cap.

This contributes to slowing down the rate of formation pressure decrease and also stipulates law values of the gas factor for wells distant from the GOC. Wells located near the GOC are characterized by very high values of the gas factor due to gas breaks.

<u>Gravity drainage drive</u>

This drive begins to manifest when only potential energy of oil pressure (gravitational force) is valid and any other energy is depleted. The following:

- ***gravitational drive with moveable oil***- drainage boundary (pressure-gravity), in which the oil under its own weight moves down the layer and fills its lowered part, flow rates are low and constant;
- ***gravity drive with fixed oil***- drainage boundary (with a free surface of liquid), in which the oil level is below the top of horizontal layer; well flow rates are lower than flow rates at pressure-gravity drive and they slowly decrease over the time.

Gravitational forces can be a major factor in oil recovery if the reservoir has sufficient vertical relief and vertical permeability. The effectiveness of gravitational forces will be limited by the rate at which fluids are withdrawn from the reservoir. If the rate of withdrawal is appreciably greater than the rate of fluid segregation, then the effects of gravitational forces will be minimized.

Combination drive

Reservoir drive mechanisms that enable the simultaneous display of dissolved gas energy, elasticity and water pressure are called ***combined drive***.

This drive mode takes place in several phases: at first elasticity energy of oil and rocks manifests, then expansion energy and further dissolved gas energy and pressure of the aquifer are added.

Generalisation and implementation of different drive machanisms

Oil reservoir drive mechanisms are also provided with additional features. There are drives with ***mobile*** and ***stationary*** oil-drainage contour. The former include water drive, gas drive, gravity drive and combined drive, and the second – volumetric expansion drive, solution gas drive and gravity drainage drive with free oil surface.

Water-, gas drive and combined drive are called ***displacement drive mechanisms*** (pressure drives) and the rest ones - ***depletion drives*** (reservoir energy depletion).

3. *Oil reserves estimation*

All reserves are estimated involving the relative degree of uncertainty, which depend on the amount of reliable geologic and engineering data available and the interpretation of those data. The relative degree of uncertainty can be expressed by dividing reserves into two principal classifications—***"proven"*** (or "proved") and ***"unproven"*** (or "unproved"). Unproven reserves can further be divided into two subcategories—***"probable"*** and ***"possible"*** — to indicate the relative degree of uncertainty about their existence.

Proven reserves are those reserves claimed to have a reasonable certainty (normally at least 90% confidence) of being recoverable under existing economic and political conditions, with existing technology.

Unproven reserves are based on geological and/or engineering data similar to those used in the estimation of proven reserves, but technical, contractual, or regulatory uncertainties preclude such reserves being classified as proven.

The amount of oil in a subsurface reservoir is called ***oil in place (OIP)***. Only a fraction of this oil can be recovered from a reservoir. This fraction is called the ***recovery factor***. The portion that can be recovered is considered to be a reserve. The portion that is not recoverable is not included unless and until methods are implemented to produce it.

There are a number of different methods of calculating oil reserves. These methods can be grouped into three general categories: "volumetric", "material balance", and "production performance". Each method has its advantages and drawbacks.

Volumetric method

Volumetric methods attempt to determine the amount of oil in place by using the size of the reservoir as well as the physical properties of its rocks and fluids. Then a recovery factor is assumed, using assumptions from fields with similar characteristics. OIP is multiplied by the recovery factor to arrive at a reserve number. Current recovery factors for oil fields around the world typically range between 10 and 60 percent; some are over 80 percent. The wide variance is due largely to the diversity of fluid and reservoir characteristics for different deposits. The method is most useful early in the life of the reservoir, before significant production has occurred.

Production decline curve method

The decline curve method uses production data to fit a decline curve and estimate future oil production. The three most common forms of decline curves are exponential, hyperbolic, and harmonic. It is assumed that the production will decline on a reasonably smooth curve, and so allowances must be made for wells shut in and production restrictions. The curve can be expressed mathematically or plotted on a graph to estimate future production. It has the advantage of (implicitly) including all reservoir characteristics. It requires a sufficient history to establish a statistically significant trend, ideally when production is not curtailed by regulatory or other artificial conditions

Oil reserves into the reservoir conditions can be calculated:

$$Q_{oil.res} = \frac{F \cdot h \cdot m_o \cdot S_{in} \cdot \rho_{oil}}{b} , \qquad (1.1)$$

where

F – oil-drainage area, m^2;

h - formation thickness, m;

m_o – effective porosity coefficient;

S_{in} – initial oil saturation;

ρ_{oil} - oil density, kg/m^3;

b - formation volume factor.

Oil-associated gas reserves can be calculated using equation:

$$Q_{oil.res} = F \cdot h \cdot m_o \cdot S_{in} \cdot G_o , \qquad (1.2)$$

G_o – initial gas factor of oil in reservoir condition, m^3/m^3.

Control questions

1. What is meant by the increase in oil recovery and what are the average values of final oil recovery factor in different countries and regions?
2. What are the main enhanced oil recovery technologies used in practice?
3. What are the main sources of reservoir energy?
4. What are the main drives mechanisms of oil reserves development?
5. What is meant by the volumetric drive of oil reserves development?
6. What is meant by the water drive of oil reserves development?
7. What is meant by the dissolved gas drive for the development of oil deposits?
8. What is meant by the gas drive for the development of oil deposits?
9. What is meant by the gravitational drive of oil reserves development?
10. What is meant by thecombination drive for the development of oil deposit?
11. What additional features are drive mechanisms for oilfields development given?
12. How are initial oil and dissolved gas reserves estimated?