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New Developments of Non-linear Singular Integral Equations in Petroleum Engineering by 4-D Multiphase Flows

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Abstract
A sophisticated method is further improved in the area of four-dimensional multiphase flows for the determination of the properties of reservoir materials, when petroleum reserves together with water are moving through porous media. This multiphase problem seems to be very important for petroleum reservoir engineering. Consequently, the above petroleum engineering problem is reduced to the solution of a ***non-linear singular integral equation***, which is numerically evaluated by using the Singular Integral Operators Method (S.I.O.M.). By the present study 4-D multiphase flows are proposed, which incorporates many 3-D multiphase flows over the same reservoir at specified intervals of time. So, by studying multiple time-lapsed 3-D surveys, or three-dimensional subsurface flows, portrays the changes in the reservoir over time. Also, several properties are analyzed and investigated for the porous medium equation of multiphase flows, defined as a Helmholtz differential equation. Hence, the estimation of the future petroleum production from a reservoir could be determined. Finally, an application is given for a well testing to be checked when a heterogeneous oil reservoir together with water in a multiphase flow is moving in a porous medium. Thus, by using the S.I.O.M., then the pressure response from the well test conducted in the above heterogeneous oil and water reservoir, is numerically calculated and investigated.

2010 Mathematics Subject Classification : 65L10, 65R20.
Key Word and Phrases
Singular Integral Operators Method (S.I.O.M.), Non-linear Singular Integral Equations, Petroleum Reserves, 4-D Multiphase Flows, Porous Media, Helmholtz Differential Equation.

1. Introduction

One of the most important problems on petroleum reservoir engineering is the study of the movement of oil reserves through porous media. Hence, very often the petroleum reservoir is mixed with water and by applying a well test analysis, then a history matching process takes place for the determination of the properties of the reservoir materials. In addition, the movement of oil reserves through porous media, produces both single-phase and multiphase flows. Hence, of primary interest is the investigation of the multiphase flows when the oil reservoir is mixed with water. Also, if a well test is conducted, then the well is subjected to a change of the flow rate and the pressure response can be further measured. Then the estimation of the future oil production from a reservoir can be determined. For the determination of several petroleum reservoir parameters, such as permeability, then numerical calculations should be used, as analytical solutions in most cases are not possible to be derived. Over the past years, several variants of the Boundary Element Method were used for the solution of petroleum engineering problems. As a start at the end of eight's Lafe and Cheng [1] proposed a BEM for the solution of steady flows in heterogeneous solids. At the same period Masukawa and Horne [2] and Numbere and Tiab [3] applied boundary elements for steady state problems of streamline tracking. Moreover, Kikani and Horne [4] solved transient problems by using a Laplace space boundary element model, for the analysis of well tests in several arbitrarily shaped reservoirs. On the contrary, Koh and Tiab [5] used boundary elements to describe the flow around tortuous horizontal wells, for homogeneous, or piecewise homogeneous reservoirs. Also, Sato and Horne [6], [7] applied perturbation boundary elements for the study of heterogeneous reservoirs. El Harrouni, Quazar, Wrobel and Cheng [8]

proposed the use of a transformed form of Darcy's law combined with dual reciprocity boundary element method to handle heterogeneity. Additionally, Onyejekwe [9] applied a Green element method to isothermal flows with second order reactions. He [10], [11] used further a combined method of boundary elements together with finite elements for the study of heterogeneous reservoirs. In addition, Taigbenu and Onyejekwe [12] applied a transient one-dimensional transport equation by using a mixed Green element method.

Over the last years, several non-linear singular integral equation methods were used successfully by Ladopoulos [13] - [22] for the solution of applied problems of solid mechanics, elastodynamics, structural analysis, fluid mechanics and aerodynamics. In addition, Ladopoulos [23] - [25] proposed a non-linear singular integral equations method in petroleum reservoir engineering, for the determination of the properties of the reservoir materials, when petroleum reserves are moving through porous solids. Hence, by the current study, the method of non-linear singular integral equations will be extended in order to determine the properties of the reservoir materials in multiphase flows, when oil reserves mixed with water are moving through porous solids.

Consequently, by using the Singular Integral Operators Method (S.I.O.M.), then the pressure response in multiphase flows from the well test conducted in a heterogeneous reservoir will be computed. Also, some properties of the porous medium equation, which is a Helmholtz differential equation, are proposed and investigated. Besides, basic properties of the fundamental solution will be analyzed and investigated.

Moreover, 4-D multiphase flows can be taken on a given area multiple times over an extended period of time. Thus, through the current study 4-D multiphase flows are proposed, which incorporates many 3-D flows over the same reservoir at specified intervals of time. Studying multiple time-lapsed 3-D surveys, or three-dimensional subsurface images, portrays the changes in the reservoir over time.

Finally, an application is given for a well testing to be investigated when a heterogeneous oil reservoir together with water in multiphase flow is moving in a porous medium. Then this problem is solved by using the Singular Integral Operators Method and so the pressure response from the well test conducted in this heterogeneous petroleum reservoir, will be computed. Hence, this is very important in petroleum reservoir engineering in order the size of the reservoir to be evaluated.

The proposed petroleum engineering method, as it is a complicated non-linear numerical method can give results for heterogeneous porous media (which of course are the solids in reality) and not only for homogeneous solids as are giving the analytical or numerical existing methods. Thus, the estimation of the properties and the future petroleum production from a new oil reservoir could be done exactly, and not estimated as by the existing methods. From the above mentioned points it can be understood the evidence of the applicability of the new method, as it is based on non-linear software. Moreover its novelty, as it is based on the theory of non-linear singular integral equations.

Thus, the non-linear singular integral equation methods which were used with big success for the solution of several engineering problems of fluid mechanics, hydraulics, aerodynamics, solid mechanics, elastodynamics, and structural analysis, are further extended by the current research for the solution of petroleum reservoir engineering problems in multiphase flows. In such a case the non-linear singular integral equations are used for the solution of one of the most important and interesting problems for petroleum reservoir engineers.

2. 4-D Multiphase Flows of Petroleum Reserves by Well Test Analysis

Petroleum well test analysis is a kind of a very important history matching process for the determination of the properties of reservoir solids. So, during the movement of petroleum reserves through porous media, then both single-phase and multiphase flow occurs. By the present paper the multiphase flows are studied when the petroleum reserves are mixed with water. Besides, when a petroleum well test is conducted then the well is subjected to a change of its flow rate and the resulting pressure response is possible to be measured. In addition, this pressure is compared to analytical or numerical models in order to estimate reservoir parameters such as permeability. Then the estimation of the future petroleum production from the reservoir can be evaluated.

A petroleum reservoir well test analysis in a multiphase flow is calculated by using the porous medium equation:

$$\nabla \bullet (k_t \nabla p) = 0 \tag{2.1}$$

with:

$$k_t = \lambda \left(\frac{\lambda_o}{\varphi_0 \xi_0} + \frac{\lambda_w}{\varphi_w \xi_w} \right) \tag{2.2}$$

in which λ denotes the relative permeability, λ_o the permeability of the oil, ϕ_o the porosity of the oil, ξ_o the viscosity of the oil and λ_w, ϕ_w, ξ_w the corresponding values of the water and p the pressure of the reservoir.

By replacing variables as follows:

$$u = (\lambda')^{1/2} p \tag{2.3}$$

then (2.1) can be written as:

$$\nabla^2 u + \lambda' u = 0 \tag{2.4}$$

with:

$$\lambda' = -\frac{\nabla^2 (k_t)^{1/2}}{(k_t)^{1/2}} \tag{2.5}$$

Thus, eqn (2.4) denotes a Helmholtz differential equation.

Additionally, consider by $u^*(\mathbf{x},\mathbf{y})$ the fundamental solution of any point $\mathbf{y}$, because of the source point $\mathbf{x}$. Then the fundamental solution can be given by the following relation:

$$\nabla^2 u^*(\mathbf{x},\mathbf{y}) + \lambda' u^*(\mathbf{x},\mathbf{y}) + \delta(\mathbf{x},\mathbf{y}) = 0 \tag{2.6a}$$

which can be further written as:

$$u^*_{,ii}(\mathbf{x},\mathbf{y}) + \lambda' u^*(\mathbf{x},\mathbf{y}) + \delta(\mathbf{x},\mathbf{y}) = 0 \tag{2.6b}$$

Thus, eqn (2.6) denotes the Helmholtz potential equation governing the fundamental solution.

Consider further by u^* the fundamental solution chosen so that to enforce the Helmholtz equation in terms of the function u, in a weak form. Then the weak form of Helmholtz equation will be written as following:

$$\int_{\Omega} (\nabla^2 u + \lambda' u) u^* d\Omega = 0 \tag{2.7}$$

in the solution domain Ω.

Moreover, by applying the divergence theorem once in (2.7), we obtain a symmetric weak form:

$$\int_{\partial\Omega} n_i u_{,i} u^* dS - \int_{\Omega} u_{,i} u^*_{,i} d\Omega + \int_{\Omega} \lambda' u u^* d\Omega = 0 \tag{2.8}$$

where **n** denotes the outward normal vector of the surface S.

Thus, in the symmetric weak form the function u and the fundamental solution u^* are only required to be first - order differentiable. Moreover, by applying the divergence theorem twice in (2.7) we have:

$$\int_{\partial\Omega} n_i u_{,i} u^* dS - \int_{\partial\Omega} n_i u u^*_{,i} dS + \int_{\Omega} u(u^*_{,ii} + \lambda' u^*) d\Omega = 0 \tag{2.9}$$

Consequently, (2.9) is the asymmetric weak form and the fundamental solution u^* is required to be second - order differentiable. On the contrary, u is not required to be differentiable in the domain Ω.

By combining eqs (2.6) and (2.9), then one obtains:

$$u(\mathbf{x}) = \int_{\partial\Omega} n_i(\mathbf{y}) u_{,i}(\mathbf{y}) u^*(\mathbf{x},\mathbf{y}) dS - \int_{\partial\Omega} n_i(\mathbf{y}) u(\mathbf{y}) u^*_{,i}(\mathbf{x}.,\mathbf{y}) dS \tag{2.10}$$

which can be further written as:

$$u(\mathbf{x}) = \int_{\partial\Omega} q(\mathbf{y}) u^*(\mathbf{x},\mathbf{y}) dS - \int_{\partial\Omega} u(\mathbf{y}) R^*(\mathbf{x},\mathbf{y}) dS \tag{2.11}$$

where $q(\mathbf{y})$ denotes the potential gradient along the outward normal direction of the boundary surface:

$$q(\mathbf{y}) = \frac{\partial u(\mathbf{y})}{\partial n_y} = n_k(\mathbf{y}) u_{,k}(\mathbf{y}) \quad , \quad \mathbf{y} \in \partial\Omega \tag{2.12}$$

and the kernel function:

$$R^*(\mathbf{x},\mathbf{y}) = \frac{\partial u^*(\mathbf{x},\mathbf{y})}{\partial n_y} = n_k(\mathbf{y}) u^*_{,k}(\mathbf{x},\mathbf{y}) \quad , \quad \mathbf{y} \in \partial\Omega \tag{2.13}$$

By differentiating (2.11) with respect to x_k , one obtains the integral equation for potential gradients $u_{,k}(\mathbf{x})$ by the following formula:

$$\frac{\partial u(\mathbf{x})}{\partial x_k} = \int_{\partial\Omega} q(\mathbf{y}) \frac{\partial u^*(\mathbf{x},\mathbf{y})}{\partial x_k} dS - \int_{\partial\Omega} u(\mathbf{y}) \frac{\partial R^*(\mathbf{x},\mathbf{y})}{\partial x_k} dS \tag{2.14}$$

3. Basic Properties of 4-D Multiphase Petroleum Flows

We rewrite the weak form of (2.6) governing the fundamental solution, by the following relation:

$$\int_{\Omega}\left[\nabla^2 u^*(\mathbf{x},\mathbf{y})+\lambda' u^*(\mathbf{x},\mathbf{y})\right]c d\Omega + c = 0, \quad \mathbf{x}\in\Omega \tag{3.1}$$

where c denotes a constant, considering as the test function.

In addition, eqn (3.1) can be further written as:

$$\int_{\Omega}\left[u^*_{,ii}(\mathbf{x},\mathbf{y})+\lambda' u^*(\mathbf{x},\mathbf{y})\right]d\Omega + 1 = 0, \quad \mathbf{x}\in\Omega \tag{3.2}$$

Moreover, (3.2) takes the form:

$$\int_{\partial\Omega} n_i(\mathbf{y}) u^*_{,i}(\mathbf{x},\mathbf{y}) dS + \int_{\Omega}\lambda' u^*(\mathbf{x},\mathbf{y}) d\Omega + 1 = 0, \quad \mathbf{x}\in\Omega \tag{3.3}$$

By considering further an arbitrary function $u(x)$ in Ω as the test function, then the weak form of (2.6) may be written as:

$$\int_{\Omega}\left[\nabla^2 u^*(\mathbf{x},\mathbf{y})+\lambda' u^*(\mathbf{x},\mathbf{y})+\delta(\mathbf{x},\mathbf{y})\right]u(\mathbf{x})d\Omega = 0, \quad \mathbf{x}\in\Omega \tag{3.4}$$

and further as:

$$\int_{\Omega}\left[u^*_{,ii}(\mathbf{x},\mathbf{y})+\lambda' u^*(\mathbf{x},\mathbf{y})\right]u(\mathbf{x})d\Omega + u(\mathbf{x}) = 0, \quad \mathbf{x}\in\Omega \tag{3.5}$$

Finally, (3.5) takes the form:

$$\int_{\partial\Omega}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS + \int_{\Omega}\lambda' u^*(\mathbf{x},\mathbf{y})u(\mathbf{x})d\Omega + u(\mathbf{x}) = 0, \quad \mathbf{x}\in\Omega \tag{3.6}$$

Besides, if $\mathbf{x}$ approaches the smooth boundary $(\mathbf{x}\in\partial\Omega)$, then the first term in (3.6) may be written as following:

$$\lim_{x\to\partial\Omega}\int_{\partial\Omega}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS = \overset{CPV}{\int_{\partial\Omega}}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS - \frac{1}{2}u(\mathbf{x}) \tag{3.7}$$

in the sense of a Cauchy Principal Value (CPV) integral.

For the understanding of the physical meaning of (3.7), eqs (3.3) and (3.6) can be written as:

$$\overset{CPV}{\int_{\partial\Omega}} \Phi^*(\mathbf{x},\mathbf{y})dS + \int_{\Omega} \lambda' u^*(\mathbf{x},\mathbf{y})d\Omega + \tfrac{1}{2} = 0, \quad x \in \partial\Omega \tag{3.8}$$

and:

$$\overset{CPV}{\int_{\partial\Omega}} \Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS + \int_{\Omega} \lambda' u^*(\mathbf{x},\mathbf{y})u(\mathbf{x})d\Omega + \tfrac{1}{2}u(\mathbf{x}) = 0, \quad x \in \partial\Omega \tag{3.9}$$

From (3.8) follows that only a half of the source function at point **x** is applied to the domain Ω, when the point **x** approaches a smooth boundary, $\mathbf{x} \in \partial\Omega$.

Additionally, consider another weak form of eqn (2.6) by supposing the vector functions to be the gradients of an arbitrary function $u(\mathbf{y})$ in Ω, chosen in such a way that they have constant values:

$$u_{,k}(\mathbf{y}) = u_{,k}(\mathbf{x}) \ , \quad \text{for } k=1,2,3 \tag{3.10}$$

Then the weak form of eqn (2.6) will be written as:

$$\int_{\Omega} \left[u^*_{,ii}(\mathbf{x},\mathbf{y}) + \lambda'' u^*(\mathbf{x},\mathbf{y}) \right] u_{,k}(\mathbf{y})d\Omega + u_{,k}(\mathbf{x}) = 0 \tag{3.11}$$

By applying further the divergence theorem, then eqn (3.11) takes the following form:

$$\int_{\partial\Omega} \Phi^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})dS + \int_{\Omega} \lambda' u^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})d\Omega + u_{,k}(\mathbf{x}) = 0 \tag{3.12}$$

Besides, the following property exists:

$$\begin{aligned} &\int_{\partial\Omega} n_i(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,k}(\mathbf{x},\mathbf{y})dS - \int_{\partial\Omega} n_k(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,i}(\mathbf{x},\mathbf{y})dS \\ &= \int_{\Omega} u_i(\mathbf{x})u^*_{,ki}(\mathbf{x},\mathbf{y})dS - \int_{\partial\Omega} u_{,i}(\mathbf{x})u^*_{,ik}(\mathbf{x},\mathbf{y})dS = 0 \end{aligned} \tag{3.13}$$

By adding eqs (3.12) and (3.13) then one obtains:

$$\begin{aligned} &\int_{\partial\Omega} n_i(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,k}(\mathbf{x},\mathbf{y})dS - \int_{\partial\Omega} n_k(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,i}(\mathbf{x},\mathbf{y})dS \\ &+ \int_{\partial\Omega} \Phi^*(\mathbf{x},\mathbf{y})u^*_{,k}(\mathbf{x})dS + \int_{\Omega} \lambda'' u^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})d\Omega + u_{,k}(\mathbf{x}) = 0 \end{aligned} \tag{3.14}$$

which takes finally the form:

$$\int_{\partial\Omega} n_i(\mathbf{y}) u_{,i}(\mathbf{x}) u^*_{,k}(\mathbf{x},\mathbf{y}) dS + \int_{\partial\Omega} e_{ikt} R_t u(\mathbf{x}) u^*_{,i}(\mathbf{x},\mathbf{y}) dS + \int_{\partial\Omega} \lambda' u^*(\mathbf{x},\mathbf{y}) u_{,k}(\mathbf{x}) d\Omega + u_{,k}(\mathbf{x}) = 0 \tag{3.15}$$

4. 4-D Multiphase Flows by Non-linear Singular Integral Equations

The porous medium equation (2.1) will be further written in another form, in order a singular integral equation representation to be applicable:

$$\nabla^2 p + \nabla \ln k_t \bullet \nabla p = 0 \tag{4.1}$$

Furthermore, by applying the Green Element Method, then eqn (4.1) reduces to the solution of a non-linear singular integral equation:

$$-\frac{\theta}{2\pi} p(r_i) + \int_{\partial\Omega} \left(p \frac{\partial[\ln(r - r_i)]}{\partial n} - \ln(r - r_i) \frac{\partial p}{\partial n} \right) dS + \iint_{\Omega} \ln(r - r_i) [-\nabla \ln \Lambda \bullet \nabla p] d\Omega = 0 \tag{4.2}$$

where:

$$\Lambda = \frac{1}{k_t} \tag{4.3}$$

In order the non-linear singular integral equation (4.2) to be numerically evaluated, then the Singular Integral Operators Method (S.I.O.M.) will be used. Hence, the non-linear singular integral equation (4.2) is approximated by the formula:

$$-\frac{\theta}{2\pi} p(r_i) + \sum_{i=1}^{M} \left[\int_{\partial\Omega} \left(p \frac{\partial[\ln(r - r_i)]}{\partial n} - \ln(r - r_i) \frac{\partial p}{\partial n} \right) dS + \iint_{\Omega} (-\nabla \ln \Lambda \bullet \nabla p) d\Omega \right] = 0 \tag{4.4}$$

where M denotes the total number of elements.

In addition, we introduce the following functions describing the pressure at any point in an element, in terms of the nodal pressures:

$$p(x, y) = N_j(x, y) p_j \tag{4.5}$$

By replacing (4.5) then eqn (4.4) takes the form:

$$\sum_{i=1}^{M}\left(A_{ij}^{e}p_i + B_{ij}^{e}q_i - C_{ijl}^{e}\ln \Lambda_i p_i\right) = 0, \qquad i,j,l = 1,2,3,4 \tag{4.6}$$

where:

$$A_{ij}^{e} = \int_{\partial\Omega} \frac{\partial\left[\ln(r-r_i)\right]}{\partial n}\Omega_j dS - \delta_{ij}\frac{\theta}{2\pi} \tag{4.7}$$

$$B_{ij}^{e} = -\int_{\partial\Omega} \ln(r-r_i)\Omega_j dS \tag{4.8}$$

$$C_{ijl}^{e} = \iint_{\Omega_j} \ln(r-r_i)\left[\frac{\partial N_j}{\partial x}\frac{\partial N_l}{\partial x} + \frac{\partial N_j}{\partial y}\frac{\partial N_l}{\partial y}\right] d\Omega \tag{4.9}$$

5. Heterogeneous Reservoirs Application of 4-D Petroleum Multiphase Flows

The previous mentioned theory will be applied to the determination of the water production history, in a well known problem where the exact Buckley - Leverett solution is valid [26].

Thus, by using the Singular Integral Operators Method (S.I.O.M.) as described in the previous paragraphs, then the computation of the water was effected and a comparison was done with exact Buckley - Leverett solution. According to this problem water is injected into one end of a one dimensional oil reservoir and fluids are produced from the other end of the reservoir. In this case the injected water forms a piston - like shock. Hence, Table 1 shows the watercut with respect to the time.

The computational results of the watercut were compared to the analytical solutions of the same problem. From Table 1 it can be seen that there is very small difference between the computational results and the analytical solutions. Finally same results are shown, in Figure 1 and in three-dimensional form in Figure 1a.

Table 1

Time (days)	Watercut (%) S.I.O.M.	Watercut (%) Analytical
0	0	0
10	0	0
20	0	0
30	0	0
40	0	0
50	0	0
51	6	0
52	20	0
53	40	0
54	60	100
55	98	100
56	100	100

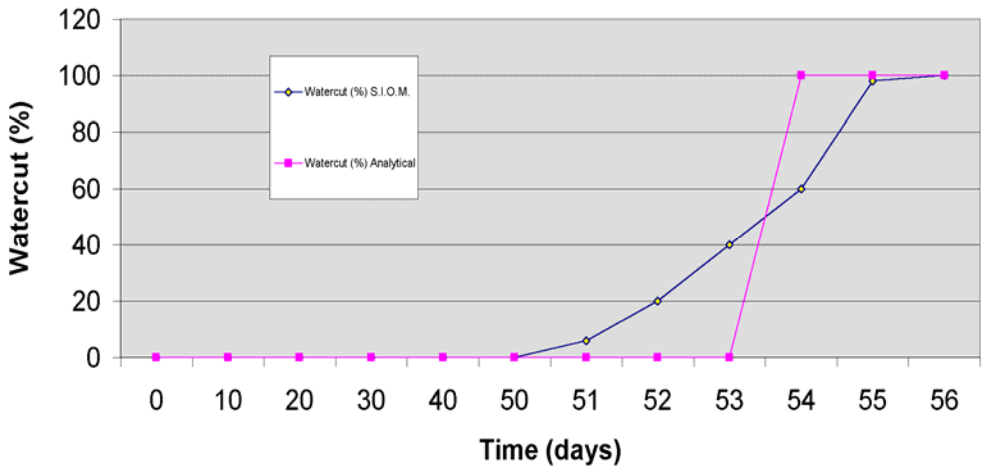

Fig. 1 Multiphase Flow of Oil Reservoir Mixed with Water.

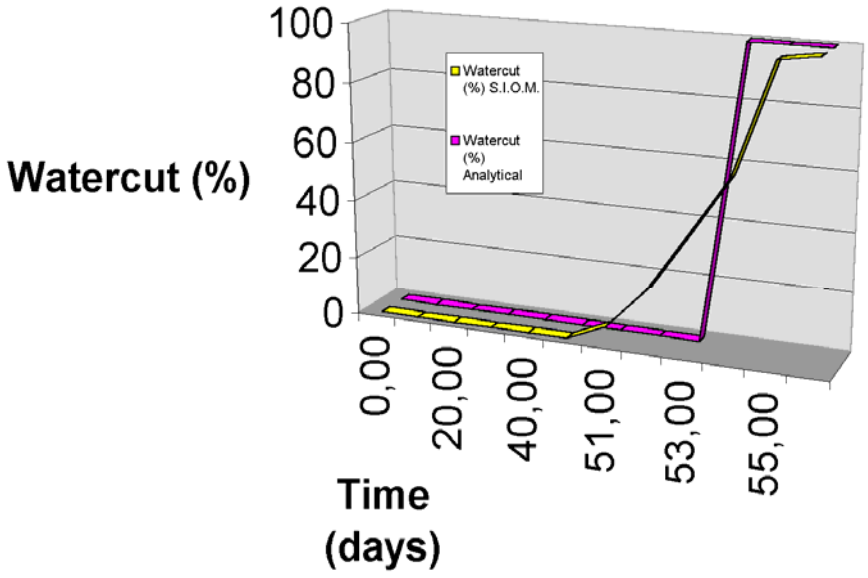

Fig. 2 3-D Distribution of Multiphase Flow of Oil Reservoir Mixed with Water.

6. Conclusions

A non-linear mathematical method has been further improved as an attempt to determine the properties of petroleum reservoir materials mixed with water in multiphase flow. Hence, the study of the movement of oil reserves through porous media is very important for petroleum reservoir

engineers. This problem was reduced to the solution of a non-linear singular integral equation, which was numerically solved by using the Singular Integral Operators Method (S.I.O.M.).

In addition, several important properties of the porous medium equation, which is a Helmholtz differential equation, were analyzed and investigated. Thus, the fundamental solution of the porous medium equation was proposed and studied. Moreover, some basic properties of the fundamental solution were further investigated. The new method, as it is a complicated non-linear numerical method can give results for heterogeneous porous media (which of course are the solids in reality) and not only for homogeneous solids as are giving the analytical or numerical existing methods. Thus, the estimation of the properties and the future petroleum production from a new oil reservoir could be done exactly, and not estimated as by the existing methods.

An application was finally given to the determination of the water production history, in a well known problem where the exact Buckley - Leverett solution is valid. The above problem was solved by using the Singular Integral Operators Method and thus the watercut, was computed. According to this problem water was injected into one end of a one dimensional oil reservoir and fluids are produced from the other end of the reservoir. In this case the injected water forms a piston - like shock.

During the past years, non-linear singular integral equation methods have been used successfully for the solution of several important engineering problems of structural analysis, elastodynamics, hydraulics, fluid mechanics and aerodynamics. For the numerical solution of the non-linear singular integral equations of the above problems, were used several aspects of the Singular Integral Operators Method (S.I.O.M.). Thus, by the present research such methods were extended for the solution of oil reserves problems in multiphase flows of petroleum reservoir engineering.

References

1. *Lafe.O.E. and Cheng A.H-D,* 'A perturbation boundary element code for steady state groundwater flow in heterogeneous aquifers', *Water Resour. Res. ,* ***23*** *(1987), 1079-1084.*
2. *Masukawa J. and Horne R.N.,* 'Application of the boundary integral method to immiscible displacement problems', *SPE Reserv. Engng. (1988), 1069-1077.*
3. *Numbere D.T. and Tiab D.,* 'An improved streamline generating technique that uses the boundary (integral) element method', *SPE Reserv. Engng., (1988), 1061-1068.*
4. *Kikani J.A. and Horne R.N.,* 'Pressure-transient analysis of arbitrarily shaped reservoirs with the boundary element method', *SPE Form. Eval.*, *(1992), 53-60.*
5. *Koh L.S. and Tiab D., '*A boundary element algorithm for modelling 3D horizontal wells problems using 2D grids', *SPE Petrol. Computer Conf.,* New Orleans, LA, pp. 91-106.
6. *Sato K. and Horne R.N.,* 'Perturbation boundary element method for heterogeneous reservoirs: Part 1 - Steady - state flow problems', *SPE Form. Eval., (1993), 306-314.*
7. *Sato K. and Horne R.N.,* 'Perturbation boundary element method for heterogeneous reservoirs: Part 2 - Transient flow problems', *SPE Form. Eval., (1993), 315-322.*
8. *El Harrouni K., Ouazar D., Wrobel L.C. and Cheng A.H.D.,* 'Global interpolation function based DRBEM applied to Darcy's flow in heterogeneous media', *Engng Anal. Bound. Elem.*, ***17*** *(1996), 281-285.*
9. *Onyejekwe O.O.,* 'A Green element treatment of isothermal flow with second order reaction', *Int. Comm. Heat Mass Transfer*, ***24*** *(1997), 251-264.*
10. *Onyejekwe O.O.,* 'A boundary element - finite element equations solution to flow in heterogeneous porous media', *Trans. Porous Media*, ***31*** *(1998), 293-312.*
11. *Onyejekwe O.O.,* 'Boundary integral procedures for unsaturated flow problems', *Trans. Porous Media*, ***31*** *(1998), 313-330.*
12. *Taigbenu A.E. and Onyejekwe O.O.,* 'Transient 1D transport equation simulated by a mixed Green element formulation', *Int. J. Numer. Meth. Engng*, ***25*** *(1997), 437-454.*
13. *Ladopoulos E.G.,* 'Non-linear integro-differential equations used in orthotropic spherical shell analysis', *Mech. Res. Commun.*, ***18*** *(1991), 111 – 119.*
14. *Ladopoulos E.G.,* 'Non-linear integro-differential equations in sandwich plates stress analysis', *Mech. Res. Commun.*, ***21*** *(1994), 95 – 102.*

15. *Ladopoulos E.G.,* 'Non-linear singular integral representation for unsteady inviscid flowfields of 2-D airfoils', *Mech. Res. Commun.,* ***22*** *(1995), 25 – 34.*
16. *Ladopoulos E.G.,* 'Non-linear singular integral computational analysis for unsteady flow problems', *Renew. Energy,* ***6*** *(1995), 901 – 906.*
17. *Ladopoulos E.G.,* 'Non-linear singular integral representation analysis for inviscid flowfields of unsteady airfoils', *Int. J. Non-Lin. Mech.,* ***32*** *(1997), 377 – 384.*
18. *Ladopoulos E.G.,* 'Non-linear multidimensional singular integral equations in 2-dimensional fluid mechanics analysis', *Int. J. Non-Lin. Mech*., ***35*** *(2000) , 701 - 708.*
19. *Ladopoulos E.G. and Zisis V.A.,* 'Non-linear finite-part singular integral equations arising in two-dimensional fluid mechanics', *Nonlin. Anal., Th. Meth. Appl.,* ***42*** *(2000), 277 - 290.*
20. *Ladopoulos E.G.,* 'Non-linear singular integral equations in elastodynamics, by using Hilbert transformations', *Nonlin. Anal., Real World Appl.,* ***6*** *(2005), 531 - 536.*
21. *Ladopoulos E.G.,* 'Non-linear two-dimensional aerodynamics by multidimensional singular integral computational analysis', *Forsch. Ingen.,* ***68*** *(2003), 105 - 110.*
22. *Ladopoulos E.G., 'Singular Integral Equations, Linear and Non-Linear Theory and its Applications in Science and Engineering',* Springer Verlag, New York, Berlin, *2000.*
23. *Ladopoulos E.G.,* 'Non-linear singular integral representation for petroleum reservoir engineering', *Acta Mech*., ***220*** *(2011), 247-253.*
24. *Ladopoulos E.G.,* 'Petroleum reservoir engineering by non-linear singular integral equations', *Mech. Engng Res*., ***1*** *(2011), 2 - 11.*
25. *Ladopoulos E.G.,* 'Petroleum and gas reserves exploration by real-time expert seismology and non-linear seismic wave motion', *Adv. Petr. Explor. Develop.*, ***4*** *(2012), 1-13.*
26. *Duke L.P., 'Fundamentals of Reservoir Engineering'*, Elsevier, Amsterdam, *1978.*