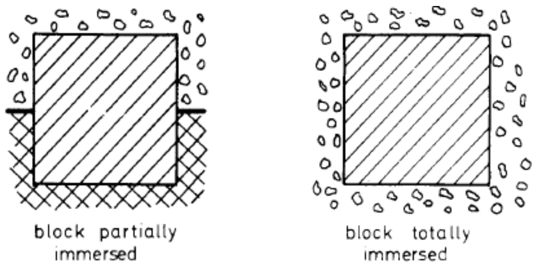
Naturally Fractured Reservoirs

Evaluation of Matrix-Fracture Fluid Exchange (b)

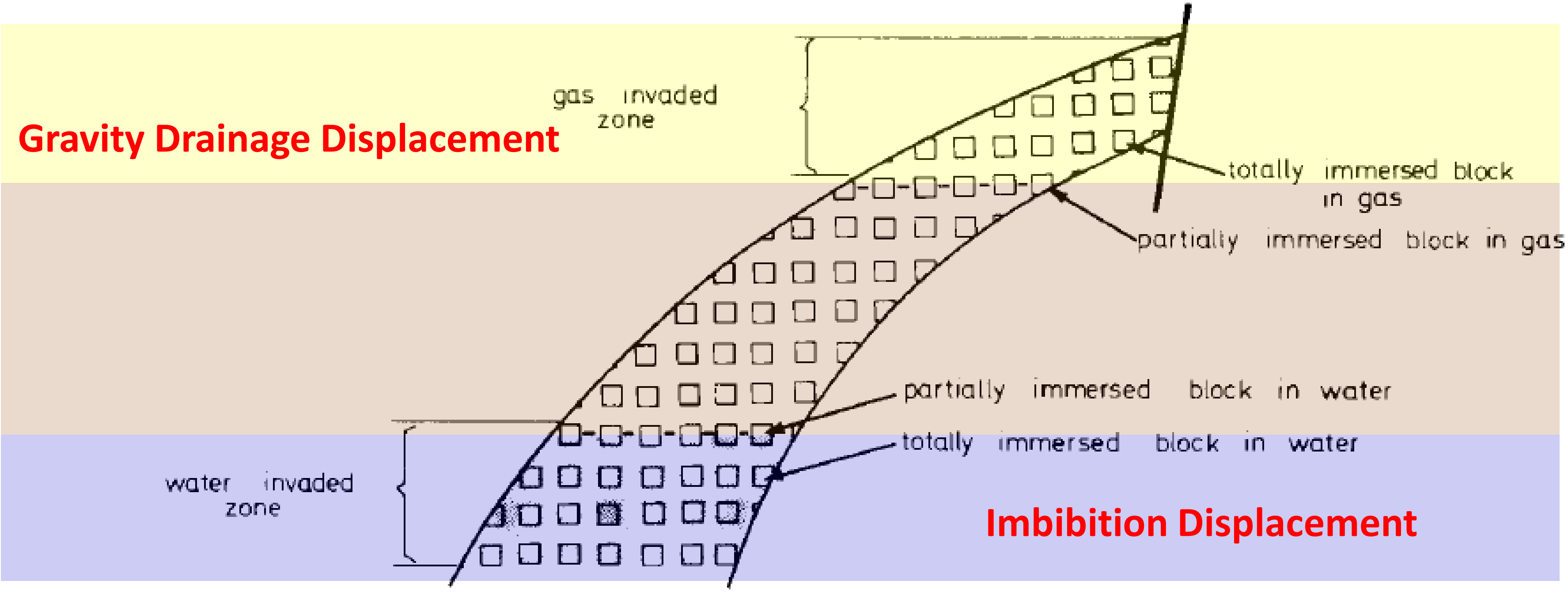
Shahab Gerami, Fall 2010

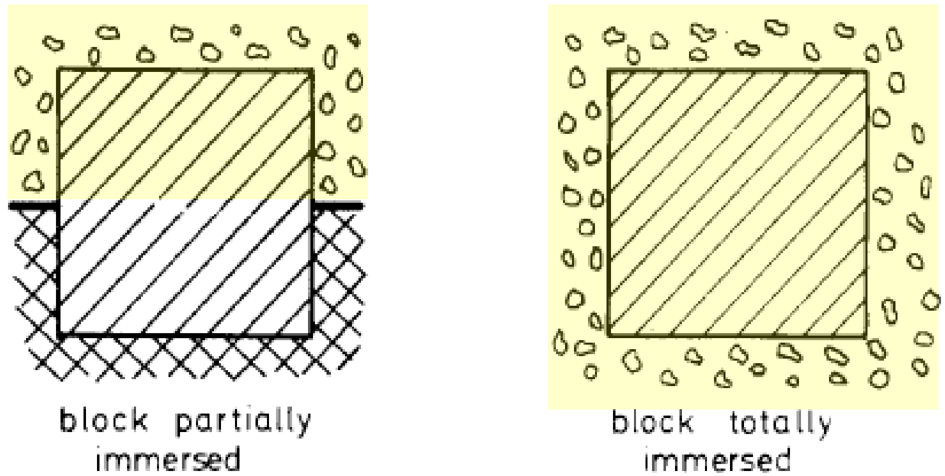
SIMPLIFIED DYNAMIC APPROACH TO MATRIX FLUID DISPLACEMENT

The displacement process in a fractured reservoir occurs when the matrix block saturated with oil is partially or entirely surrounded by another fluid, gas and/or water.

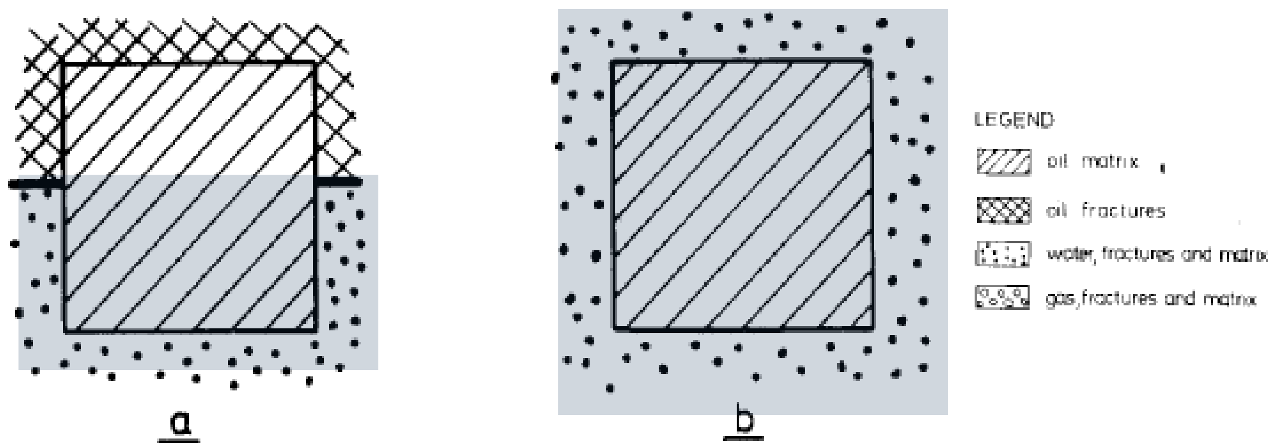


9.2 – Block invaded by gas from gas-cap (a) partially invaded (b) totally invaded.





9.2 – Block invaded by gas from gas-cap (a) partially invaded (b) totally invaded.

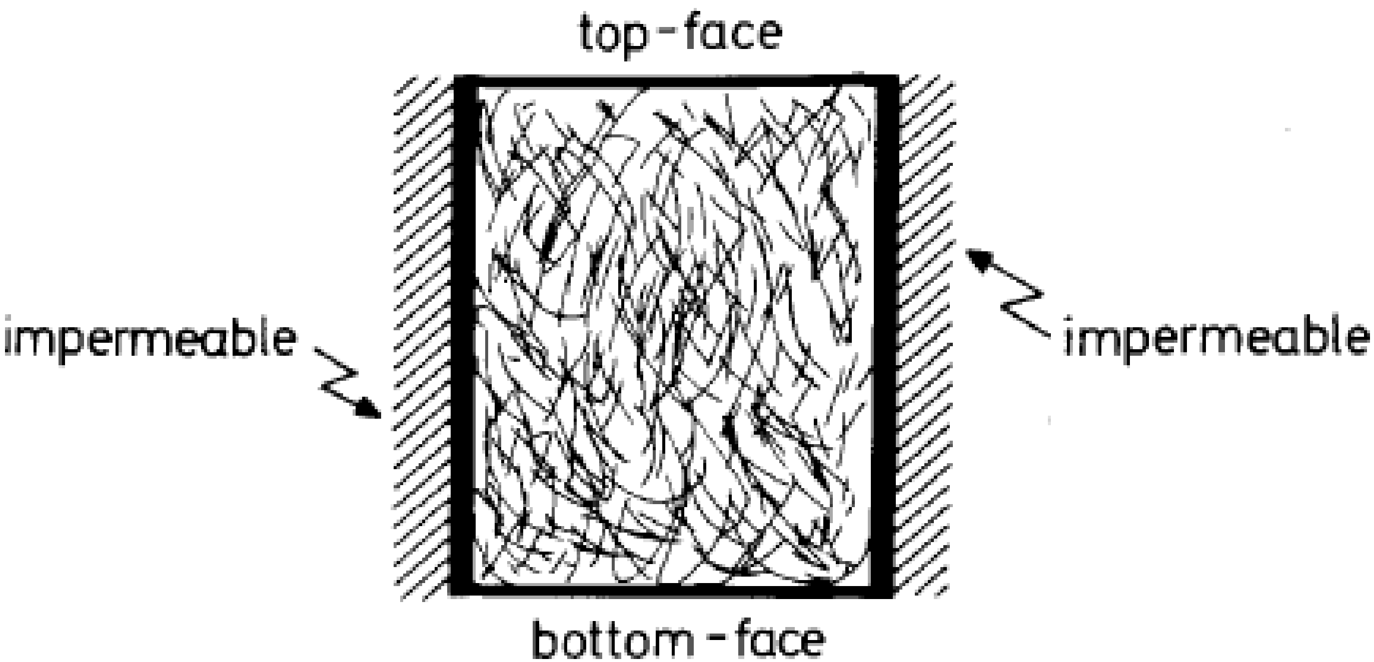


9.3 – Block immersed in water (a) partially immersed (b) totally immersed.

Simplified Displacement Model

In order to investigate the influence of some of the parameters involved in the process, a simplified displacement model having a sharp interface between the two fluids may be used.

Basic Physical Model



9.4 – Matrix block with lateral impermeable faces.

Basic assumptions :

a. The flow is considered uni-dimensional

b. The capillary pressure at the interface is assumed constant.

c. The irreducible wetting liquid saturation and residual non-wetting liquid saturation are assumed constant and, therefore the relative permeabilities are constant.

d. The uni-dimensional displacement from the matrix block is understood as lower and upper sides open to flow while the lateral faces are impermeable (figure 9.4).

e. In the surrounding fractures the pressure distribution is approximated by a hydrostatic relationship and therefore the potential **ϕ=P+ ρgZ** *is considered* constant.

f. Darcy's fluxes of the wetting (w) and the non-wetting (nw) fluids in the block are:

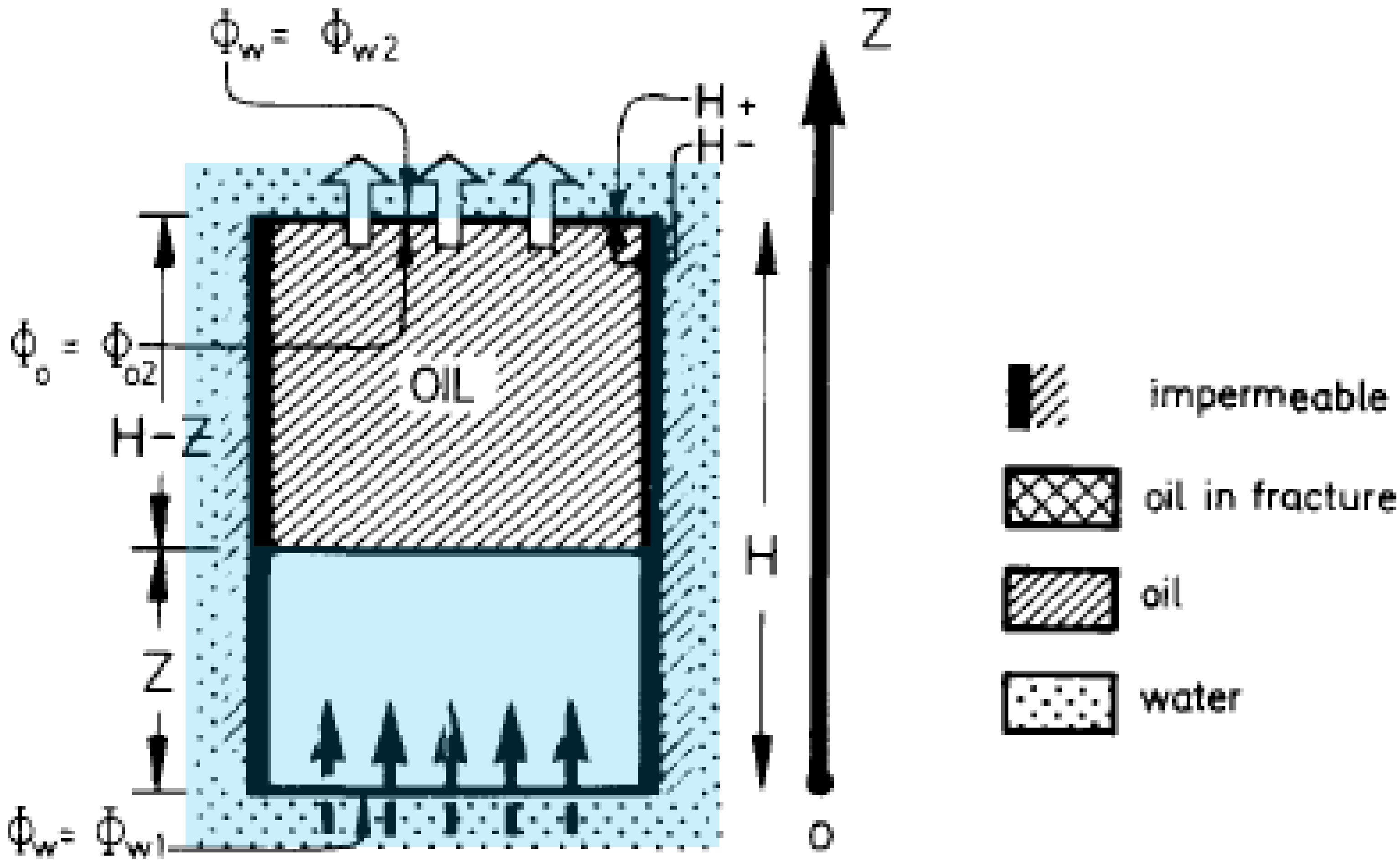
$$
\begin{aligned}
u_w &= -\frac{k\,k_{rw}}{\mu_w}\frac{\partial\Phi_w}{\partial_z} \\
u_{nw} &= -\frac{k\,k_{rnw}}{\mu_{nw}}\frac{\partial\Phi_{nw}}{\partial_z}
\end{aligned}
\qquad (9.1)
$$

g. The fluids are considered as incompressible and thus, the equations of conservation of mass in each phase are:

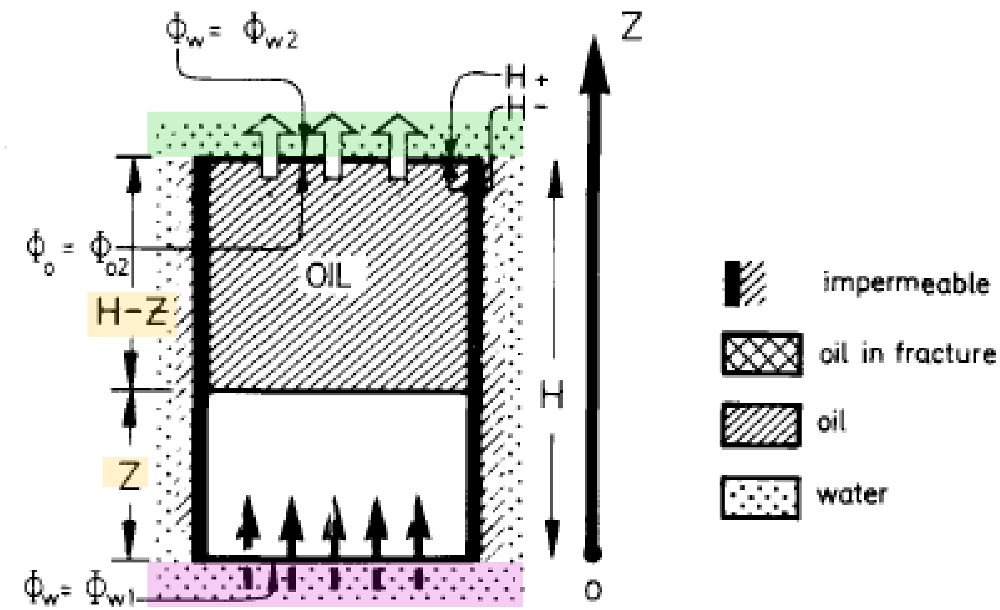
$$\partial u_{nw}/\partial z = 0 \quad , \quad \partial u_w/\partial z = 0 \qquad (9.2)$$

$$u_w = u_{nw} = u$$

Displacement of Oil by Water
Oil saturated Block Totally Immersed in Water



Water is considered a wetting phase and oil a non-wetting phase



$$u_w = -\frac{k\,k_{rw}}{\mu_w}\frac{\partial \Phi_w}{\partial_z}$$

$$u_{nw} = -\frac{k\,k_{rnw}}{\mu_{nw}}\frac{\partial \Phi_{nw}}{\partial_z}$$

$$u_w = u_{nw} = u$$

Boundary conditions:

$$Z = 0 \,;\, \Phi_w = \Phi_{w_1}$$

$$Z = H^- \,;\, \Phi_o = \Phi_{o_2} \qquad (9.3)$$

Integration of equation 9.1 under boundary conditions with equation 9.3 gives:

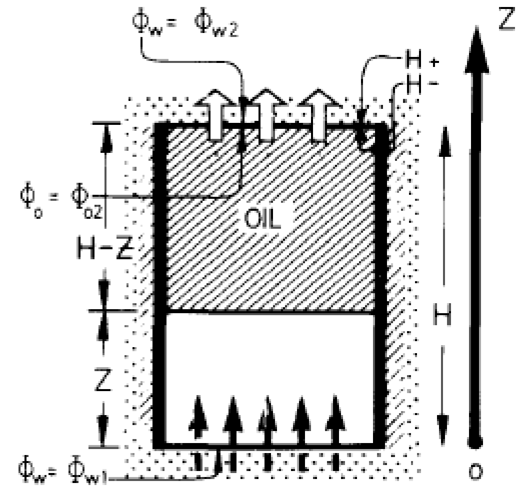
$$\Phi_{w_1} - \Phi_{wZ} = u\frac{\mu_w}{k_w}Z$$

$$\Phi_{oZ} - \Phi_{o_2} = u\frac{\mu_o}{k_o}(H-Z) \qquad (9.4)$$

$$\Phi_{w_1} - \Phi_{wZ} = u\frac{\mu_w}{k_w}Z$$

$$\Phi_{oZ} - \Phi_{o_2} = u\frac{\mu_o}{k_o}(H-Z)$$

$$\Phi_Z = p + \varrho g Z$$



$$\Phi_{w_1} - \Phi_{O_2} + P_c - gZ\Delta\varrho = u\left[\frac{\mu_w}{k_w}Z + \frac{\mu_o}{k_o}(H-Z)\right] \qquad (9.5)$$

where,

$$\Delta\varrho = \varrho_w - \varrho_o$$

The potential of ϕ_{o2} at H^- , in the block, is related to the potential ϕ_{w2} of water at the exit from the block (H^+) by:

$$\Phi_{O2} = \Phi_{W2} + P'_c - gH\Delta\varrho \qquad (9.6)$$

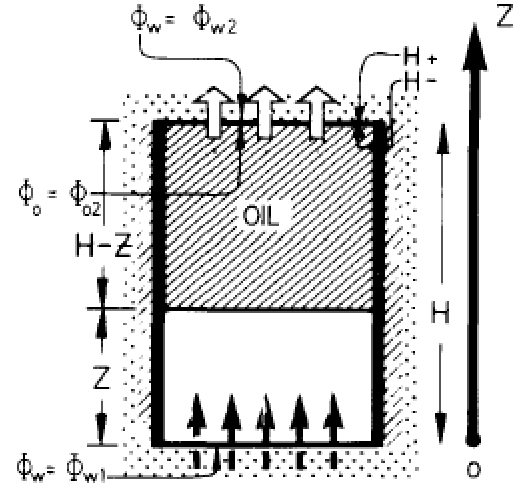
where P'_c is the capillary pressure at the producing face.

Hydrostatic equilibrium at water environment

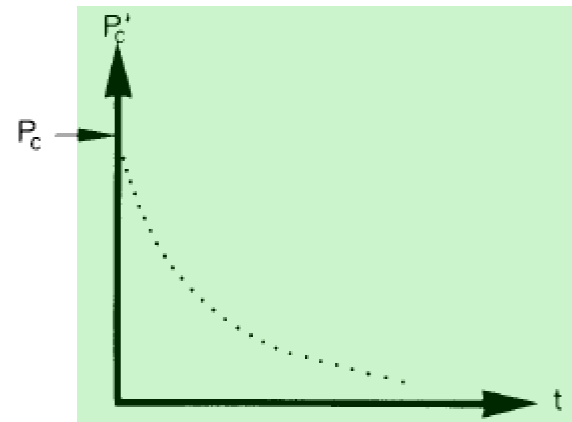
$$\Phi_{W2} = \Phi_{W1}$$

Substitution of Equation 9.6 in 9.5 yields:

$$u = \frac{P_c - P_c' + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} Z + \frac{\mu_o}{k\,k_{ro}} (H-Z)} \quad (9.7)$$



In the imbibition experiment with the sample totally immersed in water it was observed that the oil was produced as bubbles at the upper face. This production mechanism is the result of a continuous increase in time of the dimensions of the bubbles, and thus at a given stage the buoyancy exceeds the capillary forces and the bubbles leave the matrix. In fact, the capillary pressure P_c' is variable in time starting with a maximum $P_c = P_c'$, and thereafter capillary pressure in the block decreases very quickly with an increase in bubble dimension. Production of oil as bubbles at the exit face is an intermittent process. In a cycle of production of one bubble,the time during which P_c' has values close to P_c is relatively short (figure 9.6), thus P_c very quickly becomes negligible (equation 9.7) in comparison with P_c, and the following is obtained:



9.6 – Variation of bubble capillary pressure p_c vs. time.

$$u = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} Z + \frac{\mu_o}{k\,k_{ro}} (H-Z)} = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} [MH + (1-M)Z]} \quad (9.8)$$

where $M = (\mu_o/k_o)/(\mu_w/k_w)$ is the mobility ratio of constant value in the present case.

Equation 9.8

$$u = \frac{P_c + g(H-Z)\Delta\varrho}{\dfrac{\mu_w}{k\,k_{rw}} Z + \dfrac{\mu_o}{k\,k_{ro}}(H-Z)} = \frac{P_c + g(H-Z)\Delta\varrho}{\dfrac{\mu_w}{k\,k_{rw}}[MH + (1-M)Z]} \qquad (9.8)$$

Equation 9.8 is a function of the difference in magnitude between capillary and gravitational pressure, magnitude of mobility M and of front height Z, and each of these components must be examined.

- **Discussion of equation 9.8**
  - Relationship between gravitational and capillary pressure
  - Initial rate
  - Mobility vs. rate.
- **Water front advancement vs. time**
  - Case of predominant capillary pressure
  - Case of gravity and capillary imbibition
  - Case of predominant gravity (imbibition) pressure
- **Observations**
  - Relationship **t** vs. **H**.
  - Relationship **t** vs. $\mathbf{Z_D}$

Discussion of Equation 9.8-Relationship between Gravitational and Capillary Pressure

Between the two forces expressed as capillary pressure and gravitational pressure, one of them may be predominant by comparison with the other and thus displacement is governed only by one of them.

$$P_c + G = P_c + (H-Z)g\Delta\varrho = h_c\Delta\varrho + (H-Z)\Delta\varrho$$

Gravitational pressure governs displacement when

$$G = (H-Z)g\Delta\varrho >> P_c = h_c g\Delta\varrho$$

which becomes possible if:

- blocks are very high, therefore (H-Z) >> h_c, which implies also that Z is small (at the initial phase of displacement).
- wettability is small, therefore P_C, is small. In this case equation 9.8 may be rewritten as,

$$u = \frac{g(H-Z)\,\Delta\varrho}{\dfrac{\mu_w}{k \times k_{rw}}\,[MH + (1-M)\,Z]} \qquad (9.9)$$

Discussion of Equation 9.8-Relationship between Gravitational and Capillary Pressure

Between the two forces expressed as capillary pressure and gravitational pressure, one of them may be predominant by comparison with the other and thus displacement is governed only by one of them.

$$P_c + G = P_c + (H-Z)g\Delta\varrho = h_c\Delta\varrho + (H-Z)\Delta\varrho$$

Capillary pressure governs the displacement when,

$$P_c = h_c \times g \times \Delta\varrho >> (H-Z)g\,\Delta\varrho$$

Which becomes possible if:

- blocks are very small $H << h_C$,
- displacement front has already advanced so much that $Z \sim H$ and $h_C > 0$. *In* this case equation 9.8 may be rewritten as,

$$u = \frac{P_c}{\frac{\mu_w}{k \times k_{rw}} [MH + (1-M) Z]} \qquad (9.10)$$

Discussion of Equation 9.8-Initial Rate

The initial rate corresponds to $Z = 0$, thus equations 9.9 and 9.10 are reduced to the following expressions:

- for gravitational pressure

$$u = \frac{g(H-Z)\,\Delta\varrho}{\frac{\mu_w}{k \times k_{rw}}\,[MH + (1-M)\,Z]}$$

$$U = U_{GI} = \frac{K_o}{\mu_o}\, g\, \Delta\varrho = \frac{K_o}{\mu_o}\, \Delta\gamma \qquad (9.11)$$

- for capillary imbibition pressure

$$u = \frac{P_c}{\frac{\mu_w}{k \times k_{rw}}\,[MH + (1-M)\,Z]}$$

$$U = U_{CI} = \frac{K_o}{\mu_o}\, \frac{h_c}{H}\, g\Delta\varrho = \frac{K_o}{\mu_o}\, \frac{h_c}{H}\, \Delta\gamma \qquad (9.12)$$

It is observed that:

❑the initial gravity rate U_{GI} is independent of block magnitude, depending only on physical properties of rock and fluid. This equation was expressed by Muskat' for gravitational displacement in a conventional reservoir, and was called gravity rate.

❑- The initial rate under capillary conditions U_{CI} depends on the magnitude of the block height becoming negligible in the case of large H and very significant in the case of small H. This reconfirms the important role of capillary forces in the case of small matrix blocks (small H).

Discussion of Equation 9.8- Mobility vs. Rate

In order to examine the role of M it is necessary to rewrite equation 9.8 as follows:

$$u = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} Z + \frac{\mu_o}{k\,k_{ro}} (H-Z)} = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} [MH + (1-M)Z]} \qquad (9.8)$$

$$U = U_{GI} = \frac{K_o}{\mu_o} g\,\Delta\varrho = \frac{K_o}{\mu_o}\Delta\gamma \qquad 9.11$$

$$U = U_{CI} = \frac{K_o}{\mu_o}\,\frac{h_c}{H}\,g\Delta\varrho = \frac{K_o}{\mu_o}\,\frac{h_c}{H}\,\Delta\gamma \qquad 9.12$$

$$U = \frac{K_o}{\mu_o}\,\frac{h_c\,\Delta\gamma + (H-Z)\,\Delta\gamma}{H-Z+Z/M} \qquad (9.13)$$

As observed, equations 9.11 and 9.12 are obtained when the term Z/M is negligible (the initial rate corresponds to Z = 0). This corresponds to the situation of large mobility M equivalent to highly viscous (heavy) oil.

It is interesting to observe that in the case of **heavy oil reservoirs** with **tall blocks**, the gravitational velocity remains constant (equation 9.11) and independent of the relative position of the displacement front, expressed by H-Z. This observation was verified in various heavy oil fractured reservoirs.

Water Front Advancement vs. Time - Case of Predominant Capillary Pressure

The advancement of the water front in time dZ/dt expresses the real front velocity (which is related to the filtration velocity by effective porosity ϕ) through the classic relationship:

$$U = \Phi \times dZ/dt \qquad (9.14)$$

Substitution of equation 9.10 in 9.14 and integration with the initial condition t=0, Z=0 yields:

$$u = \frac{P_c}{\frac{\mu_w}{k \times k_{rw}} \left[MH + (1-M)\,Z\right]} \qquad (9.10)$$

$$t = \frac{\Phi\,\mu_w}{P_c\,k\,k_{rw}} \left[MHZ + (1-M)\,Z^2/2\right] \qquad (9.15)$$

In general the capillary pressure $\mathbf{P_c}$ is a function of saturation which can be expressed through the Leverett function **J(Sw)** as:

$$P_c = (\sigma f(\theta)/\sqrt{k/\Phi})J(S_w) \qquad (9.16)$$

For a constant value of capillary pressure $J(S_w) = 1$ and substitution of equation 9.16 in 9.15 the result is:

$$t = \frac{\mu_w H^2 \sqrt{\Phi}}{\sigma f(\theta) \sqrt{k}\, k_{rwmax}} \left[M Z_D + (1-M) Z_D^2/2\right] \qquad (9.17)$$

where $Z_D = Z/H$, represents the equivalent to recovery factor.

Equation 9.17 shows that the time required to produce a given fraction of oil (Z_D) by imbibition is directly proportional to the square of the block height (H), and inversely proportional to interfacial tension (σ), relative permeability for water (K_W) and the square root of permeability (K).

By defining the dimensionless time for displacement by capillary imbibition,

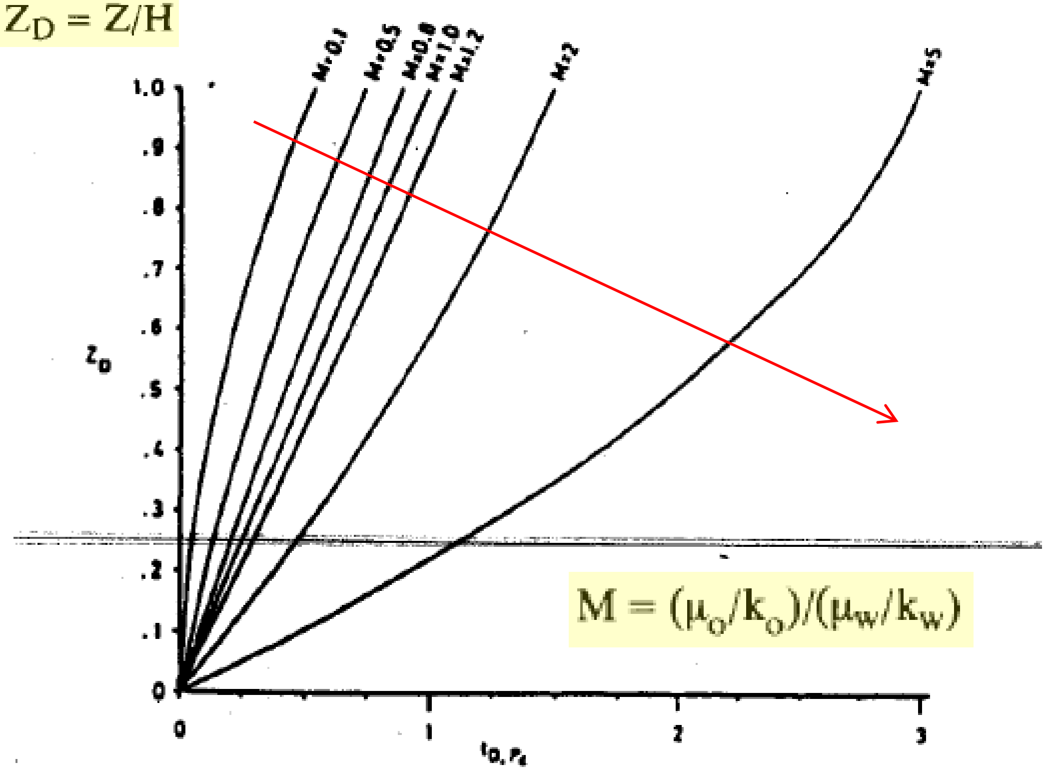
$$t_{D,P_c} = \frac{\sigma f(\theta) \sqrt{K/\Phi}\, k_{rw\,max}}{\mu_w H^2}\, t \qquad (9.18)$$

equation 9.18 may be written in a dimensionless form as,

$$t_{D,P_c} = M Z_D + (1-M) Z_D^2/2 \qquad (9.19)$$

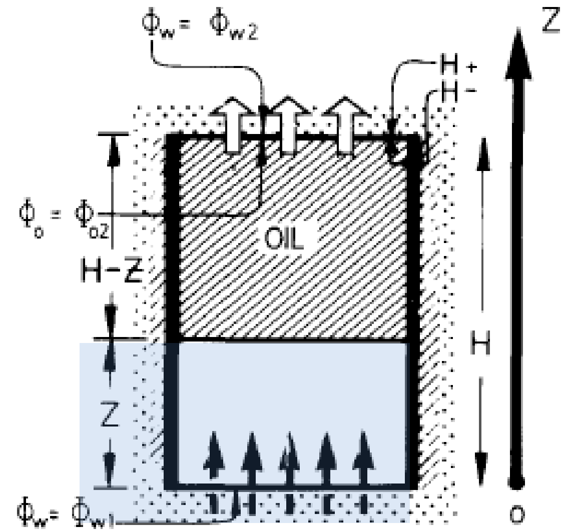
The fraction of oil recovery versus dimensionless time for different mobility ratios was elaborated by Muskat' as shown in figure 9.7.

$Z_D = Z/H$

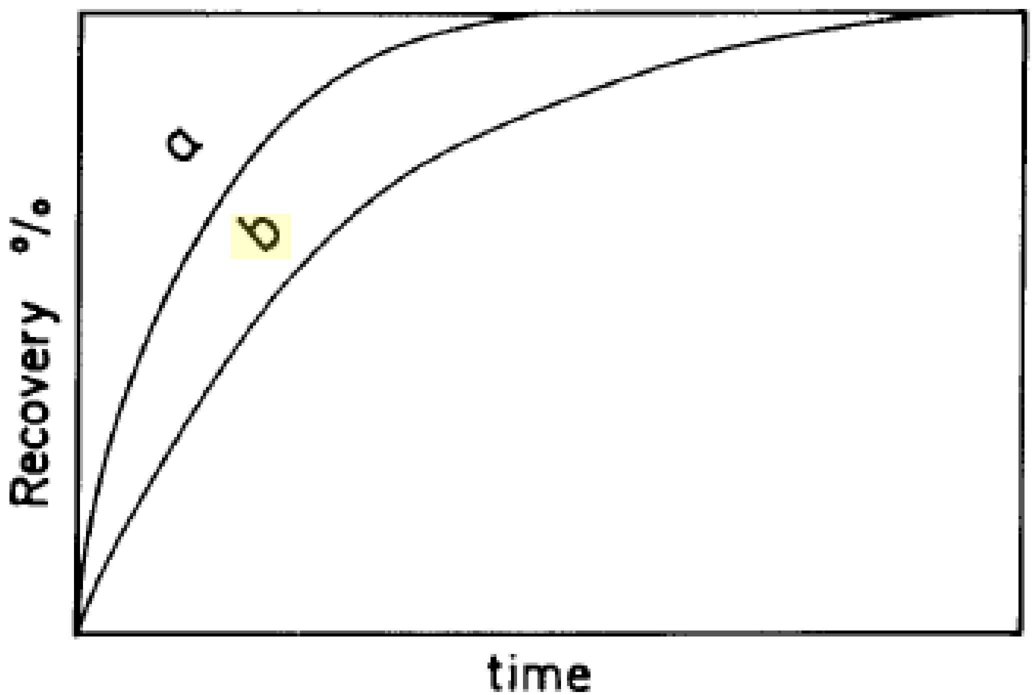


$M = (\mu_o/k_o)/(\mu_w/k_w)$

$$t_{D,P_c} = \frac{\sigma f(\theta)\sqrt{K/\Phi}\, k_{rw\,max}}{\mu_w H^2}\; t$$



Because of the assumption that relative permeabilities and capillary functions are expressed by constant values and not by functions of saturation, as in a real matrix, the time of recovery will be underestimated.



9.8 – Variation of recovery vs. time (a) based on equation 9.8 (b) based on experiments.

Water Front Advancement vs. Time - Case of gravity and capillary imbibition

If both capillary pressure and gravitational pressure are considered, the integration of equations 9.8 and 9.14 will give the following:

$$t = \frac{\mu_w \Phi H}{k\, k_{rw}\, g \Delta\varrho} \left[(M-1) Z_D - [M + (1-M)\left(1 + \frac{P_c}{H g \Delta\varrho}\right) \right] \ln\left(1 + \frac{P_c}{H g \Delta\varrho} - Z_D\right) \quad (9.20)$$

In such a case another dimensionless time is defined as,

$$t_{D,G,P_c} = \frac{k\, k_{rw\,max}\, g \Delta\varrho}{\mu_w\, \Phi\, H}\, t \quad (9.21)$$

and with this dimensionless time equation 9.20 becomes

$$t_{D,G,P_c} = (M-1) Z_D - \left[M + (1-M)\left(1 + \frac{P_c}{H g \Delta\varrho}\right) \right] \ln\left(1 + \frac{P_c}{H g \Delta\varrho} - Z_D\right) \quad (9.22)$$

Water Front Advancement vs. Time - Case of predominant gravity (imbibition) pressure

If displacement is only governed by gravitational forces, the time results either from the combination of equations 9.14 and 9.9, or by neglecting capillary pressure (**$P_C/Hg\Delta\rho$**) in equation 9.22. The result is,

$$t_{DG} = (M-1)Z_D - \ln(1-Z_D) \tag{9.23}$$

Observations-Relationship *t* vs. *H*.

From the theoretical results obtained above the following is retained:

Relationship *t vs. H*. *This relationship shows the influence of block height H on* time in both cases examined

-if capillary forces are predominant: → ***t*** is proportional to ***H²*** (equation 9.18).

$$t_{D,P_c} = \frac{\sigma f(\theta)\sqrt{K/\Phi}\, k_{rw\,max}}{\mu_w H^2}\, t \tag{9.18}$$

- if gravitational forces are predominant : → ***t*** is proportional to ***H*** (equation 9.21)

$$t_{D,G,P_c} = \frac{k\, k_{rw\,max}\, g \Delta \varrho}{\mu_w\, \Phi\, H}\, t \tag{9.21}$$

This result shows that in case of capillary predominant displacement which corresponds to small blocks (small H) the time depends parabolically of block height.

Observations- Relationship *t* vs. Z_D

This relationship is in fact showing the recovery vs. time behavior.

- If capillary forces are predominant (equation 9.19), M plays an important role

$$t_{D,P_c} = M Z_D + (1-M)Z_D^2/2 \tag{9.19}$$

$$t_{D,P_c} \cong Z_D^2/2 \quad \text{if} \quad M << 1$$

$$t_{D,P_c} \cong MZ_D \quad \text{if} \quad M \cong 1$$

- If gravity forces are predominant (equation 9.23)

$$t_{DG} = (M-1)Z_D - \ln(1-Z_D) \tag{9.23}$$

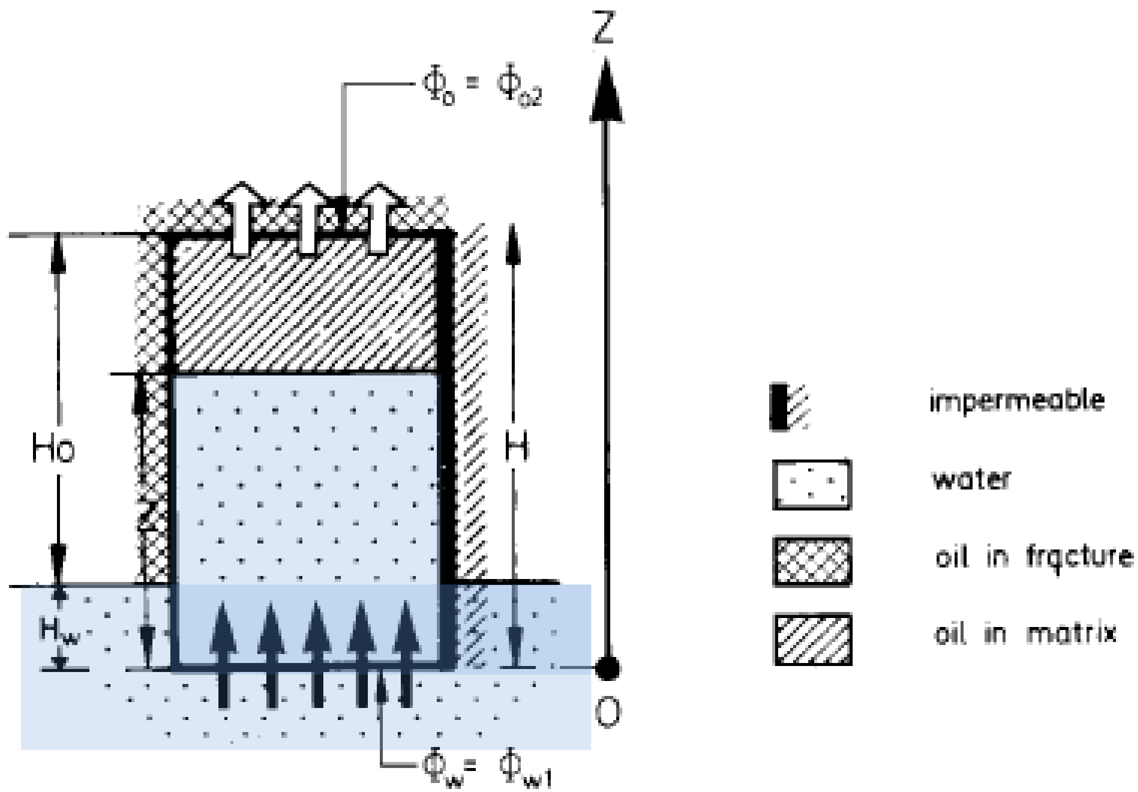
$$\begin{aligned} t_{D,G} &\cong \ln(1-Z_D) - Z_D \ \text{if } M<<1 \\ t_{D,G} &\cong \ln(1-Z_D) \quad \text{if } M \cong 1 \end{aligned} \tag{9.24}$$

Equation 9.24 is similar to results observed in experimental work, and in various theoretical approaches when recovery vs. time is written as

$$Z_D = 1-e^{t_{DG}} \tag{9.24'}$$

Oil Saturated Block Partially Immersed in Water

An oil saturated block partially immersed in water corresponds to a slow advance of water in the fracture so that the water-oil front in the block is higher than the water-oil front in the fracture. A simplified assumption is that the advance of the front in the fracture is negligible in comparison with the advance of the front in the block, i.e. H_W = const. (figure 9.9)



9.9 – Advancement of displacement front in the case of a block partially immersed in water.

$$u = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}} Z + \frac{\mu_o}{k\,k_{ro}}(H-Z)} = \frac{P_c + g(H-Z)\Delta\varrho}{\frac{\mu_w}{k\,k_{rw}}[MH + (1-M)Z]} \qquad (9.8)$$

In such a case the upper face of the block is producing in an oil environment and the potentials $\boldsymbol{\phi_{W1}}$ and $\boldsymbol{\phi_{O2}}$ (figure 9.9) are related through the capillary pressure in the fracture as follows:

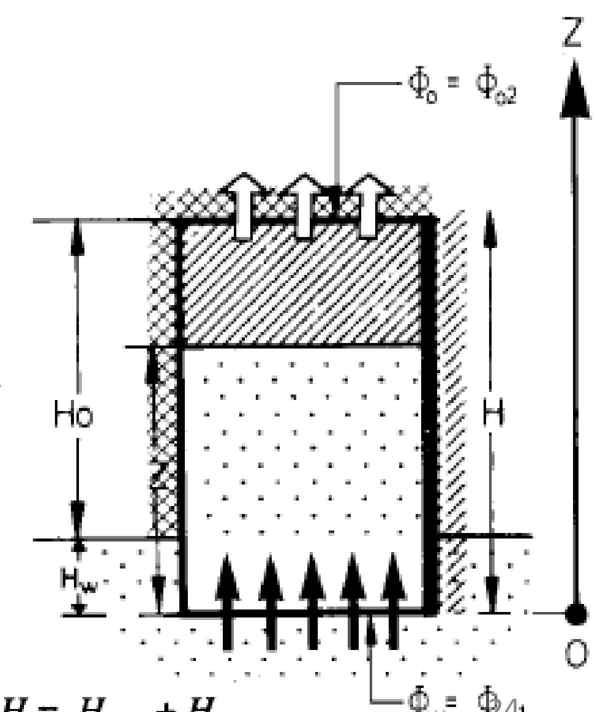
$$\Phi_{w_1} - \Phi_{o2} = -P_{cf} + gH_w\Delta\varrho \qquad \begin{aligned} \Phi_{w_1} - \Phi_{wZ} &= u\frac{\mu_w}{k_w}Z \\ \Phi_{oZ} - \Phi_{o_2} &= u\frac{\mu_o}{k_o}(H-Z) \end{aligned} \qquad (9.25)$$

Substituting equation 9.25 in 9.8 gives,

$$U = \frac{P_c - P_{cf} - g(Z - H_w)\Delta\rho}{\frac{\mu_w}{KK_{rw}}[MH + (1-M)Z]} \qquad (9.26)$$

The capillary pressure in fracture P_{cf} may be ignored being of constant value and much smaller than the capillary pressure P, in the block. Equation 9.27 is thus obtained,

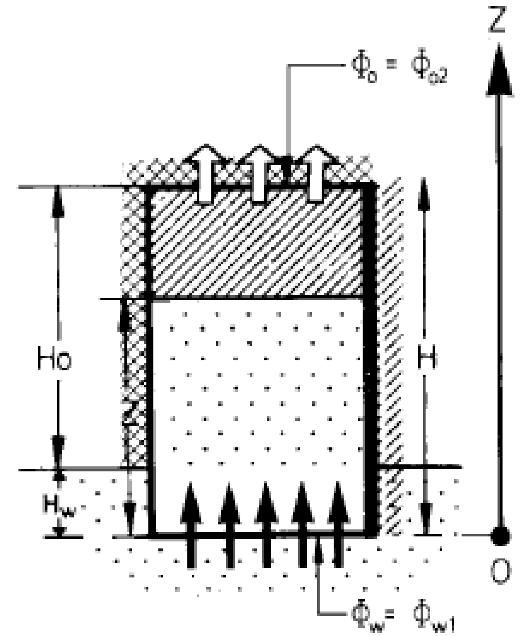
$$U = \frac{P_c + g(H_w - Z)\Delta\rho}{\mu_w / KK_{rw}\,[MH + (1-M)Z]} \qquad (9.27)$$



$H_{Block} = H = H_w + H_o$

•The uni-dimensional displacement of oil, by imbibition only, from a block with impervious lateral sides is not affected by the position of the water front in the adjacent vertical fractures as much as $h_C > H_W - Z$.

$$U = \frac{P_c + g(H_w - Z)\Delta\rho}{\mu_w / KK_{rw} \left[MH + (1 - M) Z\right]}$$



• $Z<H_W$: Gravity will contribute to oil displacement,
• $Z>H_W$: Gravity will have a retardation effect on the displacement process.

•Therefore, oil displacement from a block completely surrounded by water will occur at a faster rate than oil displacement from a block partially immersed in water, even if the lateral sides of the block are inactive.

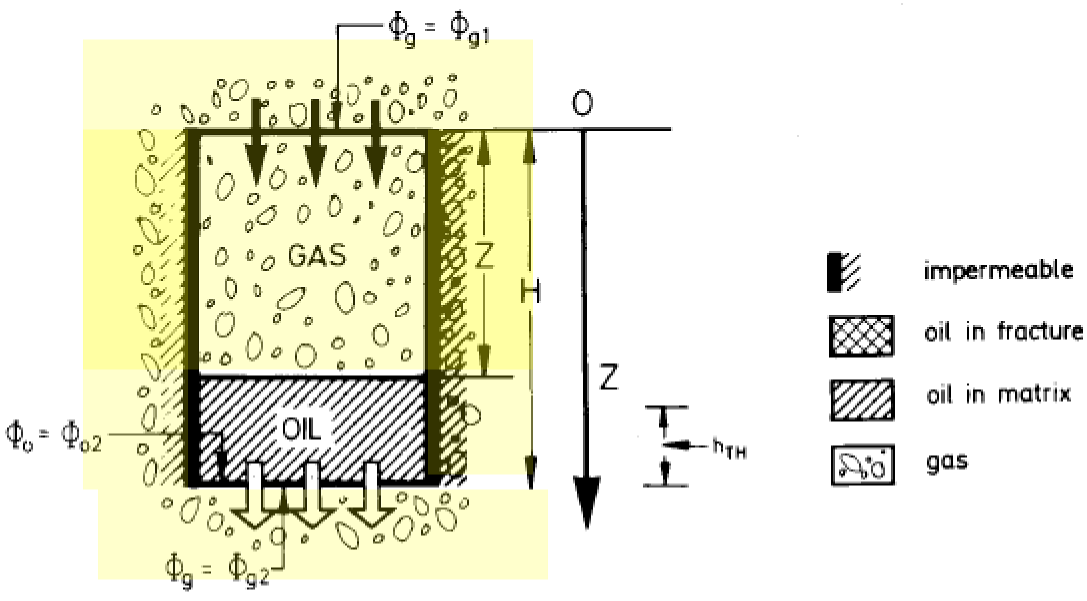
This observation is in accordance with Mattax's experiments which define, under similar conditions, a **critical rate** above which the recovery is rate-dependent and below which the recovery remains constant (the rate is understood as advancement of the water-oil contact in fractures).

Displacement of Oil by Gas

Case of an oil saturated block totally surrounded by gas

Gas entering the upper side of the block will displace oil which is produced at the bottom of the block in a gas or oil environment. The gas is considered to be the non-wetting phase and gas compressibility is ignored.

A block initially saturated with oil and totally surrounded by gas is shown in figure 9.10. The initial pressure of the gas column is considered to be above the threshold pressure, therefore, gas can enter the block.

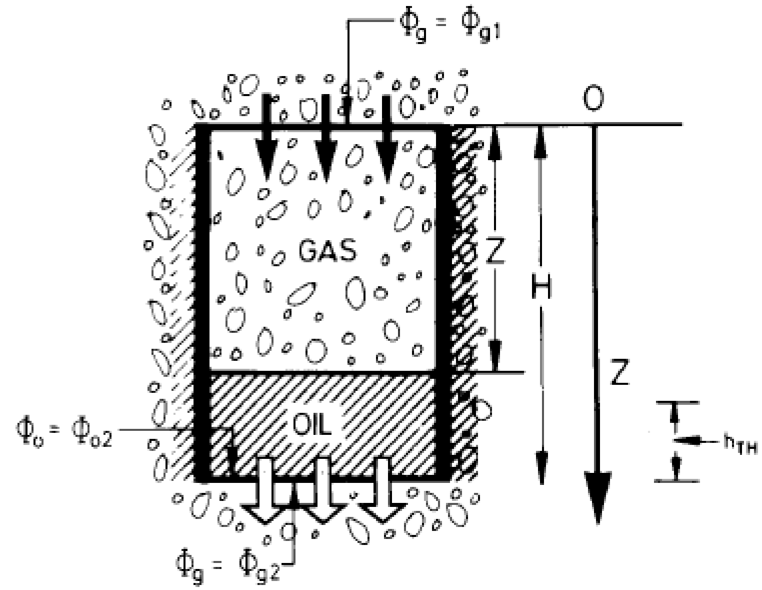


9.10 – Advancement of displacement front in the case of a block totally immersed in gas.

The boundary conditions corresponding to this case are:

$$Z = H \qquad \Phi_g = \Phi_{g1}$$
$$Z = O^+ \qquad \Phi_o = \Phi_{o2} \tag{9.28}$$

where $Z = 0^+$ is a point at the boundary within the block.



Integration of equation 9.1 with equation 9.28 gives:

$$\Phi_{g1} - \Phi_{gz} = \frac{\mu_g \; U}{K \; K_{rg}} \; Z$$

$$\Phi_{oz} - \Phi_{o2} = \frac{\mu_o \; U}{K \; K_{ro}} \; (H - Z) \qquad (9.29)$$

By adding these equations and substituting $\Phi_{gz} - \Phi_{oz} = P_c - g(H-Z)\Delta\varrho$ the following is obtained:

$$\Phi_{g1} - \Phi_{o2} - P_c + g\,(H - Z)\,\Delta\rho = \frac{U}{K}\left[\frac{\mu_g}{K_{rg}}\,Z + \frac{\mu_o}{K_{ro}}\,(H - Z)\right] \qquad (9.30)$$

where,

$$\Delta\varrho = \varrho_o - \varrho_g$$

By substituting, in equation 9.30, the relationship between the potential of oil in the block and that of the gas in the fracture at the exit face $\Phi_{o_2} = \Phi_{g_2} - P_c'$ (where P_c' is the capillary pressure at the exit face), and with $\Phi_{g_1} = \Phi_{g_2}$ the result is,

$$P_c' - P_c + g\,(H - Z)\,\Delta\rho = \frac{U}{K}\left[\frac{\mu_g}{K_{rg}}\,Z + \frac{\mu_o}{K_{ro}}\,(H - Z)\right] \tag{9.31}$$

or by ignoring the capillary pressure at the exit face,

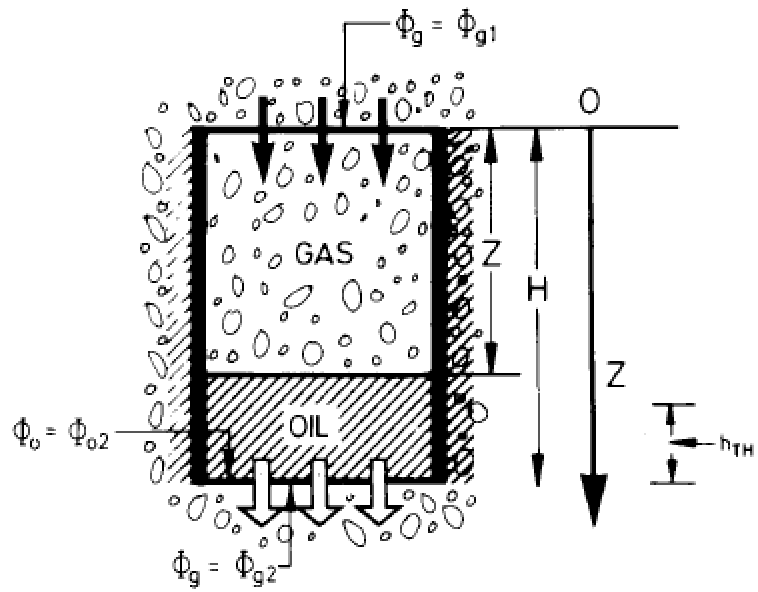
$$U = \frac{g\,(H - Z)\,\Delta\rho - P_c}{\frac{\mu_g}{KK_{rg}}\,[MH + (1 - M)\,Z]} \tag{9.32}$$

where $M = (\mu_o / K_o) / (\mu_g / K_g)$ is the mobility ratio.

In such a displacement the capillary pressure has a negative effect on production. Oil can be produced to the extent that gravitational forces exceed capillary forces

$H_g >> h_{TH}$.

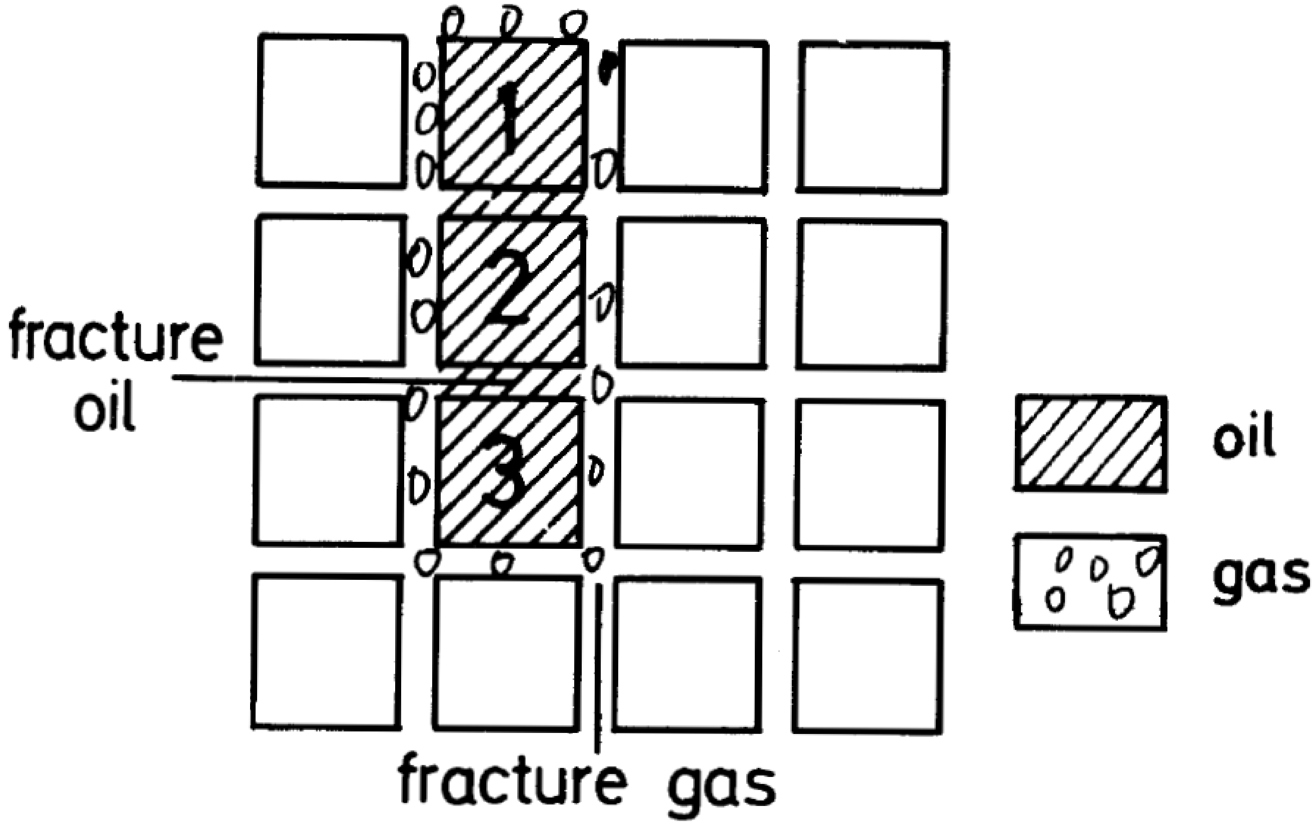
Depending on the value of the capillary pressure and the length of the block, if $H>Z_{cr}$ an equilibrium is reached when $\boldsymbol{H\text{-}Z = Z_{cr} = H - h_{TH}}$ and oil will no longer be displaced.



$$H - Z = Z_{cr} = H - h_{TH} \tag{9.33}$$

The conclusion reached is as follows: In a displacement by a sharp interface, under certain conditions (depending on the value of the gas-oil capillary pressure, and the blocklength) the block saturated with oil can be totally entrapped by gas circumventing the block if $h_{TH} > H$. This could never be possible in a displacement of oil by water.

On the other hand, to penetrate and move into the block, the gas must reach the *entry value* or the threshold pressure P_{TH}, i.e. $gH\Delta\rho > P_{cTH} = h_{TH} \times \Delta\gamma$ (equation 9.32). In the case of small blocks totally surrounded by gas, it is very unlikely that such a value of $gH\Delta\rho$ may be achieved and the oil displaced. However, it could be that considering the length of the individual block to satisfy $gH\Delta\rho > P_{cTH}$ too restrictive, since the gas reaching the bottom of individual block does not displace the oil from horizontal adjacent fractures. Thus, there is a possibility that oil will remain as a continuous phase between several blocks (figure 9.11). Gas will thus completely circumvent blocks 1, 2 and 3 (similar to a block height $H = H_1 + H_2 + H_3$) and displacement will cease only after displacement gas-oil front reaches the level $Z_{cr} = H_1 + H_2 + H_3 - h_{TH}$.



9.11 – Example of blocks where oil was not displaced in horizontal fractures between blocks forming a continuum of oil phase.

In such a case the pressure acting on the first block (block 1, figure 9.11) is the pressure corresponding to the total length (H) of the circumvented blocks (1, 2 and 3), which increases the chances of overcoming the threshold pressure P_{TH}, and thus displacing the oil from block 1.

To obtain the relationship between the fraction of the recovered oil and time, $U = \Phi dz/dt$ is substituted in equation 9.32, and when integrated with intial condition $t = 0, Z = 0$, the result obtained is:

$$t_{D,G,P_c} = Z_D(M-1) - \left[M + (1-M)\left(1 - \frac{P_C}{gH\Delta\varrho}\right)\right]\ln\left(1 - \frac{P_C}{gH\Delta\varrho} - Z_D\right) \quad (9.34)$$

where $Z_D = Z/H$ ~ is the fraction of oil produced, and $t_{D,G} = K\, K_{rg\,max}\, g\, \Delta\varrho/\Phi\mu_g H$ ~ dimensionless time (equation 9.21). The dimensionless displacing time in case $P_c << H_g\ \Delta\gamma$ will be reduced to a displacement by gravitational forces only and equation 9.34 will become

$$t_{DG} = (M-1)Z_D - \ln(1-Z_D) \quad (9.35)$$

which is similar to the gravitational dimensionless time obtained for the displacement of oil by water (equation 9.23).

Case of an oil saturated block, partially surrounded by gas

An oil saturated block partially surrounded by gas corresponds to the gas front which did not reach the lower face of the block (figure 9.12), and thus the problem will be the same as in the case of a totally immersed block.

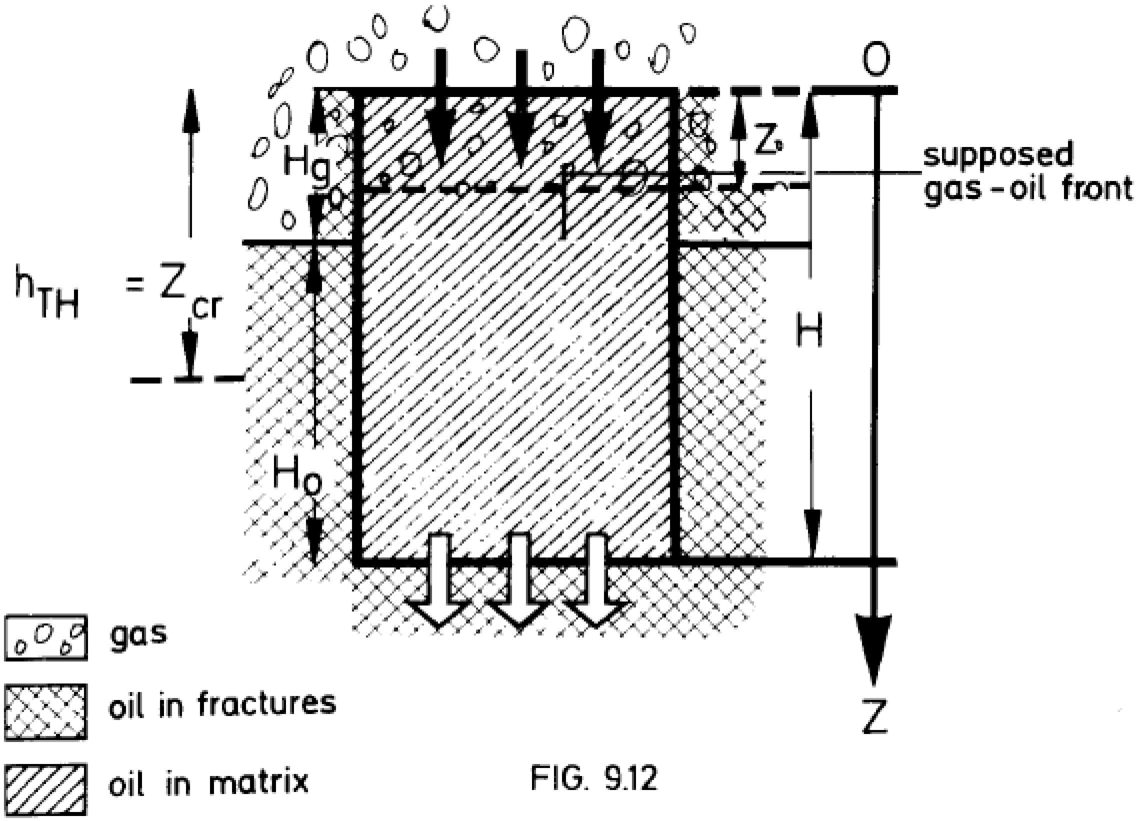


FIG. 9.12

9.12 – Displacement front in the case of a block partially invaded by gas.

- Displacement will start only if the column of gas in fractures (H_g) is higher than the threshold height, as follows:

$$H_g > P_{TH} / \Delta\varrho \times g = h_{TH} \tag{9.36}$$

- Displacement will cease when the gas-oil contact in the matrix reaches the limit height of $H - h_{TH}$ equivalent to the following height:

$$H - h_{TH} = Z_{cr} = P_{TH}/\Delta\varrho \times g = h_{TH} \tag{9.37}$$

- By analogy with equation 9.32 the rate of advancement of the gas-oil contact in the matrix will be:

$$U = \frac{g\left[H_g - (H - Z)\right] \Delta\rho - P_c}{\frac{\mu_g}{KK_{rg}}\left[MH + (1 - M)Z\right]} \tag{9.38}$$

Conclusions

From the results obtained through this simplified dynamic approach the following conclusions are reached:

a. In an imbibition displacement the *time of recovery is proportional to the square of the block height, while in a displacement by gravitational forces the time of* recovery is *proportional to the block height.*

b. Gravitational forces in an imbibition process may play an important role in the displacement if either the blocks are large in size, or if the capillary pressure is negligible.

c. In a drainage displacement of oil by gas the capillary forces will act against the displacement, and therefore the displacement will result only through gravitational forces, which must exceed the capillary pressure.

d. To displace oil (as wetting phase), the gas pressure must reach *the entry pressure* or the threshold pressure. In a reservoir of small size blocks, there is a possiblity that gas will circumvent the blocks without reaching the threshold pressure, and in such a case the oil will not remain entrapped in the blocks.