Semi Analytic-Numerical Solution of Fingero - Imbibition Phenomenon in Heterogenous Porous Medium with Magnetic Field Effect

**Amit K Parikh**

*Professor & Principal,*

*Mehsana Urban Institute of Sciences, Ganpat University,Kherva-384012, Mehsana,Gujarat, India*

**Aruna Sharma**

*Research Scholar,*

*Department of Mathematics, Mehsana Urban Institute of Sciences, Ganpat University, Kherva-384012, Mehsana, Gujarat, India.*

ABSTRACT

The present paper studies the magnetic field effect on Fingero- Imbibition phenomenon in a double phase flow in a heterogenous porous media. Fingero- Imbibition Phenomenon is due to the occurrence of two key phenomena, namely imbibition and fingering. Imbibition is the displacement of a non-wetting fluid by a wetting fluid in a porous medium, where the non-wetting fluid is oil and the wetting fluid is water. When a fluid with a higher viscosity is displaced by a fluid with a lower viscosity, protuberances occur instead of the normal displacement of the entire front and these protuberances shoot through the porous medium at a relatively rapid speed, leading to the development of fingers and this is termed as fingering phenomenon. Fingero-Imbibition phenomenon has tremendous importance in secondary oil recovery process. This phenomenon is mathematically formulated as a highly nonlinear partial differential equation, which is solved using the Multistep Hybrid Differential Transform Finite Difference Method. A solution is obtained using this Semi Analytic-Numerical Multistep Hybrid Differential Transform Finite Difference Method. The solution to this equation determines the saturation of the injected water in a double phase flow at various distances and times, as well as the effect of the magnetic field on the saturation can be obtained.

Combining the Multistep Differential Transform Method and Finite Difference Method results in the Multistep Hybrid Differential Transform Finite Difference Method. The effectiveness of the Finite Difference Method is combined with the adaptability of the Differential Transform Method. The numerical solution is acquired using an easy iterative method, which speeds up computation in comparison to the traditional Differential Transform Method. This approach has been discovered to be reliable and effective. By making all calculations simpler, it lessens computing work. In this method the Multistep Differential Transform Method (MDTM) and Finite Difference Method (FDM) have been used to achieve the solution for large values of time. Using MATLAB, the numerical solution and graphical representation were obtained. The results obtained were compared with the existing results and found to be in close agreement.

Keywords— Fingering, Imbibition, Hybrid Differential transform Method, Double phase flow, Heterogenous porous media,magenetic field

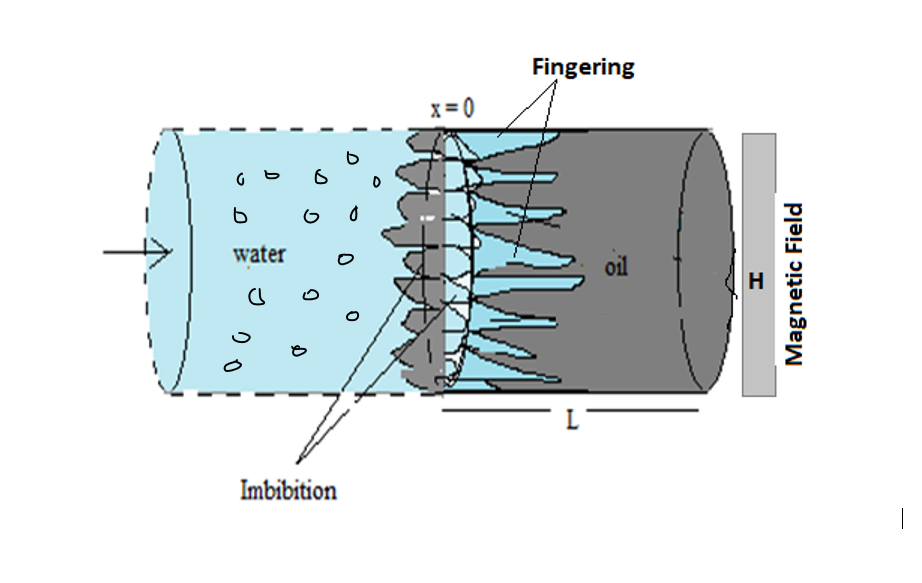
1. **INTRODUCTION**

The primary aim here is to study the effect of magnetic field on Fingero- Imbibition phenomenon in heterogenous porous media. If a porous medium saturated with a nonwetting fluid (oil) comes into contact with a wetting fluid (water), the wetting fluid spontaneously flows into the medium and the nonwetting fluid spontaneously flows out of the medium. This is referred to as the imbibition phenomena that arises due to differences in fluid wetting abilities. When a porous media filled with one fluid is displaced by another fluid of lower viscosity, protuberances occur instead of the normal displacement of the entire front and these protuberances shoot through the porous medium at a relatively rapid speed, leading to the development of fingers. Fingero-Imbibition Phenomenon is caused due to the simultaneous occurrence of fingering and imbibition. This phenomenon is observed in many engineering disciplines, including petroleum technology, soil mechanics, agricultural engineering, hydrology, etc. Many researchers are also investigating this phenomenon.

This phenomenon was investigated by Shah and Verma [5] in a heterogeneous porous media with magnetic field effect. The similarity transformation was utilized by Desai [21]. Mehta and Verma [3] investigated the composite expansion of finger imbibition in heterogeneous porous media. Patel, K. R., Mehta, M. N., and Patel, T. R. [4] investigated fingero-imbibition in double phase flow across heterogeneous porous media. The fingero-imbibition phenomenon in homogeneous porous material with magnetic field influence in vertical downward direction was discussed by Parikh, A. K., Mehta, M. N., and Pradhan, V. H. [10].

This paper aims to measure the saturation of injected water at a distance of '' and a time of '' and to examine how the magnetic field affects saturation for the Fingero-Imbibition phenomenon in heterogeneous porous media. With the proper initial and boundary conditions, the Multistep Hybrid Differential Transform Finite Difference Method was used to solve the nonlinear partial differential equation that results from the mathematical formulation.

1. **Statement of Problem**



Consider a heterogeneous porous medium that is fully saturated with native fluid oil(o) and uniformly injected with water with magnetic particles. Assume that oil is nonconductive and the injected water is conductive. This Fingero-imbibition Phenomenon is caused by the simultaneous occurrence of the imbibition and fingering phenomena for a preferentially wetting phase and a less viscous phase in the secondary oil recovery process. In a heterogeneous porous medium, rock characteristics like porosity and permeability vary from place to place. Porosity in a heterogeneous porous material is regarded as a function of space ''. The fingers vary in size and shape, but we assume that they are rectangles and only take into account the average cross-sectional area that is filled by the fingers, omitting the specific size and shape of each finger. The variable magnetic field has the effect of increasing the velocity of injected water by a gradient where is the permeability of the magnetic field. The average cross-sectional area occupied by the injected water at a distance of ' and a time of '' is defined as the saturation of injected water. The average cross-sectional area filled by fingers is taken into consideration, regardless of size or shape

1. **Mathematical Formulation**

Assuming Darcy’s Law [14,15] to be valid, the velocity of injected water and velocity of oil can be expressed as

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

The equation of continuity of injected water is

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

where,

|  |  |  |
| --- | --- | --- |
| ∅= | | represents the porosity of the heterogenous medium |
|  | Variable permeability in | | |
|  | relative permeability of water | | |
|  | relative permeability of oil | | |
|  | pressure of water (injected fluid) | | |
|  | pressure of oil (native fluid) | | |
|  | seepage velocity of water (m /s ) | | |
|  | seepage velocity of oil (m /s ) | | |
|  | constant kinematic viscosity of water | | |
|  | constant kinematic viscosity of oil | | |
|  | porosity of a medium | | |

In the counter current imbibition phenomenon, the combined velocities of the injected water and native oil are zero[25].Therefore,

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

From (1) and(2) and (4) in (5) we get,

|  |  |  |
| --- | --- | --- |
|  |  |  |

Substitute for ,we get,

|  |  |  |
| --- | --- | --- |
|  |  |  |

Simplifying we get,

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

Simplifying ,

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

According to Scheidegger [14] it is assumed ,

(7)

Substitute equation (6) and (7) in equation (1) ,we get,

Therefore,

(8)

|  |  |  |
| --- | --- | --- |
|  |  |  |

Substituting in equation (3) we get,

|  |  |  |
| --- | --- | --- |
|  | Assuming A The capillary pressure is considered as a linear function [19]  where,is a constant. | (9)  (10) |

The standard relationship between phase saturation and relative permeability [1] is considered as,

|  |  |  |
| --- | --- | --- |
|  |  | (11) |

where,is a constant.

Assume porosity and permeability are functions of only, as we are considering a uniform heterogenous porous medium [2]

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  | (12) |

where .

Since, cannot exceed unity we assume,

For simplicity we consider [12]

|  |  |  |
| --- | --- | --- |
|  |  | (13) |

where is a constant.

We express H as [4,22] , considering the magnetic field in the 'x' direction.

H=

Here ‘n’ is an integer and is a constant parameter. Using the value of H for n=1 in equation (9) with equations (10), (11), and (13), we get,

|  |  |  |
| --- | --- | --- |
|  |  | (14) |

|  |  |  |
| --- | --- | --- |
|  |  | (15) |

Using dimensionless variables,

|  |  |  |
| --- | --- | --- |
|  |  | (16) |

Since,

(Neglecting higher order terms in )

Therefore,

Substituting equation (16) simplifies to,

|  |  |  |
| --- | --- | --- |
|  | where A=, B= and | (17) |

(17) is the non-linear partial differential equation for the finger-imbibition phenomenon in the heterogenous porous medium and its solution gives the saturation of injected water at time ‘’ and distance’’.

Assuming initial and boundary conditions as follows [9]:

Initial conditions: , 0

Boundary conditions: , T

= , T

**IV. Problem Solution**

Consider Fingero-Imbibition phenomenon equation

|  |  |  |
| --- | --- | --- |
|  |  |  |

The governing equation is a nonlinear partial differential equation.

Therefore, the initial condition is ,

|  |  |  |
| --- | --- | --- |
|  | , , | (18) |

Taking appropriate boundary conditions as

|  |  |  |
| --- | --- | --- |
|  | , T  = , T | (19) |
|  |  |  |

(17) is solved using the Hybrid Differential Transform and the Finite Difference Method (HDTFDM) for small values of “T” and Multistep Hybrid Differential Transform Finite Difference Method for large values of ‘T’.

**SOLUTION BY HYBRID DIFFERENTIAL TRANSFORM FINITE DIFFERENCE METHOD (HDTFDM)**

1. **Methodology**

The nonlinear partial differential equation [17] is solved using the Hybrid Differential Transform and Finite Difference Method (HDTFDM). This method combines the Differential Transform Method (DTM) and the Finite Difference Method (FDM). The Finite Difference Method is used to approximate the spatial variables, and the Differential Transform Method is used to approximate the time variables.

Zhou [25] introduced the DTM for the solution of linear and nonlinear differential equations in electrical circuit analysis. The hybrid approach was employed by Yu, L.T., and Chen, C.K. [20].

The finite difference approach is applied to the 'X variable and the differential transform is employed for the 'T' variable. The hybrid approach is effective for solving both linear and nonlinear partial differential equations because it has been shown to converge quickly with few iterations

**B. Preliminaries**

The Differential Transform of the kth derivative of applied to the ‘t’ variable is given as

|  |  |  |
| --- | --- | --- |
|  |  | (20) |

The inverse Transformation of is given as

|  |  |  |
| --- | --- | --- |
|  |  | (21) |

where represents the original function and represents transformed function.

|  |  |  |
| --- | --- | --- |
|  |  | (22) |

where i  ­i

where h is the finite difference step interval.

The theorems are as follows [25] and [26]

**Theorem 1**.

**Theorem 2.**

**Theorem 3**.=

**Theorem 4**.=

**Theorem 5.** =

**Theorem 6.**

**Theorem 7**.

**C. Numerical Solution**

Applying HDTFDM (17),we get

|  |  |  |
| --- | --- | --- |
|  | subject to  Initial Conditions: , ,  Boundary Conditions: , T  = , T |  |

Taking

Applying, Differential Transformation to the ‘’ variable and finite difference to the ‘’ variable ,

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | | (29) |
|  | | |
| where is the original function and,­i  ­i transformed function   |  |  |  | | --- | --- | --- | |  | Initial Conditions: ,  Boundary Conditions: |  | | | |
|  | | |
|  | | |
| where N is the no. of spatial segments.  Substituting in (17) we get,  relation,  (23)  where for are  obtained. The approximate solutions for various values ‘X’ and ‘T’ are found using the inverse  transformation,   |  |  |  | | --- | --- | --- | |  |  | (24) |   i=0,   |  |  |  | | --- | --- | --- | |  |  | (25) |   where I = mesh points for  **V Results and Discussion**  The numerical saturation values obtained from equation (24) for various distances ' at fixed time =0.001,0.002,0.003,0.004,0.005,0.006,0.007,0.008,0.009,.01 are shown in Table 1 below.  **Table 1: Saturation (,) for values of distance’ ’ and time ‘’ (HDTFDM)** | | |
| |  |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | **X\T** | **0.001** | **0.002** | **0.003** | **0.004** | **0.005** | **0.006** | **0.007** | **0.008** | **0.009** | **0.01** | | **0** | **0.0002** | **0.0004** | **0.0006** | **0.0008** | **0.001** | **0.0012** | **0.0014** | **0.0016** | **0.0018** | **0.002** | | **0.1** | **0.0024** | **0.0028** | **0.0032** | **0.0035** | **0.0039** | **0.0042** | **0.0046** | **0.0049** | **0.0052** | **0.0056** | | **0.2** | **0.0084** | **0.0089** | **0.0093** | **0.0097** | **0.0101** | **0.0105** | **0.0109** | **0.0113** | **0.0117** | **0.0121** | | **0.3** | **0.0184** | **0.0189** | **0.0193** | **0.0197** | **0.0202** | **0.0206** | **0.021** | **0.0214** | **0.0219** | **0.0223** | | **0.4** | **0.0324** | **0.0329** | **0.0333** | **0.0337** | **0.0342** | **0.0346** | **0.035** | **0.0355** | **0.0359** | **0.0363** | | **0.5** | **0.0504** | **0.0509** | **0.0513** | **0.0517** | **0.0521** | **0.0526** | **0.053** | **0.0534** | **0.0538** | **0.0542** | | **0.6** | **0.0724** | **0.0728** | **0.0732** | **0.0737** | **0.0741** | **0.0745** | **0.0749** | **0.0753** | **0.0757** | **0.0761** | | **0.7** | **0.0984** | **0.0988** | **0.0992** | **0.0996** | **0.1** | **0.1004** | **0.1008** | **0.1012** | **0.1015** | **0.1019** | | **0.8** | **0.1284** | **0.1287** | **0.1291** | **0.1295** | **0.1299** | **0.1302** | **0.1306** | **0.131** | **0.1314** | **0.1318** | | **0.9** | **0.1623** | **0.1627** | **0.1631** | **0.1635** | **0.1639** | **0.1643** | **0.1648** | **0.1652** | **0.1656** | **0.1661** | | **1** | **0.2006** | **0.2012** | **0.2018** | **0.2024** | **0.203** | **0.2036** | **0.2042** | **0.2048** | **0.2054** | **0.206** |  1. **Graphical representation**:   **Fig 3** : **Saturation () for values of distance’ ’ and time ‘’ (HDTFDM)** | | |

From the graph in Fig.3, the saturation of the injected water increases when the distance 'X' increases for a fixed time ' and also increases when the time 'T' increases for a fixed distance ''.

1. **Limitation of Hybrid Differential transform Method** :

The HDFDTM is used to approximate solutions to a wide range of nonlinear problems with convergent series and easily computed components; nonetheless, it has certain limitations: In a small region, the series solution always converges quickly, but in a wider region, it converges slowly. In a very small region, this series solution provides a good approximation to the true solution. The Multi-step DTM (MDTM) and finite Difference Method (FDM) are improved methods that accelerate series solution convergence over a large region while also improving DTM accuracy.

**VI. Multistep Hybrid Differential Transform Finite Difference Method** (MHDTFDM):

The computation interval [0, T] is not small in some modelling settings, hence the full domain T is partitioned into 'N' subdomains to speed convergence and increase calculation accuracy. The key advantage of partitioning the domain is that the solution can be constructed in a small period of time using a minimal number of Taylor series terms. It is important to remember that, if necessary, the time interval might be arbitrarily tiny. The differential equations in each subdomain can be solved as a result.

1. **METHODOLGY**

DTM solutions have a small convergence interval, but multi-step DTM solutions have a wide convergence interval. This depicts how the MDTM increases the interval of convergence. Of course, by reducing the step size h and raising the number of terms in each subinterval, the accuracy can be enhanced.

Definition 1:

The Differential Transform is defined as follows

|  |  |  |
| --- | --- | --- |
|  |  | (26) |

where and ) are the original function and transformed function respectively.

The inverse transformation is defined as,

|  |  |  |
| --- | --- | --- |
|  |  | (27) |

and the function is considered as a series with finite terms

|  |  |  |
| --- | --- | --- |
|  |  | (28) |

where m represents no. of Taylor series components. Increasing the no. of terms can improve the accuracy of the solution.

**B. Solution of Partial Differential equation in in domain**

We divide the domain into N sections where H= T/N is the length of each subdomain.

So, a separate function is considered for each sub domain.

|  |  |  |
| --- | --- | --- |
|  | where | (29) |

|  |  |  |
| --- | --- | --- |
|  | where | (30) |

|  |  |  |
| --- | --- | --- |
|  | where | (31) |

The solution of equation (21) is of the form

,for

Applying Central finite difference to the spatial variable and MDTM to the variable

From (17), the following recurrence relation can be obtained

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | is the differential transform of  Here, separate functions are considered in each sub domain i.e   |  |  |  | | --- | --- | --- | |  | =  **(x,t)** = where | (33)3) | | (32) |

where is the original function and,­i ­i transformed function

Applying Multistep Differential Transform Method (MDTM) to the ‘T’ variable and Finite Difference Method ( FDM ) on the initial conditions, we have

|  |  |  |
| --- | --- | --- |
|  | Initial Conditions: ,  Boundary Conditions: |  |

where N is the no. of spatial segments.

Here and we use the continuity condition in each time subdomain.

Firstly, the DTM is applied to the given PDE over the interval [0,.005]. For the next time step, the value at T = .005 is used as an initial condition in the interval[.005,.01]

For 1,1

MDTM is implemented by dividing the solution interval [0,1] into 200 subintervals with step sizes equal to H = 0.005.

**VII. RESULTS AND DISCUSSION**

The numerical saturation values obtained from equation (32) and (33) for various distances ' at fixed time =0.01,0.02,0.03,0.04,0.05,0.06,0.07,0.08,0.09and .1, using MATLAB are shown in Table **2** below.

T**able 2**: **Saturation (X,T) for values of distance 'X' and time 'T’ by Hybrid Multistep Differential Transform and Finite Difference method for**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **X\T** | **0.01** | **0.02** | **0.03** | **0.04** | **0.05** | **0.06** | **0.07** | **0.08** | **0.09** | **0.1** |
| **0** | **0.002** | **0.004** | **0.006** | **0.008** | **0.01** | **0.012** | **0.0140** | **0.016** | **0.018** | **0.02** |
| **0.1** | **0.0056** | **0.0086** | **0.0114** | **0.0141** | **0.0167** | **0.0193** | **0.0217** | **0.0242** | **0.0266** | **0.029** |
| **0.2** | **0.0121** | **0.0158** | **0.0193** | **0.0226** | **0.0257** | **0.0287** | **0.0317** | **0.0346** | **0.0374** | **0.0402** |
| **0.3** | **0.0223** | **0.0264** | **0.0302** | **0.0339** | **0.0374** | **0.0408** | **0.0442** | **0.0474** | **0.0507** | **0.0539** |
| **0.4** | **0.0363** | **0.0405** | **0.0446** | **0.0485** | **0.0523** | **0.056** | **0.0597** | **0.0633** | **0.0669** | **0.0704** |
| **0.5** | **0.0543** | **0.0585** | **0.0626** | **0.0666** | **0.0706** | **0.0746** | **0.0785** | **0.0825** | **0.0864** | **0.0902** |
| **0.6** | **0.0761** | **0.0803** | **0.0844** | **0.0886** | **0.0928** | **0.097** | **0.1012** | **0.1054** | **0.1096** | **0.1138** |
| **0.7** | **0.102** | **0.106** | **0.1102** | **0.1146** | **0.119** | **0.1235** | **0.128** | **0.1326** | **0.1371** | **0.1417** |
| **0.8** | **0.1318** | **0.1361** | **0.1405** | **0.1452** | **0.15** | **0.1548** | **0.1597** | **0.1647** | **0.1696** | **0.1746** |
| **0.9** | **0.1661** | **0.1709** | **0.176** | **0.1812** | **0.1865** | **0.1919** | **0.1973** | **0.2027** | **0.2081** | **0.2135** |
| **1** | **0.206** | **0.212** | **0.218** | **0.224** | **0.23** | **0.236** | **0.242** | **0.248** | **0.254** | **0.26** |

From Table 2, we observe that the values of saturation converge in this interval by using MDTM.

We continue finding for the remaining intervals [.1,.2], [.2,.3] and so on and saturation at T=.1,.2,.3…… is shown in TABLE 3.

T**able 3**: **Saturation (X,T) for values of distance 'X' and time 'T’ by Multistep Hybrid Differential Transform and Finite Difference method for**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **X/T** | **0.1** | **0.2** | **0.3** | **0.4** | **0.5** | **0.6** | **0.7** | **0.8** | **0.9** | **1** |
| **0** | **0.02** | **0.04** | **0.06** | **0.08** | **0.1** | **0.1200** | **0.1400** | **0.16** | **0.18** | **0.2000** |
| **0.1** | **0.029** | **0.0528** | **0.0759** | **0.0988** | **0.1214** | **0.1436** | **0.1656** | **0.1871** | **0.2083** | **0.2292** |
| **0.2** | **0.0402** | **0.0675** | **0.0938** | **0.1197** | **0.1449** | **0.1694** | **0.1934** | **0.2166** | **0.2391** | **0.2609** |
| **0.3** | **0.0539** | **0.0847** | **0.1142** | **0.143** | **0.1709** | **0.1978** | **0.2239** | **0.2489** | **0.2729** | **0.2957** |
| **0.4** | **0.0704** | **0.1046** | **0.1374** | **0.1692** | **0.1999** | **0.2294** | **0.2577** | **0.2847** | **0.3103** | **0.3342** |
| **0.5** | **0.0902** | **0.1278** | **0.164** | **0.1988** | **0.2326** | **0.2649** | **0.2955** | **0.3247** | **0.352** | **0.3772** |
| **0.6** | **0.1138** | **0.1548** | **0.1945** | **0.2328** | **0.2697** | **0.305** | **0.3385** | **0.3701** | **0.3994** | **0.4262** |
| **0.7** | **0.1417** | **0.1864** | **0.2299** | **0.272** | **0.3126** | **0.3514** | **0.3883** | **0.4228** | **0.4545** | **0.4832** |
| **0.8** | **0.1746** | **0.2235** | **0.2713** | **0.3177** | **0.3628** | **0.4061** | **0.4473** | **0.4858** | **0.5211** | **0.5524** |
| **0.9** | **0.2135** | **0.2673** | **0.3204** | **0.3725** | **0.4234** | **0.4729** | **0.5205** | **0.5654** | **0.6069** | **0.6435** |
| **1** | **0.26** | **0.32** | **0.38** | **0.44** | **0.5** | **0.56** | **0.62** | **0.68** | **0.74** | **0.8** |

As we can see, the main advantage of the MDTM is that the obtained series solution converges for wide time region, which is not possible by the traditional DTM

From the table. we observe that the saturation () of injected water is increasing when distance ‘ ’ is increasing for fixed time ‘ ’ and saturation is also increasing when time ‘’ is increasing for fixed distance ‘’.

**Graphical Representation:**

Figure 4 : **Saturation () for values of distance' ' and time '' by Multistep Hybrid Differential Transform Finite Difference Method**

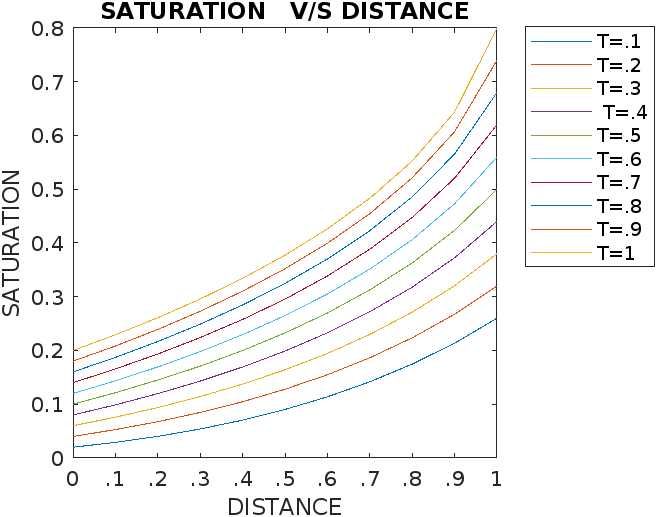


Figure 5 : **3 D plot of** **Saturation () for different values of distance' ' and time '' by Multistep Hybrid Differential Transform Finite Difference Method**

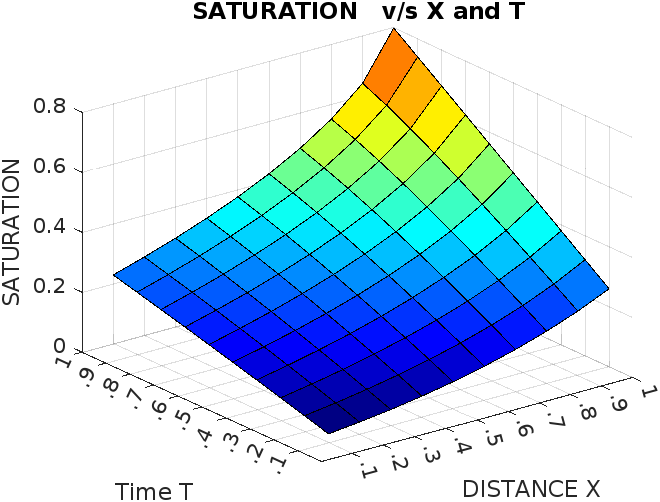


Fig.5 is a 3D plot of Saturation V/s Distance and Time. Here we can clearly observe that the saturation () of injected water is increasing when distance ‘ ’ is increasing for fixed time ‘ ’ and also increasing with time ‘’ for fixed distance’’.

The above solution was compared with Homotopy Analysis Method [9] and the results were found to be in close agreement.

Table 4**. COMPARISON OF MULTISTEP HYBRID DIFFERENTIAL TRANSFORM METHOD AND HOMOTOPY ANALYSIS METHOD [9]**



|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **X/T** | **0.1** | |  | **0.3** | |  | **0.5** | |  | **0.7** | |  | **0.9** | |
|  | **HDTFD** | **HAM** |  | **HDTFD** | **HAM** |  | **HDTFD** | **HAM** |  | **HDTFD** | **HAM** |  | **HDTFD** | **HAM** |
| **0** | **0.02** | **0.0200** |  | **0.06** | **0.06** |  | **0.1** | **0.1** |  | **0.1400** | **0.14** |  | **0.18** | **0.18** |
| **0.1** | **0.029** | **0.0295** |  | **0.0759** | **0.0759** |  | **0.1214** | **0.1213** |  | **0.1656** | **0.1654** |  | **0.2083** | **0.2081** |
| **0.2** | **0.0402** | **0.0410** |  | **0.0938** | **0.0939** |  | **0.1449** | **0.1447** |  | **0.1934** | **0.1931** |  | **0.2391** | **0.2387** |
| **0.3** | **0.0539** | **0.0548** |  | **0.1142** | **0.1142** |  | **0.1709** | **0.1706** |  | **0.2239** | **0.2235** |  | **0.2729** | **0.2723** |
| **0.4** | **0.0704** | **0.0714** |  | **0.1374** | **0.1374** |  | **0.1999** | **0.1995** |  | **0.2577** | **0.2572** |  | **0.3103** | **0.3094** |
| **0.5** | **0.0902** | **0.0912** |  | **0.164** | **0.1639** |  | **0.2326** | **0.2322** |  | **0.2955** | **0.295** |  | **0.352** | **0.351** |
| **0.6** | **0.1138** | **0.1146** |  | **0.1945** | **0.1944** |  | **0.2697** | **0.2693** |  | **0.3385** | **0.3379** |  | **0.3994** | **0.3982** |
| **0.7** | **0.1417** | **0.1422** |  | **0.2299** | **0.2297** |  | **0.3126** | **0.3121** |  | **0.3883** | **0.3875** |  | **0.4545** | **0.453** |
| **0.8** | **0.1746** | **0.1749** |  | **0.2713** | **0.2711** |  | **0.3628** | **0.3624** |  | **0.4473** | **0.4464** |  | **0.5211** | **0.5191** |
| **0.9** | **0.2135** | **0.2136** |  | **0.3204** | **0.3202** |  | **0.4234** | **0.4231** |  | **0.5205** | **0.5197** |  | **0.6069** | **0.6045** |
| **1** | **0.26** | **0.2600** |  | **0.38** | **0.38** |  | **0.5** | **0.5** |  | **0.62** | **0.62** |  | **0.74** | **0.74** |

Table 4 . shows the comparison of Multistep Hybrid Differential Transform Finite Difference Method with Homotopy Analysis Method and the results are found to be in close agreement

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **With Magnetic**  **Field** | **Without**  **Magnetic field** |  | **With Magnetic**  **Field** | **Without**  **Magnetic field** |  | **With Magnetic**  **Field** |  | **Without**  **Magnetic field** |  | **With Magnetic**  **Field** | **Without**  **Magnetic field** |  | **With Magnetic**  **Field** | **Without**  **Magnetic field** |
| **x/t** | **0.1** | **0.1** |  | **0.3** | **0.3** |  | **0.5** |  | **0.5** |  | **0.7** | **0.7** |  | **0.9** | **0.9** |
| **0.1** | **0.029** | **0.0289** |  | **0.0759** | **0.0758** |  | **0.1214** |  | **0.1212** |  | **0.1656** | **0.1654** |  | **0.2083** | **0.2082** |
| **0.2** | **0.0402** | **0.04** |  | **0.0938** | **0.0937** |  | **0.1449** |  | **0.1446** |  | **0.1934** | **0.1931** |  | **0.2391** | **0.2388** |
| **0.3** | **0.0539** | **0.0537** |  | **0.1142** | **0.114** |  | **0.1709** |  | **0.1706** |  | **0.2239** | **0.2235** |  | **0.2729** | **0.2726** |
| **0.4** | **0.0704** | **0.0702** |  | **0.1374** | **0.1371** |  | **0.1999** |  | **0.1995** |  | **0.2577** | **0.2572** |  | **0.3103** | **0.3098** |
| **0.5** | **0.0902** | **0.09** |  | **0.164** | **0.1637** |  | **0.2326** |  | **0.2322** |  | **0.2955** | **0.295** |  | **0.352** | **0.3515** |
| **0.6** | **0.1138** | **0.1136** |  | **0.1945** | **0.1942** |  | **0.2697** |  | **0.2693** |  | **0.3385** | **0.3381** |  | **0.3994** | **0.3989** |
| **0.7** | **0.1417** | **0.1415** |  | **0.2299** | **0.2296** |  | **0.3126** |  | **0.3122** |  | **0.3883** | **0.3879** |  | **0.4545** | **0.454** |
| **0.8** | **0.1746** | **0.1744** |  | **0.2713** | **0.2711** |  | **0.3628** |  | **0.3625** |  | **0.4473** | **0.4469** |  | **0.5211** | **0.5206** |
| **0.9** | **0.2135** | **0.2134** |  | **0.3204** | **0.3202** |  | **0.4234** |  | **0.4232** |  | **0.5205** | **0.5202** |  | **0.6069** | **0.6066** |
| **1** | **0.26** | **0.26** |  | **0.38** | **0.38** |  | **0.5** |  | **0.5** |  | **0.62** | **0.62** |  | **0.74** | **0.74** |

Table 5**. COMPARISON OF SATURATION OF INJECTED WATER WITH MAGNETIC EFFECT AND WITHOUT MAGNETIC EFFECT**



From table (5) we can observe that the Magnetic Field Effect increases the Saturation of injected water as compared to saturation of injected water without magnetic field effect

**Convergence Criteria**

From equation (21) we get the series solution for the nonlinear PDE as

then the convergence of the power series in ‘t’ can be found as per the following theorem [27]

**Theorem**

If ,then the series solution ,stated in equation above, follows the following criteria.

It is convergent if ,such that

It is divergent if ,such that

**VIII. CONCLUSIONS**

Numerical solution and graphs for obtaining the saturation of injected water in heterogenous porous media during the Fingero- imbibition phenomenon considering magnetic field effect, with regard to distance and time are obtained using MATLAB.

The graph given by Figure. 2 shows that saturation of injected water increases as distance X increases for given time T. The saturation of water increases with distance as well as with time, which is consistent with physical phenomena. As indicated in Table 5, the saturation of injected water with magnetic field effect is greater than the saturation of injected water without the magnetic field effect.

As a result, it is possible to deduce that the magnetic field aids in enhancing the saturation of injected water during the fingero-imbibition phenomena.

Multi-step DTM, a reliable modification of the DTM, was used in this work for the variable 'T,' which improves the convergence of the series solution. The method gives approximate numerical solutions to both linear and nonlinear differential equations. Table 1. shows that using DTM we get solutions which converge over a small interval of convergence, whereas Multi-step DTM solutions have a wide interval of convergence, as shown in Table 3. This demonstrates that the MDTM increases the interval of convergence for the series solution.

Comparative study of obtaining the result by the two methods, namely, HDTFDM and HAM shows that results closely agree with each other.

Complex symbolic computation is not necessary because the Hybrid Differential Transform Finite Difference Method calculates numerical solutions through an iterative process. It has been shown that the suggested approach can produce very precise numerical approximations and that Multistep DTM improves the obtained solution. The last and most important advantage is that we do not use linearization.

Therefore, without the use of linearization or perturbation, these techniques can be utilised to solve a wide variety of challenging partial differential equations, both linear and nonlinear.

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