CONSIDERATIONS IN CREATING AND USING A RELATIVE PERMEABILITY DATABASE

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ABSTRACT

Having reliable and readily accessible relative permeability information is a problem for many reservoir engineers, particularly for waterflooding and other reservoir simulation calculations; currently, no central repository exists and data within a company is often not centrally organized. **A** large effort was required to collect data from public and private sources and modify it to fit a common format. The central database thus constructed maintains relative permeability data in a format that is easily retrieved and processed. Categorizing and modifying the original data for applicability to similar systems is considered, allowing for variations in connate water, residual oil, and critical gas saturations. The database must be easy to use and employ both tabular and graphical results. The software is menu-driven and selects data from central relative permeability files. Information such as fluid type, wettability, lithology, geographical location, and method of measurement is used to search applicable results. The program operates under W9X or NT 4.0 systems. The database may be downloaded at no charge from a University of Missouri-Rolla web page.

INTRODUCTION

If a formation contains two or more immiscible fluids, each fluid tends to interfere with the tlow of the others. This reduction in the ability of a fluid to flow through a permeable formation is known as the relative permeability effect. It is a dimensionless quantity and is used with absolute permeability to determine a fluid's effective permeability

$$k_e = k_r k_a \qquad (1)$$

The effective permeability is a measure of the ability of a single fluid to flow through a rock when the pore spaces of the **rock** are not completely filled or saturated with the fluid. Relative permeability data are necessary since all hydrocarbon reservoirs contain more than one phase of homogeneous fluid. Relative permeability is a function of fluid distribution, pore geometry, saturation history and wettability[1,2].

Laboratory methods for measuring relative permeability first appeared in 1944[3]. Since then various methods of measuring relative permeability have been developed. In general, these methods can be categorized into two major groups which consist of steady-state and unsteady-state methods. For mixed (intermediate) wettability rocks, steady-state methods are prefered to unsteady-state methods by some reserchers[4]. Unsteady-state methods however, almost always give faster results compared to the steady-state methods due to the nature of processes involved in each method.

In the steady-state method, two fluids are injected simultaneously at a constant rate through a core until the produced fluid ratio achieves an equilibrium condition with the injected fluid ratio. At this saturation, the effective permeability to each phase is obtained by using Darcy's law. The ratio of the effective permeability to base permeability will yield the relative permeability at that saturation value. Relative permeability values for different saturations are obtained by changing the ratio of injection rate'.

In the unsteady-state method however, in-situ fluid is displaced by a driving fluid at a constant rate. The saturation within the core changes with time. The changes in pressure and fluid produced are measured with respect to time. Relative permeability values of the in-situ and the driving fluid are then calculated using an equation originally developed by Buckley and Leverett[6].

Laboratory measurement of relative permeability using either steady-state or unsteady-state methods can be expensive and time consuming.

OBJECTIVES

Realizing that an ample amount of published relative permeability data could be extracted from the Society of Petroleum Engineers' literature (published from 1950 through 1998) plus unpublished data from various oil and gas companies and individuals, a database of relative permeability measurements was created.

The criteria employed in selecting data (relative permeability curves and other pertinent information) to be included in the database were:

1. The relative permeability data was measured from either steady-state or unsteady-state experiments. In other words, relative permeability data obtained from correlations or data obtained from hypothetical simulation studies are excluded in this study;
2. The core used in the experiment must be a naturally formed rock. Data obtained from synthetic or man-made cores such as Alundum cores is not considered; rock types were categorized as sandstone, limestone, dolomite, or shale;
3. Only imbibition data are used for oil-water and gas-water systems whereas for gas-oil and gas-condensate systems, only drainage data are used in the analysis; and
4. Only the primary data is selected when multiple imbibition or drainage processes are presented.

WETTABILITY CLASSIFICATION

While some data sets included a wettability classification, most required a method to assign a wettability. Initially Craig's Rule' was selected; however, many oil-water curves did not strictly follow Craig's rule. This is not unexpected because Craig's rule was not based on detailed experimental studies but simply a heuristic rule dating prior to 1971; therefore it will not be true for all cases. Some adjustments to the rule were made by introducing tolerances into it without changing its basic principle in order to categorize data which slightly violated the original rule. Table 1 summarizes the modified Craig's rule that was used in determining the wettability in this study. While many data sets had no additional wettability indicators, data having an Amott's Index or Modified U.S.B.M. Wettability Test was in agreement with the modified Craig's rule.

DATA NORMALIZATION

The relative permeability data used in this study did not originally have the same format, i.e., some of the data sets were presented in the classical form while the rest were in normalized form as shown in Figure 1. Additional problems arose with gas-water systems, where the normalization process was not consistent. Some of the data sets defined the absolute permeability as the effective permeability of gas at S_{wc} ($k_{rgw} = 1.0$ at S_{wc} where k_{rgw} is the relative permeability of gas with respect to water), while others defined the absolute permeability as the 100 percent water saturation permeability ($k_{rw} = 1.0$ at $S_g = 0$).

It was necessary to convert these data sets into the same format (either the classical or the normalized) in the database. Since less than half of the data collected were in the classical form, the normalized form was chosen to be the standard form throughout this study. Moreover, it was easier to convert the classical data into the normalized form than converting the normalized data into the classical form. This is due to the difficulties in locating the classical relative permeability end-point absolute permeability values (which most authors did not supply) in the articles reviewed. The classical data form was usually found in much older data, which is another justification to convert all of the data into the more current normalized form. In the case of the gas-water systems, the first definition of absolute permeability ($k_{rgw} = 1.0$ at S_{wc}) was chosen to be the standard form since most of the data obtained from the literature were presented in this manner. For the gas-condensate systems, the same normalization procedure as in the gas-oil systems is employed where the effective permeability of liquid (condensate) at $S_g = 0$ is defined as the absolute permeability.

Since the collected data sets did not have the same range of saturation values (as far as the abscissa is concerned) due to the fact that some of the sets contained more values than others owing to differences in the critical wetting and non-wetting phase saturations, a technique was needed to plot both data sets in a category on the same horizontal scale. This can be accomplished by normalizing either the wetting phase saturation or the non-wetting phase saturation which results in the horizontal axis always ranging from zero to one.

For oil-water systems, the normalized water saturation is defined as[8]:

$$S_w* = \frac{S_w - S_{wc}}{1 - S_{wc} - S_{orw}} \qquad (2)$$

Except for the oil-water system, the rest of the systems have relative permeability *to* liquid with respect to gas **(k,)** data which are almost always longer than the relative permeability to gas (k_{rg}) data due to the presence of the critical gas saturations (S_{gc}). Therefore, separate saturation normalization equations must be used for each dataset as follows:

$$S_g* = \frac{S_g - S_{gc}}{1 - (S_{gc} + S_{lc})} \qquad (3)$$

$$S_l* = 1 - \left(\frac{S_g}{1 - S_{lc}} \right) \qquad (4)$$

For gas-oil systems, $S_{lc} = S_{wc} + S_{org}$, and for gas-water systems, $S_{lc} = S_{wc}$.

A total of 416 data sets were included in this study. A breakdown of the data sets by varying selection criteria is shown in Table ***2***. Note that in some cases the totals do not agree; this was due to a lack of complete information available for those cases.

Table 2 also indicates the selection criteria available. For water-oil systems, wettability selection allows water-wet (which includes strongly water-wet data), mixed (intermediate) wet, or oil-wet systems. Data is also available for gas-oil, gas-water, and gas-condensate systems. When either a water-oil or gas-oil system is selected, the complementary two-phase system may also be selected (*i.e.*, the gas-oil data corresponding to the water-oil data for this reservoir).

Formation categorization includes sandstones, limestones, dolomites, and shales. Measurement methods were simply characterized as steady-state or unsteady-state rather than the actual procedure employed, again due to lack of information.

Geographical locations included North and South America, Africa, Asia, Europe, and Australia.

EMPLOYING THE DATABASE

The basic menu for the relative permeability database is shown in Figure 2. After selecting a system, wettability (if applicable), formation, location and measurement method, the number of data sets available will appear. Data may be viewed based on selection criteria as shown in Figure 3. Use of saturation normalization as shown in Equations 2, 3 and 4 allows adjustment to desirable end-point values (Figure 4). If a companion gas-oil (or oil-water) data set is available, it may also be selected.

The database may also be searched using selected saturation endpoint values within a given range (Figure 5). When using this option, data are automatically adjusted using saturation normalization.

The database developed was also used to formulate two-phase relative permeability prediction equations' and may be downloaded in compressed (.zip) format from *http://www.umr.edu/~koe*; *to* install the relative permeability suite of programs on a PC system, unzip the file, select *Start,* then ***Run,*** and choose *Setup.exe* in the unzipped file. The program is written in Visual Basic 6.0 and is compatible with Win 9X and NT 4.0 systems.

CONCLUSIONS

A database using all publicly available and many industrial source relative permeability data sets has been constructed. Wettability criteria have been modified as a result of reviewing the data supplied. The database contains 416 sets of data which may be accessed based on fluid system, wettability, formation type, geographical location, and measurement method. Various search methods allow data adjustment.

NOMENCLATURE

Capital Letters

S_g = gas saturation, fraction
S_{gc} = critical gas saturation
S_l = liquid saturation, fraction
S_{lc} = total of critical liquid saturations present in the system, fraction
S_{org} = residual oil saturation in oil-gas system, fraction
S_{orw} = residual oil saturation in oil-water system, fraction
S_w = water saturation, fraction
S_{wc} = critical (connate) water saturation, fraction

Lowercase Letters

k_a = absolute permeability, md
k_e = effective permeability, md
k_r = relative permeability, fraction
k_{rcg} = relative permeability of condensate with respect to gas, fraction
k_{rg} = relative permeability of gas, fraction
k_{rgw} = relative permeability of gas with respect to water, fraction
k_{rlg} = relative permeability of liquid with respect to gas, fraction
k_{rog} = relative permeability of oil with respect to gas, fraction
k_{row} = relative permeability of oil with respect to water, fraction
k_{rw} = relative permeability of water, fraction

Superscript

$*$ = normalized value

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Table **1**
Modified Craig's rule

Rock Wettability	S_{wi}	S_w at which k_{ro}* and k_{rw}* are equal (%)	k_{rw}* at S_w = 100-S_{orw} (fraction)
Strongly Water-Wet:	$\geq$ 15%	$\geq$ 45%	$\leq$ 0.07
Water-Wet:	$\geq$ 10%	$\geq$ 45%	$0.07 < k_{rw}* \leq 0.3$
Oil-Wet:	$\leq$ 15%	$\leq$ 55%	$\geq$ 0.5
Intermediate: (Mixed-Wet)	$\geq$ 10%	45% $\leq S_w \leq$ 55%	$>$ 0.3
		OR	
	$\leq$ 15%	45% $\leq S_w \leq$ 55%	$<$ 0.5

Table 2
Summary **of** Data Sets Included in this Study

System	Wettability	Number of Data Sets
Water-Oil	Water-Wet	151
	Mixed Wettability (Intermediate)	72
	Oil-Wet	51
Gas-Oil		106
Gas-Water		19
Gas-Condensate		17
Formation Type		
Sandstone		305
Limestone		62
Dolomite		38
Shale		1
Geographical Location		
North America		300
South America		1
Africa		32
Asia		28
Europe		44
Australia		1
Method of Measurement		
Steady-State		208
Unsteady-State		155

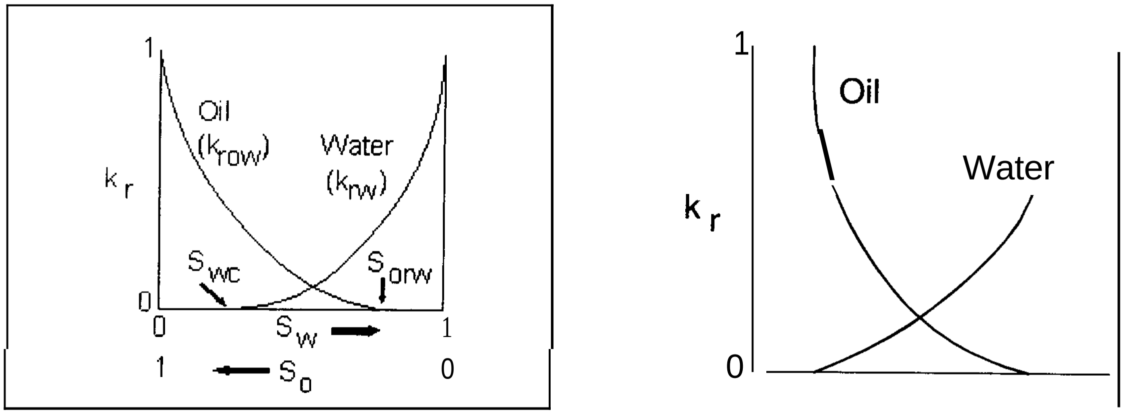
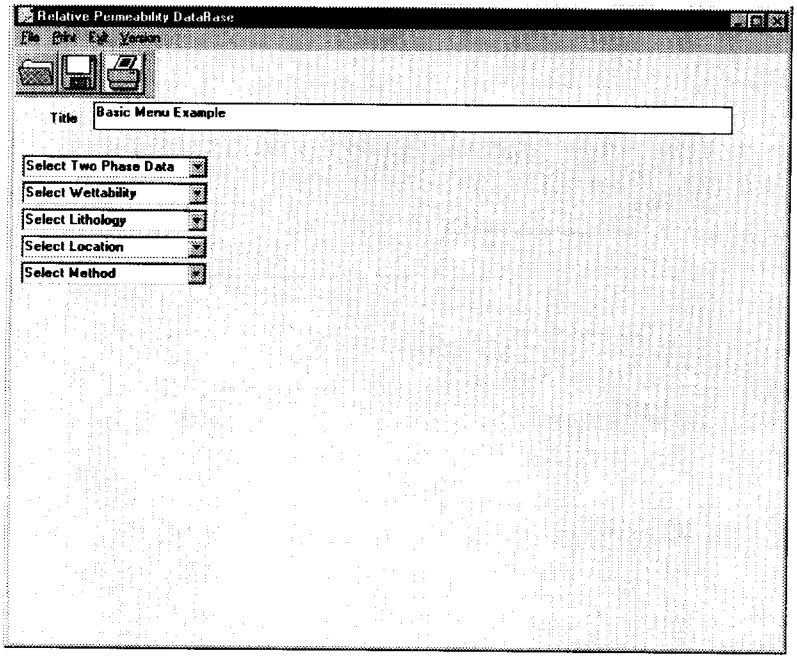
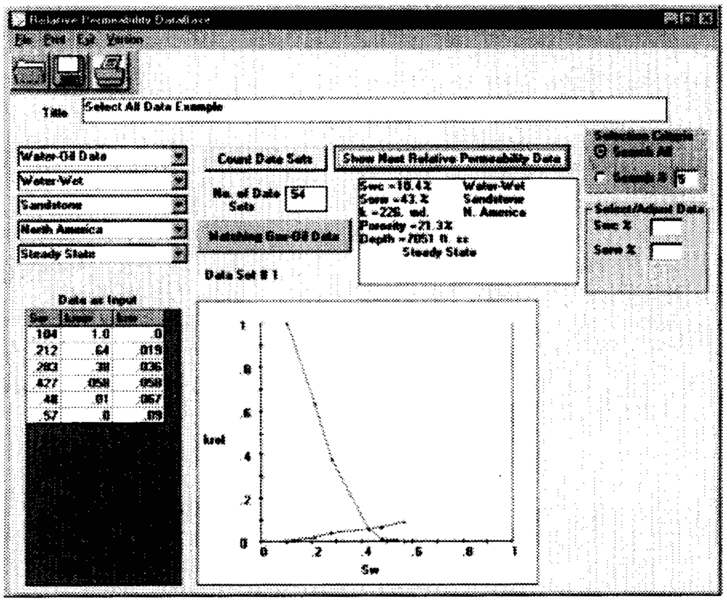


Figure 1 - Classical and Normalized Relative Permeability Data



Title: Basic Menu Example

Figure 2 - Basic Menu



Title: Select All Data Example

Water-Oil Data
Water-Wet
Sandstone
North America
Steady State

No. of Data Sets: 54

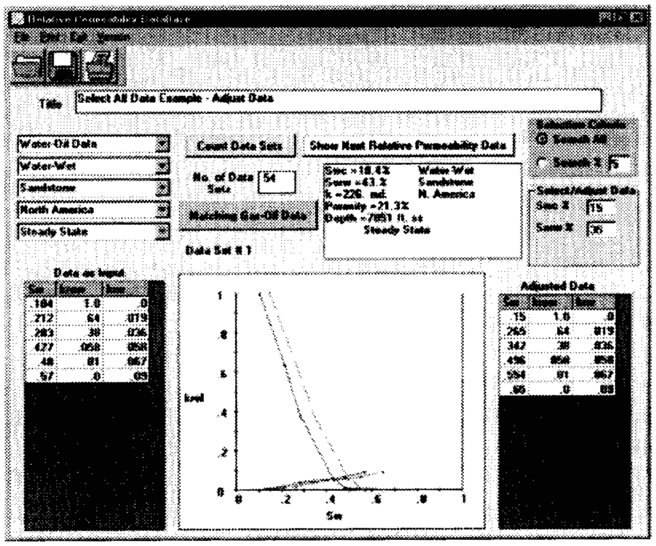
Swc =10.4% Water-Wet
Sorw =43.% Sandstone
k =226. md. N. America
Porosity =21.3%
Depth =7051 ft. ss
Steady State

Data Set # 1

Data as Input

.104	1.0	.0
.212	.64	.019
.283	.38	.036
.427	.058	.058
.48	.01	.067
.57	.0	.09

Figure 3 - All Data Sets Viewed



Title: Select All Data Example - Adjust Data

Water-Oil Data
Water-Wet
Sandstone
North America
Steady State

No. of Data Sets: 54

Swc =10.4% Water-Wet
Sorw =43.% Sandstone
k =226. md. N. America
Porosity =21.3%
Depth =7051 ft. ss
Steady State

Select/Adjust Data
Swc %: 15
Sorw %: 36

Data Set # 1

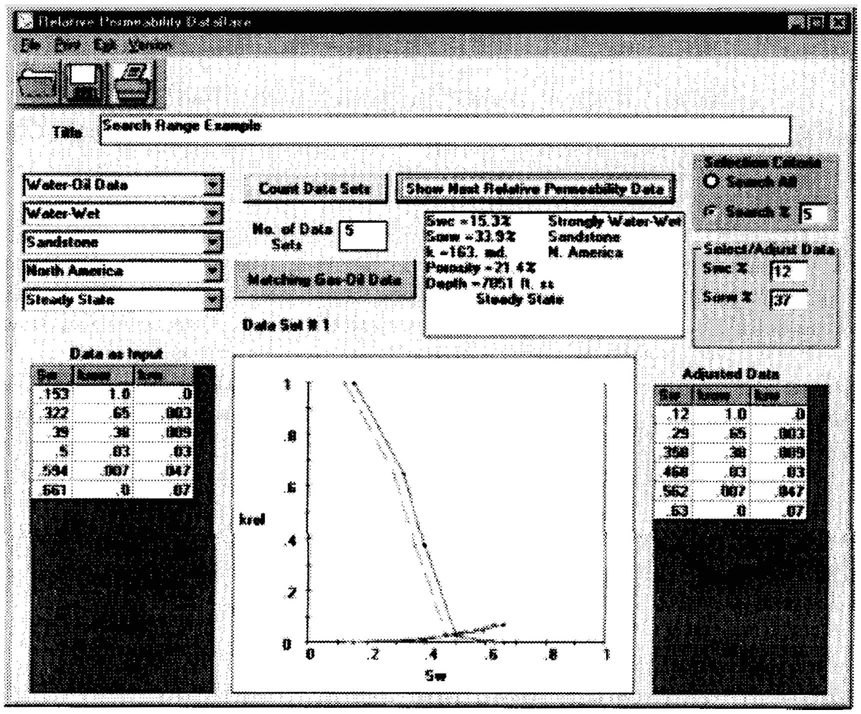
Data as Input

.104	1.0	.0
.212	.64	.019
.283	.38	.036
.427	.058	.058
.48	.01	.067
.57	.0	.09

Adjusted Data

.15	1.0	.0
.265	.64	.019
.342	.38	.036
.496	.058	.058
.554	.01	.067
.65	.0	.09

Figure 4 - Select All



Title: Search Range Example

Water-Oil Data
Water-Wet
Sandstone
North America
Steady State

No. of Data Sets: 5

Swc =15.3% Strongly Water-Wet
Sorw =33.9% Sandstone
k =163. md. N. America
Porosity =21.4%
Depth =7051 ft. ss
Steady State

Search %: 5

Swc %: 12
Sorw %: 37

Data Set # 1

Data as Input

Sw	krow	krw
.153	1.0	.0
.322	.65	.003
.39	.38	.009
.5	.03	.03
.594	.007	.047
.661	.0	.07

Adjusted Data

Sw	krow	krw
.12	1.0	.0
.29	.65	.003
.358	.38	.009
.468	.03	.03
.562	.007	.047
.63	.0	.07

Figure 5 - Tolerance Search