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RELATIVE PERMEABILITY DETERMINATION OF RESERVOIR ROCKS USING IMAGE ANALYSIS METHODS

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Abstract. *Determining the petrophysical properties of the reservoir is of fundamental importance in Petroleum Engineering, because through this knowledge you can apply appropriate techniques to optimize the exploitation of oil deposits. Among the properties of the porous media, there are singularities such as capillary pressure and relative permeability. The curves of relative permeability help in the description of multiphase flow in the reservoir. The experimental methods used to determine these properties demand time are costly, and require samples of good quality (core). The numerical methods, which include image analysis, appear as rapid, efficient and low cost methods in the determination of petrophysical properties. This article present a project for a master's thesis the objective being to develop a computational method for determining the relative permeability of the oil reservoir rocks, using image analysis methods. Among the models to be modified and optimized is the model to determine the equilibrium configuration and the serial connection graph model.*

Keywords: *image analysis, relative permeability, oil reservoir rock, computational analysis, algorithms.*

1. INTRODUCTION

The procurement of quantitative information from the reservoir through images processing can be performed using various techniques, among which are: images acquisition through optical or electronic microscopes; segmentation, using methods described in Parker (1997); characterization, using Mathematical Morphology and their morphological operations (Marques Filho and Vieira Neto, 1999), (Gomes and Velho, 1994), (Gonzales and Woods, 1993); labeling algorithms (Hoshen and Kopelman, 1976), (Bueno, Magnani and Philippi, 2002); three-dimensional reconstruction (among the methods used for the three-dimensional recontruction are: truncated gaussian from Zhirong et al. (1998), revised truncated gaussian from Bueno et al. (2002) and overlapping spheres from Santos et al. (2002)) and calculation of intrinsic permeability using the serial connection graph (Bueno and Philippi, 2002a). The numerical determination of the relative permeability curves are inferred from data collected and applied on a method, being the JBN method (Johnson, Bossler, and Naumann, 1959) one of the most used.

This paper aims to present the problems of methods and algorithms used by Magnani et al. (2000), and present a methodology to be followed in developing the thesis, looking to solve the presented problems. The methods and algorithms cited are implemented in lib_ldsc (a library for image analysis of porous media), which will undergo the proposed fixes.

2. BIBLIOGRAPHIC REVIEW

It is here that a review of methodologies that are more directly related to this work are presented. Addressed are concepts and definitions of image processing and analysis and some methods of three-dimensional reconstruction. Greater focus is given to the operations of mathematical morphology and models of the equilibrium configuration from Magnani et al. (2000) and serial connection graph to determine the intrinsic permeability from Bueno and Philippi (2002a).

2.1 Segmentation

Segmentation aims to find the significant units in an image, i.e., the objects of interest within it. When it comes to the segmentation of porous materials, the goal is to identify and separate the solid phase from the porous. To do so, an image is transformed from grayscale or color into a binary image. All care must be taken so that the morphological (shape) and topological (connections) information of the porous media are not changed, because the segmented image is the basis for the next steps of characterization and three-dimensional reconstruction. A more detailed description of the concepts of segmentation can be found in (Gomes and Velho, 1994) and (Gonzales and Woods, 1993).

Different algorithms of segmetation are found in Parker (1997) and are implemented in lib_ldsc. For the proposed work a computational module was developed which includes access to these methods.

2.2 Three-dimensional Reconstruction

Three-dimensional reconstruction aims to create, from a 2D image, a porous structure in 3D that represents the original means without failing to comply with its properties, i.e., preserving the characteristics measured in the two-dimensional image.

In recent years, various methods of three-dimensional reconstruction were developed using single-scale models or multi-scale. The JQA method is a single-scale method that emerged from a method for two-dimensional medium which was subsequently extended to three-dimensional means. The method makes use of two filters, one linear and one non-linear. An evolution of the JQA method called the Mixed Reconstruction Method from Ioannidis, Kwiecien and Chatzis (1995), partially substituted the linear filter implementation obtaining a series of images by two-dimensional Fourier transform. This uses only the linear filter to correlate the 2D images in the z direction, in this way obtaining the three-dimensional image.

Zhirong (1997) developed the method of the truncated Gaussian, completely replacing the application of the linear filter by the use of the Discrete Fourier Transform. The method makes use of porosity data and of the autocorrelation function seeking to better represent the porous media. Bueno (2001) made an evaluation of the method of Truncated Gaussian and noted that relatively small representations can not retrieve the connected porosity of the sample. Therefore, the Revised Truncated Gaussian method was then developed eliminating the approximation inherited from the JQA method.

Another method shown to be efficient in three-dimensional reconstruction is the Method of Overlapping Spheres from Santos et al. (2002). The method use as data input the size of solids distribution function and offers as advantages the possibility of generating images of rebuilt structure in large dimensions ($600^{(}3)$)) and low sampling factor (n=1). This presents good reproduction of the autocorrelation curves and of pore size distribution.

The selection of the best three-dimensional representation is made according to criteria defined in (Bueno, 2001). Basically, the selection should begin with the analysis of the plans of the three-dimensional representations, then an analysis is made of the representative qualities of the image through 3D visualization; the next step is to identify the best amplification factor by comparing the autocorrelation curves and pore size distribution; and finally defining the size of the representation considering the relationship of optical and connected porosities. Examples can be seen in (Bueno et al. 2002).

2.3 Mathematical Morphology

The mathematical morphology seeks to extract by way of an analysis element called structuring element (*EE*), information concerning the geometry and topology of the objects that compose an image. The morphological operations, when applied to segmented images of reservoir rocks make it possible to obtain a simplification of the porous media through skeletonization, the determination of the size distribution of pores and grains, determination of boundaries and the elimination of noise. The principal operations of mathematical morphology are dilation and erosion, having as derived operations the opening and the closing.

In the case of binary images (*I*), the simplest form of dilation is to enable all of the neighboring pixels in relation to those turned-on in an original image. In a more complex form you can use a structuring element which acts as an operator on the image. Thus, the dilation of the original binary image *I* by a *EE*, denoted $I \oplus EE$ is defined as:

$$I \oplus EE = \{x \,|\, [(EE^r)_x \cap I] \neq \oslash\} \tag{1}$$

where $\oplus$ is the dilation operator, the operation consists of obtaining the reflection of the structuring element at its origin and then shifting this reflection of x $(EE^r)_x$. Thus the dilation of *I* by a *EE* is equal to the set of all pixels x for which the intersection between *I* and $(EE^r)_x$ includes at least one pixel turned on.

As opposed to dilation, erosion consists of turning off all neighboring pixels in relation to those turned-off in the original image. Therefore the objects of the image will suffer a thinning out and isolated points will no longer exist. The erosion operation applied to *I* by a *EE*, is denoted $I \ominus EE$ and defined as:

$$I \ominus EE = \{x \,|\, (EE)_x \subseteq I\} \tag{2}$$

where $\ominus$ is the erosion operator and $(EE)_x$ represents the structuring element translated to the point x. The expression should be understood as follows: the erosion of the image *I* by a *EE* is the set of all pixels x such that *EE* translated to x, is contained in *I*.

The opening operation is made through the application of the erosion operation followed by dilation operation. Its use has the effect of smoothing the contour of the image, the loss of objects linked by close ties and the elimination of small elevations. With the application of the opening operation, structures smaller than the *EE* will disappear from the image.

The denotation of the opening operation is given by: $I \circ EE$, representing the opening of a set (image) *I* by a structuring element *EE*. Its definition is presented below:

$$I \circ EE = (I \ominus EE) \oplus EE \tag{3}$$

and interpreted as: the opening of *I* by a *EE* is equal to the erosion of *I* by *EE* followed by the dilation of the result by the same *EE*. To obtain the closing first apply dilation and then erosion. The closing of the set *I* by the structuring element *EE* is denoted as: $I \bullet EE$ and defined as:

$$I \bullet EE = (I \oplus EE) \ominus EE \tag{4}$$

where the closing of *I* by *EE* is equal to the dilation of *I* by *EE*, following the erosion of the result by *EE*.
These operations are implemented in the lib_ldsc and in use in the proposed work.

2.4 Equilibrium Configuration

The technique of image analysis to determine the Equilibrium Configuration presented here was developed by Magnani et al. (2000) and makes use of the opening operation applied in three-dimensional reconstructions of the porous media.

Some concepts related to multiphase flow and the interaction between fluid and solid matrix, such as: porosity, saturation, compressibility, interfacial tension and capillary pressure, are described in Bueno, Magnani and Philippi (2002). The concepts presented below are published in (Magnani et al. 2000) and are presented here so the reader can understand the methodology (section 3) and the identified problems (section 4).

Types of Approaches to Porous Media

There are two basic types of approaches to the problem of prediction of physico-chemical phenomena that occur within the porous structures. These are classified according to the scale length (ε) of porous media observed in: microscopic approaches and macroscopic approaches.

Magnani (1996) states that the macroscopic approach ε must be large enough to statistically represent the solid matrix and pore space, so that macroscopic properties such as permeability, viscosity and hydraulic conductivity can be defined, and small enough for these not to present high gradients and come to distort the solution.

In turn, the microscopic approach varies in regards to the measurement scale being used and is presented here in the pore, where ε must be large enough so that properties such as viscosity and surface tension can be defined in its interior and small to the point that it is able to represent, with definition, the simple substances in the system such as its interfaces.

The method of determining the equilibrium configuration developed by Magnani (1996) is based on the microscopic approach at the pore level, and deterministic in relation to the geometric utilization.

Simplifying Assumptions

The following describes some simplifying hypotheses considered by Magnani et al. (2000) in determining the Equilibrium Configuration: the gravitational effects are disregarded both at the pore and at the system levels, the effects of chemical interaction and the action of magnetic fields of force are not considered, the porous structure is non-deformable and the pores identified by the microscope are considered as part of the solid matrix. The conditions of equilibrium are reached instantaneously, the fluids used are considered ideally compressible or ideally incompressible; The processes of phase change are not taken into consideration, allowing that the time required for the fluid to come in equilibrium is small in relation to what is neceessary for phase change to occur in significant volume, the fluids are immiscible or the time required for mixing to occur is greater than the time required for the system to enter into mechanical equilibrium, the flows are primary and isothermal spatially and temporally, occurring in a quasi-static manner such that each small variation of a thermodynamic property, the time required for the system to come into equilibrium is expected, the pressure of a fluid at a given moment is equal at all the points, and in the invasion processes the penetrating fluid is always connected to the chambers.

Determination of Equilibrium Configuration

To determine the Equilibrium Configuration of two-phase flow in porous media reconstructed through image analysis, it is necessary to determine the regions of the porous media occupied by each phase at a given moment, as well as being necessary to locate the interface between two fluids at each pressure step.

Based on the work of Magnani (1996), Magnani et al. (2000) developed an algorithm to determine the interfaces of wetting and non-wetting fluids in fixed three-dimensional representations of the porous media. The algorithm simulates the process of mercury intrusion in a virtual porosimetry, transforming the physical problem into a geometric problem. For this, it creates a three-dimensional representation of the chamber of a porosimetry, including its representation of the porous media. Thereby self-generating membranes at the interface of the wetting chambers with the porous media. Through the opening operation the regions that satisfy certain geometric conditions related to physical problem in question are determined, thereby determining the Equilibrium Configuration of the water and oil phases in the three-dimensional reconstructed mean. The work developed by Magnani et al. (2000) was reviewed and redrafted by Bueno, Magnani and Philippi (2002) and validated by Bueno and Philippi (2002b). In the new algorithm the use of dynamic chambers was adopted and eliminated the need of the membrane, which allowed the determination of Equilibrium Configuration in systems with multiple chambers and delivering results in more complex representations.

Figure 1 illustrates the geometric regions of the problem addressed: *U* being the composite universe of a sample of porous media *M* ($M \subset U$). The porous media is formed by the union of the solid matrix *S* with the pore space *P*, i.e., $M = S \cup P$. The regions identified by *W* represents the chamber walls from which the sample is placed. *L* are the chamber's free regions, comprising all empty space, i.e., comprising non-solid regions except the pore space, thereby excluding the walls of the system, i.e., $L = A \cup W$. Between M and L may be a semi-permeable membrane, m, which is located adjacent to one of the horizontal edges of the porous media region. The fluidic region F includes the empty spaces of the porous media in addition to the chamber's empty spaces ($F = U - W \cup S$).

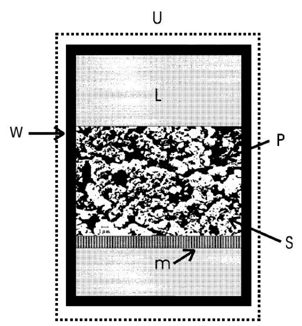

Figure 1. Illustration of the geometric problem. Modified from (Magnani et al. 2000).

Once defined geometric regions can define an invasion process where a fluid B expelled from the P region a fluid A which initially fills this region. Concerning immiscible fluids, one is containded in the region's lower part L and the other at the top. The process is divided into steps where each step i ($i = 0, 1, ..., i_e$), B^i and A^i are distinctive geometric regions occupied by fluids B and A respectively. At the beginning of the process, when $i = 0$, the fluid A occupies all the porous space, the invading fluid B has null intersection with P ($B^0 \cap P = \oslash$). In the following steps for each step (i), B^i form a single and fully connected region, while A^i is the union of all regions *k* occupied by Fluid *A*. This process can be represented as:

$$A^i = A_0^i + \bigcup_{k=1}^{n(i)} A_k^i \tag{5}$$

where A_0^i includes the geometric region occupied by fluid A in which step i of the invasion process is still linked to the free region L and A_k^i is on of the $n(i)$ fluid regions that is disconnected from L due to the isolation caused by the fluid B invasion.

The difference between the geometric space occupied by A and the region A_0^i calculated at each step i of the process, corresponding to the isolated region is now denoted Y, i.e.:

$$Y^i = A^i - A_0^i \tag{6}$$

being $1 \leq i \leq p$, where p represents the number of regions A^i that are isolated during the invasion.

Defining E_x^i as a ball centered on a point x such that $x \in F$ and that its radius r^i satisfies the Young-Laplace equation:

$$r^i = \left| \frac{(d-1)\,\sigma_{AB}}{p_{A_0^i} - p_{B^i}} \right| \tag{7}$$

where *d* is the Euclidean dimension of space, σ_{AB} the interfacial tension between fluids A and B, $p_{A_o^i}$ the pressure in the fluid *A* connected to the free region *L* and p_{B^i}) the fluid *B* pressure in step i.

It also defines a new ball when E_x^i intersects the contour of F:

$$E_x^{*i} = \begin{cases} E_x^i, & d_x \geq r^i \\ \oslash, & d_x < r^i \end{cases} \tag{8}$$

where d_x is the smallest distance between x and the contour of F.

The union of all balls of radius r^i which satisfy the equation 9 provides an opening region H:

$$H^i = \bigcup_x E_x^{*i} \tag{9}$$

such that $x \in F$. For simulation, a new opening region denoted G, is defined for each step *i*, such that the radius of curvature used in the construction of the contour L is finite:

$$G^i = L \cup H^i \tag{10}$$

note that the chambers always exist as part of G^i, preventing the wetting fluid from using the chambers as a means of invasion.

Define the complementary region of G denoted $\underline{G}$, at each step i in order to find the distribution of phases in the porous space:

$$\underline{G}^i = F - G^i \tag{11}$$

Figure 2 illustrates a invasion process in a single cavity environment, where the regions H, G and $\underline{G}$ are most easily distinguished after the application of an opening operation with a ball E^i. In (a) the region F and the ball E^i can be observed, in (b) the opening region H and in (c) the opening region G and its complement $\underline{G}$.

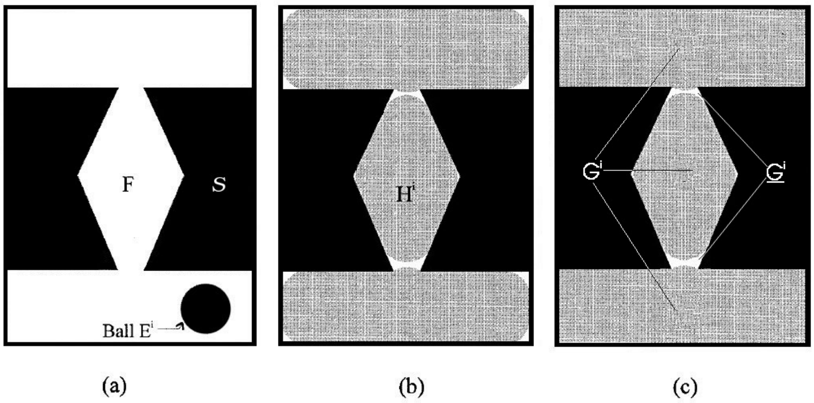

Figure 2. Application of the opening operation in a single cavity environment. Modified from (Magnani et al. 2000).

Given J and Q as any two regions of F, a union operator K is defined, such that $K(J, Q)$ is the union of the components J_j connected by non-null intersection with Q, i.e.:

$$K(J, Q) = \bigcup_{k=1}^{n(J)} \begin{cases} J_j, & J_j \cap Q \neq \emptyset \\ \emptyset, & J_j \cap Q = \emptyset \end{cases} \tag{12}$$

so that $K(K(J, Q), Q) = K(J, Q)$.

And finally, the solution of B^i is given by:

$$B^i = \Omega^i - u_A Y^i \tag{13}$$

where u_A is the compressibility factor of the fluid A ($u_A = 0$ if A is ideally compressible and $u_A = 1$ if A is ideally incompressible) and Ω^i is given by:

$$\Omega^i = K\left\{\left[(w_B)\,\underline{G}^i \cup K\left(G^i, B^0\right)\right], B^0\right\} \tag{14}$$

where w_B is the fluid B wetting factor ($w_B = 1$ if B is wetting and $w_B = 0$ if B is non-wetting).

The authors suggest an approximation from the isolated region Y^i for the isolated region of the previous step Y^{i-1}, ie $Y^i \approx Y^{i-1} = A^{i-1} - A_0^{i-1}$, explaining that this approximation is necessary due to the fact that the domain B^i depends on the isolated region Y^i, which is not known in step i when A is ideally incompressible $u_A = 1$.

The process presented corresponds to the solution proposed by Magnani et al. (2000), the revision of the model by Bueno, Magnani and Philippi (2002) is presented below. The main change was the removal of the membrane and the ability to handle more complex geometric arrangements. Additionally, the opening region is determined on a more restricted region (excluding the region of the wetting chambers), reducing the number of calculations to perform the opening operation. With this some equations have been reformulated:

The opening operation is now held in the region defined by the union of the porous phase (*P*) with the region of non-wetting chambers (C_j^{nw}), as shown in equation (15).

$$H^i = \bigcup E_x^{*\mathrm{i}} \quad x \in \left(P \bigcup \left(\bigcup_{\mathrm{j}=0}^{n(C^{nw})} C_j^{nw}\right)\right) \tag{15}$$

The region G^i is now defined as the union of the opening region with the region of the non-wetting chambers.

$$G^i = H^i \bigcup \left(\bigcup_{\text{j=0}}^{n(C^{nw})} C_j^{nw} \right) \quad (16)$$

The region $\underline{G}^i$ is now given by the difference of the region P with the region consisting of $(G^i \bigcap P)$, which corresponds to the complement of the opening operation considering only the region P.

$$\underline{G}^i = P - (G^i \bigcap P) \quad (17)$$

Thus the solution is:

$$\Omega^i_{w_B} = (w_B)K(\underline{G}^i, B^0) \cup (1 - w_B)K(G^i, B^0) \quad (18)$$

Some results obtained with the new algorithm are presented in (Philippi, Magnani and Bueno, 2000).

2.5 Serial Connection Graph - Calculation of Permeability

Model Serial Connection Graph (SCG) is a general formulation based on the concepts of percolation theory and the theory of graphs. Part of the principle in which the mass flow occurs between two-dimensional planes of the reconstructed porous media is that these planes are formed by connected objects as illustrated in Figure 3. A group of connected pixels form an object, the objects are labeled by the labeling algorithm of Hoshen and Kopelman (1976) and identified plane to plane. Below, the connection between objects in consecutive planes is assessed. Each object, aside from the label, should contain a list of objects which are connected and a property (in the case of the hydraulic radius or conductance). A connection is a physical or conceptual link between objects, or may not have an associated property. The form of the connections varies according to the type of the object graphed.

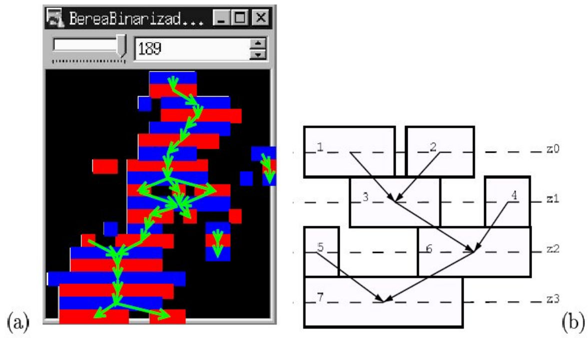

Figure 3. Berea 500 section (a) and diagram (b) illustrates the Serial Connection Graph (Bueno and Philippi, 2002a).

The steps to determine the permeability with the SCG should be: i) Determine the Serial Connection Graph. ii) Define the values of pressure at the interfaces z_0 and z_n (pressure imposed on the contour objects). iii) Define the initial values of pressure in other sites of the graph (initial condition). iv) Convert the values of hydraulic radius of each connection in conductance through the Poiseuille equation. v) Define the parameters of the *solver* and then solve the system of equations with a numerical *solver*. vi) Evaluate the mass flow at the interfaces z_0 and z_n. vii) Compare the mass flows and define the necessity to refine the solution obtained. viii) Determine the permeability.

The SCG is used to determine the permeability of the regions defined by the equilibrium configuration method. For details of the method see (Bueno and Philippi, 2002a).

3. METHODOLOGY

The following steps describe the methodology being used in developing this work.

- The work began through bibliographic review where among other concepts, knowledge was sought in image analysis, discrete metrics, mathematical morphology and labeling methods. The knowledge acquired serves as a reference in the study of the concepts that will be discussed during the work. At this time ~ 90% of the bibliographic review has been completed.
- Learning of the programming language C++, the Qt graphics library, the image analysis of porous media library lib_ldsc and Imago software (Philippi et al. 2002) (~ 80% complete).

- Development of the program framework in the programming language C++, using object-oriented means, with an interface generated by the Qt graphics library and making use of the library lib_ldsc (~ 70% complete).
- Identification of the main problems of the existing methods (~ 70% complete).
- Problems solution: physical (section 4.1), of memory (section 4.2) and algorithms efficiency (section 4.3). Optimization of the serial connection graph will also be studied (section 4.4).
- Relative permeability simulation comparing the processing time between old and new algorithms.
- Results analysis and conclusions.

4. PROBLEMS IDENTIFIED IN EXISTING METHODS AND ALGORITHMS

During the bibliographical review of the models and algorithms for determining the Equilibrium Configuration developed by Magnani et al. (2000) and modified by Bueno, Magnani and Philippi (2002), we identified some problems which are presented in the following topics. The solution to these problems by the development of new models and algorithms is the proposed work objective.

4.1 Physical Errors

Using the labeling method of Hoshen and Kopelman (1976), despite having great efficiency and speed, should be avoided in models that use the opening operation to determine the balance settings, as it presents physical inconsistency as illustrated in Figure 4.

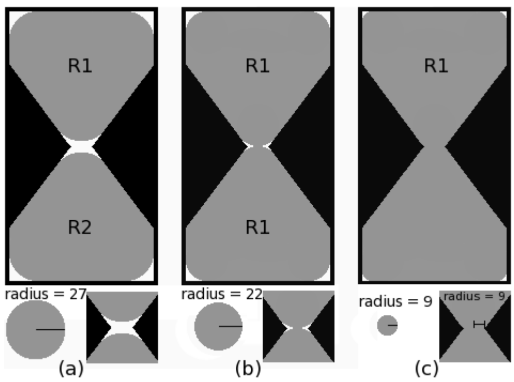

Figure 4. Representation of the physical problem caused by the labeling algorithm of Hoshen and Kopelman (1976).

The algorithm of Hoshen and Kopelman (1976), when applied to Figure 4 (a) presents as a result two objects R1 and R2, which is physically consistent because the regions 1 and 2 are not connected. Note that the ball's radius (EE) used is greater than the radius of the throat. In the case of the Figure 4 (b), the algorithm of Hoshen and Kopelman (1976) presents as a result a single object (R1), which for the Equilibrium Configuration determination is physically inconsistent. Note that although the two regions are connected by a pixel (or a small group of pixels), this connection does not allow the invasion of the upper region, because the ball's radius used is greater than the radius of the throat, being unsuccessful. The correct labeling is illustrated in Figure 4 (c) where the ball's radius is less than or equal to the throat's radius. This indicates the need to replace or limit the algorithm of Hoshen and Kopelman (1976), which is one of the stages of the proposal dissertation.

Figure 5 presents a comparative graph between a relative permeability curve (kr-sim) versus experimental (exp-kr). Note that the divergence in the permeability result to saturation equal to 70% is mainly due to the physical problem identified in this section.

4.2 Memory Consumption

As observed in (Bueno, Magnani and Philippi, 2002), good results are obtained when the three-dimensional representation is reconstructed with amplification factor equal or less to 3, i.e., n = 1, 2 or 3. In practice, this implies the need for three-dimensional representations with dimensions, in most cases, exceeding 300 pixels (300x300x300).

To store a three-dimensional binary image in computer memory, we need $nx * ny * nz * sizeof(type)$ bytes, respectively nx, ny and nz, are the x, y, and z dimensions of the image represented and $sizeof(type)$ bytes, the quantity required to store the values of the dimensions in accordance with the $type$ used (in C++, the types char, int and double consume

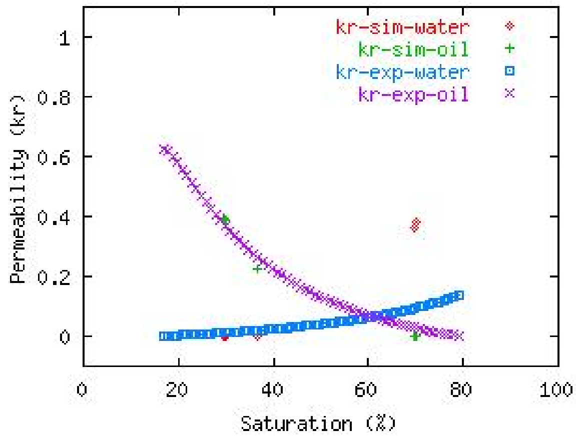

Figure 5. Results of relative permability curves obtained by Bueno, Magnani and Philippi (2002).

respectively 1, 4 and 8 bytes on machines with 64 bits operations). The critical algorithms in memory consumption terms are: 3D reconstruction with Truncated Gaussian using double precision and Equilibrium Configuration determination.

One of the activities of this work is to calculate in regards to the theoretical aspect, the memory consumption of each of the steps involved. The following will be a survey of the use of real memory consumption, analyzing the memory consumption of Imago software and lib_ldsc at every process step.

It is important to clarify that we will find differences between the theoretical and practical consumption, because neither Imago (version 1.06-H4.9) nor lib_ldsc have been optimized. As the compiler being utilized (GNU C++ 4.3.0) allows optimizations, we will analyze the use of real memory with different computational optimization levels.

The goal is not only to map the theoretical and real memory consumption, but confirm the need for consistent use of programming languages and methods, i.e., the use of software engineering.

4.3 Efficiency of Algorithms

Figure 6 presents a summary flowchart with steps for obtaining the relative permeability.

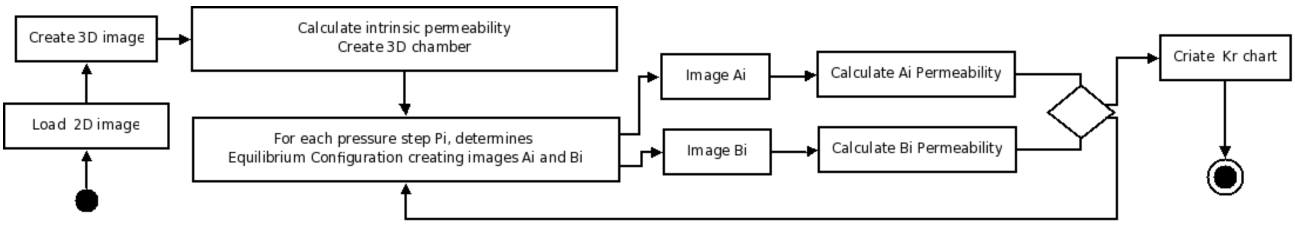

Figure 6. Flowchart of computational procedure for determining the relative permeability.

As you can see, the entire process is quite extensive and complex. The algorithm that implements the opening method is slow, because each "ball" (structuring element) of the opening region is painted on the image region of the opening region in a very slow process and that worsens exponentially as the ball's radius grows.

In the algorithms implemented in Imago and in lib_ldsc this problem has been reduced by providing the opening region from the Images Distance Fund (IDF), which are determined using discrete control metrics and masks, such as: d4, d8, d34 and d5711 (Moschetti, 1991), (Fernandes, 1994).

However, the algorithm for determining the equilibrium configuration from Magnani et al. (2000) did not take into account the fact that the invading fluid never retrocedes (simplified hypothesis of the method). As one of the stages of this work we will take into account this feature of the method. Diverging from the current algorithm, the intention is to modify the algorithm which applies to the opening operation taking into account that the invading fluid does not retrocede. A reduction in the processing time of the opening stage is expected as the radius of the EE increases (contrary to what happens today). In fact, there were two contrary effects: i) The increase of the EE's radius generates larger balls, increasing the processing time. ii) When considering the fact that the invading fluid does not retrocede, we can numerically alter the porous region, so that the volume where the opening operator is applied decreases, reducing the processing time.

It is still intended, after the changes, to make parallel the algorithm of equilibrium configuration determination using

MPI (Message Passing Interface) in order to reduce the processing time when run on computer clusters or making use of other cores commonly available in current processors.

4.4 Serial Connection Graph Optimization

Another problem that needs to be solved is to optimize the Serial Connection Graph algorithm. In this, the intention is to replace the existing Solver (which uses the iterative relaxation method) by Generalized Minimum Residual (GMRES). The following is intended to implement a parallel version of the GMRES solver using MPI.

5. CONCLUSIONS

This paper presents in a summarized form, a bibliographic review and the concepts needed for the correction of the methods and algorithms used to determine the relative permeability of oil reservoir rocks through three-dimensional reconstructed images. Also presented is the methodology to be used and the identified problems in the methods currently used. It is believed that the solution of physical problems, memory consumption and the optimization of algorithms will significantly improve the relative permeability results making use of these models viable in practice.

6. ACKNOWLEDGEMENTS

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8. Responsibility notice

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