

## CHAPTER 3

### METHODOLOGY OF CENTRIFUGE AND UNSTEADY STATE

#### RELATIVE PERMEABILITY

##### **3-1 Relative Permeability:**

Relative permeability data can be get from the Special Core Analysis Lab (SCAL) test but in many cases, relative permeability data on actual samples from the reservoir under study may not be available, in which case it is necessary to obtain the desired relative permeability data in some other manner. Field relative permeability data can usually be calculated. The field data are unavailable for future production, however, and some substitute must be devised. Several methods have been developed for calculating relative permeability relationships. Various parameters have been used to calculate the relative permeability relationships, including:

- Residual and initial saturations.
- Capillary pressure data.

##### **3-1-1 Wyllie and Gardner Correlation**

Wyllie and Gardner (1958) observed that, in some rocks, the relationship between the reciprocal capillary pressure squared ( $1/P_c^2$ ) and the effective water saturation  $S_w^*$  is linear over a wide range of saturation.

Honapour et al. (1988) conveniently tabulated Wyllie and Gardner correlations as shown below:

**Table (3-1): Drainage Oil-Water Relative Permeabilities Equation (Tareq Ahmad, 2005)**

Type of formation	$k_{ro}$	$k_{rw}$
Unconsolidated sand, well sorted	$(1 - S_w^*)$	$(S_w^*)^3$
Unconsolidated sand, poorly sorted	$(1 - S_w^*)^2 (1 - S_w^*)^{1.5}$	$(S_o^*)^{3.5}$
Cemented sandstone, oolitic limestone	$(1 - S_o^*)^2 (1 - S_w^*)^2$	$(S_o^*)^4$

##### **3-1-2 Torcaso and Wyllie Correlation**

Torcaso and Wyllie (1958) developed a simple expression to determine the relative permeability of the oil phase in a gas-oil system. The expression permits the

calculation of kro from the measurements of krg. The equation has the following form:

$$K_{ro} = K_{rg} \left[ \frac{(S_o^*)^2}{(1-S_o^*)^2(1-(S_o^*)^2)} \right] \dots\dots\dots(3-1)$$

**3-1-3 Pirson’s Correlation**

From petrophysical considerations, Pirson (1958) derived generalized relationships for determining the wetting and nonwetting phase relative permeability for both imbibition and drainage processes. The generalized expressions are applied for water-wet rocks.

**For the water (wetting) phase**

$$K_{ro} = \sqrt{S_o^*} S_w^3 \dots\dots\dots(3-2)$$

For the nonwetting phase (Imbibition)

$$(K_r)_{nonwetting} = \left[ 1 - \left( \frac{S_w - S_{wc}}{1 - S_{wc} - S_{wn}} \right) \right]^2 \dots\dots\dots(3-3)$$

**3-1-4 Corey’s Method**

Corey (1954) proposed a simple mathematical expression for generating the relative permeability data of the gas-oil system. The approximation is good for drainage processes, i.e., gas-displacing oil.

$$K_{ro} = (1 - S_g^*)^4 \dots\dots\dots(3-4)$$

$$K_{rg} = (S_g^*)(2-S_g^*) \dots\dots\dots(3-5)$$

**3-1-5 Relative Permeability from Capillary Pressure Data**

That capillary pressure  $P_c$  is a measure of the fundamental characteristics of the formation and could also be used to predict the relative permeabilities. All modules use water saturation and lithology factor obtained from capillary pressure except Corey which assumes lithology factor index is equal to 2 .In this section Purcell, Burdine, Corey, Brook-Corey .

**3-1-5-1 Purcell model**

Purcell model was given as:

- (i) The relative permeability for the wetting phase can be calculated as follows:

$$K_{rw} = \frac{\int_0^{S_w} \partial S_w / (Pc)^2}{\int_0^1 \partial S_w / (Pc)^2} \dots\dots\dots(3-6)$$

- (ii) Similarly, the relative permeability for nonwetting phase can be calculated as following :

$$K_{rnw} = \frac{\int_{S_w}^1 \partial S_w / (Pc)^2}{\int_0^1 \partial S_w / (Pc)^2} \dots\dots\dots(3-7)$$

Where:

$K_{rw} \equiv$  relative permeability of the wetting phase.

$S_w \equiv$  Saturation of wetting phase

$Pc \equiv$  Capillary pressure.

$K_{rnw} \equiv$  relative permeability of the nonwetting phase

### 3-1-5-2 Burdine Model

It is given as:

$$K_{rw} = (\lambda_{rw})^2 \frac{\int_0^{S_w} \partial S_w / (Pc)^2}{\int_0^1 \partial S_w / (Pc)^2} \dots\dots\dots(3-8)$$

Where:

$\lambda_{rw} \equiv$  is the tortosity ratio of the wetting phase

which is defined a follows:

$$\lambda_{rw} = \frac{\tau_w(1.0)}{\tau_w(S_w)} = \frac{S_w - S_m}{1 - S_m} \dots\dots\dots(3-9)$$

$$K_{rnw} = (\lambda_{rnw})^2 \frac{\int_{S_w}^1 \partial S_w / (Pc)^2}{\int_0^1 \partial S_w / (Pc)^2} \dots\dots\dots(3-10)$$

$\lambda_{rnw} \equiv$  is the tortosity ratio of the non wetting phase

which is defined a follows:

$$\lambda_{rnw} = \frac{\tau_{nw}(1.0)}{\tau_{nw}(S_w)} = \frac{1 - S_w - S_m}{1 - S_m - S_e} \dots\dots\dots(3-11)$$

Where:

$S_m \equiv$  minimum non wetting phase saturation

### 3-1-5-3 Corey Model

It is expressed as:

$$K_{rw} = (S_w^*)^4 \dots \dots \dots (3-12)$$

$$K_{mw} = (1 - S_w^*)^2 [1 - S_w^*]^2 \dots \dots \dots (3-13)$$

Where:

$S_w^*$  ≡ The normalized wetting phase saturation ,which could be expressed as following for drainage process.

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}} \dots \dots \dots (3-14)$$

Where:

$S_{wr}$  ≡ the residual saturation of wetting phase.

For imbibitions processes:

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{nwr}} \dots \dots \dots (3-15)$$

$S_{nwr}$  ≡ the residual saturation of non wetting phase saturation.

### 3-1-5-4 Brooks-Corey Model

It was given for both conditions (wetting and nonwetting phase ) as:

$$K_{rw} = (S_w^*)^{\frac{2+3\lambda}{\lambda}} \dots \dots \dots (3-16)$$

$$K_{mw} = (1 - S_w^*)^2 [1 - S_w^*]^{\frac{2+\lambda}{\lambda}} \dots \dots \dots (3-17)$$

$\lambda$  ≡ the pore size distribution index (Equals 2 for Corey Model).

### 3-1-6 Relative Permeability Measurement Methods

There are some methods to measurement relative permeability such steady state ,unsteady state and centrifuge methods .This research is concentration about two method:

### 3-1-6-1 Unsteady state method:

This method for calculating the relative permeabilities are available. All of this method is based on the assumption that the core is homogeneous, and that capillary pressure and gravity neglected. It used to calculate  $k_{r1}$  and  $k_{r2}$  by injecting fluid 1 into a sample saturated with fluid 2. The procedure consists in measuring the volumes of fluids 2 and 1 leaving the sample as a function of time. Hence these are essentially volumetric measurements .

### 3-1-6-2 Centrifuge method:

Hassler and Brunner (1945) presented the basic concepts involved in the use of the centrifuge by relating the performance of a small core in a field of high acceleration.

If the cylindrical core of length  $L$  is subjected to an acceleration  $a_c = -\omega^2 r$  where  $\omega$  is angular velocity of the centrifuge and  $r$  is the distance from the axis of rotation, then from Eq. (3.18) we have :

$$\frac{\partial P_c}{\partial r} = \Delta\rho a_c \dots\dots\dots(3-18)$$

The capillary pressure at the outer face of the core is zero,  $P_c(r_2) = 0$ , so

$$P_c(r) = \frac{1}{2} \Delta\rho \omega^2 (r_2^2 - r^2) \dots\dots\dots(3-19)$$

and for a continuous phase, the capillary pressure at the inner face of the core is

$$P_{cL} = P_c(L) = \frac{1}{2} \Delta\rho \omega^2 (r_2^2 - r_1^2) \dots\dots\dots(3-20)$$

A complete capillary pressure curve by this method may be obtained in a few hours, and several samples are run simultaneously.

### 3-1-7 Refine, Normalization, and De-Normalization

The data from laboratory measurement are always in error and need a correction. This correction is called refinement. Also if there is more than one sample available for the same zone, the averaging of these samples is called normalization and de-normalization. To achieves the refined plot the following steps should be used:

**Step one:**

Check the data by plotting the lab data on linear and semi-log scales. X-axis comprehensive the water saturation  $S_w$ , while the Y-axis comprehensive the oil relative permeability  $K_{ro}$  and water relative permeability  $K_{rw}$ .

**Step two :**

Always the residual oil saturation ( $S_{or}$ ) from the laboratory data is incorrect so a true  $S_{or}$  have to be achieved by using the following procedure:

- 1-Assume 4 values of  $S_{or}$  that falls around the lab  $S_{or}$  value.
- 2-Calculate  $S_{on}$  and plot it against  $k_{ro}$  in a logarithmic plot.
- 3-The true  $S_{or}$  gives a straight line.
- 4- The high  $S_{or}$  concaves upwards.
- 5-The low  $S_{or}$  concaves downwards.

Normalized oil saturation is calculated using the following equation:

$$S_{on} = (1.0 - S_w - S_{or}) / (1.0 - S_{wi} - S_{or}) \dots \dots \dots (3-21)$$

**Step three:**

Achieve the real water end point Real permeability (using the true  $S_{or}$ )

- 1-The lab end point is always lower than the actual end point.
- 2- Calculate  $S_{wn}$  and plot it versus  $k_{rw}$  a log-log plot.
- 3- Extrapolate the most correct part of the data (step 1) to  $S_w=1$  and get  $k_{rw}$  end point.

Normalized water saturation ( $S_{wn}$ ) calculated using the following equation:

$$S_{wn} = (S_w - S_{wi}) / (1.0 - S_{wi} - S_{or}) \dots \dots \dots (3-22)$$

**Step four :**

Calculation of Cory exponent for oil ( $N_o$ ) and water ( $N_w$ )

- $N_o = \text{Log} ( k_{ro} ) / \text{Log} (S_{wn}) \dots \dots \dots (3-23)$
- $N_w = ( \text{Log} ( k_{rw}^* ) - \text{Log} ( k_{rw} ) ) / ( \text{Log} (1) - \text{Log} (S_{wn}) ) \dots \dots \dots (3-24)$
- Plot  $N_o$ ,  $N_w$  versus  $S_w$ .
- A single value could taken visually or by averaging
- Average value of  $N_o$ ,  $N_w$  should be taken from the most correct bart of data (step 1)

**Step five :**

Calculation of the Refined (corrected )  $K_r$  and compared io lab data by using the following equation:

$$R - K_{ro} = S_{on}^{No} \dots\dots\dots(3-25)$$

$$R - K_{rw} = K_{rw} * S_{wn}^{Nw} \dots\dots\dots(3-26)$$

Where :

R-Kro  $\equiv$  refined oil relative permeability

R-Krw  $\equiv$  refined water relative permeability

Son  $\equiv$  normalized oil saturation

**Average Relative Permeability For More Than One Sample**

**Step One :**

Calculation of the Normalized Real Permeability curve Sw\*, Kro\* and Krw\* by using the following equation:

$$Sw^* = (Sw - Swc) / (1.0 - Swc - Sor) \dots\dots\dots(3-27)$$

$$Kro^* = Kro / Kro^*(@Swc) \dots\dots\dots(3-28)$$

$$Krw^* = Krw / Krw^*(@Soc) \dots\dots\dots(3-29)$$

Where :

Sw\*  $\equiv$  normalized water saturation

Kro\*  $\equiv$  normalized oil relative permeability

Krw\*  $\equiv$  normalized water relative permeability

**Step two:**

Averaging the Normalized curve :

There are three steps to average the normalized curves :

1-plot the normalized curves

2- select arbitrary values of Sw\*

3- calculate the averaging Kro\* and Krw\* for the arbitrary values of Sw\* using the following equations:

$$Kro^*_a = \frac{\sum(h*k*k_{ro}^*)}{\sum(h*k)} \dots\dots\dots(3-30)$$

$$Krw^*_a = \frac{\sum(h*k*k_{rw}^*)}{\sum(h*k)} \dots\dots\dots(3-31)$$