LECTURE №1-2-3-4
BASIC HYDRODYNAMIC CALCULATIONS UNDER WATER FLOODING

Plan of lecture:

1. Location injection wells.
2. Determination of the amount of water injected.
3. Determination of the number injection wells.
4. Requirements for injected water.

We have seen that the natural formation energy does not always ensure complete recovery of the oil or the required production rate. To achieve higher recovery factors and the necessary rate of oil production, extensive use is now made of reservoir pressure maintenance by injecting water or gas into the reservoir.

The rate of development of a reservoir, i.e., the rate of withdrawal of its reserves, is determined by its specific productivity index and by the reserves. The specific productivity index itself id determined by the size and shape of the reservoir, the physical properties of the rocks and fluids, the number of wells and their pattern, external boundary and bottom-hole pressures and the distance from bottom holes to the external boundary. The number of wells and their arrangement as well as bottom-hole pressures are generally controlled by the field personnel; the other factors are natural and uncontrollable.

When the boundary pressure is not great and the boundary itself very remote, assuming an optimum well spacing and maintaining optimum bottom-hole pressures, a low withdrawal rate can sometimes be maintained.

By applying marginal flooding the external boundary can be displaced right now up to the reservoir and a sufficiently high pressure maintained in it.

In gas-cap reservoirs the cap is the drainage area as it were and the gas-oil contact may be taken as the drainage boundary. Injection of gas into the gas cap helps to maintain the pressure in it and therefore to maintain a steady rate of production or to increase it.

Injection of a working agent into the reservoir not only intensifies production and ensures the maximum recovery factor inherent in pressure drives but also increases reservoir pressure and the bottom-hole pressures in the producing wells, prolonging thus the following life of the reservoir.

The rate of oil withdrawal depends on the shape and size of the reservoir, and also on a number of others factors. Other things being equal, the output of a reservoir depends on the length of the rows of producing wells, i.e., on the length of the oil drainage boundary, and the productive life depends on the reserves, which are approximately proportional to the area and thickness of the deposit. Thus, the rate of withdrawal is determined to a considerable extent by the ratio of the length of the drainage boundary to the area of the deposit. This ratio may be such that the productive life of the reservoir is unduly prolonged in view of the conversation of the central part of the reservoir. The productive life can be shortened by more intensive exploitation and to achieve this, edge flooding can be supplemented by pattern flooding. The reservoir is then divided up into a number of separate fields by means of rows of injection wells, thereby considerably lengthening the drainage boundary and, therefore, also the outer rows of producing wells. Rows of producing wells must be provided on either side of the row of injection wells used in pattern flooding. The recommended procedure is to have not more than 5-7 producing rows between the rows of injection wells. In this way the entire reservoir can be brought into production, the current rate of oil production increased and productive life is shortened.

Conditions favouring the application of pattern flooding are the presence of water underlying the lowermost sections of the formation and continuity of the formation which helps to accelerate the effect of the injection wells.

The productive life of steep formations can be reduced by injecting gas (or air) near the crest of the reservoir to create an artificial gas cap, which also increases the total length of the drainage boundary and the length of the outer rows of producing wells.

In field practice, the method selected to maintain reservoir pressure depends on geological conditions and economic considerations.

Laboratory experimental researches of oil displacement by water held in the models of the reservoir and the shown in Fig. 1.

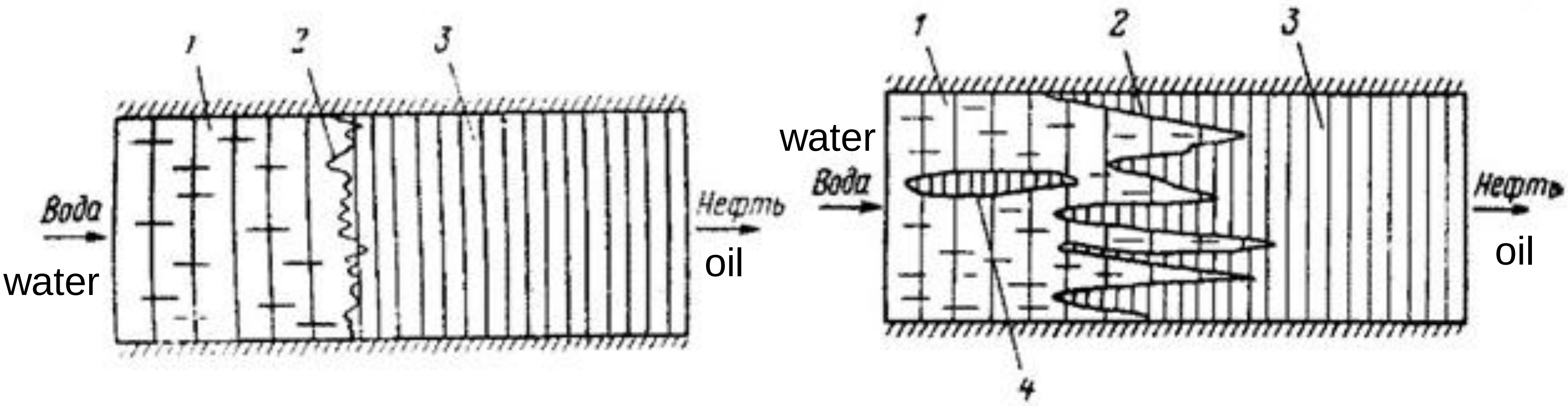


Fig. 1 – Scheme of movement WOC in layer under: а) $\mu_0 = 1 \div 5$; б) $\mu_0 = 20 \div 30$
1- one zone that is occupied water and residual oil; 2 – WOC; 3 - a zone that is occupied by oil; 4 - accumulations of oil remaining behind WOC

System development put by pumping water into the reservoir helps:

a) increase the oil production and accelerate the process of development of the field;

b) preservation for a long period of stable oil-dominated than the fountain method of operation of oil wells;

c) increase of the final oil recovery factor for cost-effective generic term of its development;

d) reduction of capital expenditures;

d) increase productivity;

e) reduce the cost of oil.

Water flooding is carried to increase oil recovery factor and intensify the development process. In deciding to maintain reservoir pressure injection of water addresses the following tasks:

1) determine the location injection wells;

2) determine the amount of water injected;

3) determine the number of injection wells;

4) establishing requirements for injected water.

1. Location injection wells

Location line of injection wells is determined mainly by geological considerations. The choice of location options wells is carried out taking into account the specific geological conditions and the state of development of the field based on hydrodynamic researches and feasibility calculations. The problem is that in order to choose a location of injection wells in which ensured the most efficient connection between the injection zone and selection zone and uniform displacement of oil by water. One of the main methods of effective communication between the injection zone and selection zone is maximum approximation line injection or injection wells to production wells. But this approach can lead to disruption uniform displacement of WOC.

Depending on the location of water injection wells are distinguished such systems flooding:

- edge flooding;
- marginal flooding;
- inside contour flooding;

- block systems of development;
- focal flooding;
- pattern flooding;
- selective flooding;
- barrier flooding.

Edge flooding. Edge flooding is used for developing small deposits of oil reserves. Pressure maintenance by edge flooding is effected by injecting water into special wells located outside the drainage boundary or the oil-bearing contour (external WOC) on a distance 100-1000 m (Fig. 2).

Inasmuch as water injection creates an artificial external drainage boundary in closer proximity to the producing zone, the question arises concerning the optimal distance between the injection and recovery wells. Increasing the distance between the injection and recovery wells is good practice because the high pressure gradients created near the injection wells do not affect the shape of the drainage boundary and will not cause fingering. However, if the distance the recovery and the injection wells is more than 1.5-2 kilometers, the artificial drainage boundary is not very effective.

Now is a water flooding is rare.

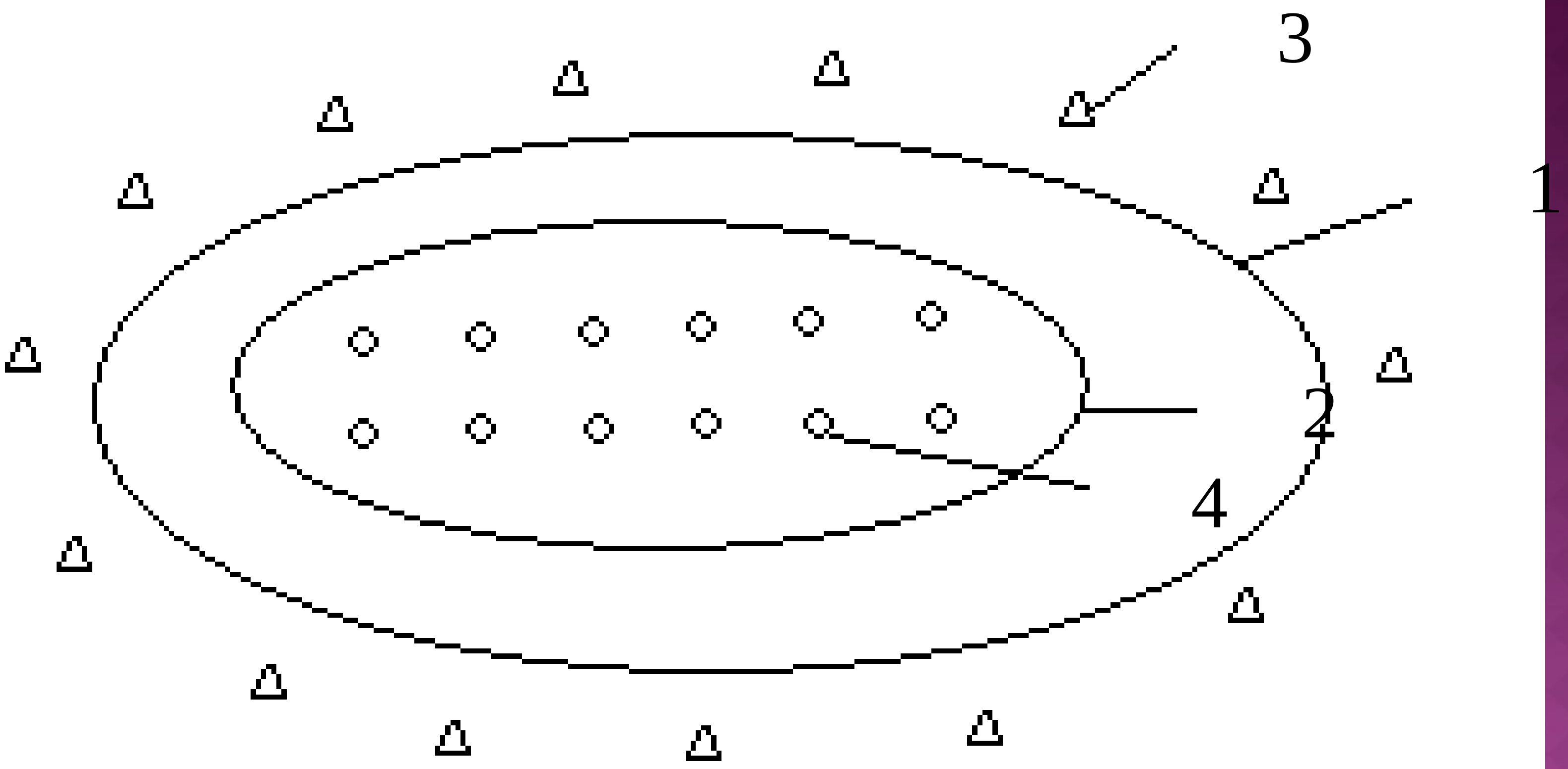


Fig. 2 – Edge water flooding: 1 – external oil-bearing contour (external WOC); 2 – internal oil-bearing contour (internal WOC); 3 – injection wells; 4 – producing wells

In some cases the specific geological features of the formation make it necessary to place the injection wells right on the drainage boundary (so-called marginal flooding).

Marginal flooding. Marginal flooding it is used when injection wells located in an oil-bearing part of deposit very near external oil-bearing contour (Fig. 3). It is used in a low mobility or real estate WOC. Marginal flooding apply:

- with impaired hydrodynamic communication with external reservoir zone;

- to develop smaller deposits width not more than 4-5 km;

- to intensify the operation.

This flooding is used in fields, layers which have a high permeability and low viscosity oil. Marginal flooding - least intensive type of inside contour flooding and is the kind of transition between the edge flooding and inside contour flooding.

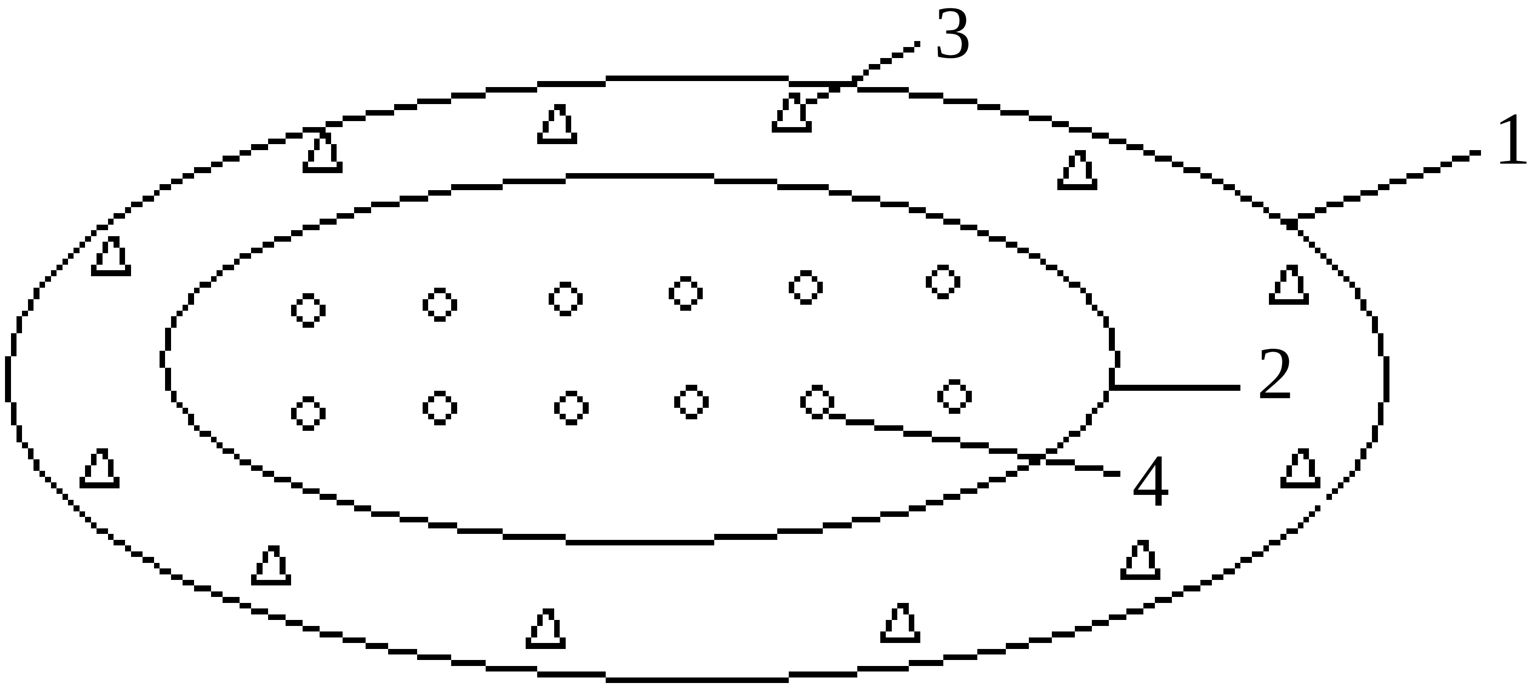


Fig. 3 – Marginal water flooding: 1 – external oil-bearing contour (external WOC); 2 – internal oil-bearing contour (internal WOC); 3 – injection wells; 4 – producing wells

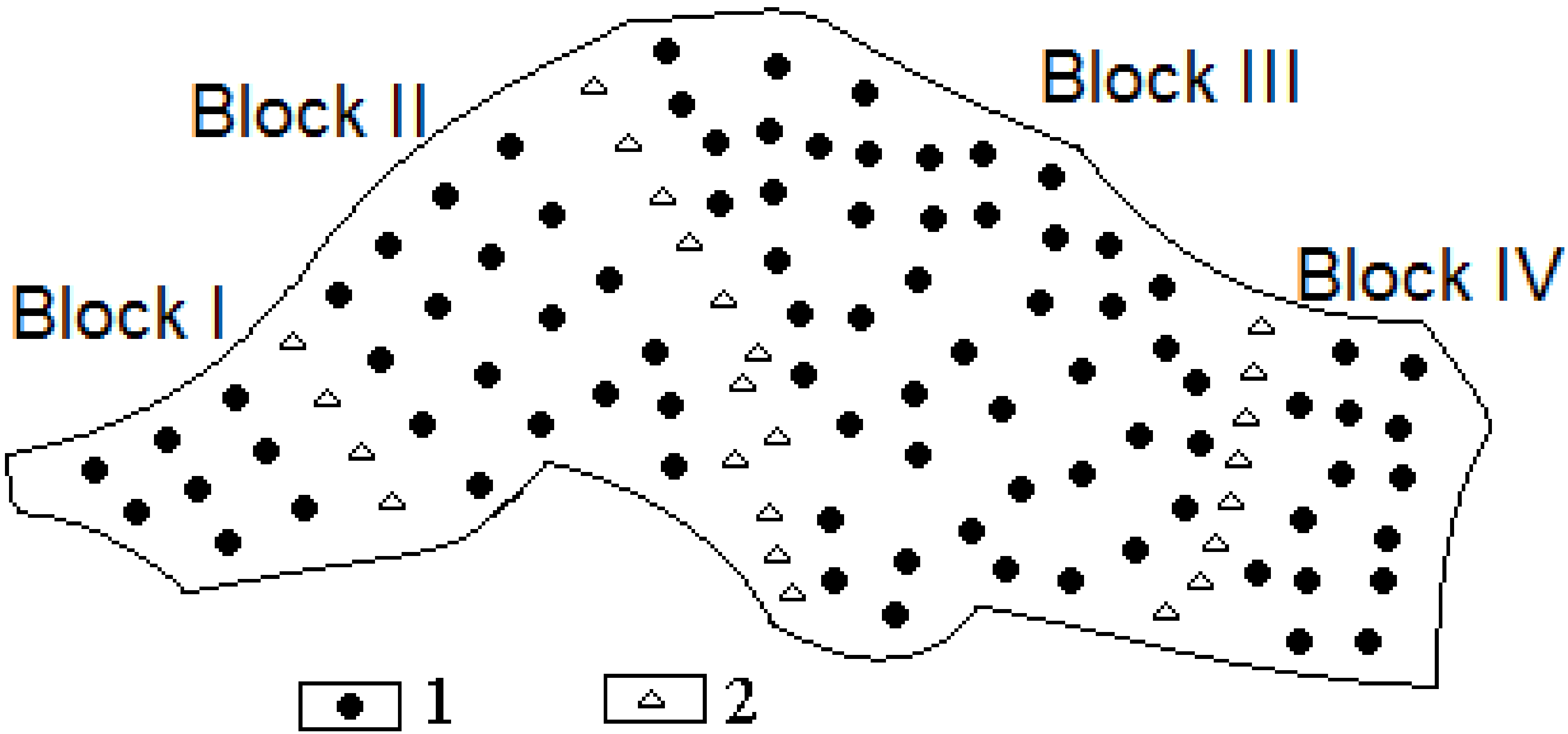
These results edge flooding and marginal flooding caused further improvement and development of oil fields led to the feasibility of using inside contour flooding.

Inside contour flooding. Inside contour flooding is used mainly for the development of oil deposits of very large areas. It is used in the Romashkinskoye field in Tatarstan, the largest in the U.S.S.R. in the early 50s. In the USA, this flooding was used in 1948 on a small field Uisson in Arkansas. Later inside contour flooding has found application in other fields of the United States, including such large fields as Kelly-Snyder and Spraberri. The transition from the edge flooding to the inside contour flooding can significantly accelerate the development Romashkinskoye field was a major step in the development of oil fields. Action to layer in this case is carried out through injection wells placed at varying schemes inside oil-bearing contour. This system is the most intense action on oil deposit. The advantage of the inside contour flooding is a possibility to start developing any area and, in particular, to introduce the development of the first area with the best geological and exploration characteristics, the largest reserves and high production flow rate of wells.

Inside contour flooding allows in 2-2.5 times increase the rate of development compared to the edge flooding significantly improve technical and economic indicators of development.

A variety of systems inside contour flooding are block systems of development.

Block systems of development. Block systems of development are used in the fields of elongated placing rows of injection wells mostly in cross section (Fig. 4). As shown in the Fig. 4, the rows of water injection wells cut only deposit in certain areas (blocks) development. Reservoir there may be developed by blocks independently. Block systems of development have many advantages. Block systems can increase in 2-3 times the rate of oil recovery, reduce the number of injected water and accelerate input field in development compared to the edge flooding. The most modular distribution block systems of development is acquired in the fields .



1 – producing wells; 2 – injection wells

Fig. 4 - Block systems of development

Focal flooding. Focal flooding is used as a supplement to the already undertaken inside contour flooding or edge flooding and aims at strengthening already carried out system of development. Injection wells located in areas with a layer of relatively low production flow rate of wells. In some cases, when good understood geological structure of the reservoir focal flooding can be used as an independent system of development. For this flooding possible drilling one injection well or group of injection wells (Fig. 5). Focal flooding was first used in the fields of Tatarstan.

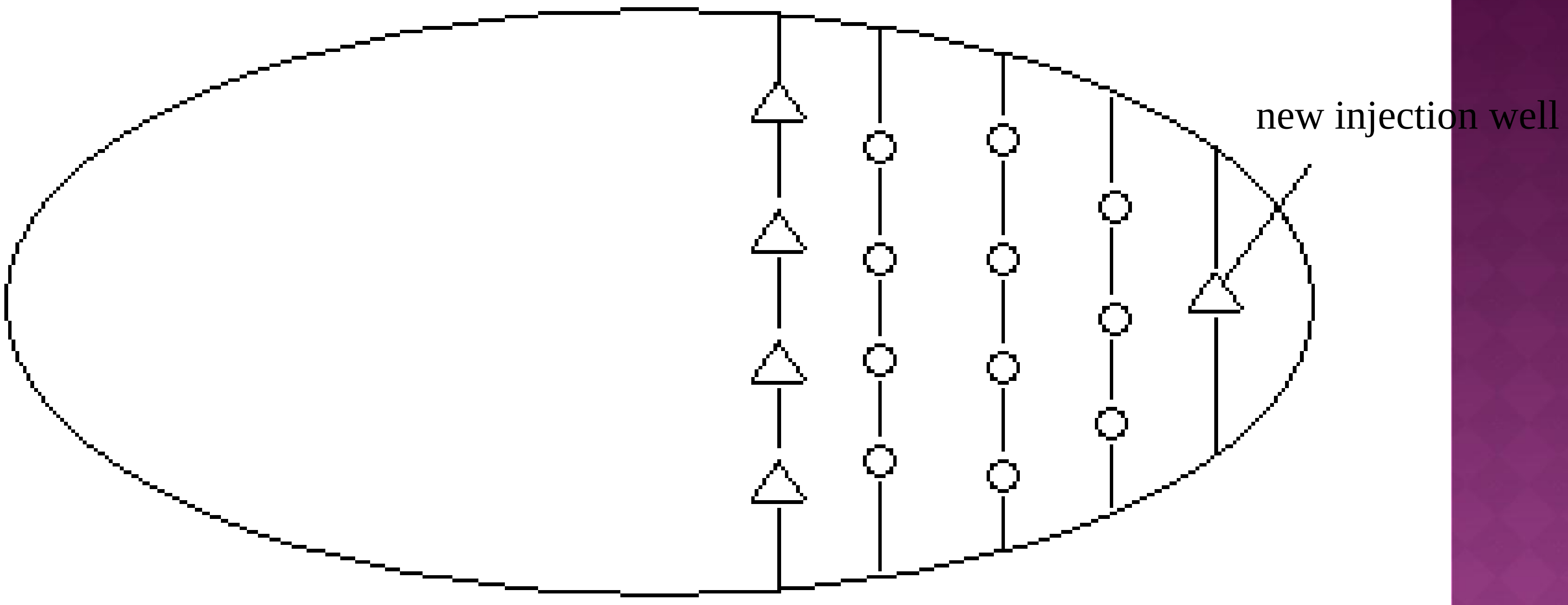


Fig. 5 - Focal flooding

Pattern flooding. Pattern flooding is the most intensive action on the layer system, which ensures on-highest rate of development. In the USSR, it flooding was started in 1943 in the fields of Kazakhstan - Dosor and Makati. This system of flooding is used to develop reservoirs with very low permeability. Efficiency pattern flooding depends on the heterogeneity of the reservoir, the reservoir thickness, viscosity of the oil and the depth of the deposit. A feature of this system of flooding is the placement production and injection wells evenly on the area. Water injection is performed through the injection wells that are placed with production wells and between them hold the same distances. Pattern flooding systems used for experimental works to enhance oil recovery. Pattern flooding can be effectively used in the early stages of development under good learning geological feature of reservoir. In this system producing and injection wells are placed at the uniform grids. There are four-, five-, seven-, and nine- systems. Formulas for definition flowrates and validities for each of these systems.

Selective flooding. Selective flooding is a form of pattern flooding, which is used in oil fields with significant heterogeneity as the focal flooding.

Wells not placed in a row, but based on the distribution of reservoir properties of reservoir area. Location injection wells are chosen after drilling area and study reservoir properties according to industrial-geophysical and hydrodynamic researches. During those selected injection wells, pumping water that provide the most complete excavation around the reservoir, that is the well where the biggest productivity factor and the well, which discovered the layer of high permeability and good hydrodynamic coupling to the surrounding wells. Drilling carried out at a uniform triangular or square grids. All wells originally commissioned as oil producing. And then producing wells become injection wells.

Barrier flooding. Barrier flooding is used in the development of gas-oil fields with a large volume of gas caps, when a possible simultaneous selection of oil from the oil part and gas from the gas cap. As a result of water injection into wells forms a water barrier, which "cuts off" the gas cap from the oil deposit. When the barrier flooding apply a single cutting oil and gas deposits in certain areas of self-development. Injection wells are placed in the area of GOC (gas-oil contact) and injection water and selection of oil and gas regulating such a way that there was water-oil and gas displacement in case of exclusion of mutual flows of oil in the gas reservoir and the gas to the oil part (Fig. 6).

2. Determination of the amount of water injected

The total volume of water that is injected depends on the projected selection of fluid put, the pressure at the line injection, and also from a collection and elastic properties of the layers. There are pressures: the pressure at the line injection and injection pressure.

The pressure at the line injection – it is the pressure in the row between injection wells on a distance $\frac{\sigma}{\pi}$ from the well (σ - a half distance between the wells) (Fig. 7). Represented P_{line} .

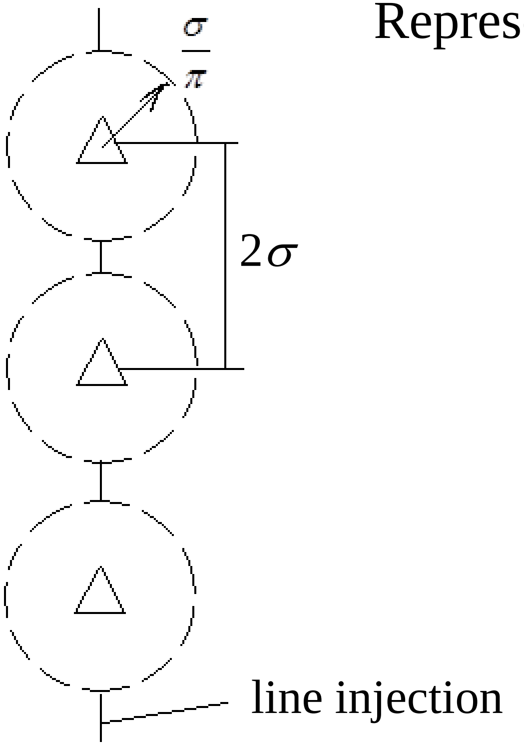


Fig. 7

Injection pressure - is the pressure at the head of water injection well with pumping water into it. In practice waterflooding injection pressure ranges from 5 MPa to 16-20 MPa, and in some cases even 20-30 MPa and 40 MPa, accounting for an average of 13 MPa. The injection pressure should be greater than the pressure losses of water, which is pumped into the reservoir. Represented P_{inj} .

In general, the amount of water injected is determined

$$Q_{inj}=Q_{sel}+Q_{los}, \qquad (1)$$

where Q_{sel} – amount of fluids (oil + water), which are selected; Q_{los} – loss of water that escapes the contour.

Q_{sel} determined by hydrodynamic calculations. Q_{los} depends on the pressure at the line injection wells and the average reservoir pressure in the aquifer of the reservoir.

Depending on the values of pressure at the line injection and the average reservoir pressure for the contour of the reservoir are three cases:

1) If $P_{line} > P_f$, then the water pumped flows into the aquifer area. In this case $Q_{inj}= Q_{sel} + Q_{los}$. It is necessary to take into account the elastic properties of reservoir and fluid out the line injection.

2) If $P_{line} < P_f$, then $Q_{inj}= Q_{sel} - Q_{los}$. This case is rarely used in practice.

3) When $P_{line} = P_f$ no loss of water and $Q_{los} = 0$. This case is used most often. In this case, the impact of external area completely isolated and reservoir works due to the energy of water injection. In this case, water is injected into injection wells completely used to displacement oil.

In the literature suggested many formulas for determination Q_{los}, one of which is

$$Q_{los} = \frac{kBh}{\mu_w} \frac{P_{line} - P_f}{\sqrt{3}\sqrt{\chi t}}, \qquad (2)$$

where B - length of injection line, m; χ - piezoconductivity factor, m2/sec; t – the period of time, sec; μ_w - dynamic viscosity of water (μ_w = 1 mPa·sec).

To assess the degree of compensation selections of fluids from the reservoir injected water introduce the concept of factor compensation. There are factors of current and accumulated compensation.

A factor of current compensation - is the ratio of injected water to flowrates liquids that are selected, reduced to formation conditions per unit of time (year, month, day and etc.)

$$m_{cur} = \frac{Q_{inj} b_w}{\left(Q_{oil} b_{oil} + Q_w b_w' + Q_{los}\right) k}, \qquad (3)$$

where Q_{inj} - volumetric flowrate injected water under standard conditions; b_w – volume formation factor for the injected water ($b_w \cong 1{,}01$); Q_{oil} - volumetric flowrate for the oil under standard conditions; b_{oil} – volume formation factor for the oil; Q_w - volumetric flowrate selected water under standard conditions; b_w' - volume formation factor for the selected water, which is different from the volume formation factor for fresh water; Q_{los} – loss of water that escapes the contour; k - factor for the loss of water in the periodic work injection wells, under breaks in water lines and other technological reasons. This ratio is assumed to be k = 1,1-1,15.

A factor of current compensation shows how forcing compensated selection at any given time. According to the current values of the coefficient compensation can make the following conclusions.

If $m_{cur} < 1$ injection behind the selection and expect the average formation pressure should drop.

If $m_{cur} > 1$ injection exceeds the selection and the formation pressure should rise.

When $m_{cur} = 1$ should have been the stabilization of the current formation pressure at the current level, no matter what it was in early development.

A factor of accumulated compensation is the ratio of injected water to flowrates liquids that are taken to the consolidated formation conditions during the whole period of injecting

$$m_{acum} = \frac{\int_0^t (Q_{inj} b_w)(t)dt}{\int_0^t \left[\left(Q_{oil} b_{oil} + Q_w b_w{}' + Q_{los} \right) k \right] (t)dt} \quad . \qquad (4)$$

3. Determination of the injection wells number

In general, the number of injection wells

$$n_{inj} = \frac{Q_{inj}}{q_{ing}}, \qquad (5)$$

where q_{ing} - the amount of water pumped into one well (acceleration), which is determined by the formula

$$q_{ing} = \frac{2\pi k_w h \left(P_{bh\,inj} - P_{line} \right)}{\psi \mu_w \ln \dfrac{\sigma}{\pi r_{rwinj}}}, \qquad (6)$$

where k_w - phase permeability for water in the near wellbore zone of injection well k_w = (0.5-0.6)k; $P_{bh\ inj}$ – bottomhole pressure of injection well; P_{line} - pressure at the line injection; ψ - formation damage coefficient, ($\psi \geq 2$). Determined according to research by injection or industrial data obtained in similar fields; μ_w - coefficient of dynamic viscosity of water (μ_w = 1 mPa·sec); σ – a half distance between injection wells; $r_{rw\ inj}$ – reduce radius of injection wells.

A half distance between injection wells is determined

$$\sigma = \frac{B}{2n_{inj}}, \qquad (7)$$

where B - length of injection line.

Bottom hole pressure of injection well is determined by the formula

$$P_{bh\ inj} = \rho_w g H + P_{inj} - \Delta P_{los\ pr}, \qquad (8)$$

where ρ_w – density of water (ρ_w = 1000 kg/m3); g= 9.81 m/sec2 - acceleration of gravity; H – depth of injection well; P_{inj} - injection pressure; $\Delta P_{los\ pr}$ - pressure loss due to friction, which are determined by the Darcy-Weisbach equation.

Darcy-Weisbach equation has the form

$$\Delta P_{los\ pr} = \lambda \frac{H}{d} \frac{\upsilon^2}{2} \rho_w, \quad (9)$$

where λ - coefficient of hydraulic resistance that depends on the Reynolds number and the roughness of the pipe, $\lambda = f(Re, \Delta)$; d - the inner diameter of the pipe on which is pumping water; υ - speed of the water.

The first, determine the speed of movement

$$\upsilon = \frac{Q}{F},$$

where F - sectional area of the pipe.

Reynolds number is determined

$$\mathrm{Re} = \frac{\upsilon d}{\nu},$$

where ν - kinematic viscosity of water.

If $Re < Re_{cr}$ (Re_{cr} =2320), then the mode of movement is laminar and λ determined by the formula Stokes

$$\lambda = \frac{64}{\mathrm{Re}}.$$

If $Re > Re_{cr}$ (Re_{cr} =2320), then the mode of movement is turbulent and λ determined by the formula Blaziusa

$$\lambda = \frac{0{,}3164}{\mathrm{Re}^{0,25}}.$$

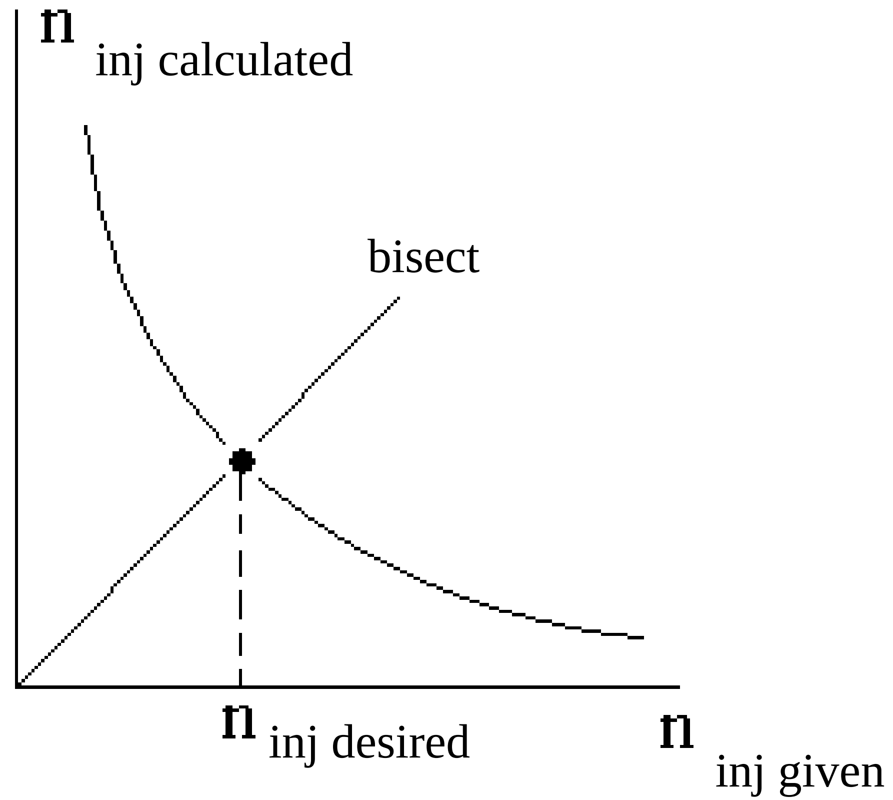
Substituting equations (6) and (7) in (5), we obtain an expression for the number of injection wells

$$n_{inj} = \frac{Q_{inj}\varphi\mu_w\left(\ln\frac{B}{2\pi r_{rwinj}} - \ln n_{inj}\right)}{2\pi k_w h\left(P_{bh\ inj} - P_{line}\right)}. \quad (10)$$

As can be seen from the equation (10) in the left and right sides of the equation is the desired number n_{inj}. The method of solution of equation (10) semigraphical. Let us take a number of values n_{inj} on the right side of equation (10) and each time counting n_{inj} on the left side. Calculation begin with one. The calculations are summarized in the table.

n_{inj} (given) the right side of equation	n_{inj} (calculated) the left side of equation

Building a graph.



Scale axis is same. From the origin hold bisect and determine the number of injection wells. As shown from equation (10), the higher the bottom-hole pressure of injection wells, the less injection wells, and consequently, lower capital costs for process waterflooding. The injection pressure of injection wells depends on the number of injection wells.

The choice of injection pressure and the number of wells is based on economic calculations.

4. Requirements for injected water

Industrial implementation of secondary extraction methods and techniques to maintain reservoir pressure by waterflooding in the oil reservoir is closely associated with finding appropriate sources of supply. Consumption of water during flooding is 1.5-2 m^3 of water per 1 ton of oil produced. However under pattern flooding depleted reservoirs need 10-15 m^3 of water per 1 ton of oil produced. Therefore, the question is, to have a source of water supply. At the same time as the issue is not only the quantity but also the quality of water.

Under flooding oil deposits could be used the following sources of water:

1) surface water (from rivers and lakes);

2) upper water horizons;

3) water formation of oil-bearing horizons;

4) lower water horizons.

Only a few cases of water supply sources may be eligible for flooding without preparation. In most cases, have to start preliminary preparation of water.

In water treatment, depending on the need to perform the following steps: 1) remove the oil; 2) aeration; 3) sterilization; 4) stabilization of water; 5) coagulation; 6) defending; 7) filtering.

The suitability of water used for injection into reservoirs usually determined in the laboratory by filtering water through the core. Water is considered suitable for injection into reservoirs if the permeability of the core remains constant. Reliable data on the quality of water used for flooding and about the optimum pressure at the line injection can only be the result of water injection test into oil deposits.

The injected water into deposit pose the following requirements:

1. Water must not enter into a chemical reaction with formation waters, because the possible loss of sediment and pore sealing layer.

2. The number of solids in water should be small, because it can lead to contamination of the wellbore zone and loss acceleration of well. The content of impurities in the water taken from the experience of pumping water.

3. Water shall not contain impurities hydrogen sulphide and carbon dioxide, in order not to cause corrosion of the surface and underground equipment.

4. Injected water should not cause swelling of clay particles, leading to clogging of pores in the reservoir and fracture wellbore zones.

5. Water used for injection should be subjected to biological treatment cultivation from microorganisms.

The injected water should have a good ability to wash oil from rock. For this purpose, conduct water treatment using chemicals.