Knowledge – Based Reservoir Simulation – A Novel Approach

M. Enamul Hossain menamul@kfupm.edu.sa
Department of Petroleum Engineering
King Fahd University of Petroleum & Minerals
Dhahran 31261, Saudi Arabia

M. Rafiqul Islam rafiq.islam@dal.ca
Department of Civil and Resource Engineering
Dalhousie University
Sexton Campus, 1360 Barrington Street, Halifax, NS B3J 2X4, Canada

Abstract

It is well known that reservoir simulation studies are very subjective and vary from simulator to simulator. While SPE benchmarking has helped accept differences in predicting petroleum reservoir performance, there has been no scientific explanation behind the variability that has frustrated many policy makers and operations managers and puzzled scientists and engineers. In a recent book by the research group of R. Islam, a new approach is taken to add the Knowledge dimension to the problem. For the first time, reservoir simulation equations are shown to have embedded variability and multiple solutions that are in line with physics rather than spurious mathematical solutions. With this clear description, a fresh perspective in reservoir simulation is presented. Unlike the majority of reservoir simulation approaches available today, the 'knowledge-based' approach does not stop at questioning the fundamentals of reservoir simulation but offers solutions and demonstrates that proper reservoir simulation should be transparent and empower decision makers rather than creating a black box. Mathematical developments of new governing equations based on in-depth understanding of the factors that influence fluid flow in porous media under different flow conditions are introduced. Behavior of flow through matrix and fractured systems in the same reservoir, heterogeneity and fluid/rock properties interactions, Darcy and non-Darcy flow are among the issues that are thoroughly addressed. For the first time, the fluid memory factor is introduced with a functional form. The resulting governing equations are solved without linearization at any stage. A series of clearly superior mathematical and numerical techniques are also presented that allow one to achieve this objective. Mathematical solutions that provide a basis for systematic tracking of multiple solutions that are inherent to non-linear governing equations. This was possible because the new technique is capable of solving non-linear equations without linearization. To promote the new models, a presentation of the common criterion and procedure of reservoir simulators currently in use is provided. The models are applied to difficult scenarios, such as in the presence of viscous fingering, fractures, and others. It is demonstrated that the currently available simulators only address very limited range of solutions for a particular reservoir engineering problem. Examples are provided to show how the Knowledge-based approach extends the currently known solutions and provide one with an extremely useful predictive tool for risk assessment.

Keywords: Emulation, Newtonian Mechanics, New Energy Balance Formulation, Energy Pricing, Non-Linear Mathematics

1. INTRODUCTION

In reservoir simulation, the principle of GIGO (Garbage in and garbage out) is well known [1]. This principle implies that the input data have to be accurate for the simulation results to be acceptable. Petroleum industry has established itself as the pioneer of subsurface data collection [2]. Historically, no other discipline has taken so much care in making sure input data are as accurate as the latest technology would allow. The recent superflux of technologies dealing with subsurface mapping, real time monitoring, and high speed data transfer is an evidence of the fact that input data in reservoir simulation are not the weak link of reservoir modelling.

However, for a modelling process to be knowledge-based, it must fulfill two criteria, namely, the source has to be true (or real) and the subsequent processing has to be true [3]. As indicated earlier, the source is not a problem in the petroleum industry. The potential problem lies within the processing of data. For the process to be knowledge-based, the following logical steps have to be taken:

- Collection of data with constant improvement of the data acquisition technique. The data set to be collected is dictated by the objective function, which is an integral part of the decision making process. Decision making, however, should not take place without the abstraction process. The connection between objective function and data needs constant refinement. This area of research is one of the biggest strength of the petroleum industry, particularly in the information age.
- The gathered data should be transformed into Information so that they become useful. With today's technology, the amount of raw data is so huge, the need for a filter is more important than ever before. However, it is important to select a filter that doesn't skew data set toward a certain decision. Mathematically, these filters have to be non-linearized [4]. While the concept of non-linear filtering is not new, the existence of non-linearized models is only beginning to be recognized [2].
- Information should be further processed into 'knowledge' that is free from preconceived ideas or a 'preferred decision'. Scientifically, this process must be free from information lobbying, environmental activism, and other forms of bias. Most current models include these factors as an integral part of the decision making process [5], whereas a scientific knowledge model must be free from those interferences as they distort the abstraction process and inherently prejudice the decision making. Knowledge gathering essentially puts information into the big picture. For this picture to be distortion-free, it must be free from non-scientific maneuvering.
- Final decision making is knowledge-based, only if the abstraction from 1) through 4) has been followed without interference. Final decision is a matter of Yes or No (or True or False or 1 or 0) and this decision will be either knowledge-based or prejudice-based. Figure 1 shows the essence of the knowledge based decision making.

The process of aphenomenal or prejudice-based decision-making is illustrated by the inverted triangle, proceeding from the top down (Figure 2). The inverted representation stresses the inherent instability and unsustainability of the model. The source data from which a decision eventually emerges already incorporates their own justifications, which are then massaged by layers of opacity and disinformation.

The disinformation referred to here is what results when information is presented or recapitulated in the service of unstated or unacknowledged ulterior intentions [6]. The *methods* of this disinformation achieve their effect by presenting evidence or raw data selectively, without disclosing either the fact of such selection or the criteria guiding the selection. This process of selection obscures any distinctions between the data coming from nature or from any all-natural pathway, on the one hand, and data from unverified or untested observations on the other. In social science, such manoeuvering has been well known, but the recognition of this aphenomenal model is new in science and engineering [7].

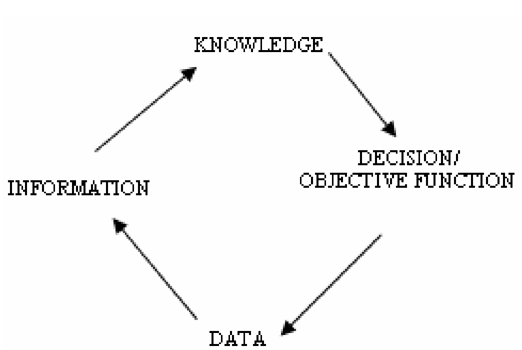

FIGURE1: The knowledge model and the direction of abstraction

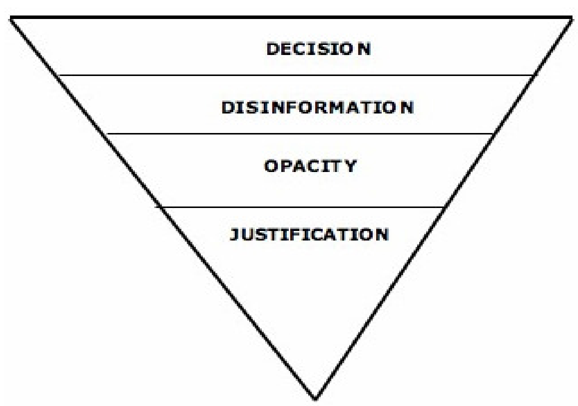

FIGURE 2: Aphenomenal decision-making

2. SHORTCOMINGS OF THE CONVENTIONAL APPROACH

Recently, Mustafiz and Islam [8] published a comprehensive review of currently available reservoir simulation approaches. In this paper, the discussion is limited to finite difference approach because that is the most commonly used technique in the petroleum reservoir modelling community.

The history of differential calculus dates back to the time of Leibnitz and Newton. In this concept, the derivative of a continuous function to the function itself is related. In the core of differential calculus is the Newton's formula that has the following approximation attached to it: the magnitude and direction change independently of one another. There is no problem in having separate derivatives for each component of the vector or in superimposing their effects separately and regardless of order. That is what mathematicians mean when they describe or discuss Newton's derivative being used as a "linear operator". Following this, comes Newton's difference-quotient formula. When the value of a function is inadequate to solve a problem, the rate at which the function changes, sometimes, becomes useful. Therefore, the derivatives are also important in reservoir simulation. In Newton's difference-quotient formula, the derivative of a continuous function is obtained. This method relies implicitly on the notion of approximating instantaneous moments of curvature, or infinitely small segments, by means of straight lines. This alone should have tipped everyone off that his derivative is a linear operator precisely because, and to the extent that, it examines change over time (or distance) within an already established function. This function is applicable to an infinitely small domain, making it non-existent. When, integration is performed, however, this non-existent domain is assumed to be extended to finite and realistic domain, making the entire process questionable.

Zatzman and Islam [9] identified the most significant contribution of Newton in mathematics as the famous definition of the derivative as the limit of a difference quotient involving changes in space or in time as small as anyone might like, but not zero, *viz.*

$$\frac{d}{dt}f(t) = Lim_{\Delta t \to 0}\ \frac{f(t+\Delta t)-f(t)}{\Delta t} \qquad (1)$$

Without regards to further conditions being defined as to when and where differentiation would produce a meaningful result, it was entirely possible to arrive at "derivatives" that would generate values in the range of a function at points of the domain where the function was not defined or did not exist. Indeed: it took another century following Newton's death before mathematicians would work out the conditions – especially the requirements for continuity of the function to be differentiated within the domain of values – in which its derivative (the name given to the ratio-quotient generated by the limit formula) could be applied and yield reliable results. Kline [10] detailed the problems involving this breakthrough formulation of Newton. However, no one in the past did propose an alternative to this differential formulation, at least not explicitly. The following figure (Figure 3) illustrates this difficulty.

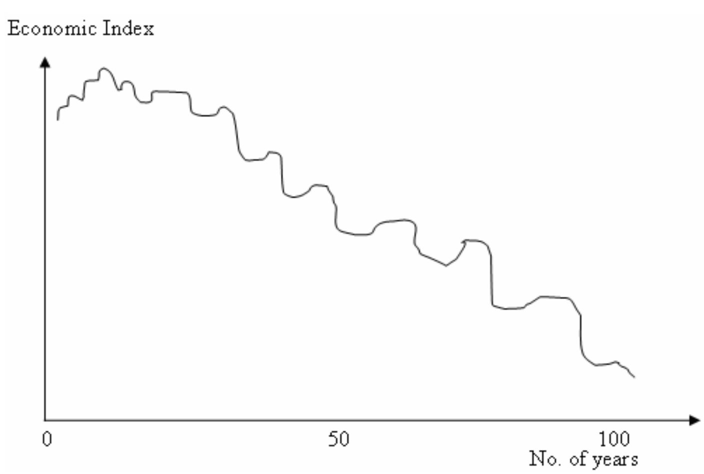

FIGURE 3: Economic wellbeing is known to fluctuate with time

In this figure, economic index (it may be one of many indicators) is plotted as a function of time. In nature, all functions are very similar. They do have local trends as well as global trend (in time). One can imagine how the slope of this graph on a very small time frame would quite arbitrary and how devastating it would be to take that slope to a long-term. One can easily show the trend, emerging from Newton's differential quotient would be diametrically opposite to the real trend. Zatzman and Islam [9] provided a basis for determining real gradient, rather than local gradient that emerges from Newtonian's differential quotient. In that formulation, it is shown that the actual value of Δt, over which a reliable gradient has to be observed, needs to be several time greater than the characteristic time of a system. The notion of Representative Elemental Volume (REV), as first promoted by Bear [11] is useful in determining a reasonable value for this characteristic time. The second principle is that at no time Δt be allowed to approach 0 (Newton's approximation), even when the characteristic value is very small (e.g. phenomena at nano scale). With the engineering approach, it turns out such approximation is not necessary [12] because this approach bypasses the recasting of governing equations into Taylor series expansion, instead relying on directly transforming governing equations into a set of algebraic equations. In fact, by setting up the algebraic equations directly, one can make the process simple and yet maintain accuracy [4]. Finally, initial analysis should involve the extension Δt to ∞ in order to determine the direction, which is related to sustainability of a process [13].

Figure 4 shows how formulation with the engineering approach ends up with the same linear algebraic equations if the inside steps are avoided. Even though the engineering approach was known for decades (known as the control volume approach), no one identified in the past the advantage of removing in-between steps. In analyzing further the role of mathematical manipulation in solving a natural problem, the following extremely simple example can be cited. Consider the function, *y* = 5. Following steps show how this function simple function can take route of knowledge or prejudice, based on the information that is exposed or hidden, respectively.

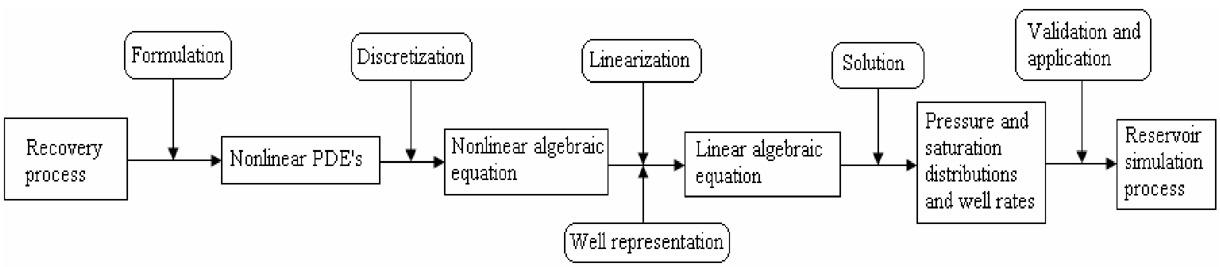

FIGURE 4: Major steps used to develop reservoir simulators (redrawn from Abou-Kassem et al., 2006, Hossain et al., 2009)

Step 1: *y* = 5. This is an algebraic equation that means, y is a constant with a value of 5. This statement is an expression of tangibles, which becomes clear if the assumptions are pointed out. The assumptions are: a) *y* has the same dimension as 5 (meaning dimensionless); b) nothing else matters (this one actually is a clarification of the condition a). Therefore, the above function implies that *y* cannot be a function of anything (including space and time). The mere fact that there is nothing in nature that is constant makes the function aphenomenal. However, subsequent manipulations (as in Step 2) make the process even more convoluted.

Step 2: dy/dx = 0. This simple derivation is legitimate in calculus that originates from Newton's ratio of quotient theory. In this, even partial derivative would be allowed with equal legitimacy as nothing states in conventional calculus that such operation is illegitimate. By adding this derivative in *x* (as in x direction in Cartesian coordinate), a spurious operation is performed. In fact, if Step 1 is true, one can add any dimension to this the differential would still be 0 – statement that is 'technically' true but hides background information that becomes evident in Step 3.

Step 3: If one integrates dy/dx, one obtains, y = C, where C is a constant that can have infinite number of values, depending on which special case it is being solved for. All of a sudden, it is clear that the original function. All of a sudden, it is clear that the original function (y = 5) has disappeared.

Step 4: One special case of *y* = C is, y = 5. To get back the original and unique function (as in Step 1), one now is required to have boundary conditions that are no longer attached to the mathematical formulation. If a special case of C = 5 is created, similarly one can have *y*=1, 2, 3, 4, 5, 6,... How does one know which solution will give the 'true' solution. In this particular case, all but one solution are called 'spurious' solutions, because they failed to match the solution of interest, i.e., y = 5.

This simple example shows how imposing Newton's differential and integrating procedure convolutes the entire process, while losing information that would allow anyone to trace back the original algebraic function.

On the other hand, if one is looking at an actual phenomenon, then dy/dx = 0 could mean that we are at the very start of something, or at the very end of something. If we look at $\partial y/\partial x$, on the other hand, then we have to look also at $\Delta y/\Delta t$, and then we also have to consider the situation where $\Delta y/\Delta x=0$ but $\Delta y/\Delta t$ is non-0. This might very well be a branch-point, a point of bifurcation or, generally speaking, something marking a change from an old state to a new state. Branch-points in physical natural reality clearly imply infinite solutions, since the process could go, literally, anywhere from that branch-point. This approach of locating bifurcation phenomena has eluded previous researchers engaged in modelling chaos [14]. With the engineering approach, the following steps can be taken. Note the similarity of these steps with the one shown above regarding a simpler function.

Step 1) Mass balance + Darcy's law → It is an algebraic equation.
Step 2a) Time variable is added to it through Newton's differential quotient → time increment is allowed to approach to 0.
Step 2b) Space variable is added through Newton's differential quotient → space increment is allowed to approach 0.
Step 2c) Differential equations emerge, burying assumptions added in 2a and 2b.
Step 3) Differential equation integrated analytically, original solutions will not be recovered. The integrated values will have the possibility of having infinite solutions, depending on the boundary conditions, initial conditions, etc.
Step 4) Three special cases (out of infinite number of solutions possible) are identified as part of the integrated solution of the Differential equation in Step 3. They are:
Step 4a) Steady state, compressible. This is Mass balance and Darcy's law as in Step 1.
Step 4b) Unsteady state, slightly compressible fluid. This is the typical equation that gives rise to the Diffusivity equation. This one would have liquid density as the only equation of state (density as a function of pressure).
Step 4c) Unsteady state, compressible fluid case. This is the typical gas flow equation. This would have gas compressibility (z factor that is a function of pressure and temperature). Here the term 'unsteady' means there is a time derivative. As time extends to infinity, this term drops off, making the model steady state. This alone shows that these 'unsteady state' models are not dynamic models and do not emulate nature that is dynamic at all time.
Step 5) Because analytical methods are very limited in solving a PDE and require their additional assumptions regarding boundary conditions, numerical techniques were introduced. This one essentially involves discretisation through Taylor series approximation and subsequent elimination of higher order terms, arguing that at higher order they are too small (e.g. if Δx is less than 1, Δx^2 is $<< 1$; Δx^3 $<<< 1$).
Step 6) The removal of higher order terms, as in Step 5, is equivalent to eliminating the additions of space and time variables as in Steps 2a and 2b. We, therefore, recover original mass balance and Darcy's law (Momentum balance equation) as in Step 1. The Engineering approach works with these algebraic equations (Step 1) rather than working with PDE and subsequent discretized forms. This explains why Engineering approach coefficients are the same as the 'mathematical approach' coefficients.

When we go from y = 5 to dy/dx = 0, we add the possibility of adding an infinite series. When we then go from dy/dx to y = constant, we are left with infinite solutions, all because of the previous addition. On the other hand, if we do this integration numerically (by invoking Taylor series approximation), we end up having the original solution only if we ignore the left over terms of the infinite series that may or may not be convergent. It is important to see the actual derivation of Taylor series expansion.

3. NUMERICAL CHALLENGES

3.1. Theory of Onset and Propagation of Fractures due to Thermal Stress

Fundamental work needs to be performed in order to develop relevant equations for thermal stresses. Similar work has been initiated by Wilkinson et al. [15], who used finite element modelling to solve the problem. There has been some progress in the design of material manufacturing for which in situ fractures and cracks are considered to be fatal flaws. Therefore, formulation complete equations are required in order to model thermal stress and its effect in petroleum reservoirs. It is to be noted that this theory deals with only transient state of the reservoir rock.

3.2. 2-D and 3-D solutions of the governing equations

In order to determine fracture width, orientation, and length under thermal stresses as a function of time, it is imperative to solve the governing equations first in 2-D. The finite difference is the most accepted technique to develop the simulator. An extension of the developed simulator to the cylindrical system is useful in designing hydraulic fractures in thermally active reservoirs. The 3-D solutions are required to determine 3-D stresses and the effects of permeability tensor. Such simulation will provide one with the flexibility of determining fracture orientation in the 3-D mode and guide as a design tool for hydraulic fracturing. Although the 3-D version of the hydraulic fracturing model can be in the framework put forward earlier [15], differences of opinion exist as to how thermal stress can be added to the in situ stress equations.

3.3 Viscous fingering during miscible displacement

Viscous fingering is believed to be dominant in both miscible and immiscible flooding and of much importance in a number of practical areas including secondary and tertiary oil recovery. However, modelling viscous fingering remains a formidable task. Only recently, researchers from Shell have attempted to model viscous fingering with the chaos theory. Islam (1993) has reported in a series of publications that periodic and even chaotic flow can be captured properly by solving the governing partial differential equations with improved accuracy (Δx^4, Δt^2). This needs to be demonstrated for viscous fingering. The tracking of chaos (and hence viscous fingering) in a miscible displacement system can be further enhanced by studying phenomena that onset fingering in a reservoir. It eventually will lead to developing operating conditions that would avoid or minimize viscous fingering. Naami et al. [[16] conducted both experimental and numerical modelling of viscous fingering in a 2-D system. They modelled both the onset and propagation of fingers by solving governing partial differential equations. Recent advances in numerical schemes [17 – 18] can be suitably applied in modelling of viscous fingering. The scheme proposed by Bokhari and Islam [18] is accurate in the order of Δx^4 in space and Δt^2 in time. This approach has been used to model viscous fingering with reasonable agreement with experimental results [19]. Similar approach can be extended for tests in a 3-D system in future. Modelling viscous fingering using finite element approach has been attempted as well [20].

4. CHALLENGES OF MODELLING SUSTAINABLE PETROLEUM OPERATIONS

Recently, Khan and Islam [21 – 22] outlined the requirements for rending fossil fuel production sustainable. This scientific study shows step by step how various operations ranging from exploration to fuel processing can be performed in such a manner that resulting products will not be toxic to the environment. However, modelling such a process is a challenge as the conventional characterization of matter does not make any provision for separating sustainable operations from unsustainable ones. In order to avoid some of the difficulties associated with conventional approach, Khan et al. [23] recently introduced simultaneous characterization of matter and energy. This renders time a characteristic of matter itself within the overall context of mass-energy-momentum conservation. In other words, time ceases to be mainly or only a derivative of some spatial displacement of matter. In this way, it becomes possible at last to treat time, consistently, as a true fourth dimension — and no longer as merely the independent variable. This description is consistent with Einstein's revolutionary relativity theory, but does not rely on Maxwell's equations as the starting point. The resulting equation is shown to be continuous in time, thereby allowing transition from mass to energy. As a result a single governing equation emerges. This equation is solved for a number of cases and is shown to be successful in discerning between various natural and artificial sources of mass and energy. With this equation, the difference between chemical and organic fertilizers, microwave and wood stove heating, and sunlight and fluorescent light can be made with unprecedented clarity. This analysis would not be possible with conventional techniques. Finally, analysis results are shown for a number of energy- and material-related prospects. The key to the sustainability of a system lies within its energy balance. Khan et al. recast the combined energy-mass balance equation in the following form:

$$\int_{t=0}^{t=\infty} \int_{s=1}^{s=\infty} m\, v = constant \qquad (2)$$

Dynamic balances of mass, energy and momentum imply conditions that will give rise to multiple solutions, at least with the currently available mathematical tools. When it comes to the Nature, a portion of the space-time continuum in which real physical boundary conditions are largely absent, a mathematics that requires $\Delta t \rightarrow 0$ is clearly inappropriate. What is needed are non-linear algebraic equations that incorporate all relevant components (unknowns and other variables) involved in any of these critical balances that must be preserved by any natural system. In this context, Eq. 2 is of utmost importance. This equation can be used to define any process, for which the following equation applies:

$$Q_{in} = Q_{acc.} + Q_{\text{out}} \qquad (3)$$

In the above equation classical mass balance equation, Q_{in} in expresses Eq. 2 for inflow matter, Q_{acc} represents the same for accumulating matter, and Q_{out} represents the same for outflowing matter. Q_{acc} will have all terms related to dispersion/diffusion, adsorption/desorption, and chemical reactions. This equation must include all available information regarding inflow matters, e.g., their sources and pathways, the vessel materials, catalysts, and others. In this equation, there must be a distinction made among various matter, based on their source and pathway. Three categories are proposed: 1) biomass (BM); 2) convertible non-biomass (CNB); and 3) non-convertible non-biomass (NCNB). Biomass is any living object. Even though, conventionally dead matters are also called biomass, we avoid that denomination as it is difficult to scientifically discern when a matter becomes non-biomass after death. The convertible non-biomass (CNB) is the one that due to natural processes will be converted to biomass. For example, a dead tree is converted into methane after microbial actions, the methane is naturally broken down into carbon dioxide, and plants utilize this carbon dioxide in presence of sunlight to produce biomass. Finally, non-convertible non-biomass (NCNB) is a matter that emerges from human intervention. These matters do not exist in nature and their existence can be only considered artificial. For instance, synthetic plastic matters (e.g. polyurethane) may have similar composition as natural polymers (e.g. human hair, leather), but they are brought into existence through a very different process than that of natural matters. Similar examples can be cited for all synthetic chemicals, ranging from pharmaceutical products to household cookwares. This denomination makes it possible to keep track of the source and pathway of a matter. The principal hypothesis of this denomination is: all matters naturally present on Earth are either BM or CNB, with the following balance:

$$\text{Matter from natural source} + CNB_1 = BM + CNB_2 \qquad (4)$$

The quality of CNB_2 is different from or superior to that of CNB_1 in the sense that CNB_2 has undergone one extra step of natural processing. If nature is continuously moving to better environment (as represented by the transition from a barren Earth to a green Earth), CNB_2 quality has to be superior to CNB_1 quality. Similarly, when matter from natural energy sources come in contact with BMs, the following equation can be written.

$$\text{Matter from natural source} + B_1M = B_2M + CNB \qquad (5)$$

Applications of this equation can be cited from biological sciences. When sunlight comes in contact with retinal cells, vital chemical reactions take place that results in the nourishment of the nervous system, among others [24]. In these mass transfers, chemical reactions take place entirely differently depending on the light source, the evidence of which has been reported in numerous publications [25]. Similarly, sunlight is also essential for the formation of vitamin D, which is in itself essential for numerous physiological activities. In the above equation, vitamin D would fall under B_2M. This vitamin D is not to be confused with the synthetic vitamin D, the latter one being the product of artificial process. It is important to note that all products on the right hand side are of greater value than the ones on the left hand side. This is the inherent nature of natural processing – a scheme that continuously improves the quality of the environment and is the essence of sustainable technology development.

Following equation shows how energy from NCNB will react with various types of matter.

$$\text{Matter from unnatural source} + B_1M = NCNB_{\mathbf{2}} \qquad (6)$$

An example of the above equation can be cited from biochemical applications. For instance, if artificially generated UV is in contact with bacteria, the resulting bacteria mass would fall under the category of NCNB, stopping further value addition by nature. Similarly, if bacteria are destroyed with synthetic antibiotic (pharmaceutical product, pesticide, etc.), the resulting product will not be conducive to value addition through natural processes, instead becoming trigger for further deterioration and insult to the environment.

$$\text{Matter from unnatural source} + CNB_1 = NCNB_{\mathbf{3}} \qquad (7)$$

An example of the above equation can be cited from biochemical applications. The $NCNB_1$ which is created artificially reacts with CNB_1 (such as N_2, O_2) and forms NCNB3. The transformation will be in negative direction, meaning the product is more harmful than it was earlier. Similarly, the following equation can be written:

$$\text{Matter from unnatural source} + NCNB2_1 = NCNB_2 \qquad (8)$$

An example of this equation is that the sunlight leads to photosynthesis in plants, converting NCBM to MB, whereas fluorescent lighting would freeze that process can never convert natural non-biomass into biomass.

4.1 Implications of the Simultaneous Characterization

The principles of the knowledge-based model proposed here are restricted to those of mass (or material) balance, energy balance and momentum balance. For instance, in a non-isothermal model, the first step is to resolve the energy balance based on temperature as the driver for some given time-period, the duration of which has to do with characteristic time of a process or phenomenon. Following the example of the engineering approach employed by Abou-Kassem, [12] and Abou-Kassem et al. [2], the available temperature data are distributed block-wise over the designated time-period of interest. Temperature being the driver, as the bulk process of interest, i.e., changes with time, a momentum balance may be derived. Velocity would be supplied by local speeds, for all known particles. This is a system that manifests phenomena of thermal diffusion, thermal convection and thermal conduction, without spatial boundaries but giving rise nonetheless to the “mass” component.

The key to the system’s sustainability lies with its energy balance. Here is where natural sources of biomass and non-biomass must be distinguished from non-natural, non-characteristic industrially synthesised sources of non-biomass.

Figure 5 envisions the environment of a natural process as a bioreactor that does not and will not enable conversion of synthetic non-biomass into biomass. The key problem of mass balance in this process, as in the entire natural environment of the earth as a whole, is set out in Figure 6: the accumulation rate of synthetic non-biomass continually threatens to overwhelm the natural capacities of the environment to use or absorb such material.

In evaluating Eq. 3, it is desirable to know all the contents of the inflow matter. However, it is highly unlikely to know the all the contents, even at macroscopic level. In absence of a technology that would find the detailed content, it is important to know the pathway of the process to have an idea of the source of impurities. For instance, if de-ionised water is used in a system, one would know that its composition would be affected by the process of de-ionisation. Similar rules apply to products of organic sources, etc. If we consider combustion reaction (coal, for instance) in a burner, the bulk output will likely to be CO_2. However, this CO_2 will be associated with a number of trace chemicals (impurities) depending upon the process it passes through. Because, Eq. 3 includes all known chemicals (e.g. from source, adsorption/desorption products, catalytic reaction products), it would be able to track matters in terms of CNB and NCNB products. Automatically, this analysis will lead to differentiation of CO_2 in terms of pathway and the composition of the environment, the basic requirement of Eq. 2. According to Eq. 4, charcoal combustion in a burner made up of clay will release CO_2 and natural impurities of charcoal and the materials from burner itself. Similar phenomenon can be expected from a burner made up of nickel plated with an exhaust pipe made up of copper.

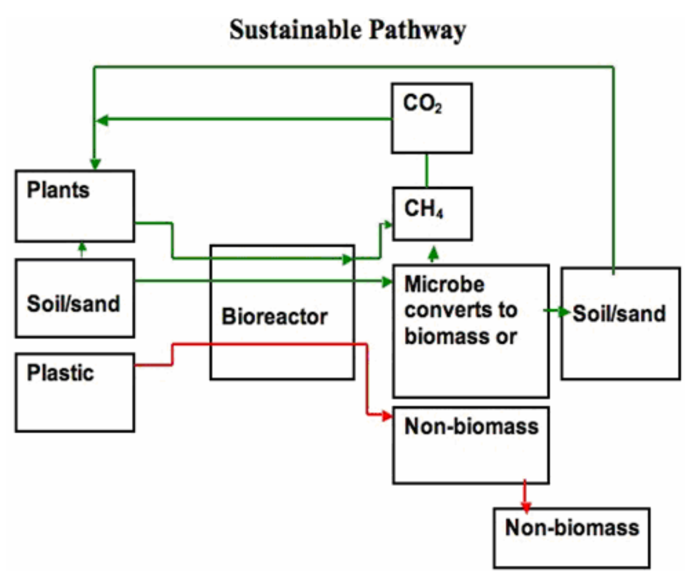

FIGURE 5: Sustainable pathway for material substance in the environment

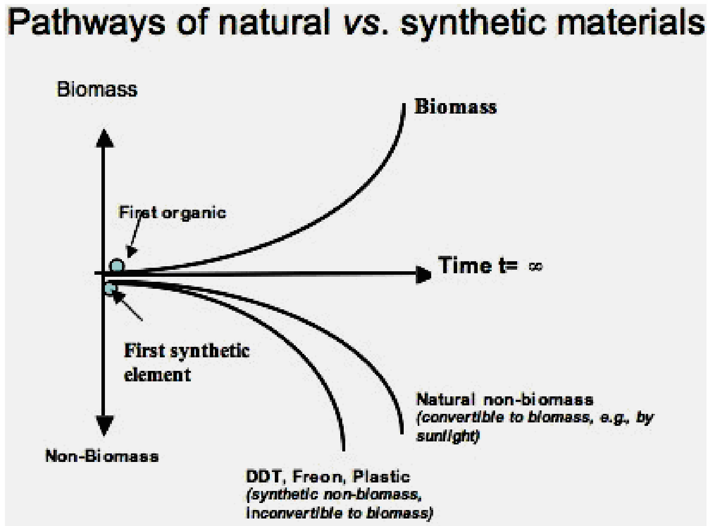

FIGURE 6: Transitions of natural and synthetic materials

Anytime, CO_2 is accompanied with CNB matter, it will be characterised as beneficial to the environment. This is shown in the positive slope of Figure 7. On the other hand, when CO_2 is accompanied with NCNB matter, it will be considered to be harmful to the environment, as this is not readily acceptable by the eco-system. For instance, the exhaust of the Cu or Ni-plated burner (with catalysts) will include chemicals, e.g. nickel, copper from pipe, trace chemicals from catalysts, beside bulk CO_2 because of adsorption/desorption, catalyst chemistry, etc. These trace chemicals fall under the category of NCNB and cannot be utilised by plants (negative slope from Figure 7). This figure clearly shows that on the upward slope case is sustainable as it makes an integral component of the eco-system. With conventional mass balance approach, the bifurcation graph of Figure 7 would be incorrectly represented by a single graph that is incapable of discerning between different qualities of CO_2 because the information regarding the quality (trace chemicals) are lost in the balance equation. Only recently, the work of Sorokhtin et al. [26] has demonstrated that without such distinction, there cannot be any scientific link between global warming and fossil fuel production and utilisation. In solving Eq. 3, one is likely encounter a set of non-linear equations. These equations cannot be linearised. Recently, Moussavizadegan et al. [27] proposed a method of solving non-linear equations. The principle is to cast Eq. 3 in engineering formulation, as outlined by Abou-Kassem et al. [2], whose principles were further elaborated in Abou-Kassem [12].

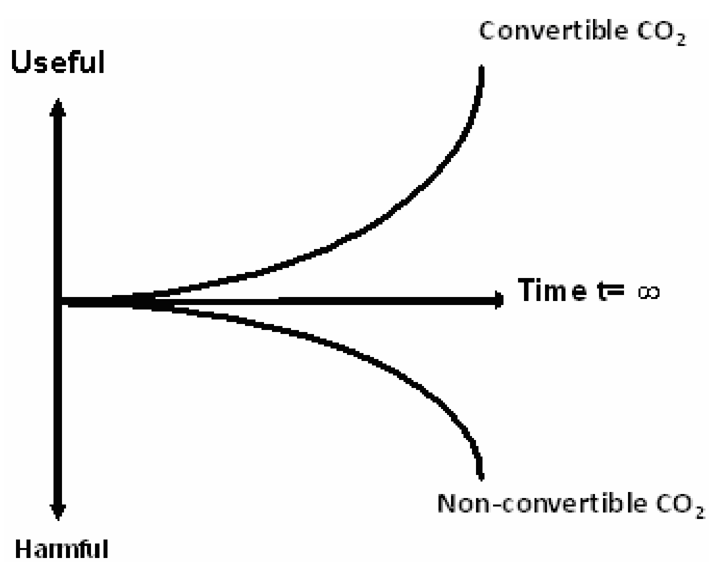

FIGURE 7: Divergent results from natural and artificial

The non-linear algebraic equations then can be solved in multiple solution mode. Mousavizadegan [27] recently solved such an equation to contemporary professionally acceptable standards of computational efficiency. The result looked like what is pictured in Figure 8.

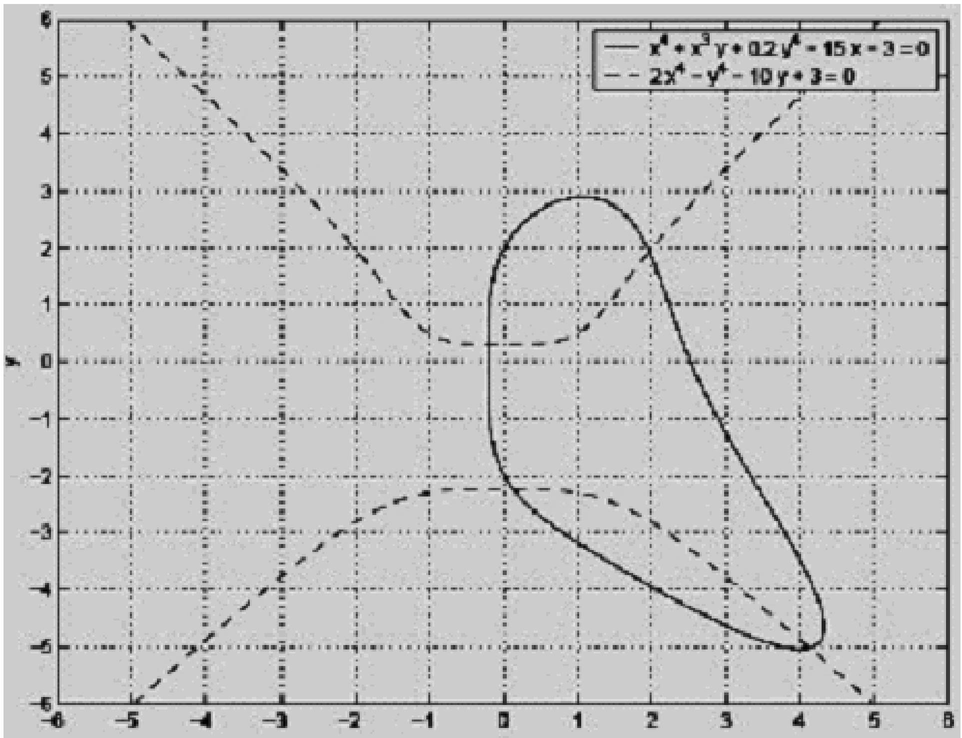

FIGURE 8: The solution behaviour manifested by just two non-linear bivariate equations, $x^4 + x^3y + 0.5y^4 - 15x - 3 = 0$ and $2x^4 - y^4 - 10y + 3 = 0$, suggests that a "cloud" of solutions would emerge.

5. EXAMPLES OF KNOWLEDGE-BASED SIMULATION

A series of computer simulation runs were performed, using the knowledge-based approach. The first series involved the solution of the 1-D multiphase flow problem. The Buckley-Leverett approach involves neglecting the capillary pressure term, leading to spurious multiple solutions. In order to remedy this problem, the well known 'shock' is introduced. While this approach is a practical solution to the problem, it is scientifically inaccurate. The knowledge-based approach requires that à priori simplification and/or linearisation be avoided. The governing 1-D multiphase equation, including the capillary pressure term, was solved using Adomian domain decomposition technique. This technique is capable of solving non-linear equations. The details of the approach are available elsewhere [28]. Figure 9 shows the results obtained for this case. This figure shows how the spurious multiple solutions disappear in favour of a set of monotonous functions. However, one would easily recall that such solutions also appear with conventional finite difference approach, even though this method does use linearisation, albeit at a later stage (during matrix inversion).

In order to determine the role of this linearisation, a series of numerical runs was performed using a non-linear solver. No linearisation was performed during the solution of these multiphase flow problems.

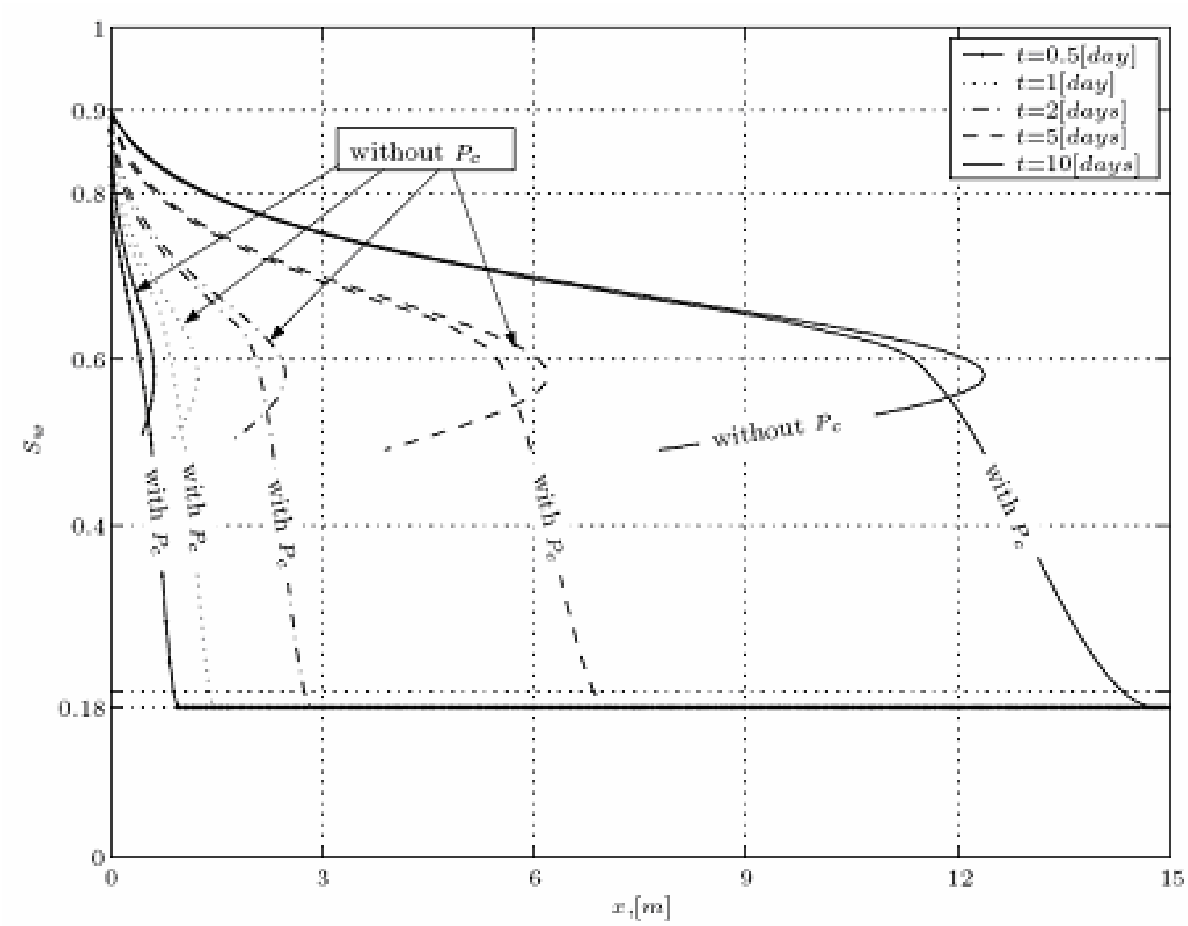

FIGURE 9: 1D multiphase problem solved without linearisation (classical Buckley Leverett equation)

The flow depends on two types of parameters. The first types are those that is changed with the variation of pressure, such as the fluid formation volume factor, the viscosity of the oil and the porosity of the formation. The second type depends on the variation of water saturation. These are the relative permeability of oil and water and the capillary pressure. The parameters are categorised based on their dependency on the pressure or water saturation and the effect of each group are studied separately. A complete description of these runs is available elsewhere [29]. In the first series of runs, the value of the fluid formation volume factor in the process of oil production was varied between 1.2063 to 1.22 from the reservoir pressure to the bubble point pressure. We neglect the compressibility of the fluid and take that B_o = 1.22 during the production process. The pressure and water saturation distribution are computed for a year with Δt = 1(day) and n = 256. The result for t = 3, 6, 9 and 12 (months) are given in Figure 10. The obtained results are then compared with the solutions when the fluid formation volume factor is changed with change in pressure. There are no significant differences at early months of production. But, the differences are increased with time and with the increase in production time. However, it shows that the variation of B_o has a minor effect on the distribution of p_o and S_w.

The variation of the viscosity with the pressure is neglected and it is assumed that μ_o = 1.1340 cp during the production process. This corresponds to the viscosity at the initial reservoir pressure, P_R = 4000 psia. The computations are carried out for a year with Δt = 1(day) and m = 256. The pressure and water saturation distributions are shown in Figure 11 for t = 3, 6, 9 and 12 (months). The results are compared with the the case when $\mu_o = f(p_o)$ as given in (4). There are not significant differences between the results when μ_o = Const. and $\mu_o = f(p_o)$ for various depicted times. It indicates that the variation of viscosity has not a major effect on the pressure and water saturation distributions.

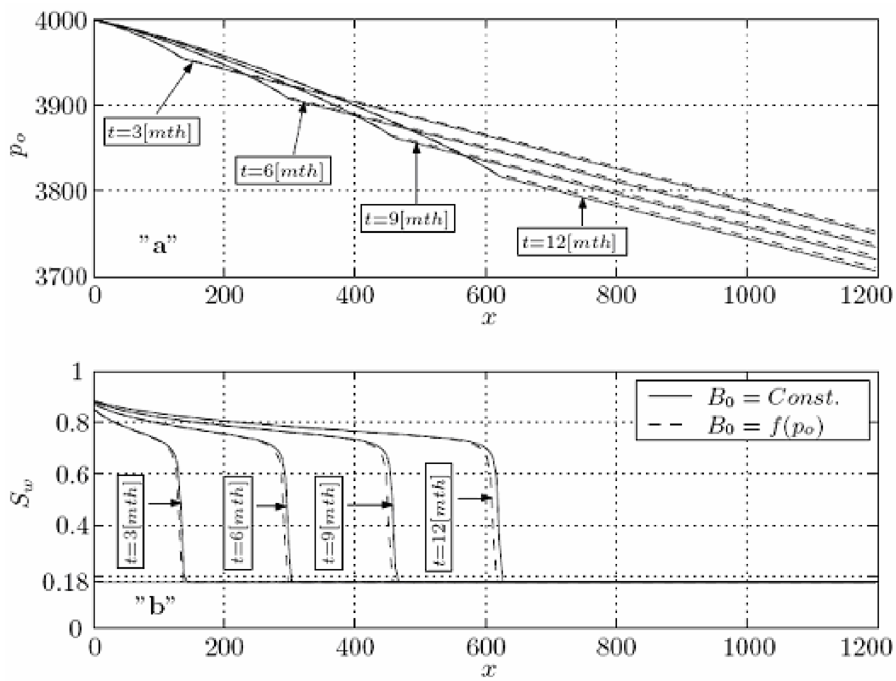

FIGURE 10: Distribution of oil phase pressure and water saturation for constant and variable fluid formation volume factors

The porosity variation due to pressure change is neglected in this part. It is assumed that $\varphi = \varphi_0 = 0.27$ during the production process. The computations are carried out for a year with Δt = 1(day) and m = 256. The pressure and water saturation distributions do not demonstrate any difference between two cases of φ = Const. and $\varphi = f(p_o)$. The pressure and water distributions are shown in Figure 12. There is not any difference between the graphs at a certain time with constant and variable φ, respectively, and the diagrams coincide completely.

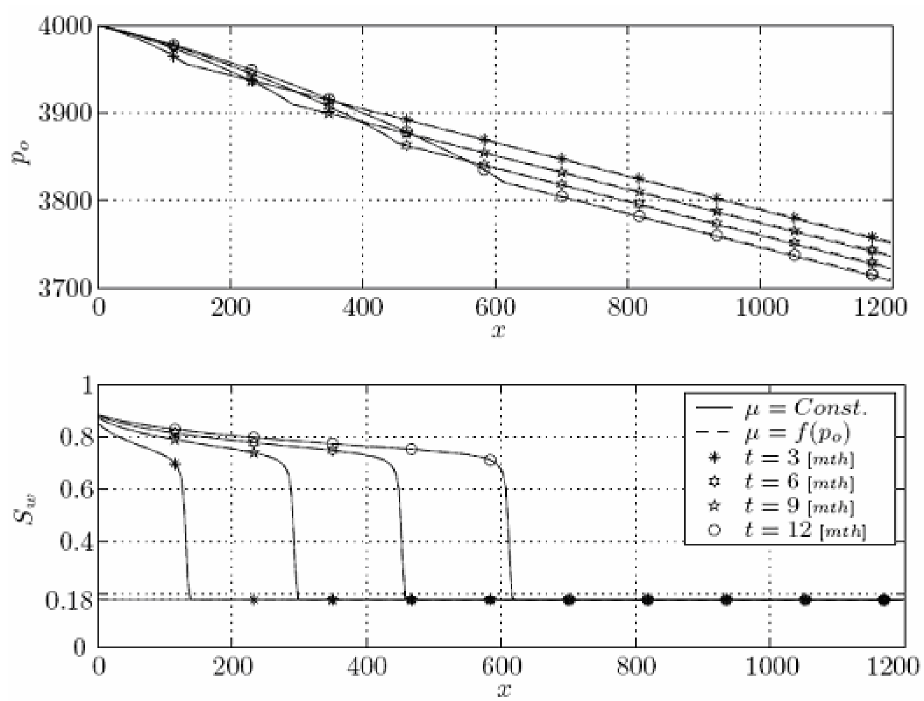

FIGURE 11: The distribution of oil phase pressure and water saturation for constant and variable oil viscosity

In order to study the combined effects, a series of runs was conducted. It was assumed that Bo = 1.22, μ_o = 1.1340 cp and $\varphi = \varphi_o = 0.27$ during the production process. The computations are carried out for a year with Δt = 1(day) and n = 256. The pressure and water saturation distributions are given in Figure 12 for t = 1(year). The results are compared for various cases. Note that, all the results were obtained without linearization at any stage. From these results, it appears that the oil formation volume factor, Bo has major effects while the porosity variation has the minor effect on the oil pressure and water saturation distributions. The water permeability of water and oil and the capillary pressure are dependent on the variation of water saturation. The pressure distribution of the single and double phase flows are given for t = 1(year) in Figure 13. The pressure distribution with neglecting the variation of the pressure dependent parameters is also depicted to provide a comparison and to find out the effect of different parameters on the final results. The effect of the pressure dependent parameters is very small compared with the influence of the water saturation variation.

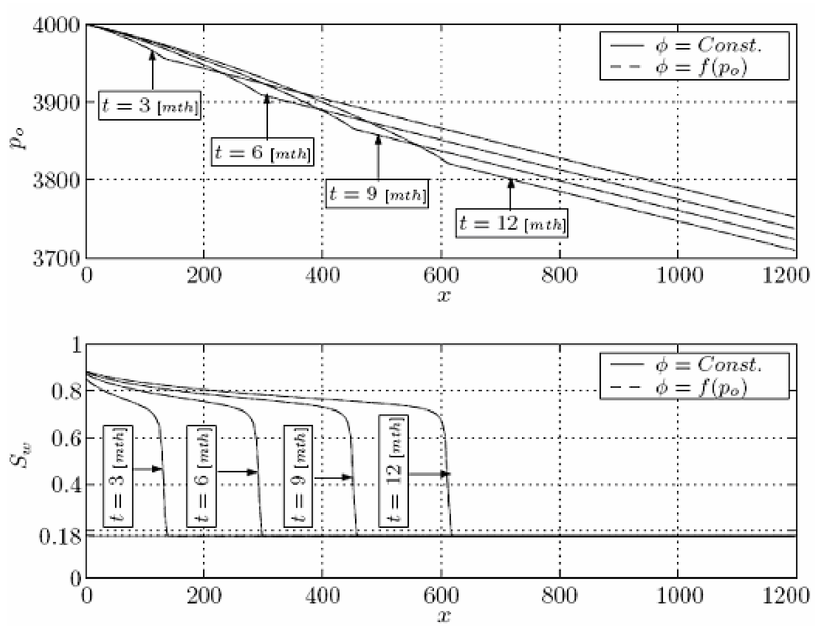

FIGURE 12: Distribution of oil phase pressure and water saturation for constant and variable porosity

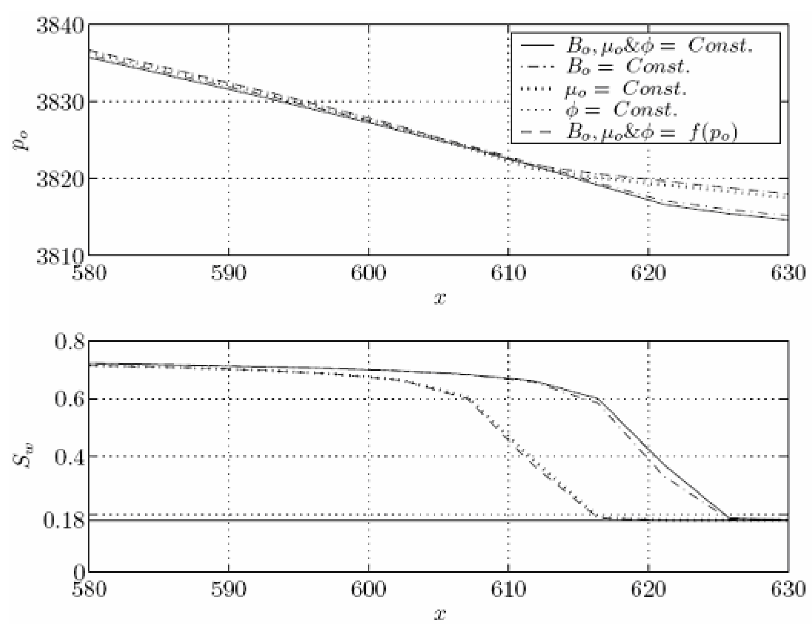

FIGURE 13: Distribution of oil phase pressure and water saturation for constant and variable pressure dependent parameters

The effective permeabilities to water and oil and the capillary pressure are dependent on the variation of water saturation. The pressure distribution of the single and double phase flows are given for t = 1(year) in Figure 14. The pressure distribution with neglecting the variation of the pressure dependent parameters is also depicted to provide a comparison and to find out the effect of different parameters on the final results. The effect of the pressure dependent parameters is very small compared with the influence of the water saturation variation.

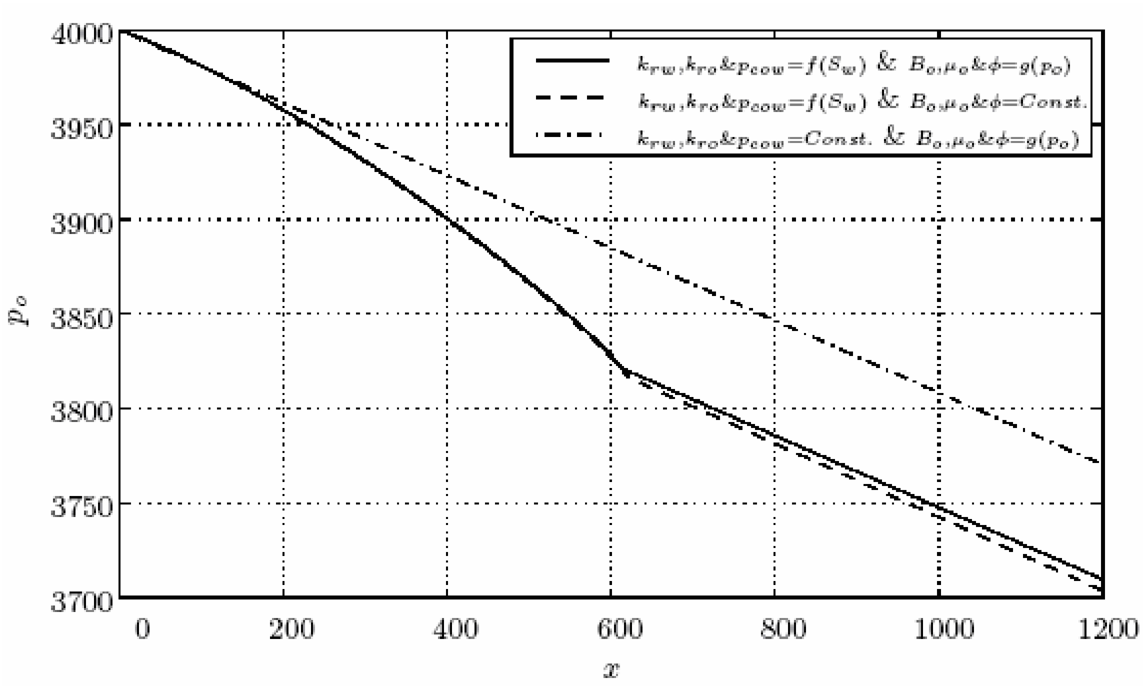

FIGURE 14: Distribution of pressure and water saturation for constant and variable cases

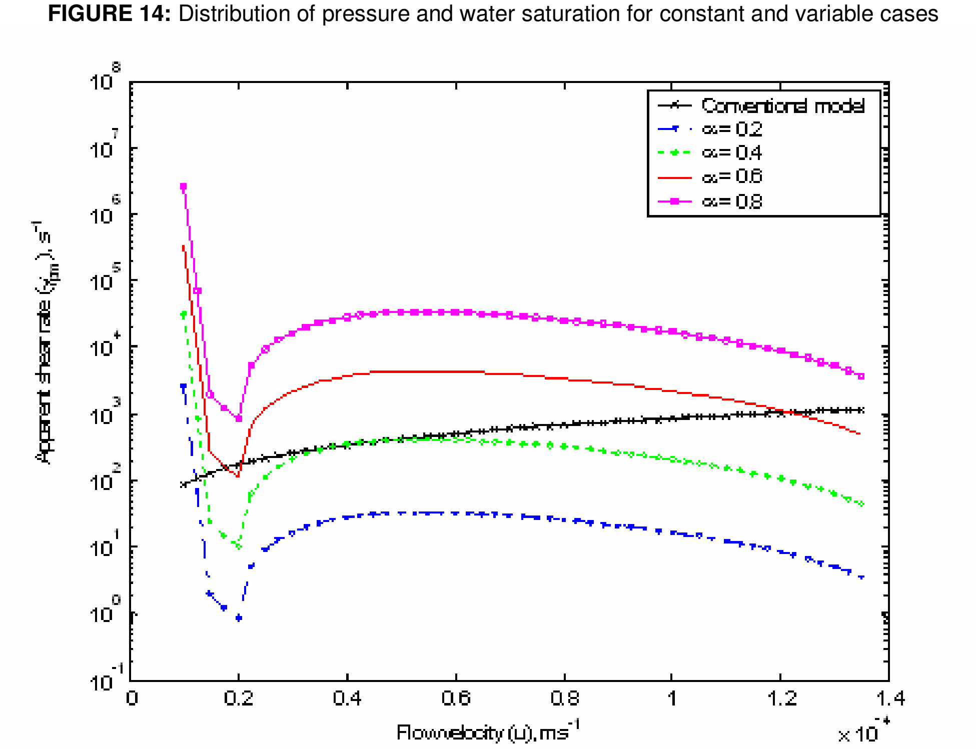

FIGURE 15: The role of memory function in determining apparent viscosity

Finally, results using a recently developed fluid rheology model that includes fluid memory are presented in Figure 15. Once again, fluid memory is considered to be the continuous time function. With the inclusion of the memory, results deviate significantly from the conventional approaches. When, this rheology is coupled with the momentum balance equation, classical cases of multiple solutions arise. Because the exact form of the memory is never known, this depiction would give one an opportunity to refine the prediction envelop, rather than putting too much emphasis on a single solution. Further details of this technique are available in recent work of Hossain and Islam [30].

6. FUTURE RESEACH

Recent research has shown, the source of this uncertainty is the linearization of all governing equations – a standard practice in reservoir simulation. If this linearization is eliminated, the accuracy of the results can improve as much as 30%. A more accurate scenario of the reservoir would add science to the risk analysis, which is often left to arbitrary assignment of the risk factor. A more accurate range of predicted values will reduce the uncertainty to a great extent. The most important aspect of the knowledge-based approach is that it leaves the open the option of multiple solutions, generating a set of cloud points rather than single point solution. The same model is applicable to other fields of engineering, including aviation engineering and biomedical engineering.

Concrete justifications on their results in order to prove that with their knowledge-based approach, results are significantly different for most of the solution regime.

The results and successes reported by recent works of Mousavizadegan et al. (2007), Mustafiz et al. (2008a, 2008b), and Mousavizadegan et al. (2008) in solving equations without linearization promise the success of the knowledge-based approach The benefits of the knowledge-based approach are two-fold. For a specific study, if the results show significant differences between the solutions of the linearized and non-linearized models, the stage will be set to seriously consider the new approach in reservoir simulation. If however the results show insignificant differences for a given range of parametric values, then the proposed research reaffirms that current method of linearization of model equations is appropriate for the given range and, therefore, delineates the range for which fine tuning of the current techniques is necessary.

7. CONCLUSION

In the paper, the concept of knowledge-based modelling is presented. Proposals are made to overcome a number of challenges encountered during modelling of petroleum reservoirs. It is shown that with the knowledge-based approach, results are significantly different for most of the solution regime. This finding would help determine more accurate range of risk factors in petroleum reservoir management. With the proposed technique, sustainable petroleum operations can be modelled to yield different results from unsustainable practices. This also allows one to distinguish between materials that cause global warming and the ones that don’t. Such distinction was not possible with conventional modelling techniques.

8. ACKNOWLEDGMENTS

This paper summarizes recent work of a number of current and former PhD students, such as, Dr Shabbir Mustafiz, Dr Enamul Hossain, Dr Hadi Belhaj, and Mr M. Moniruzzaman Khan. They were funded by various funding agencies and industries. That funding is gratefully acknowledged. The first author gratefully acknowledges the support of King Fahd University of Petroleum & Minerals during the preparation of the manuscript.

9. NOMENCLATURE

All symbols and notations are explained in the text.

10. REFERENCES

1. Rose W. Myths about later-day extensions of Darcy's law. J. Pet. Sci. Eng. 2000: 26(1-4), May; 187-198.
2. Abou-Kassem JH, Farouq Ali, SM. and Islam, MR. A Basic Approach to Reservoir Simulation. Gulf Publishing Co., Houston, Texas, 2006; 455.
3. Zatzman GM and Islam MR. Truth, consequences and intentions: The study of natural and anti-natural starting points and their implications. J. Nature Science and Sustainable Technology 2007; 1(3): 169-174.
4. Mustafiz S. Mousavizadegan H. and Islam, MR. The effects of linearization on solutions of reservoir engineering problems. Pet. Sci. Tech. 2008: 26(11-12): 1224-1246.
5. Eisenack K. Matthias KB. Lüdeke MKB. Petschel-Heldl G. Scheffran J. and Kropp JP. Qualitative modelling techniques to assess patterns of global change, in advanced methods for decision making and risk management in sustainability science, Kropp, J. and Scheffran, J. (eds.), Nova Science Publishers 2007; 83-127.
6. Zatzman GM. and Islam MR. Truth, consequences and intentions: The study of natural and anti-natural starting points and their implications. J. Nature Science and Sustainable Technology 2007a; 1(2): 169-174.
7. Shapiro R. Zatzman GM. and Mohiuddin Y. Towards understanding disinformation. J. Nature Science and Sustainable Technology 2007; 1(3): 471-504.
8. Mustafiz S. and Islam MR. State of the art of reservoir simulation. Pet. Sci. Tech. 2008; 26(11-12): 1303-1329.
9. Zatzman, GM. and Islam MR. Economics of intangibles. Nova Science Publishers: 431; 2007b.
10. Kline M. Mathematical thought from ancient to modern times. Oxford University Press, New York, USA, 1238: 1972.
11. Bear J. Dynamics of fluids in porous media. American Elsevier Publishing Co., New York, 761; 1972.
12. Abou-Kassem JH. Engineering approach vs the mathematical approach in developing reservoir simulators, J. Nature Science and Sustainable Technology. 2007; 1(1): 35-68.
13. Zatzman GM. Khan MM. and Islam MR. The use of newly formulated comprehensive mass and energy balance equation to develop an atmospheric model. paper ID: 588-301, WSEAS Transaction; 2008.
14. Gleick J. Chaos – making a new science. Penguin Books, NY; 352; 1987.
15. Wilkinson DS. Maire E. and Embury JD. The role of heterogeneity on the flow and fracture of two-phase materials. Materials Science and Engineering. A. Structural 997; 233: 145-154.
16. Naami AM. Catania P. and Islam MR. Numerical and experimental modelling of viscous fingering in two-dimensional consolidated porous medium. CIM paper no. 118, CIM conference, Regina, Oct. 1999.
17. Aboudheir A. Kocabas I. and Islam MR. Improvement of numerical methods in petroleum engineering problems. Proceedings IASTED International Conference, Applied Modelling and Simulation, Cairns, Australia, Sept. 1-3. 1999.
18. Bokhari K. and Islam MR. Improvement in the time accuracy of numerical methods in petroleum engineering problems – A new combination. Energy Sources 2005; 27(1-2): 45-60.
19. Bokhari K. Mustafiz S. and Islam MR. Numerical modelling of viscous fingering under combined effects of thermal, solutal and mixed convection in liquid-liquid miscible displacements. Journal of Petroleum Science and Technology. accepted for publication, May, 2006.
20. Saghir, Z., Chaalal, O. and Islam, M.R., 2000, "Experimental and Numerical Modeling of Viscous Fingering", *J. Pet. Sci. Eng.*, vol. 26(1-4), 253-262.
21. Khan MI. and Islam MR. The petroleum engineering handbook: sustainable operations. Gulf Publishing Co., Houston, USA, 461: 2007.
22. Khan MI. and Islam MR. True Sustainability in technological development and natural resources management. Nova Science Publishers, New York, USA, 381: 2007b.
23. Khan MM. Zatzman GM. and Islam MR. The formulation of a comprehensive mass and energy balance equation, ASME International Mechanical Engineering Congress and Exposition, Nov. 2-6, Boston, MA.: 2008.
24. Chhetri AB. and Islam MR. Inherently sustainable technology developments, Nova Science Publishers, New York, 452; 2008.
25. Lim, M.L., Land, M.F., 2007, "Sex-specific UV and Fluorescence Signals in Jumping Spiders", Jan. 26:315 (5811), pp. 481.
26. Sorokhtin OG. Chilingar GV. and Khilyuk LF. Global warming and cooling. Elsevier, 313; 2007.

27. Mousavizadegan SH. Mustafiz S. and Rahman M. The adomian decomposition method on solution of non-linear partial differential equations, J. Nature Science and Sustainable Technology 2007; 1(1): 115-131.
28. Mustafiz S. Mousavizadegan H. and Islam MR. Adomian decomposition of Buckley Leverett equation with capillary terms, Pet. Sci. Tech.: in press.
29. Islam MR. Mousavizadeghan and Mustafiz S. Handbook of knowledge-based reservoir simulation. Gulf Publishing Company, Houston, TX, to be published in March 2009.
30. Hossain, ME and Islam, MR. An Advanced Analysis Technique for Sustainable Petroleum Operations. VDM Verlag Dr. Muller Aktiengesellschaft & Co. KG, Germany, 2009.
31. Hossain, M.E., Mousavizadegan, S.H. and Islam, M.R. (2009). The Mystery and Uncertainty Cloud during Reservoir Simulation in Petroleum Industry. *Advances in Sustainable Petroleum Engineering Science*, in press.