PNG 512

Numerical Reservoir Simulation

Final Project

Development of a Three-Phase Two-Dimensional Reservoir Simulator

Final report

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Chapter 1 Programming Algorithm

This project is built to simulate the reservoir production through the production period or setting period. Reservoir is restricted under 2D and 3 Phases. Before simulation, certain data should be provided like the structure, thickness, porosity and permeability, etc.

Project contains several subroutines, here lists the detailed explanation of each of them and the main algorithm for each subroutine.

1. **Critical variables explanation:**

- Index: matrix which marks the roles of grid blocks. '1' represents normal grid block, '2' represents grid blocks which contains wells. '0' marks the boundary.
- [numi,numj]: size of the grid block to represent the whole reservoir along the I direction and j direction. (boundary included)
- Grid_number: matrix size of [numi,numj] which marks the grid block number. Noticing that the grid blocks follows the direction that North is downwards, East is right, which means North is i direction and East is j direction meanwhile. And the numbering applied **the standard ordering by columns.**
- Coordinate [a,b] and [x,y]: used to mark the coordinate when derivative need to be calculated. [a,b] is the grid block which remains the same PVT properties and [x,y] is the one which disturbance is introduced.
- Kx,ky: matrix size of [numi,numj] save the permeability along the x direction and y direction.(mD)
- Iter: iteration number
- Po: matrix size of [numi,numj] keeps oil pressure, psia, for the next iteration step in current time step.
- Po_old: matrix size of [numi,numj] storage oil pressure, psia, record oil pressure from the previous time step
- Sw_new,Sg_new: water and gas saturation for the next iteration step in current time step.
- Sw_old, Sg_old: water and gas saturation from the previous time step.
- Phi or (ϕ) : porosity, extracted and estimated from the isoporosity map
- Qg,Qo,Qw: Production rate of each grid block for each phase, gas is SCFD, oil is STBD and water is STBD. Matrix. Matrix size of [numi,numj].
- Sp_condition: Matrix size of [numi,numj]. Used to mark the specification cases, ranging from 1 to 8. For the detailed explanation for the number please refer to the **Flowrate** subroutine explanation.
- Sp_data: Matrix size of [numi,numj]. Used to feed the input of the specific condition for each well grid block which corresponds with Sp_condition
- Tag_com and tag_inc: tag marks used to mark the Material balance check results. If accumulative/incremental check passed, tag_com/tag_inc would be 1 otherwise would be 0; Noticing that only under the conditions that both 3 phases pass the check this tag would be marked.
- Count: number of grid block which is not boundary
- J: Jacobian matrix used to compute the Newton Raphson protocol. Matrix size of [3*count,3*count]

- B: Vector which stores the negative residual values of principle unknowns which used to compute the Newton Raphson protocol.
- X: $X = J^{-1} * B$which is the results to update the value of principle unknowns. (Sw,Sg and Po in 3 phases case)

2. Critical Subroutine explanation:

Flowrate

This subroutine is meant to determine the flow rate based on the specified conditions. For all possible specification scenarios, 8 cases are considered which including

i. Total flow rate is specified
ii. Oil flow rate is specified
iii. Water flow rate is specified
iv. Gas flow rate is specified
v. Total liquid flow rate is specified
vi. Water injection flow rate is specified
vii. Sand face pressure is specified

Which should be noticed that all the oil flow rate is in STBD, water flow/injection rate is STBD, gas flow/injection rate is in SCFD meanwhile total flow rate is in STBD and the bottom hole sand face pressure is in psia.

And the reference equations for the flow are listed below.

$$q_o = \frac{2\pi k k_{ro} h r}{\mu_o B_o}\left(\frac{\partial \Phi_\mathrm{o}}{\partial r}\right)(STBD)$$

$$q_w = \frac{2\pi k k_{rw} h r}{\mu_w B_w}\left(\frac{\partial \Phi_\mathrm{w}}{\partial r}\right)(STBD)$$

$$q_g = \frac{2\pi k k_{rg} h r}{\mu_g B_g}\left(\frac{\partial \Phi_g}{\partial r} + R_{so} q_o + R_{so} q_w\right)$$
$$= 2\pi k h r \frac{\partial \Phi_g}{\partial r}\left(\frac{k_{ro}}{\mu_o B_o} R_{so} + \frac{k_{rg}}{\mu_g B_g} + \frac{k_{rw}}{\mu_w B_w} R_{sw}\right)\ (SCFD)$$

Therefore, in this subroutine four principle unknows should be considered which are q_o, q_g, q_w & P_{sf}. If one of these variables is specified, the rest 3 could refer the 3 equations above to be determined.

PVT_gas/PVT_oil/PVT_water/relaperm

For these 4 subroutines, both should be considered as the PVT data preparation. Certain PVT data should be prepared in advance. Linear interpolation technique is applied to estimate the actual data between the two give data points for simplification.

Transmissibility

This subroutine is meant to pre-treat the transmissibility for each grid block. Input is PVT data (which has been calculated in advance based on the S_g, S_w and oil pressure data of next iteration step. Output is transmissibility of 4 directions of 3 phases, 12 matrixes size of [numi,numj] would be outputted.

Inside the subroutine, take the north side, oil phase transmissibility as an example,

$$T_{ox,i+\frac{1}{2}} = \left[\frac{A_x k_x}{\Delta x}\right]_{i+\frac{1}{2}} \left[\frac{1}{\mu_o B_o}\right]_{i+\frac{1}{2}} [k_{ro}]_{i+\frac{1}{2}}$$

The geometric factor $\left[\frac{A_x k_x}{\Delta x}\right]_{i+\frac{1}{2}}$ applied harmonic averaging method, and $\left[\frac{1}{\mu_o B_o}\right]_{i+\frac{1}{2}}$ is averaged arithmetically since weekly nonlinearity and relative permeability is weighted by single point upstream approach.

$$k_{ro,i+\frac{1}{2}} = \begin{cases} k_{ro}(S_{oi}), & \Phi_{oi} > \Phi_{o,i+1} \\ k_{ro}\left(S_{o,i+1}\right), & \Phi_{oi} < \Phi_{o,i+1} \end{cases}$$

Residual

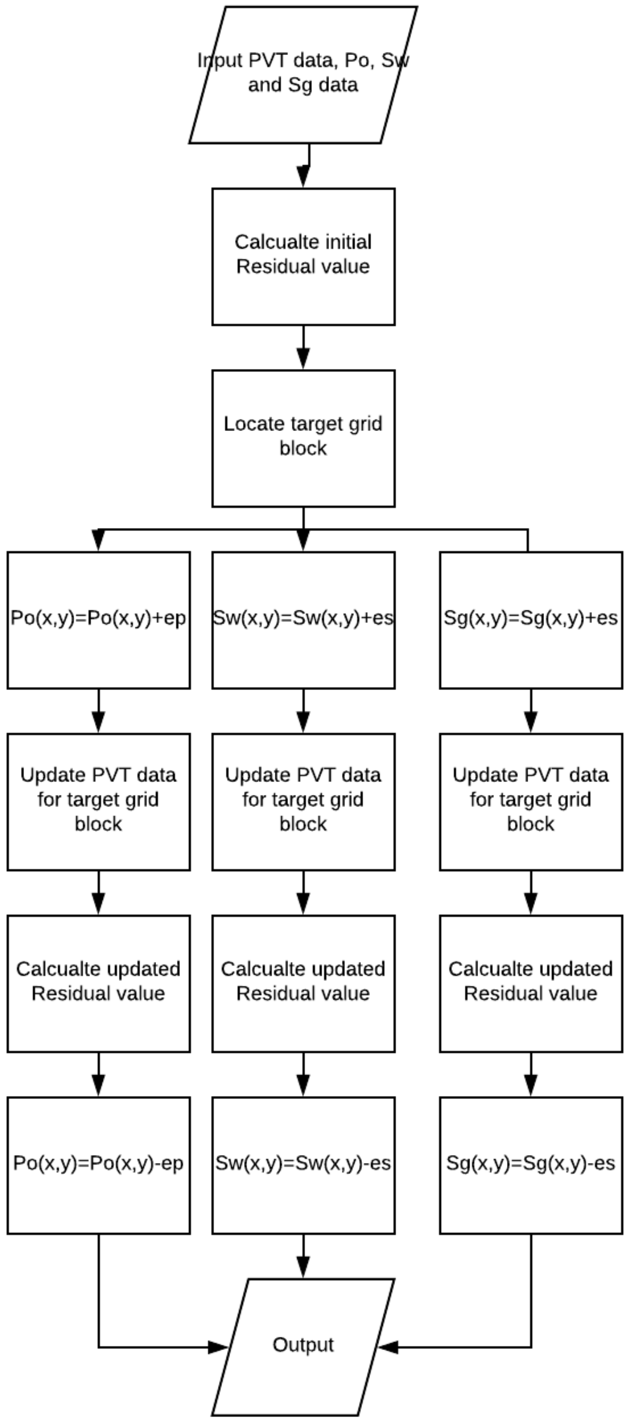
Based on the output of the transmissibility, residual could be calculated. Transmissibility subroutine is recalled and each grid block has three residuals which represent oil phase, water phase and gas phase. Outputs are also three matrixes size of [numi,numj].

Jacobian_cell

Since the construction of the Jacobian is complicated and time consuming, the decomposition of Jacobian matrix into small 'cell' 3*3 matrixes is a good concept to tackle this problem. And in each 'cell' matrix, all the elements should be placed as the following order. Supposed grid block No. n is fixed and disturbance is introduced in to grid block No. m and at iteration level k. This 'cell' matrix should be placed in the Jacobian matrix at the coordinate from $[3*m-2, 3*n-2]$ to $[3*m, 3*n]$.

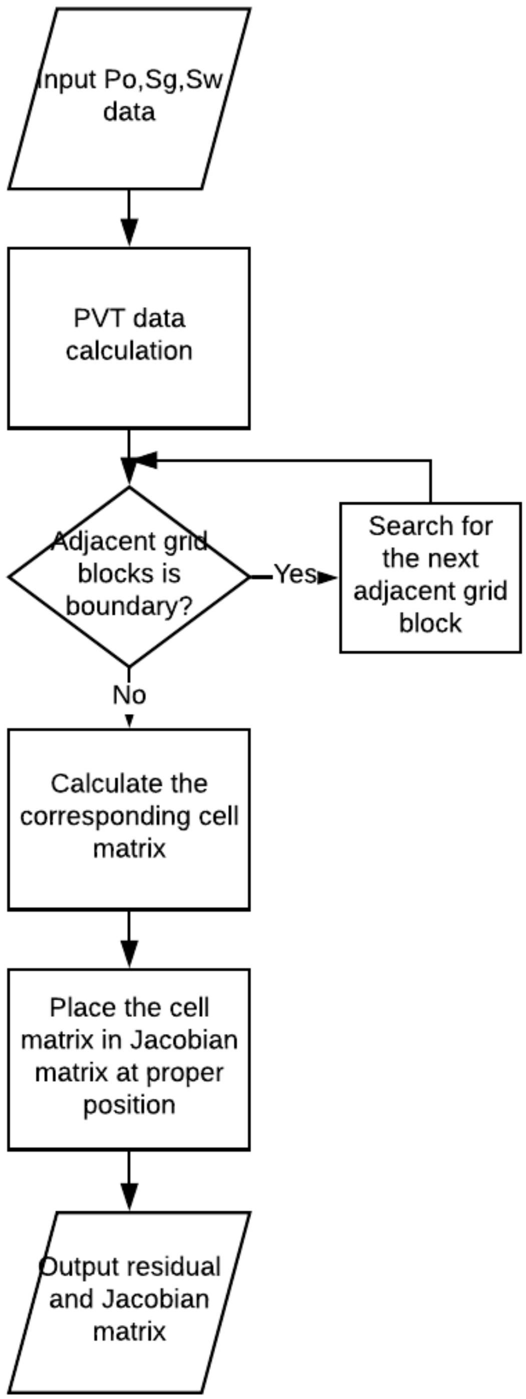
$$J_{cell} = \begin{bmatrix} \left(\frac{\partial R_{o,n}}{\partial P_{o,m}}\right)^k & \left(\frac{\partial R_{o,n}}{\partial S_{w,m}}\right)^k & \left(\frac{\partial R_{o,n}}{\partial S_{g,m}}\right)^k \\ \left(\frac{\partial R_{w,n}}{\partial P_{o,m}}\right)^k & \left(\frac{\partial R_{w,n}}{\partial P_{o,m}}\right)^k & \left(\frac{\partial R_{w,n}}{\partial S_{g,m}}\right)^k \\ \left(\frac{\partial R_{g,n}}{\partial P_{o,m}}\right)^k & \left(\frac{\partial R_{g,n}}{\partial P_{o,m}}\right)^k & \left(\frac{\partial R_{g,n}}{\partial S_{g,m}}\right)^k \end{bmatrix}$$

And the flow chart for this subroutine is listed below.



Jacobian

This subroutine is meant to construct the Jacobian matrix based on the ***Jacobian_cell*** subroutine results. And the main algorithm is listed below as a flow chart.



Also, for the Newton Raphson Method, is SIP notation is applied. Therefore, the Jacobian matrix to update the principle unknown's values and the equation is shown below.

$$\begin{bmatrix} C_1^{\overset{k}{n+1}} & N_1^{\overset{k}{n+1}} & 0 & 0 & \dots & E_1^{\overset{k}{n+1}} & 0 & 0 & 0 \\ S_2^{\overset{k}{n+1}} & C_2^{\overset{k}{n+1}} & N_2^{\overset{k}{n+1}} & 0 & 0 & \dots & E_2^{\overset{k}{n+1}} & 0 & 0 \\ 0 & S_3^{\overset{k}{n+1}} & C_3^{\overset{k}{n+1}} & N_3^{\overset{k}{n+1}} & 0 & 0 & \dots & E_3^{\overset{k}{n+1}} & 0 \\ 0 & 0 & S_4^{\overset{k}{n+1}} & & & & 0 & \dots & E_n^{\overset{k}{n+1}} \\ \dots & 0 & 0 & & \ddots & & 0 & 0 & 0 \\ W_1^{\overset{k}{n+1}} & \dots & 0 & & & & N_{n-3}^{\overset{k}{n+1}} & 0 & 0 \\ 0 & W_2^{\overset{k}{n+1}} & \dots & 0 & 0 & S_{n-2}^{\overset{k}{n+1}} & C_{n-2}^{\overset{k}{n+1}} & N_{n-2}^{\overset{k}{n+1}} & \dots \\ 0 & 0 & W_3^{\overset{k}{n+1}} & \dots & 0 & 0 & S_{n-1}^{\overset{k}{n+1}} & C_{n-1}^{\overset{k}{n+1}} & N_{n-1}^{\overset{k}{n+1}} \\ 0 & 0 & 0 & W_n^{\overset{k}{n+1}} & 0 & 0 & 0 & S_n^{\overset{k}{n+1}} & C_n^{\overset{k}{n+1}} \end{bmatrix} \times \begin{bmatrix} \Delta p_{o,1}^{\overset{k+1}{n+1}} \\ \Delta S_{w,1}^{\overset{k+1}{n+1}} \\ \Delta S_{g,1}^{\overset{k+1}{n+1}} \\ \vdots \\ \Delta p_{o,n}^{\overset{k+1}{n+1}} \\ \Delta S_{w,n}^{\overset{k+1}{n+1}} \\ \Delta S_{g,n}^{\overset{k+1}{n+1}} \end{bmatrix} = \begin{bmatrix} -R_{o,1}^{\overset{k}{n+1}} \\ -R_{w,1}^{\overset{k}{n+1}} \\ -R_{g,1}^{\overset{k}{n+1}} \\ \vdots \\ -R_{o,n}^{\overset{k}{n+1}} \\ -R_{w,n}^{\overset{k}{n+1}} \\ -R_{g,n}^{\overset{k}{n+1}} \end{bmatrix}$$

MBcheck

Based on the Material Balance check subroutine, all the results should satisfy the convergence results. The Material Balance check equation is used as the following equation.
For Incremental Material Balance Convergence check, 3 equations are listed below to check the convenience.

$$MB_o = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{z=1}^{N_z}\left[\frac{V_b}{5.615} * \left(\phi * \frac{S_o}{B_o}\right)^{n+1} - \frac{V_b}{5.615} * \left(\phi * \frac{S_o}{B_o}\right)^{n}\right]}{\sum_{l=1}^{N_w}(q_{ol}^{n+1})\Delta t}$$

$$MB_w = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{z=1}^{N_z}\left[\frac{V_b}{5.615} * \left(\phi * \frac{S_w}{B_w}\right)^{n+1} - \frac{V_b}{5.615} * \left(\phi * \frac{S_w}{B_w}\right)^{n}\right]}{\sum_{l=1}^{N_w}(q_{wl}^{n+1})\Delta t}$$

$$MB_g = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{z=1}^{N_z}\left[\frac{V_b}{5.615} * \left(\phi * \frac{S_g}{B_g}\right)^{n+1} - \frac{V_b}{5.615} * \left(\phi * \frac{S_g}{B_g}\right)^{n}\right]}{\sum_{l=1}^{N_w}(q_{gl}^{n+1})\Delta t}$$

Meanwhile, for Cumulative Material Balance check

$$CMB_o = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{z=1}^{N_z}\left[\frac{V_b}{5.615} * \left(\phi * \frac{S_o}{B_o}\right)^{n+1} - \frac{V_b}{5.615} * \left(\phi * \frac{S_o}{B_o}\right)^{t=0}\right]}{\sum_{m=1}^{n+1}\sum_{l=1}^{N_w}(q_{ol}^{n+1})\Delta t_m}$$

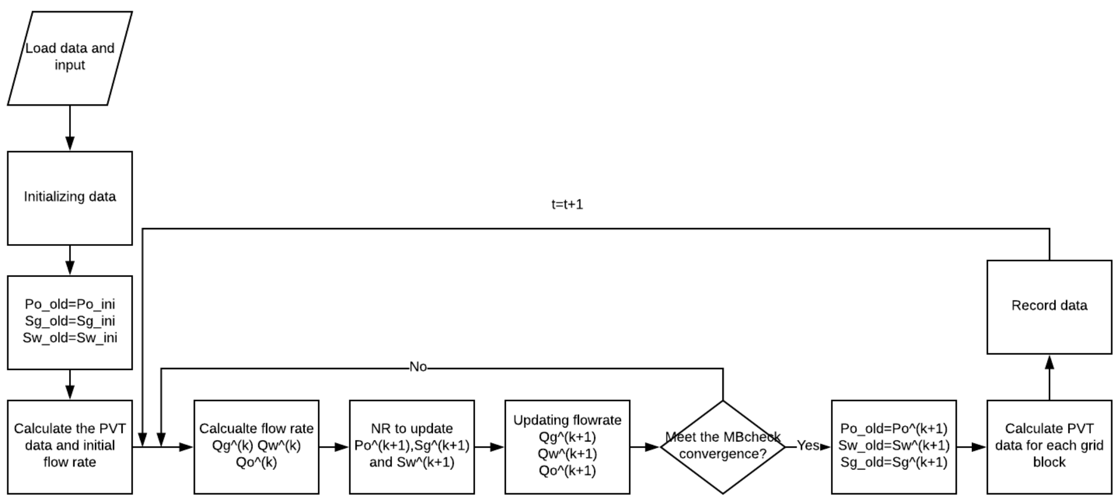
$$CMB_w = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{z=1}^{N_z}\left[\frac{V_b}{5.615} * \left(\phi * \frac{S_w}{B_w}\right)^{n+1} - \frac{V_b}{5.615} * \left(\phi * \frac{S_w}{B_w}\right)^{t=0}\right]}{\sum_{m=1}^{n+1}\sum_{l=1}^{N_w}(q_{wl}^{n+1})\Delta t_m}$$

$$CMB_o = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{z=1}^{N_z}\left[\frac{V_b}{5.615} * \left(\phi * \frac{S_o}{B_o}\right)^{n+1} - \frac{V_b}{5.615} * \left(\phi * \frac{S_o}{B_o}\right)^{t=0}\right]}{\sum_{m=1}^{n+1}\sum_{l=1}^{N_w}\left(q_{gl}^{n+1}\right)\Delta t_m}$$

Till the difference between all the ratios above and 1 should be less than the criteria (which 10^{-5} is applied), the Material Balance check could be passed.

Main

In General, the main solver code's algorithm is illustrated as the following flow chart.



Chapter 2 Case Study Validation-Canvas example

1. Data input

The reservoir is a 3*3 block system and the blocks are surrounded by null block which means the total grid block is a 5*5 system in the program.

(1,1)	(1,2)	(1,3)	(1,4)	(1,5)
(2,1)	(2,2)	(2,3)	(2,4)	(2,5)
(3,1)	(3,2)	(3,3) Φ	(3,4)	(3,5)
(4,1)	(4,2)	(4,3)	(4,4)	(4,5)
(5,1)	(5,2)	(5,3)	(5,4)	(5,5)

index=[0 0 0 0 0; 0 1 1 1 0; 0 1 2 1 0;0 1 1 1 0; 0 0 0 0 0];
index2=[0 0 0 0 0; 0 1 1 1 0; 0 1 1 1 0;0 1 1 1 0; 0 0 0 0 0];

Δx= 500.*index2;(ft)

Δy= 500.*index2;(ft)

Perm x = 100.*index2;(mD)

Perm y = 100.*index2;(mD)

depth = 4000.*index2;(mD)

Reservoir thickness = 50.*index2;(ft)
Cr=0*10^-6.*index2;(psi^-1)
Poo=4800.*index2;
Sw=0.3.*index2;
Sg=0.1*index2;

And the PVT information is listed below.

OIL				
P	density	Bo	viscosity	Rso
1500	49.0113	1.20413	1.7356	292.75
2000	48.5879	1.2321	1.5562	368
2500	48.1774	1.26054	1.4015	443.75
3000	47.6939	1.29208	1.2516	522.71
3500	47.1788	1.32933	1.1024	619
4000	46.5899	1.37193	0.9647	724.92
4500	45.5756	1.42596	0.918	818.6
5000	45.1925	1.46387	0.92	923.12
5500	45.4413	1.44983	0.9243	965.28
6000	45.7426	1.43831	0.9372	966.32

Water				
P	density	Bw	viscosity	Rsw
1500	62.228	1.0253	0.52	0
2000	62.413	1.0222	0.52	0
2500	62.597	1.0192	0.52	0
3000	62.782	1.0162	0.52	0
3500	62.968	1.0132	0.52	0
4000	63.153	1.0102	0.52	0
4500	63.337	1.0073	0.52	0
5000	63.523	1.0051	0.52	0
5500	63.708	1.0017	0.52	0
6000	63.893	0.9986	0.52	0

Gas			
P	density	Bg	viscosity
1500	5.8267	0.0018	0.015
2000	8.0573	0.00133	0.0167
2500	10.228	0.00105	0.0185
3000	12.208	0.00088	0.0204
3500	13.942	0.00077	0.0222
4000	15.431	0.00069	0.0241
4500	16.705	0.00064	0.026
5000	17.799	0.0006	0.0278
5500	18.748	0.00057	0.0296
6000	19.577	0.00055	0.0313

Relative permeability data							
sw	krw	krow	Pco w	sg	krg	krog	Pcgo
0.1 8	0	1	9	0	0	1	0
0.2 1	0	0.926 92	7.26	0.0 4	0.011 03	0.707 78	0.01
0.2 4	2.00E- 05	0.854 41	5.04	0.0 8	0.029 12	0.558 44	0.062
0.2 7	0.0001 4	0.792 88	3.78	0.1 2	0.051 38	0.445 4	0.114
0.3	0.0004 5	0.713 12	3	0.1 6	0.076 87	0.355 62	0.166
0.3 3	0.0011 1	0.645 26	2.63 4	0.2	0.105 06	0.283 02	0.218

0.36	0.00232	0.5798	2.268
0.39	0.0043	0.51709	1.902
0.42	0.00733	0.45744	1.666
0.45	0.01175	0.4011	1.495
0.48	0.01791	0.34831	1.324
0.51	0.02623	0.29924	1.168
0.54	0.03714	0.25403	1.042
0.57	0.05116	0.21278	0.916
0.6	0.06882	0.17552	0.79
0.63	0.09069	0.14228	0.682
0.66	0.11741	0.11301	0.574
0.69	0.14963	0.08763	0.466
0.72	0.18807	0.06603	0.364
0.75	0.23347	0.04803	0.265
0.78	0.28664	0.03344	0.166
0.81	0.34842	0.02199	0.09
0.84	0.41968	0.0134	0.06
0.87	0.50135	0.00733	0.03
0.9	0.59439	0.0034	0

0.24	0.13561	0.22392	0.27
0.28	0.16827	0.17574	0.366
0.32	0.20286	0.13656	0.462
0.36	0.23923	0.10485	0.580667
0.4	0.27725	0.07938	0.722
0.44	0.31683	0.05912	0.863333
0.48	0.35788	0.04319	1.004667
0.52	0.40031	0.03084	1.175
0.56	0.44408	0.02143	1.355
0.6	0.48911	0.01442	1.563
0.64	0.53536	0.00933	1.855
0.68	0.58279	0.00574	2.147
0.72	0.63134	0.00332	2.652

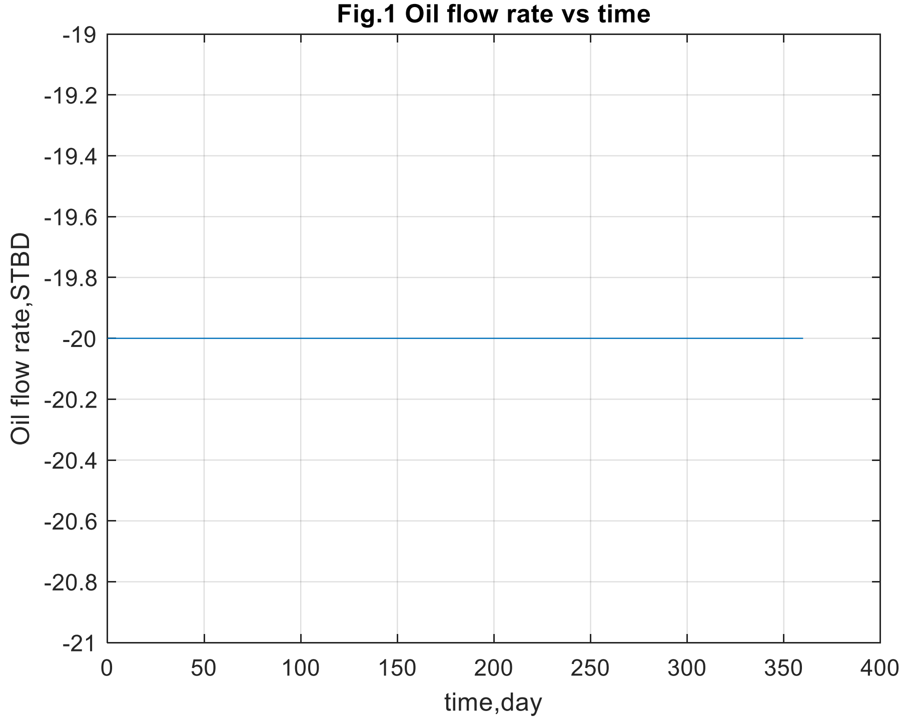
2. Results

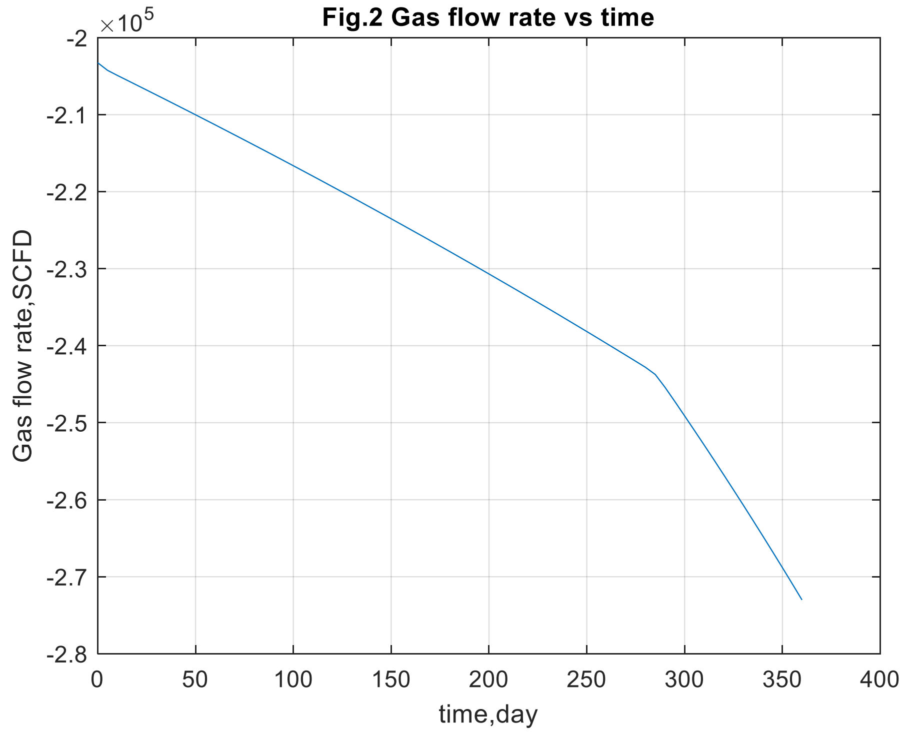
Well operation data

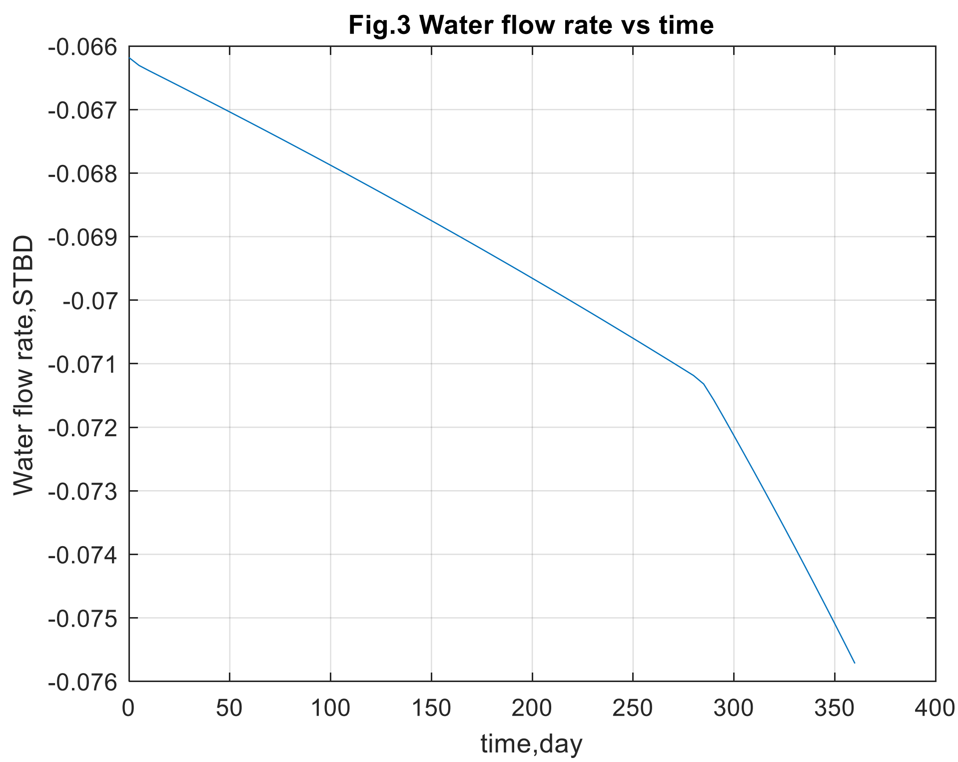
Well #	Well address	Well Type	Flow rate specification	Sandface pressure specification	skin factor
1	(3,3)	Production	20 STBD	N/A	0

For this example, only the oil flow rate of center grid block is specified. And the flow rate for this center grid block, O/W/G phases flow rates are illustrated below,

Fig.1 Oil flow rate vs time







Meanwhile for the cumulative production for 3 phases are shown in Fig.4 and Fig.5 respectively.

Fig.4 Liquid cumulative production vs time

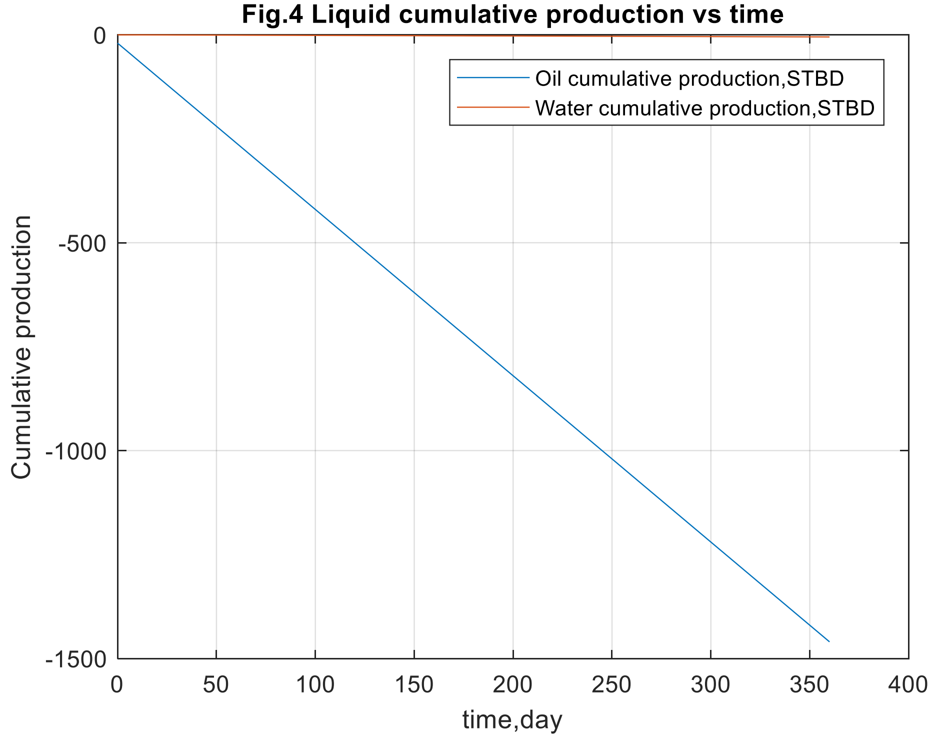
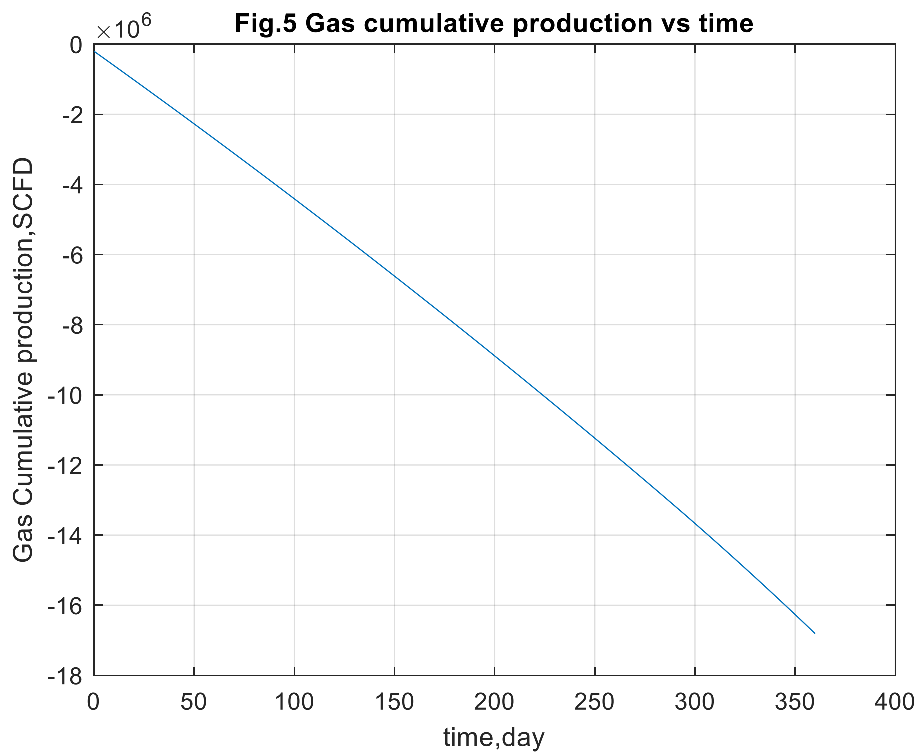


Fig.5 Gas cumulative production vs time



For pressure, 90 days are chosen as a proper interval.

1. Pressure distribution after 90 days (psi)

0	0	0	0	0
0	4710.053	4709.281	4710.053	0
0	4709.281	4706.191	4709.281	0
0	4710.053	4709.281	4710.053	0
0	0	0	0	0

2. Pressure distribution after 180 days (psi)

0	0	0	0	0
0	4616.072	4615.286	4616.072	0
0	4615.286	4612.141	4615.286	0
0	4616.072	4615.286	4616.072	0
0	0	0	0	0

3. Pressure distribution after 270 days (psi)

0	0	0	0	0
0	4518.542	4517.741	4518.542	0
0	4517.741	4514.538	4517.741	0
0	4518.542	4517.741	4518.542	0
0	0	0	0	0

4. Pressure distribution after 360 days (psi)

0	0	0	0	0
0	4362.729	4361.885	4362.729	0
0	4361.885	4358.509	4361.885	0
0	4362.729	4361.885	4362.729	0
0	0	0	0	0

For Material Balance check, Fig.6 and Fig 7 show Incremental and Cumulative respectively, we could easily discover that oil phase is the most stable and fastest to converge.

Fig.6 Incremental MB Check vs time

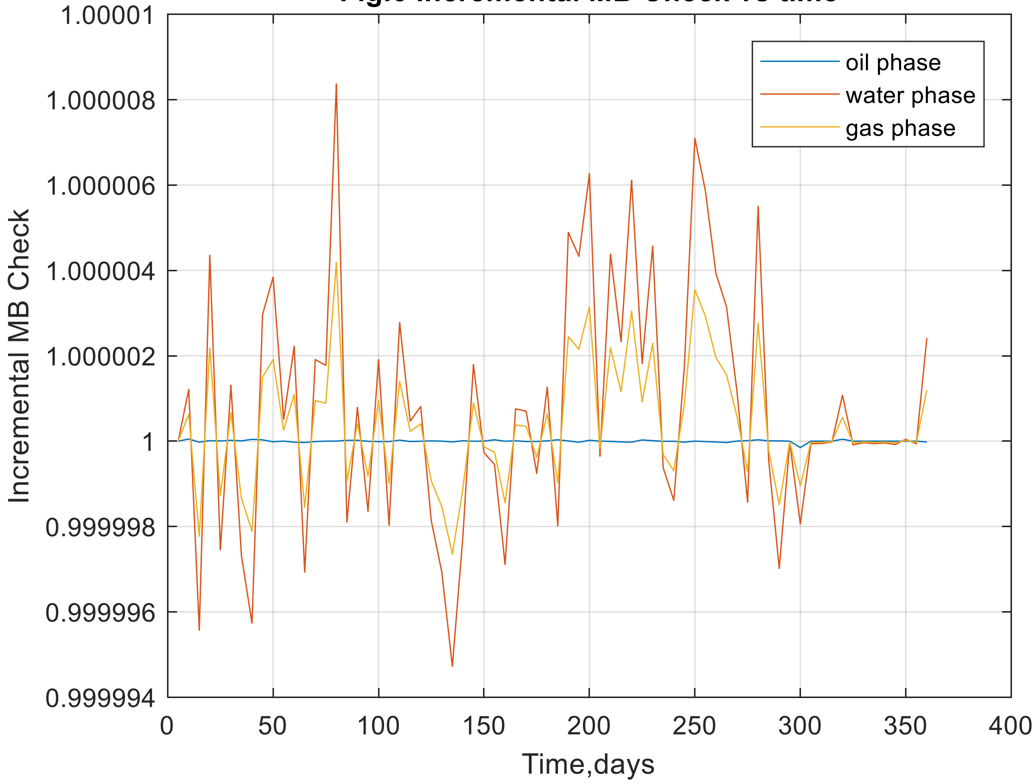
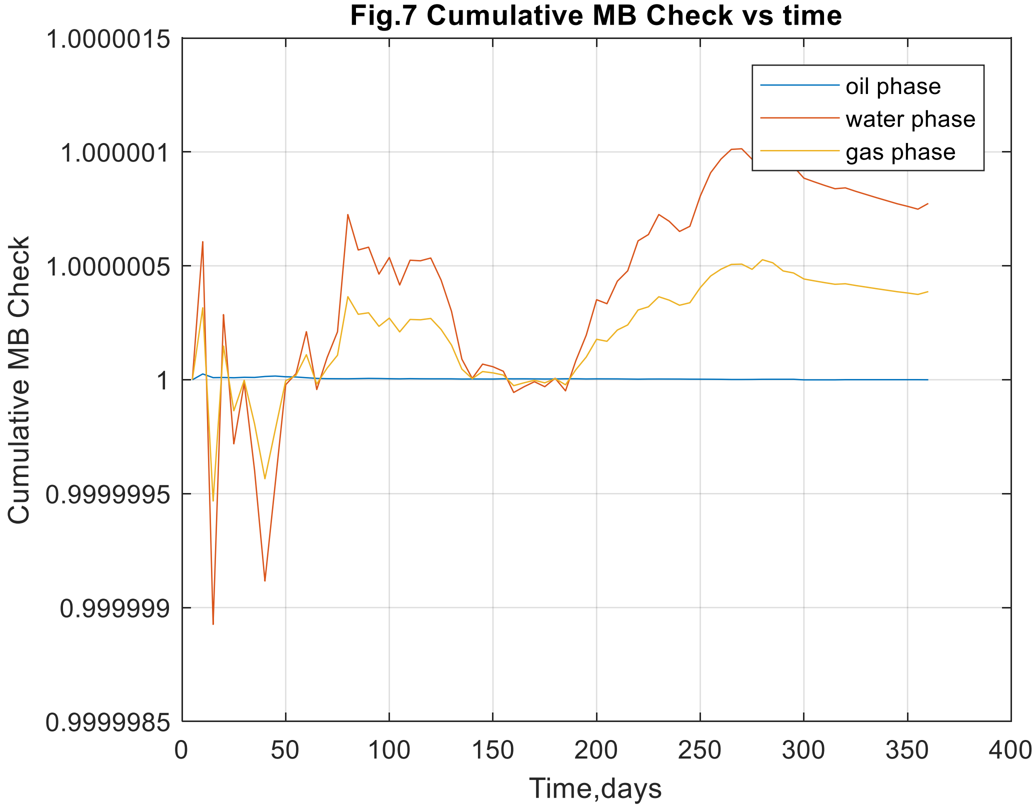


Fig.7 Cumulative MB Check vs time



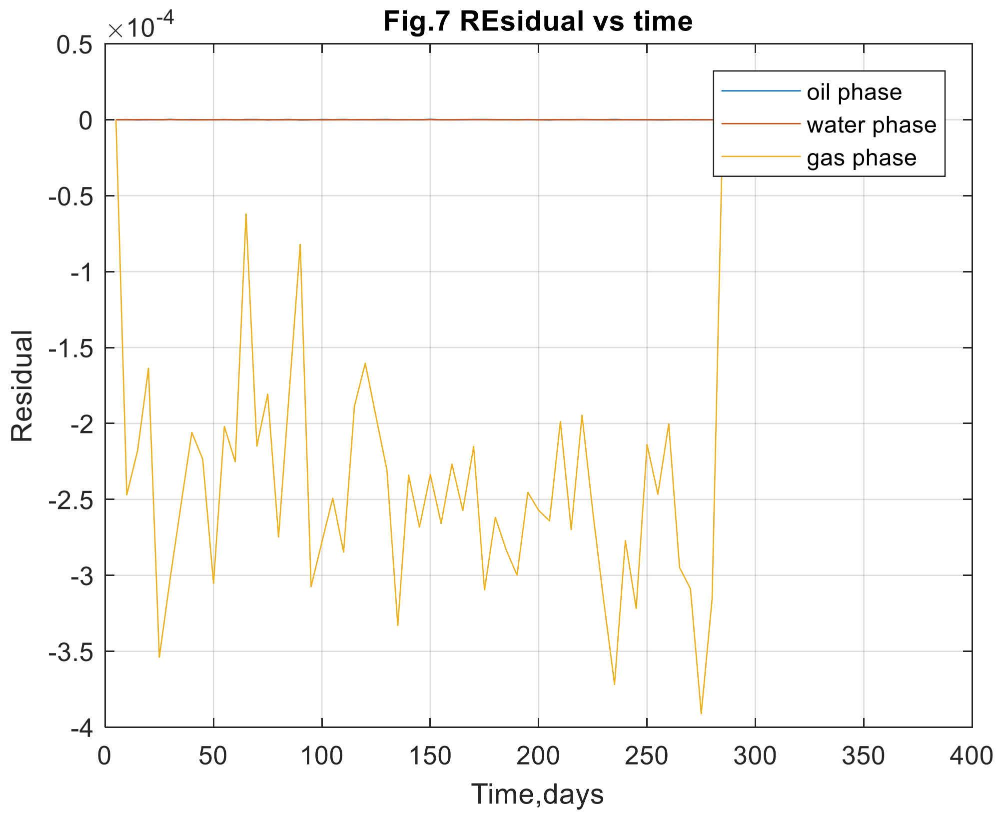


Fig.7 REsidual vs time
×10^-4
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
Residual
0
50
100
150
200
250
300
350
400
Time,days
oil phase
water phase
gas phase

Chapter 3 Case Study Validation-Book Example

1. Data input

The reservoir is a 14*11 block system and the blocks are surrounded by null. If '1' represents grid block, '2' represents grid block contains a well, '0' represents the boundary.

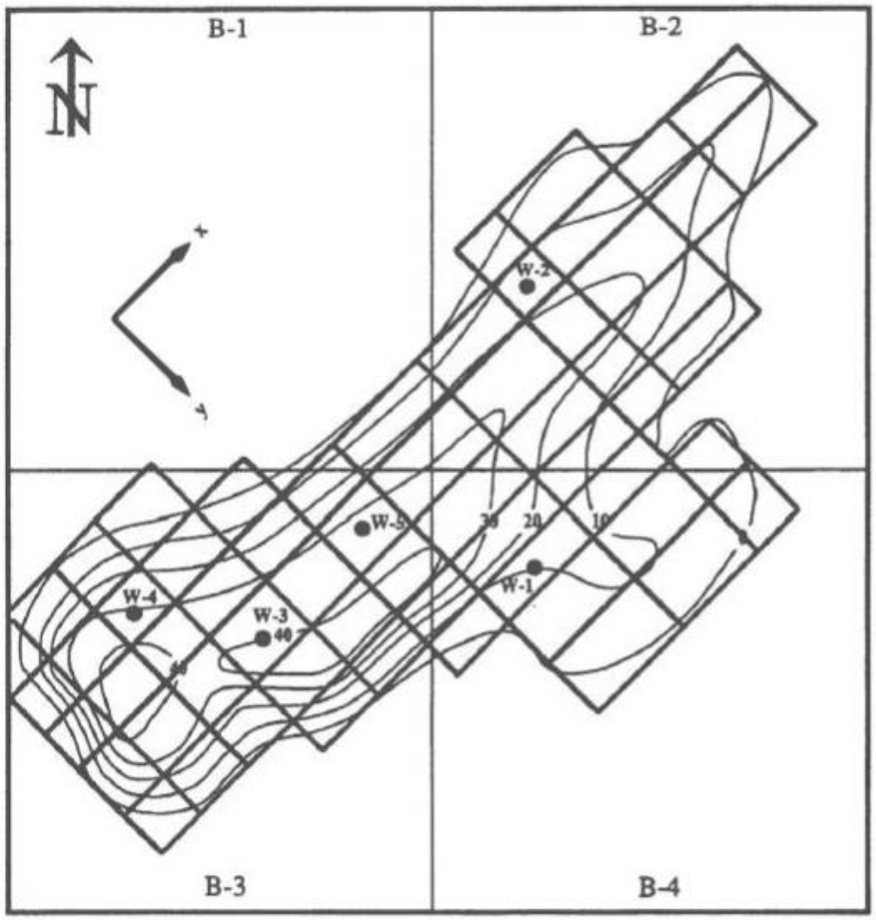


Fig 3.1 Reservoir Structure

0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	1	1	0	0	0	0	0	0	0	0	0
0	1	1	2	1	1	0	0	0	1	1	0	0	0
0	1	1	1	1	1	1	1	1	2	1	1	1	0
0	1	1	1	2	1	2	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	1	1	0	0	0
0	0	0	0	1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	1	2	1	0	0	0	0	0
0	0	0	0	0	0	0	1	1	1	0	0	0	0
0	0	0	0	0	0	0	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig 3.2 Grid block index

This is the original direction. For convenience the matrix has been transposed and now x direction is downwards and y direction is rightwards.

TABLE 9.13—WELL DATA FOR THREE-PHASE FLOW EXERCISE

Name	Gridblock	Type	Radius, r_w (ft)	Specification
W-1	(7,7)	Producer	0.25	$q_{tsc} = -100{,}000$ STB/D
W-2	(9,3)	Producer	0.25	$p_{sf} = 3{,}400$ psia
W-3	(4,4)	Producer	0.25	$q_{osc} = -100$ STB/D
W-4	(3,2)	Producer	0.25	$q_{gsc} = -1$ MMscf/D
W-5	(6,4)	Producer	0.25	$q_{Lsc} = -150$ STB/D

TABLE 9.14—INITIAL CONDITIONS AND OTHER RESERVOIR PARAMETERS FOR THREE-PHASE EXERCISE

S_{oi}	0.50
S_{gi}	0.08
S_{wi}	0.42
p_{oi}, psia	4,800
c_R, psi^{-1}	3.0×10^{-6}
T_R, °F	190
T_{sc}, °F	60
p_{sc}, psia	14.7

Here listed the initial condition and the well information.

Fig.1 Oil flow rate vs time

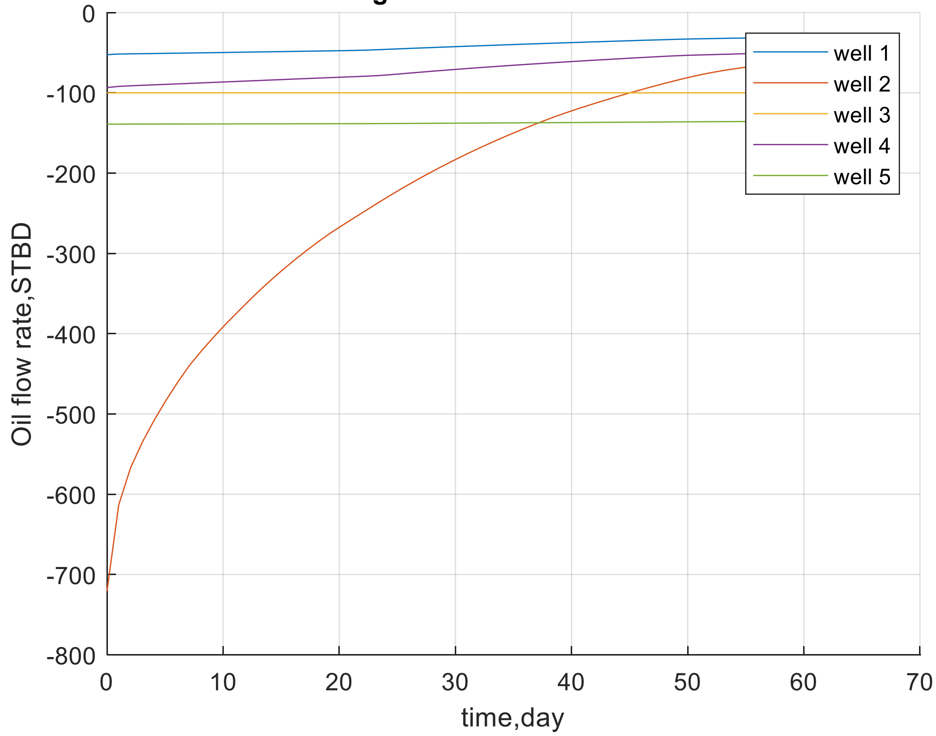
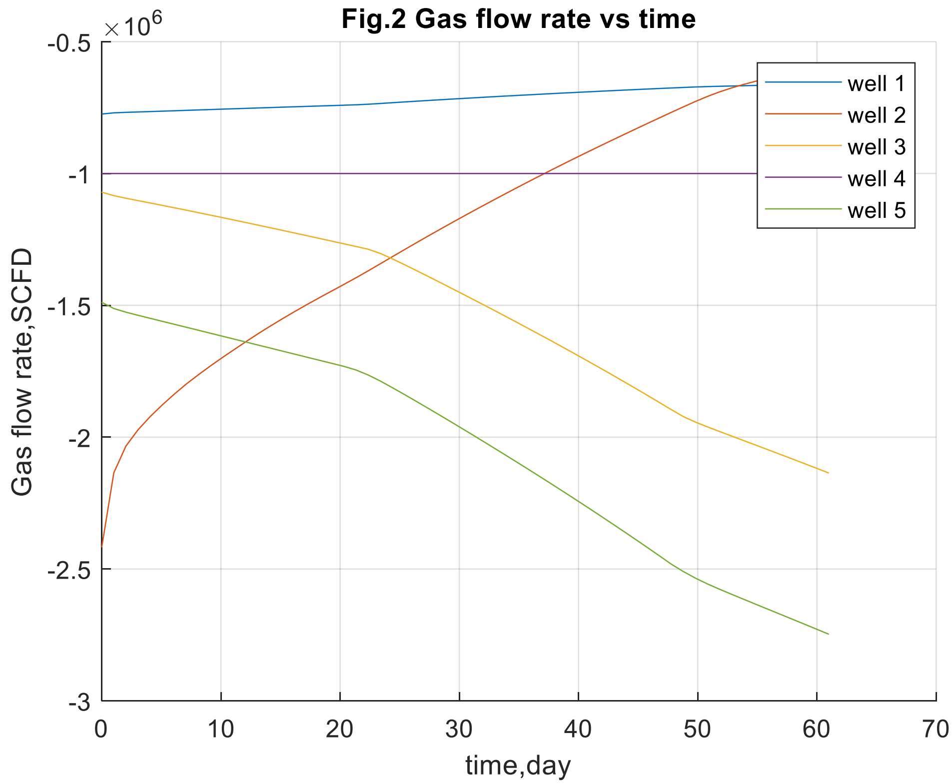
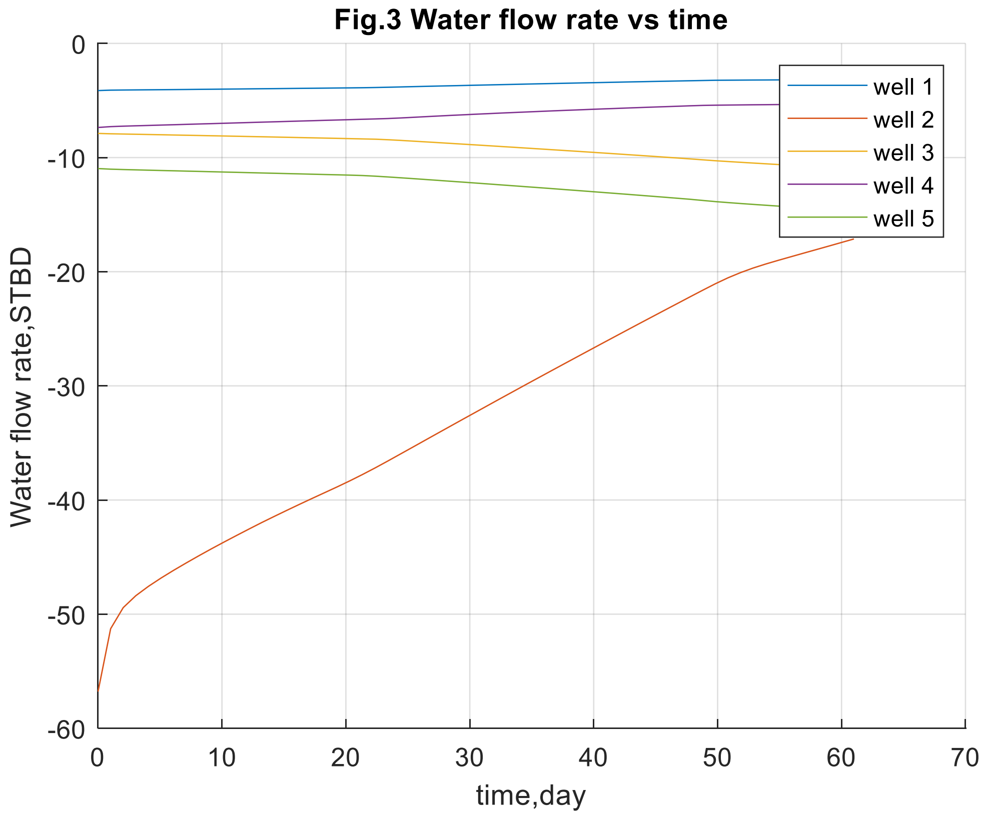


Fig.2 Gas flow rate vs time





Since both wells are production wells therefore all the flow rates are negative. And Well 2 is pressure specified. Therefore, due to the reservoir pressure drop, the production for 3 phases would decline.

Fig.4 Accumulative Water Production vs time

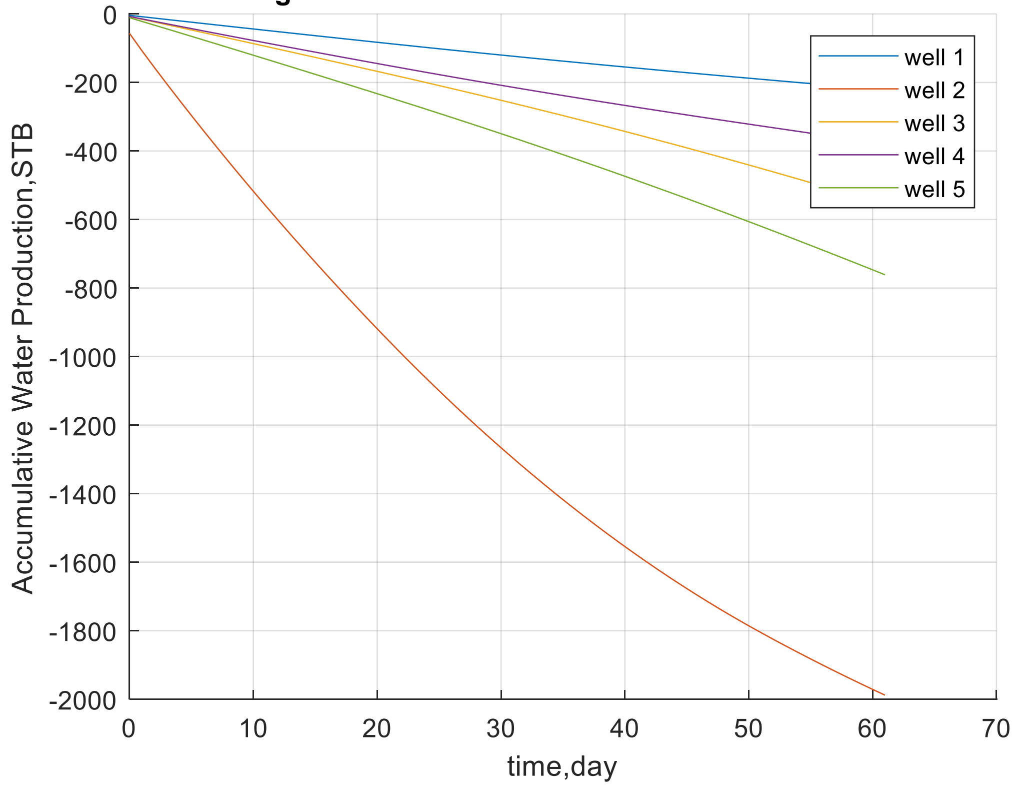


Fig.5 Accumulative Gas Production vs time

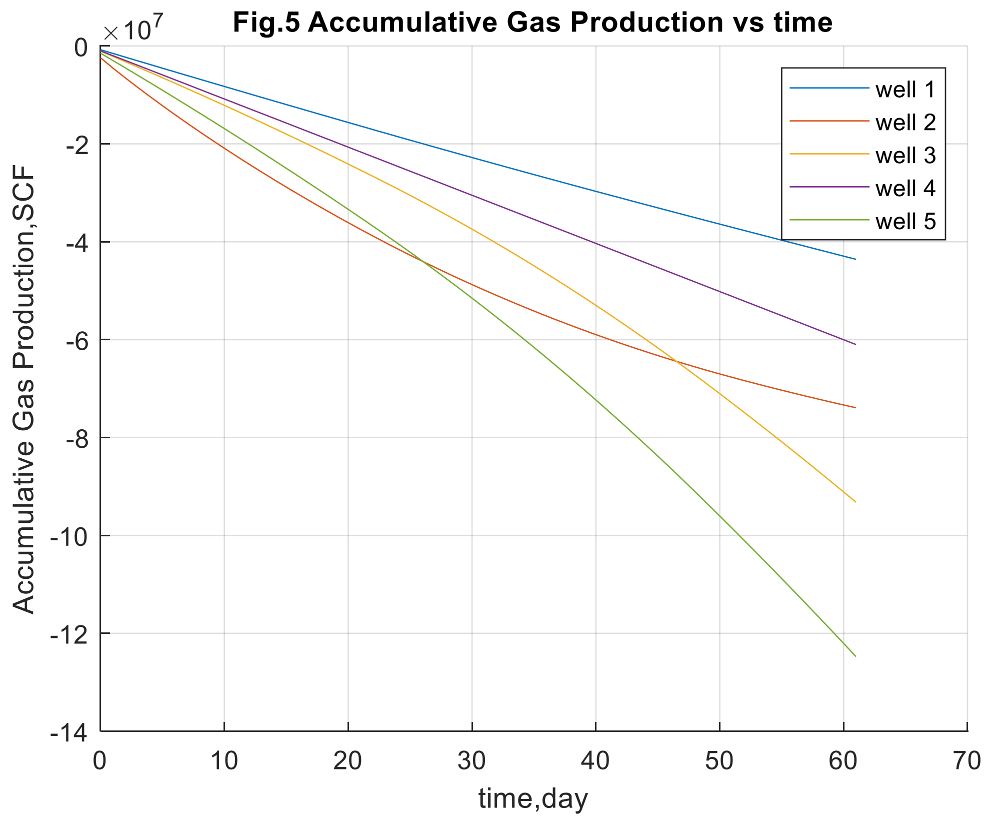


Fig.6 Accumulative Gas Production vs time

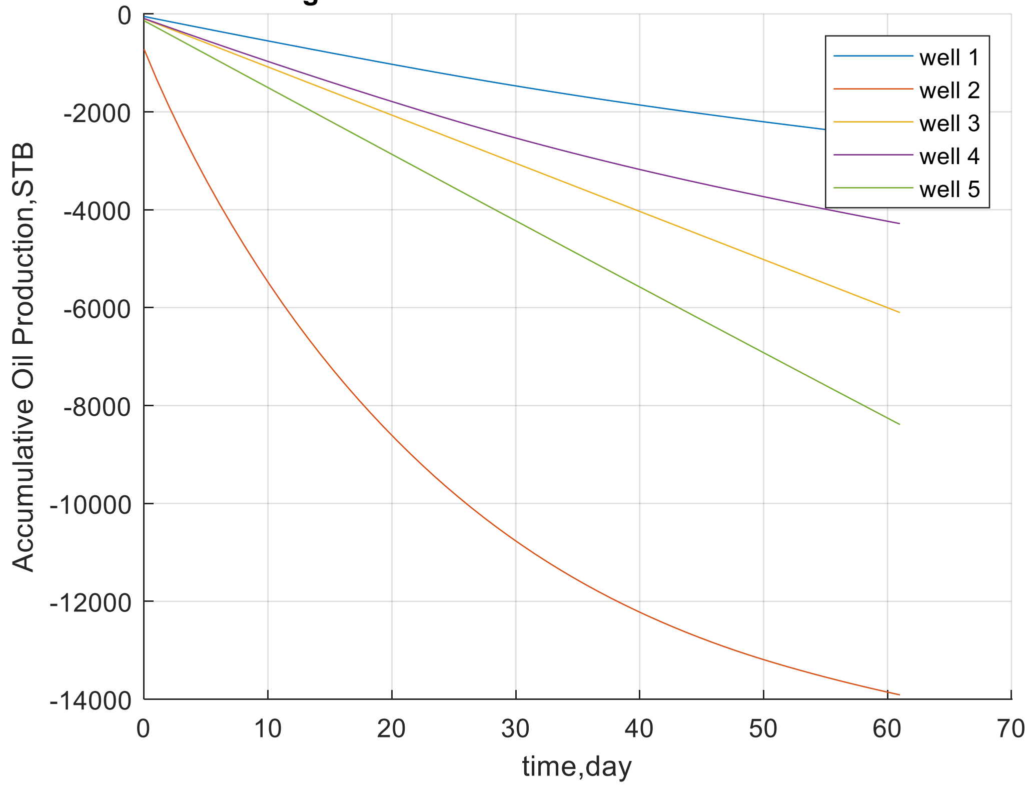


Fig.7 Cumulative MB Check vs time

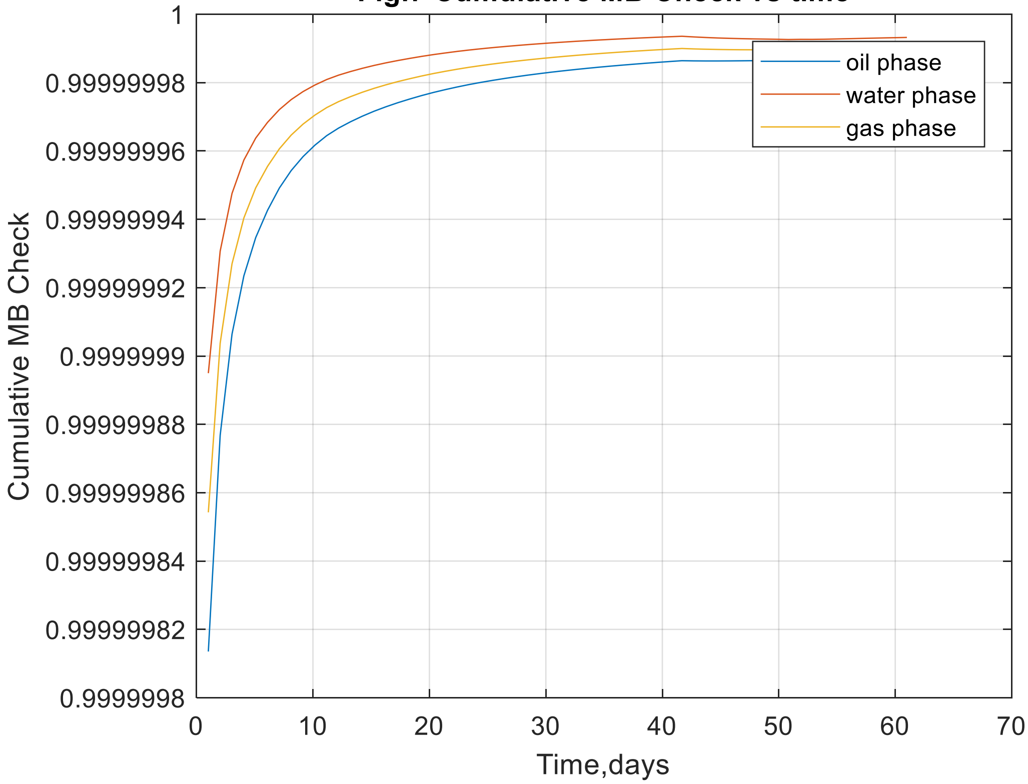
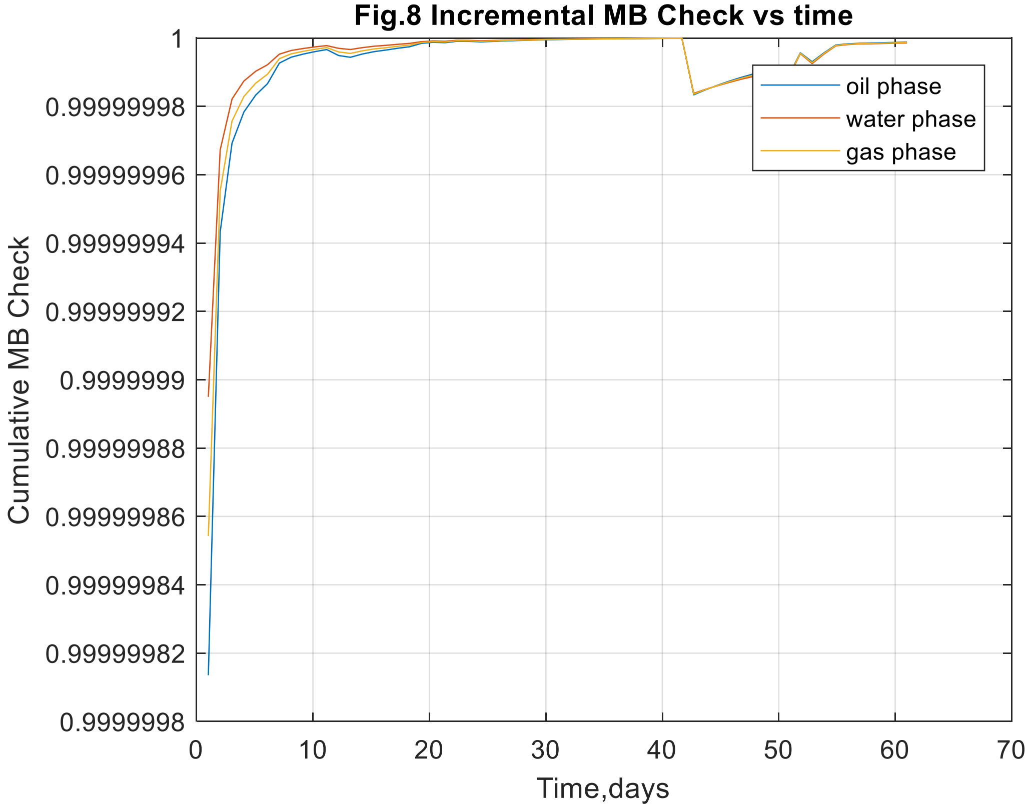
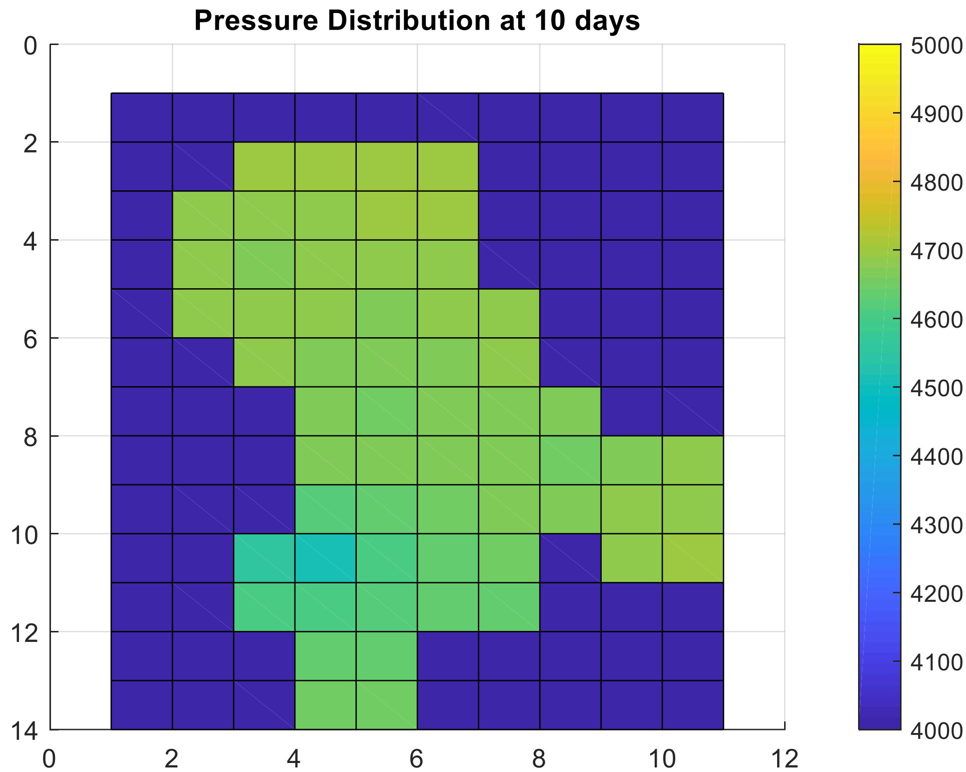


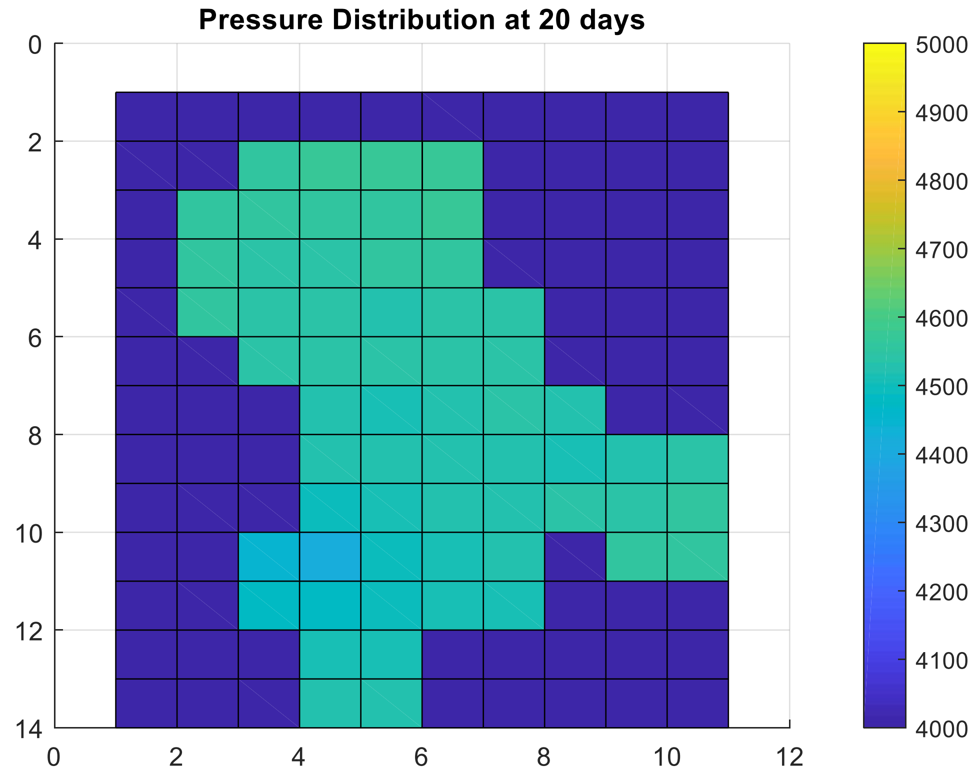
Fig.8 Incremental MB Check vs time

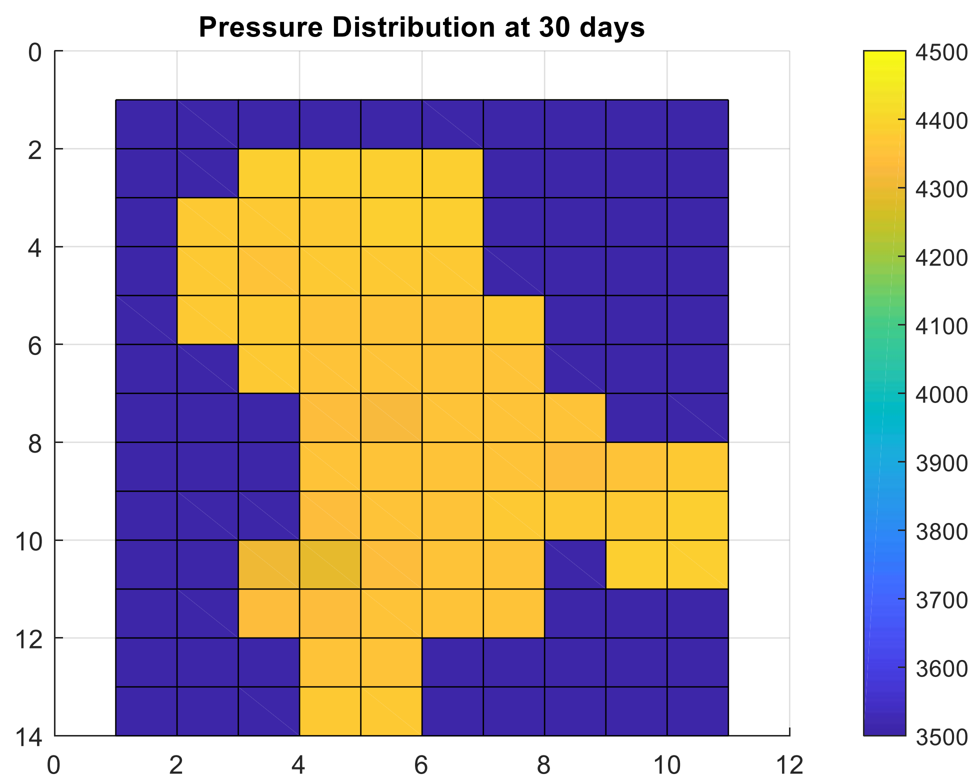


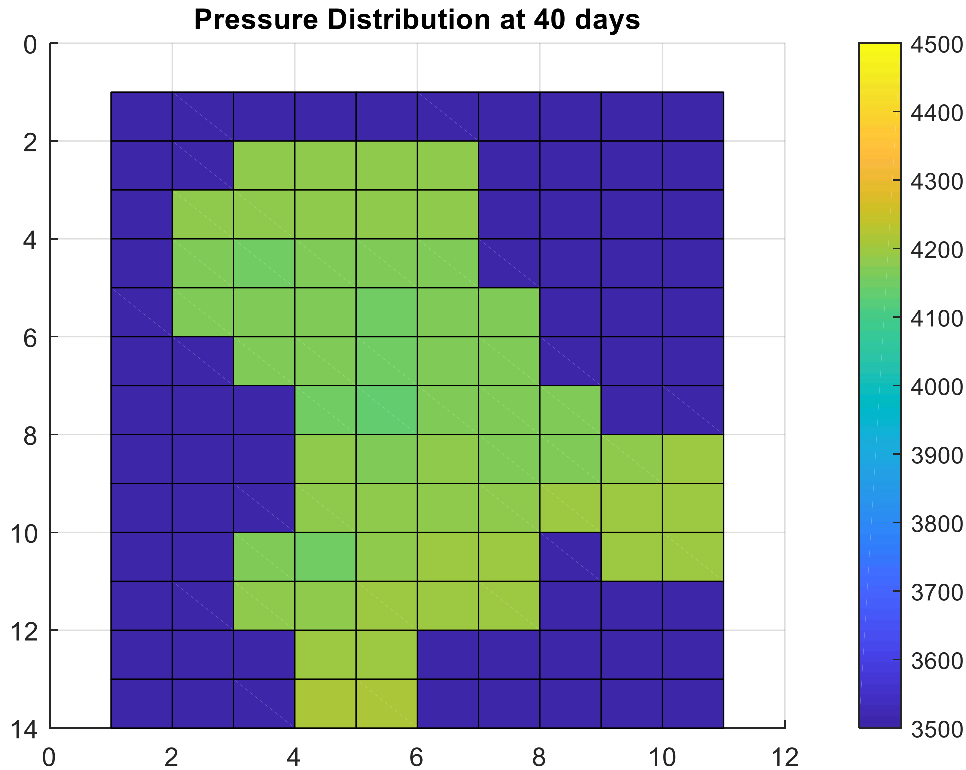
From Fig 7.8, both would tend to be flat during the late times which means convergence efficiency would be increased for the late producing time.

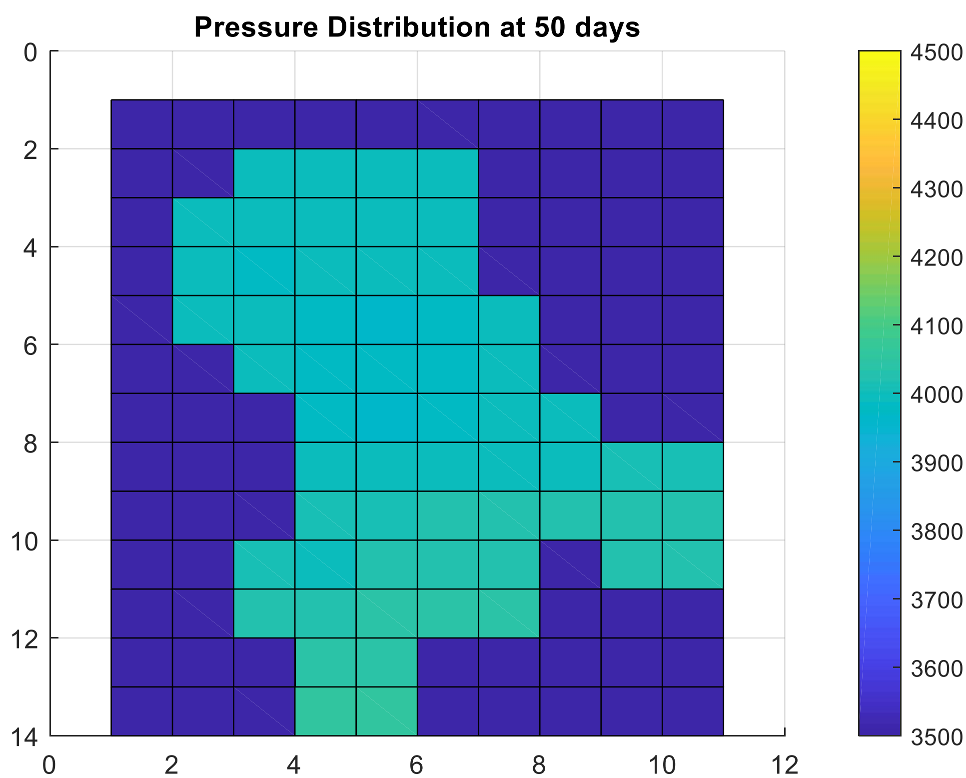
And the following 6 figures and the pressure distribution from beginning to 60 days with 10 days incremental.

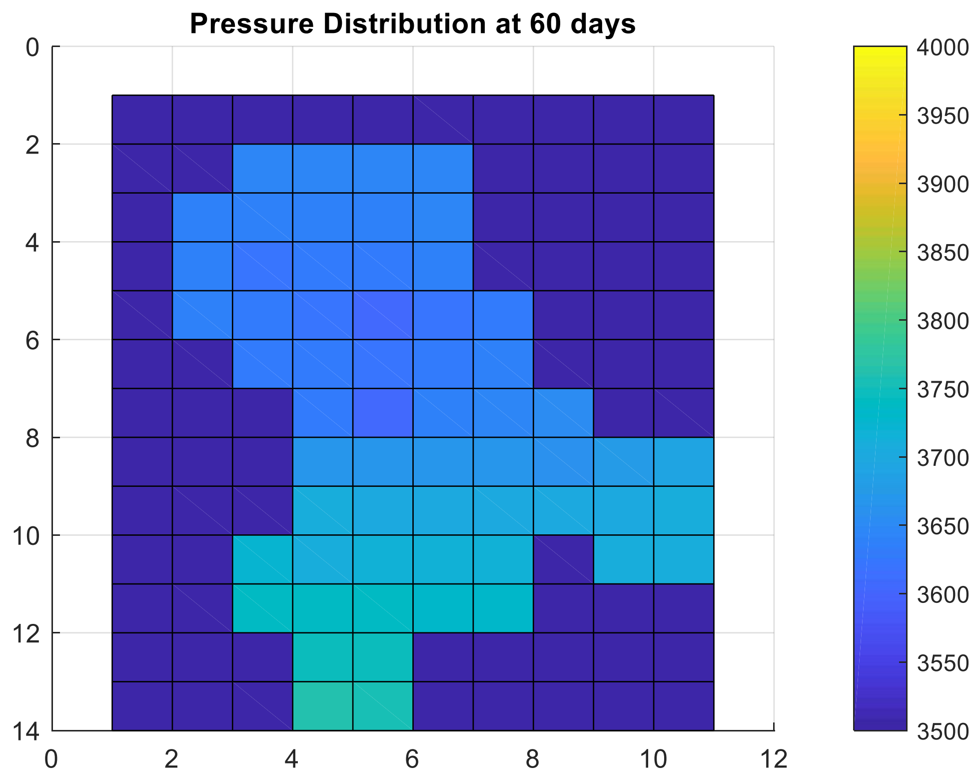


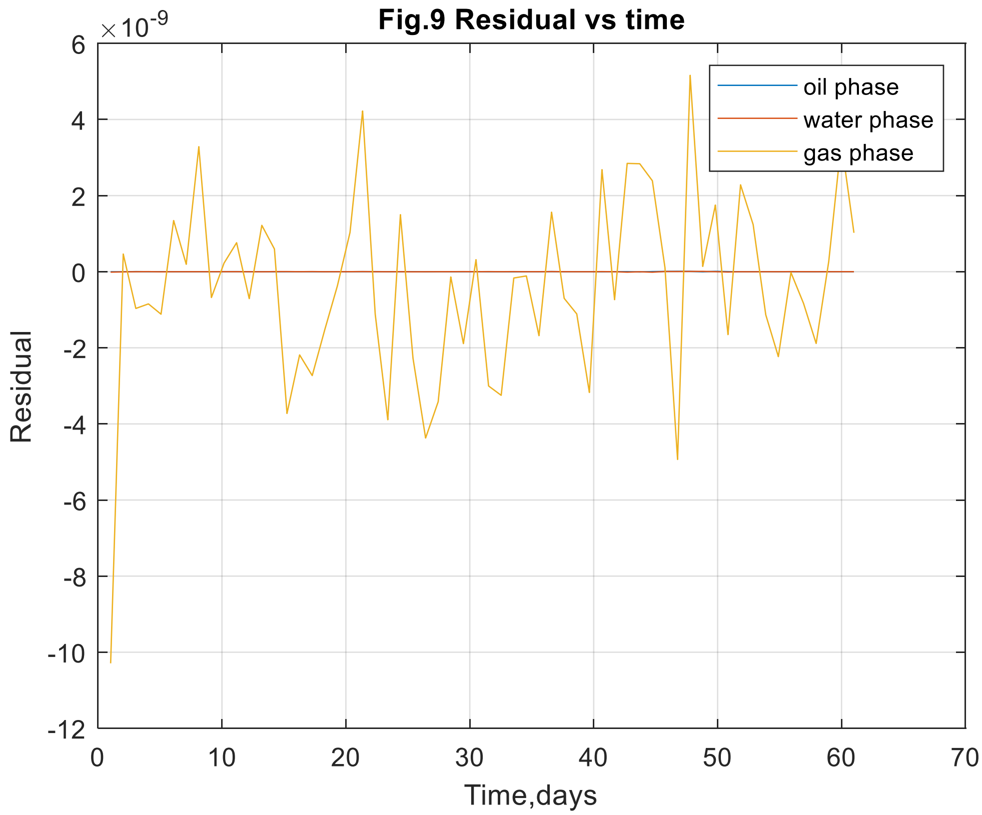

Pressure Distribution at 20 days
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
5000
4900
4800
4700
4600
4500
4400
4300
4200
4100
4000


Pressure Distribution at 30 days
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3500

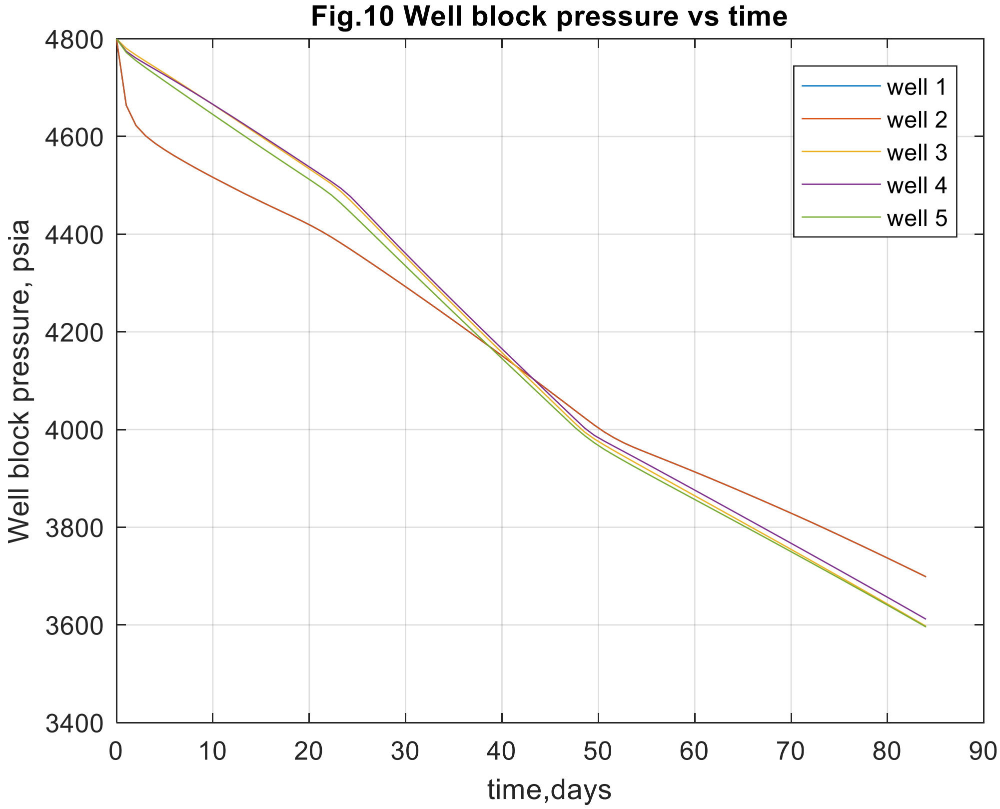

Pressure Distribution at 40 days
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3500


Pressure Distribution at 50 days
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3500


Pressure Distribution at 60 days
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
4000
3950
3900
3850
3800
3750
3700
3650
3600
3550
3500



Here is the residual of the last grid block at (13,5). Compare with Water phase and Oil phase, Gas phase implies the trend of unstable and harder to converge.



Based on the pressure profile, with production, all the grid block pressure will drop, however, due to the fixed sand face pressure of well 2, the dropping speed would reach the peak at beginning and then decline.

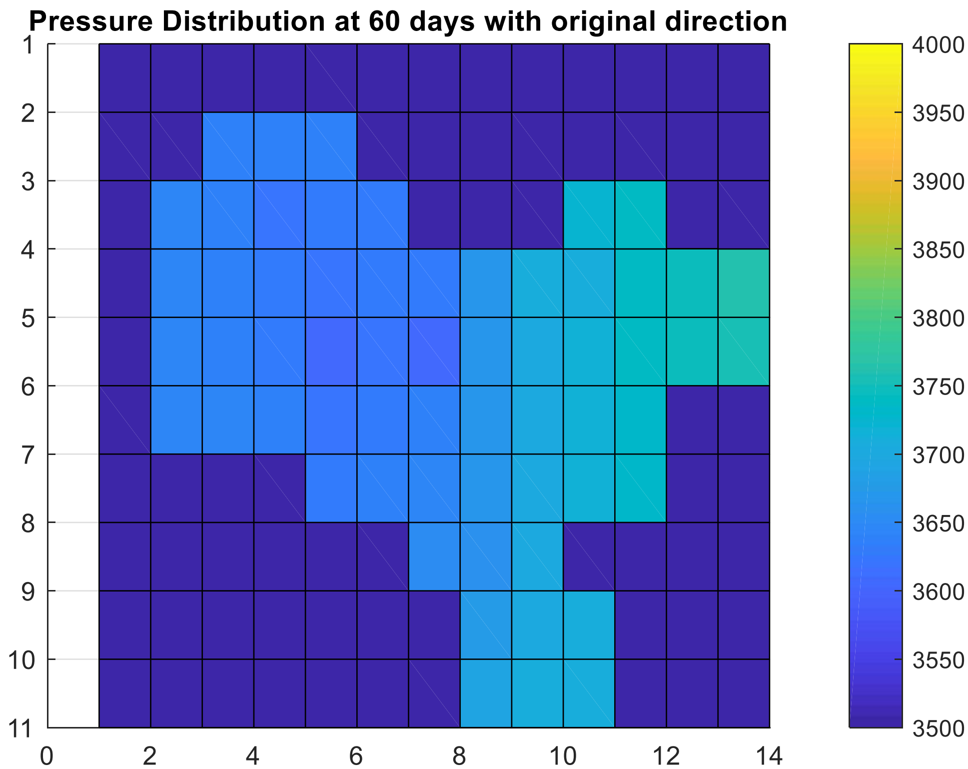


Fig. 11 Pressure Distribution at 60 days at original direction

WATER-PHASE PRESSURE DISTRIBUTION AT 60 DAYS (psia)

*	3615.5	3609.2	3608.0	*	*	*	*	*	*	*	*
3619.0	3611.9	3596.0	3598.0	3592.8	*	*	*	3542.8	3571.9	*	*
3619.5	3612.5	3601.1	3589.0	3583.2	3568.1	3585.2	3577.3	3522.7	3573.8	3588.7	3599.5
3620.7	3613.2	3598.0	3571.5	3574.6	3548.0	3585.7	3587.5	3574.1	3583.5	3590.5	3598.7
3621.0	3614.3	3600.1	3584.9	3583.1	3578.1	3591.5	3594.4	3587.9	3588.2	*	*
*	*	*	3589.1	3586.5	3585.2	3592.3	3599.6	3593.0	3590.8	*	*
*	*	*	*	*	3588.0	3587.3	3606.7	*	*	*	*
*	*	*	*	*	*	3602.8	3616.4	3624.5	*	*	*
*	*	*	*	*	*	3615.8	3624.2	3627.8	*	*	*

OIL-PHASE PRESSURE DISTRIBUTION AT 60 DAYS (psia)

*	3617.1	3610.8	3609.7	*	*	*	*	*	*	*	*
3620.7	3613.6	3597.7	3599.6	3594.4	*	*	*	3544.4	3573.5	*	*
3621.1	3614.2	3602.8	3590.6	3584.8	3569.7	3586.9	3578.9	3524.3	3575.5	3590.4	3601.2
3622.3	3614.8	3599.7	3573.2	3576.2	3549.6	3587.3	3589.1	3575.7	3585.1	3592.1	3600.4
3622.6	3615.9	3601.7	3586.5	3584.8	3579.7	3593.1	3596.1	3589.5	3589.9	*	*
*	*	*	3590.8	3588.2	3586.9	3593.9	3601.2	3594.6	3592.4	*	*
*	*	*	*	*	3589.6	3589.0	3608.3	*	*	*	*
*	*	*	*	*	*	3604.4	3618.0	3626.1	*	*	*
*	*	*	*	*	*	3617.5	3625.9	3629.5	*	*	*

GAS-PHASE PRESSURE DISTRIBUTION AT 60 DAYS (psia)

*	3617.2	3610.9	3609.8	*	*	*	*	*	*	*	*
3620.8	3613.7	3597.8	3599.7	3594.5	*	*	*	3544.5	3573.6	*	*
3621.2	3614.3	3602.9	3590.8	3584.9	3569.9	3587.0	3579.0	3524.4	3575.6	3590.5	3601.3
3622.4	3614.9	3599.8	3573.3	3576.3	3549.7	3587.4	3589.2	3575.8	3585.2	3592.2	3600.5
3622.8	3616.0	3601.8	3586.6	3584.9	3579.8	3593.2	3596.2	3589.6	3590.0	*	*
*	*	*	3590.9	3588.3	3587.0	3594.0	3601.3	3594.7	3592.5	*	*
*	*	*	*	*	3589.8	3589.1	3608.4	*	*	*	*
*	*	*	*	*	*	3604.5	3618.1	3626.2	*	*	*
*	*	*	*	*	*	3617.6	3626.0	3629.6	*	*	*

Fig. 9.25—Phase pressure distributions in the A-1 reservoir at $t = 60$ days.

WATER-PHASE SATURATION DISTRIBUTION AT 60 DAYS

*	0.4241	0.4241	0.4240	*	*	*	*	*	*	*	*
0.4242	0.4239	0.4240	0.4242	0.4240	*	*	*	0.4243	0.4243	*	*
0.4241	0.4237	0.4237	0.4241	0.4243	0.4241	0.4240	0.4242	0.4241	0.4240	0.4240	0.4241
0.4241	0.4239	0.4239	0.4239	0.4240	0.4243	0.4240	0.4240	0.4242	0.4240	0.4239	0.4239
0.4241	0.4240	0.4242	0.4239	0.4239	0.4239	0.4240	0.4240	0.4240	0.4239	*	*
*	*	*	0.4244	0.4239	0.4240	0.4239	0.4239	0.4240	0.4239	*	*
*	*	*	*	*	0.4240	0.4240	0.4239	*	*	*	*
*	*	*	*	*	*	0.4239	0.4238	0.4239	*	*	*
*	*	*	*	*	*	0.4239	0.4238	0.4238	*	*	*

OIL-PHASE SATURATION DISTRIBUTION AT 60 DAYS

*	0.4605	0.4606	0.4598	*	*	*	*	*	*	*	*
0.4621	0.4586	0.4590	0.4609	0.4589	*	*	*	0.4583	0.4597	*	*
0.4610	0.4573	0.4567	0.4591	0.4604	0.4579	0.4583	0.4613	0.4630	0.4584	0.4587	0.4598
0.4611	0.4594	0.4584	0.4566	0.4579	0.4587	0.4580	0.4585	0.4610	0.4581	0.4579	0.4580
0.4609	0.4599	0.4613	0.4574	0.4569	0.4572	0.4587	0.4587	0.4584	0.4577	*	*
*	*	*	0.4618	0.4574	0.4578	0.4580	0.4588	0.4587	0.4581	*	*
*	*	*	*	*	0.4583	0.4579	0.4591	*	*	*	*
*	*	*	*	*	*	0.4587	0.4586	0.4597	*	*	*
*	*	*	*	*	*	0.4594	0.4591	0.4590	*	*	*

GAS-PHASE SATURATION DISTRIBUTION AT 60 DAYS

*	0.1155	0.1153	0.1162	*	*	*	*	*	*	*	*
0.1136	0.1175	0.1170	0.1149	0.1171	*	*	*	0.1174	0.1160	*	*
0.1149	0.1190	0.1196	0.1168	0.1153	0.1181	0.1177	0.1145	0.1129	0.1176	0.1173	0.1160
0.1148	0.1167	0.1177	0.1195	0.1181	0.1169	0.1180	0.1175	0.1149	0.1179	0.1182	0.1181
0.1151	0.1161	0.1145	0.1187	0.1192	0.1188	0.1172	0.1173	0.1177	0.1183	*	*
*	*	*	0.1138	0.1187	0.1182	0.1181	0.1173	0.1173	0.1179	*	*
*	*	*	*	*	0.1177	0.1181	0.1170	*	*	*	*
*	*	*	*	*	*	0.1173	0.1176	0.1164	*	*	*
*	*	*	*	*	*	0.1167	0.1170	0.1172	*	*	*

Fig. 9.26—Phase saturation distributions in the A-1 reservoir at $t = 60$ days.

Fig. 12 Results from book example, (Ertekin et al,2001)

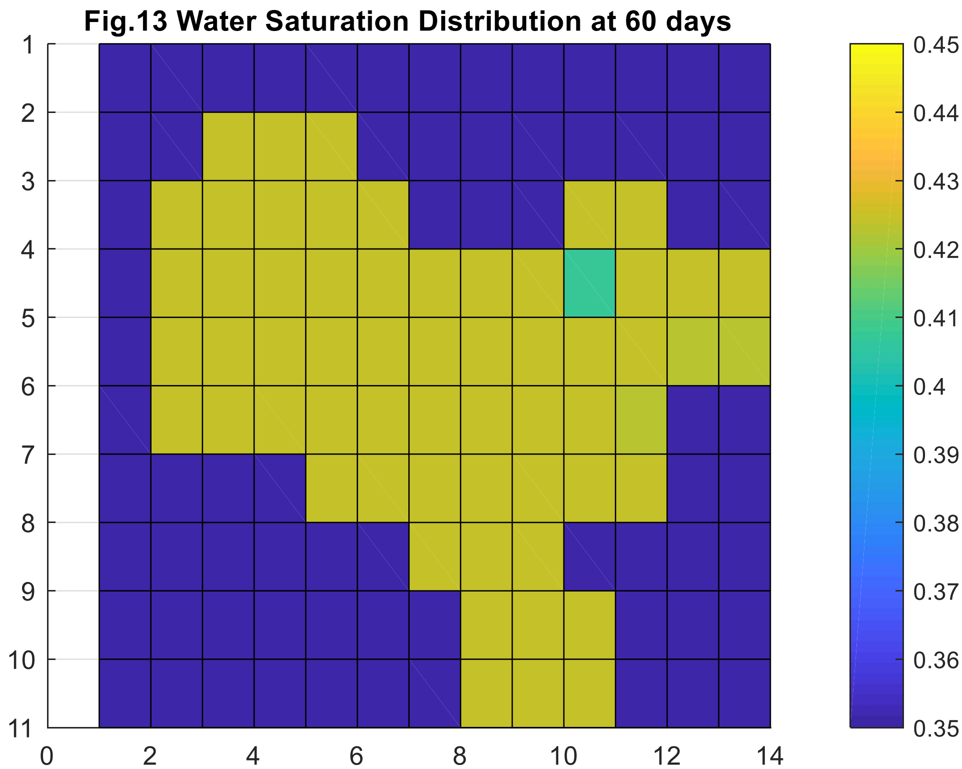


Fig.13 Water Saturation Distribution at 60 days

0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	3640.128	3634.933	3636.087	0	0	0	0	0	0	0	0	0
0	3643.887	3637.218	3623.065	3629.599	3631.14	0	0	0	3721.999	3737.533	0	0	0
0	3644.849	3638.644	3629.931	3623.83	3627.145	3625.494	3666.344	3703.843	3708.298	3735.349	3747.554	3758.975	0
0	3646.586	3640.453	3629.053	3608.832	3620.898	3607.158	3664.331	3702.325	3717.352	3735.924	3746.773	3757.436	0
0	3647.446	3642.477	3633.375	3624.695	3630.832	3635.917	3666.981	3700.615	3716.942	3734.087	0	0	0
0	0	0	0	3630.932	3635.644	3643.808	3665.759	3698.471	3715.261	3733.312	0	0	0
0	0	0	0	0	0	3648.996	3659.118	3697.045	0	0	0	0	0
0	0	0	0	0	0	0	3676.319	3700.138	3706.847	0	0	0	0
0	0	0	0	0	0	0	3690.265	3704.815	3708.599	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig.14 Oil Pressure Distribution at 60 days

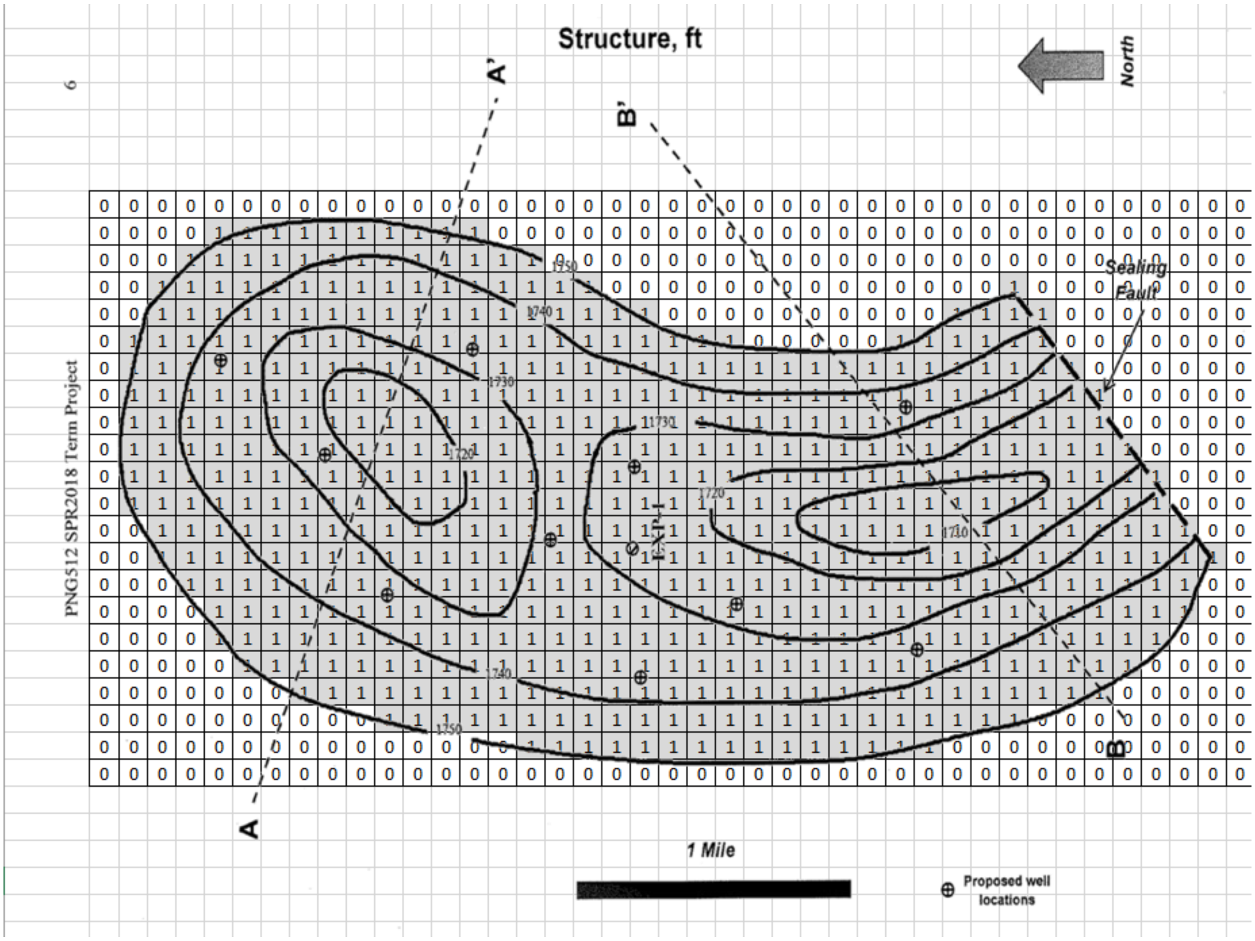
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0.424037	0.42409	0.423981	0	0	0	0	0	0	0	0	0
0	0.424255	0.423756	0.423961	0.424218	0.423936	0	0	0	0.423787	0.423728	0	0	0
0	0.424066	0.423526	0.423522	0.42397	0.424179	0.423876	0.423675	0.423646	0.406414	0.423414	0.423486	0.4236	0
0	0.424087	0.423854	0.423781	0.42373	0.423872	0.424169	0.423651	0.423594	0.423543	0.423469	0.423369	0.42331	0
0	0.424043	0.423954	0.424199	0.423735	0.42364	0.423708	0.423752	0.423556	0.423503	0.423382	0	0	0
0	0	0	0	0.424392	0.423693	0.423724	0.423642	0.423553	0.423493	0.423436	0	0	0
0	0	0	0	0	0	0.423778	0.424098	0.423603	0	0	0	0	0
0	0	0	0	0	0	0	0.423681	0.423499	0.423622	0	0	0	0
0	0	0	0	0	0	0	0.423675	0.42354	0.423491	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig.15 Water Saturation Distribution at 60 days

Compare two results from either the simulation and the book example, basically the difference between two are not obvious (~23 or 24psia for pressure and water saturation around 0.02%). However, the well block at (10,4), since fixed sand face pressure, the water saturation is slightly smaller than the reference answer. Nevertheless, generally, the convergence and the results are still acceptable.

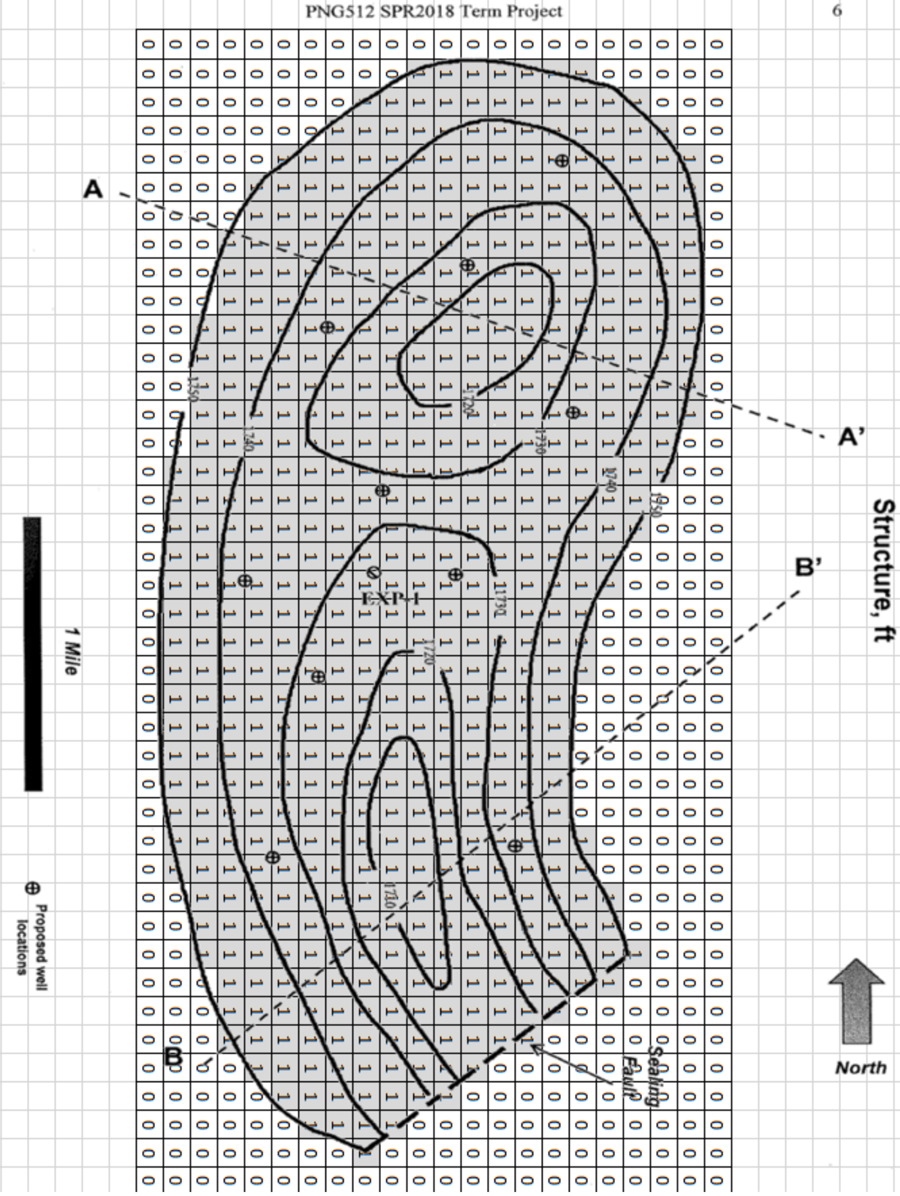
CH4 Case Study-Final Project

3.1 Reservoir Digitization Explanation



This is the detailed digitization of this reservoir. And for all the wells, here listed the detailed location and specified condition of the wells.

For simplification, North direction is downwards, East direction is rightwards, and i direction is align with the North direction and x direction, j direction is aligning with the East direction and y direction. Therefore, the grid block should be illustrated below.

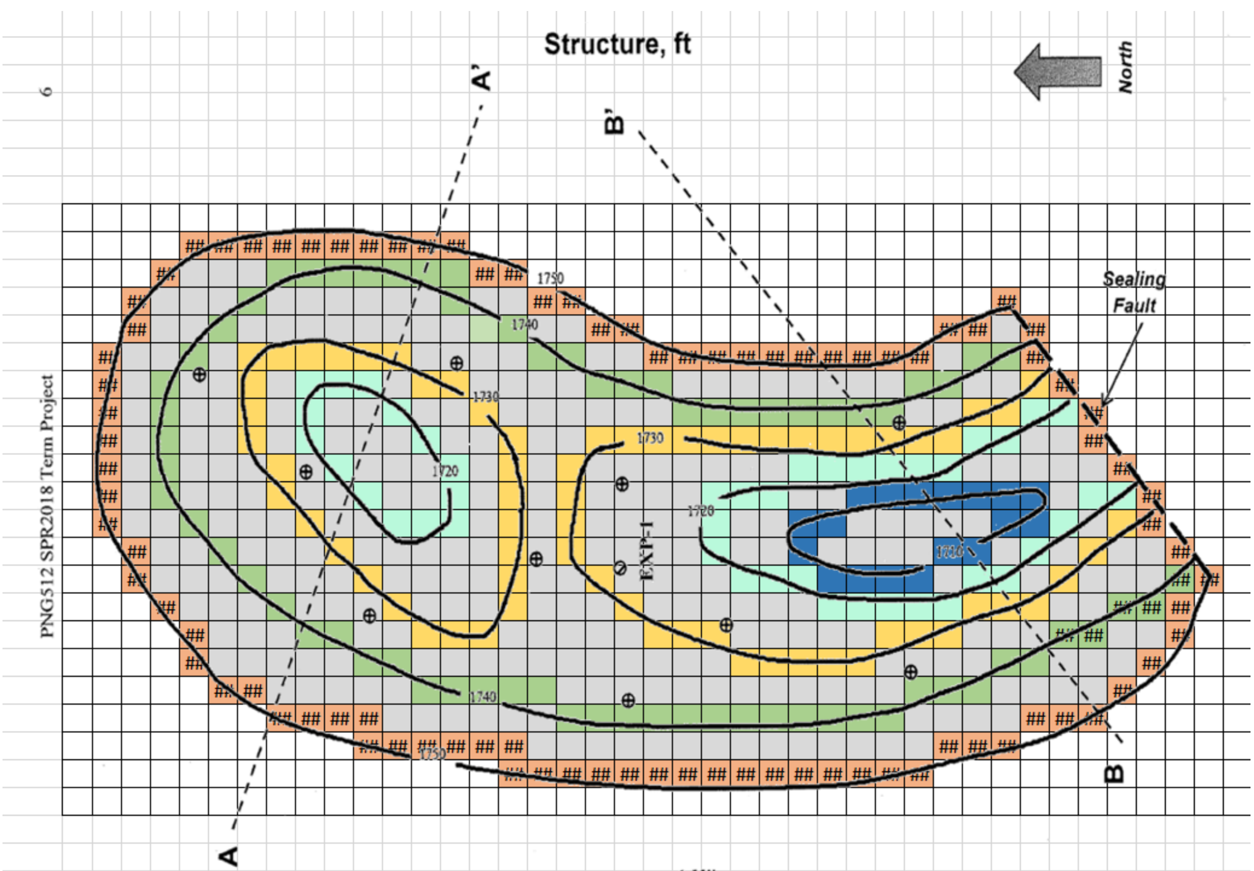

Structure, ft
North
Sealing Fault
A
A'
B
B'
EXP-1
1720
1730
1740
1750
1 Mile
Proposed well locations

2. Data Input

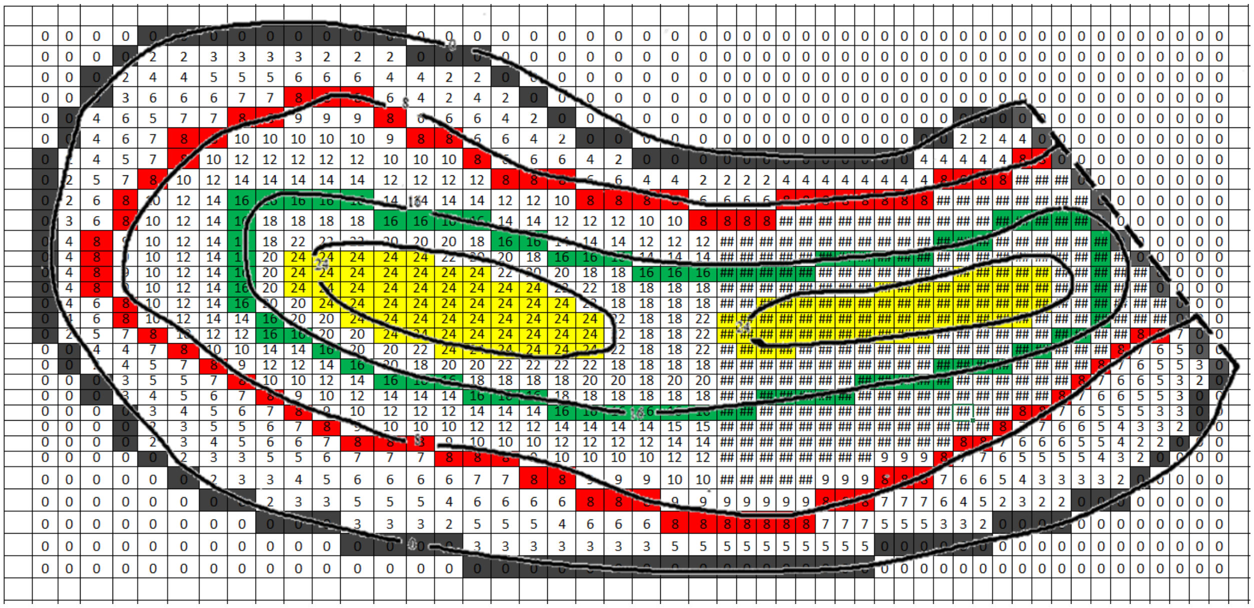
For this final project, initial water saturation is set 0.3 and initial gas saturation is set as 0.1. Meanwhile the initial pressure for the reservoir is 2000 psia.
And the well specification condition is arbitrarily decided which is illustrated in the table below.

Well #	Well address	Well Type	Flow rate specification	Sand face pressure specification	skin factor
1	(46,22)	Production	N/A	1600 psia	0
2	(42,16)	Production	Oil, 25 STBD	N/A	0
3	(40,10)	Production	N/A	1600 psia	0
4	(37,23)	Production	N/A	1600 psia	0
5	(34,12)	Production	Total, 50000 STBD	N/A	0
6	(31,15)	Production	Liquid, 30 STBD	N/A	0
7	(31,12)	Production	N/A	1600 psia	0
8	(30,6)	Production	GAS, 0.9 MMSCFD	N/A	0
9	(26,19)	Production	N/A	1600 psia	0
10	(26,7)	Production	N/A	1600 psia	0

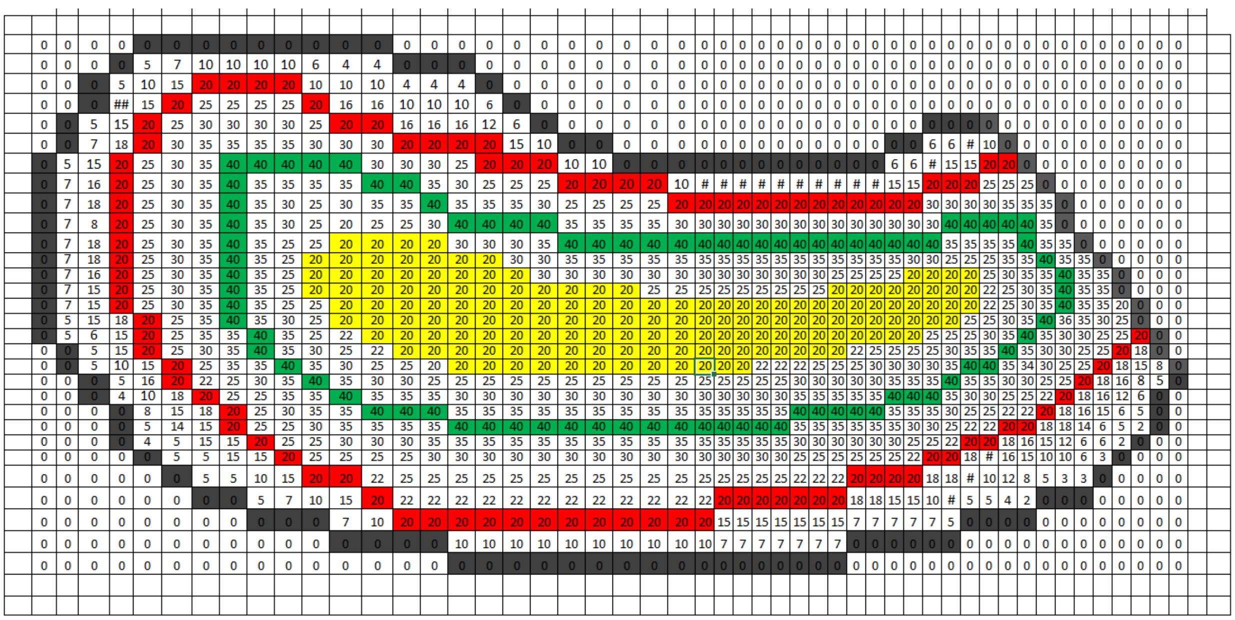
a. Structure, ft



b. Porosity



c. Permeability (N-S/x direction)



d. PVT data

Table 1 – PVT data of oil					
	Pressure (psia)	**ρ_o (lb/ft^3)**	**B_o (RB/STB)**	**μ_o (cP)**	**Solution R_{so} (SCF/STB)**
Saturated	14.7	45.36	1.062	1.04	1
	270	44.08	1.15	0.975	90.5
	520	42.93	1.207	0.91	180
	1015	41	1.295	0.83	371
	2015	39.04	1.435	0.695	636
	2515(p_b)	38.52	1.5	0.641	775
	3015	37.55	1.565	0.594	930
	4015	36.81	1.695	0.51	1270
	5015	36.05	1.827	0.449	1618
	9015	34.4	2.357	0.203	2984
Under-saturated	2515	38.52	1.5	0.641	775
	9015	41.35	1.397	0.93	775

Table 2 – PVT data of water					
	Pressure (psia)	**ρ_w (lb/ft^3)**	**B_w (RB/STB)**	**μ_w (cP)**	**Solution R_{sw} (SCF/STB)**
Saturated	14.7	62.24	1.041	0.31	0
	270	62.28	1.0403	0.31	0
	520	62.33	1.0395	0.31	0
	1015	62.42	1.038	0.31	0
	2015	62.6	1.035	0.31	0
	2515	62.69	1.0335	0.31	0
	3015	62.78	1.032	0.31	0
	4015	62.96	1.029	0.31	0
	5015	63.16	1.0258	0.31	0
	9015	63.96	1.013	0.31	0
Under-saturated	2515	62.69	1.0335	0.31	0
	9015	63.96	1.013	0.31	0

Table 3 – PVT data of gas			
Pressure (psia)	ρ_g **(lb/ft³)**	B_g **(RB/SCF)**	μ_g **(cP)**
14.7	0.0647	0.166666	0.008
270	0.8916	0.012093	0.0096
520	1.7185	0.006274	0.0112
1015	3.3727	0.003197	0.014
2015	6.6806	0.001614	0.0189
2515	8.3326	0.001294	0.0208
3015	9.9837	0.00108	0.0228
4015	13.2952	0.000811	0.0268
5015	16.6139	0.000649	0.0309
9015	27.9483	0.000386	0.047

Table 4 – Water relative permeability and capillary pressure data			
S_w	k_{rw}	k_{row}	P_{cow}
0.22	0	1	7
0.3	0.08	0.41	4
0.4	0.17	0.128	3
0.5	0.26	0.0645	2.5
0.6	0.35	0.0045	2
0.8	0.68	0	1
0.9	0.85	0	0.5
1	1	0	0

Table 5 – Gas relative permeability and capillary pressure data			
S_g	k_{rg}	k_{rog}	P_{cgo}
0	0	1	0
0.04	0.005	0.602	0.21
0.1	0.022	0.333	0.55
0.2	0.1	0.104	1.03
0.3	0.24	0.021	1.54
0.4	0.34	0	2.09
0.5	0.42	0	2.51
0.6	0.5	0	3.05
0.7	0.8125	0	3.5
0.78	1	0	3.93

3. Results

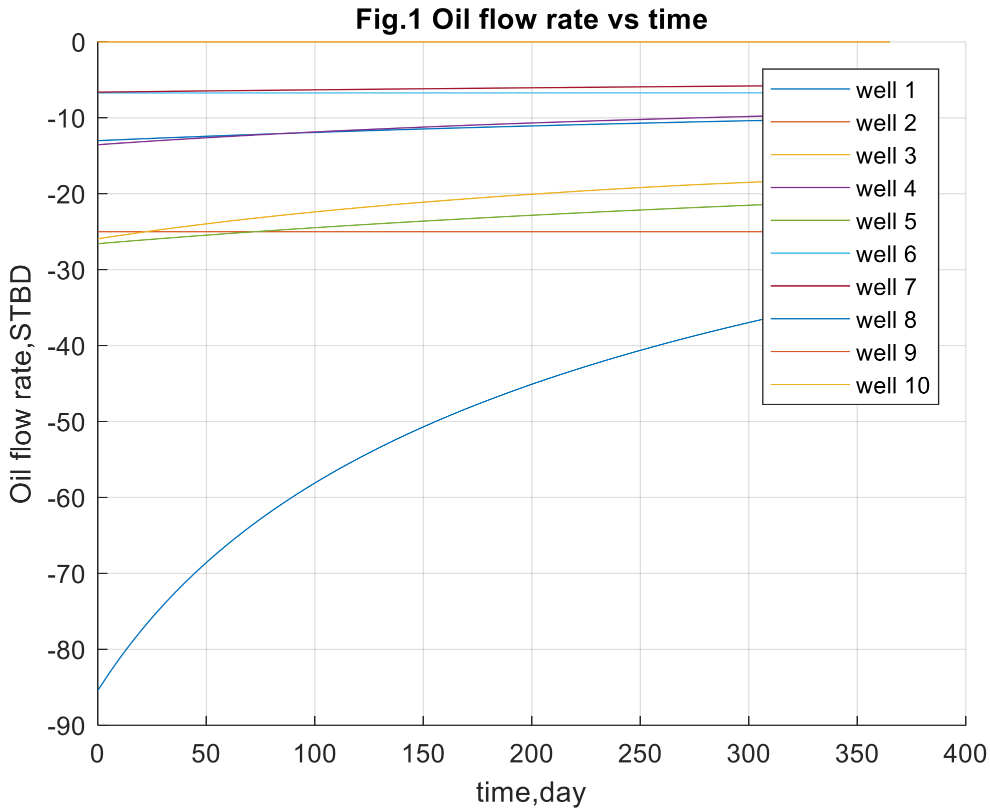


Fig.1 Oil flow rate vs time
Oil flow rate,STBD
time,day
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0
50
100
150
200
250
300
350
400
well 1
well 2
well 3
well 4
well 5
well 6
well 7
well 8
well 9
well 10

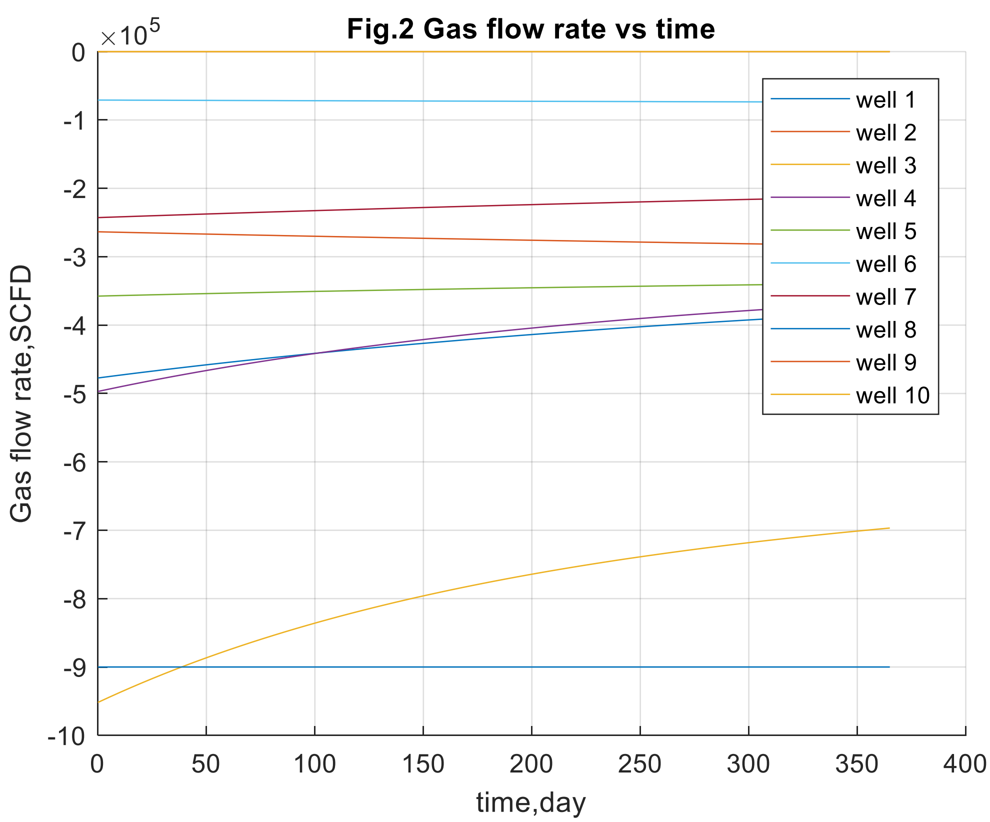


Fig.2 Gas flow rate vs time
$\times 10^5$
Gas flow rate,SCFD
time,day
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
50
100
150
200
250
300
350
400
well 1
well 2
well 3
well 4
well 5
well 6
well 7
well 8
well 9
well 10

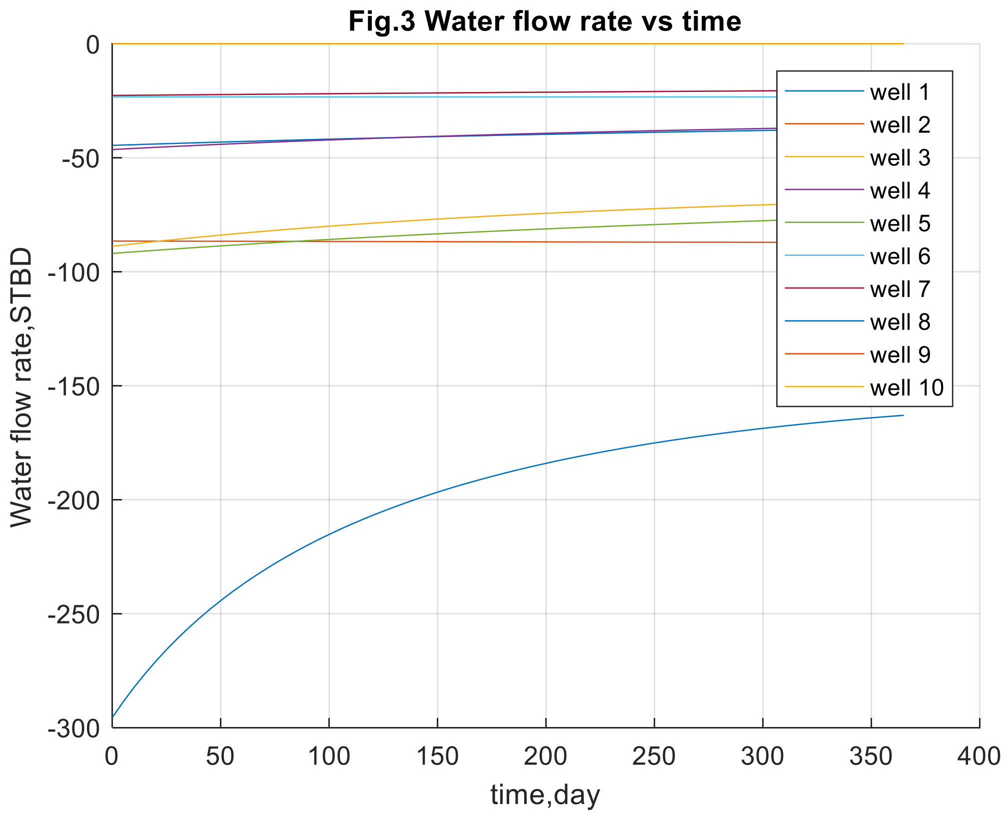


Fig.1 to Fig 3 shows the O/W/G flow rates at 10 wells from the beginning to the end of 1 year. However, the simulation could still continue. Here just demonstrate the results at 1 year.

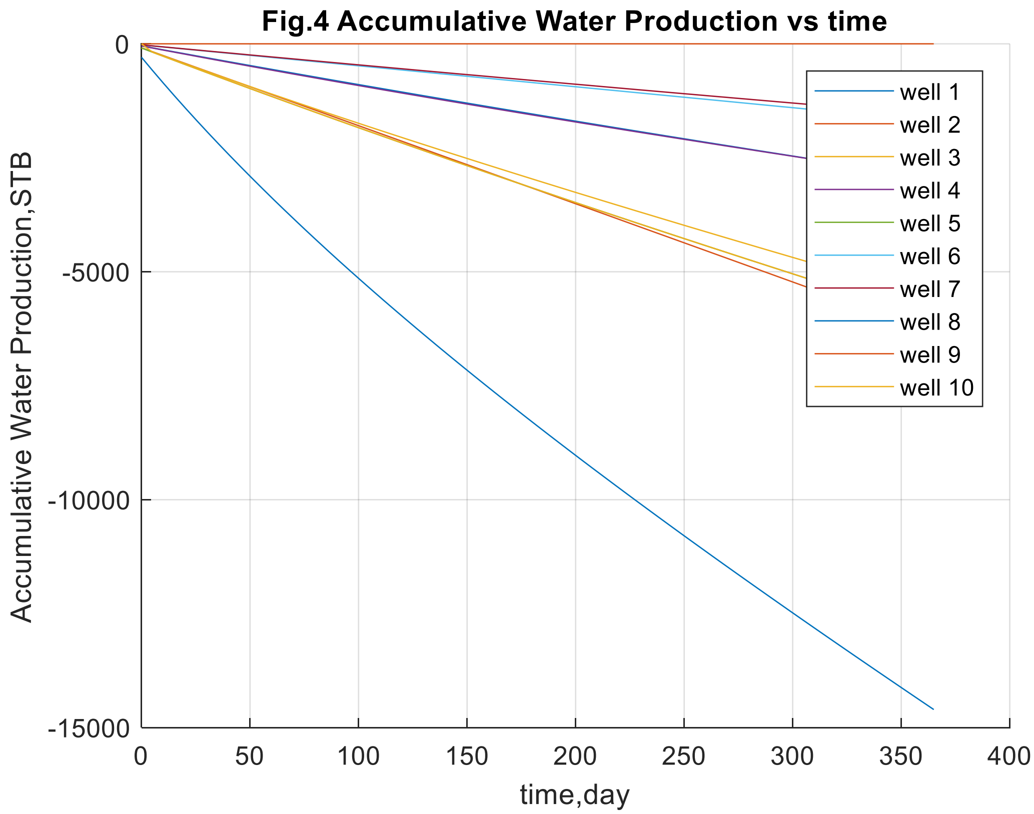


Fig.4 Accumulative Water Production vs time
Accumulative Water Production,STB
time,day
0
-5000
-10000
-15000
0
50
100
150
200
250
300
350
400
well 1
well 2
well 3
well 4
well 5
well 6
well 7
well 8
well 9
well 10

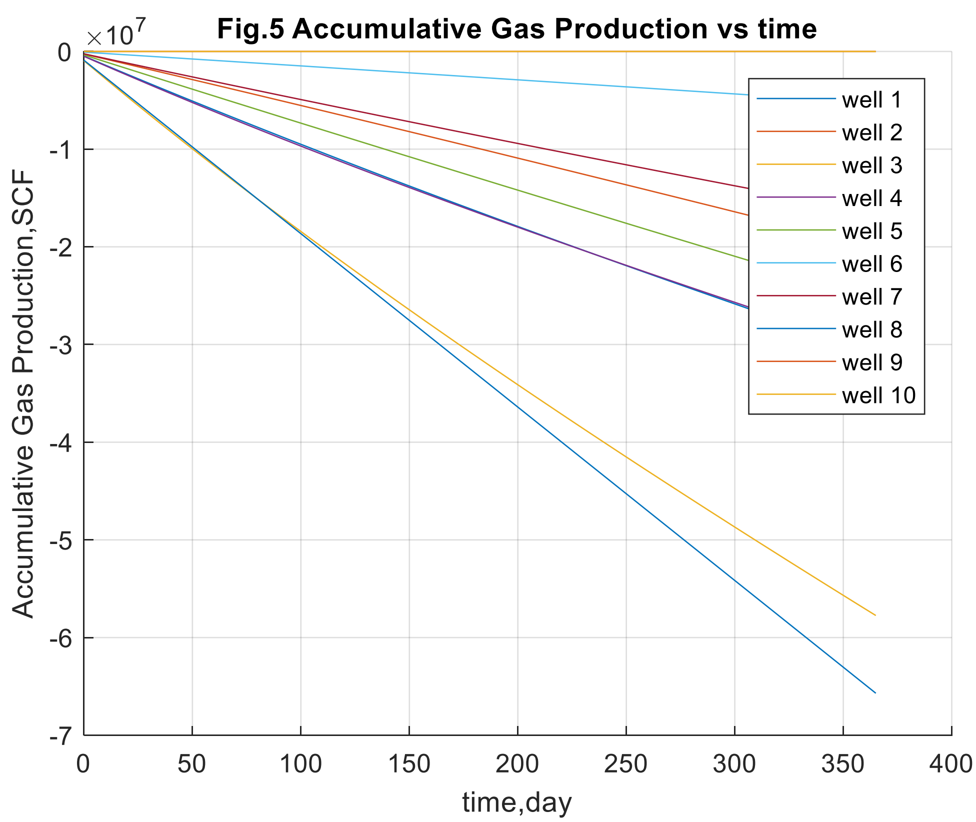
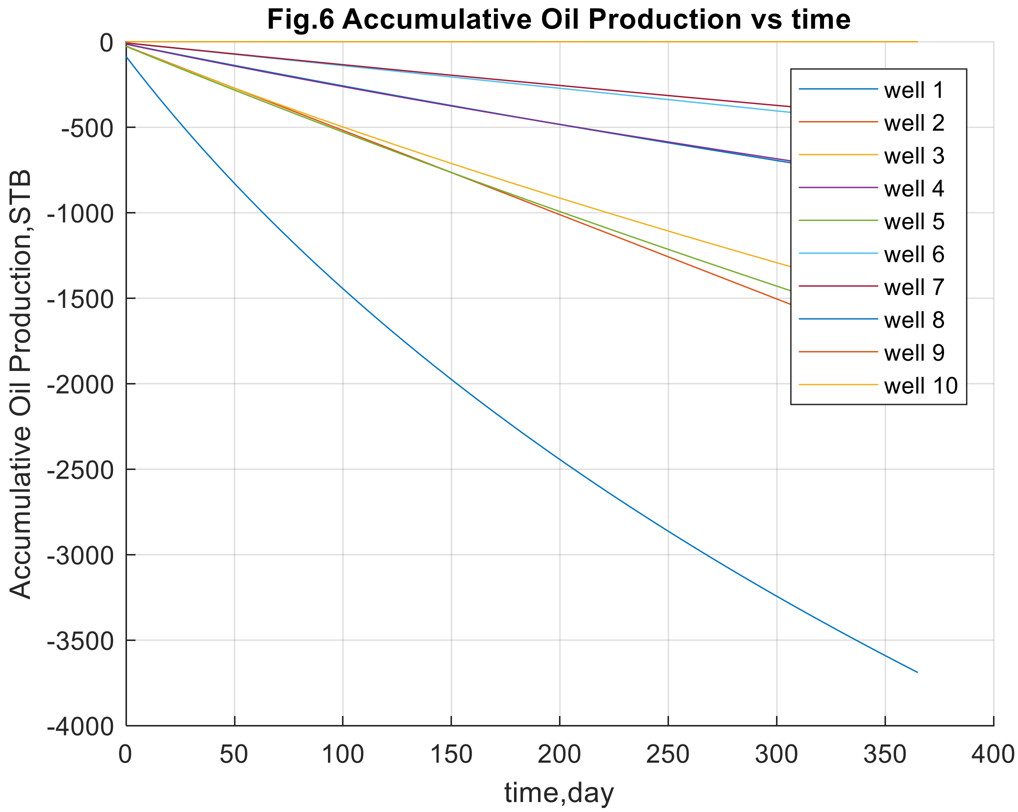


Fig.5 Accumulative Gas Production vs time
$\times 10^7$
Accumulative Gas Production,SCF
time,day
0
-1
-2
-3
-4
-5
-6
-7
0
50
100
150
200
250
300
350
400
well 1
well 2
well 3
well 4
well 5
well 6
well 7
well 8
well 9
well 10



With 6 sand face pressure fixed grid blocks, with other well grids, these well appear to demonstrate high capability to produce large amount of flow rate during the beginning time however the flow rates decline. Meanwhile if large rates are fixed, the pressure would drop faster than other well grids.

Fig.7 Incremental MB Check vs time

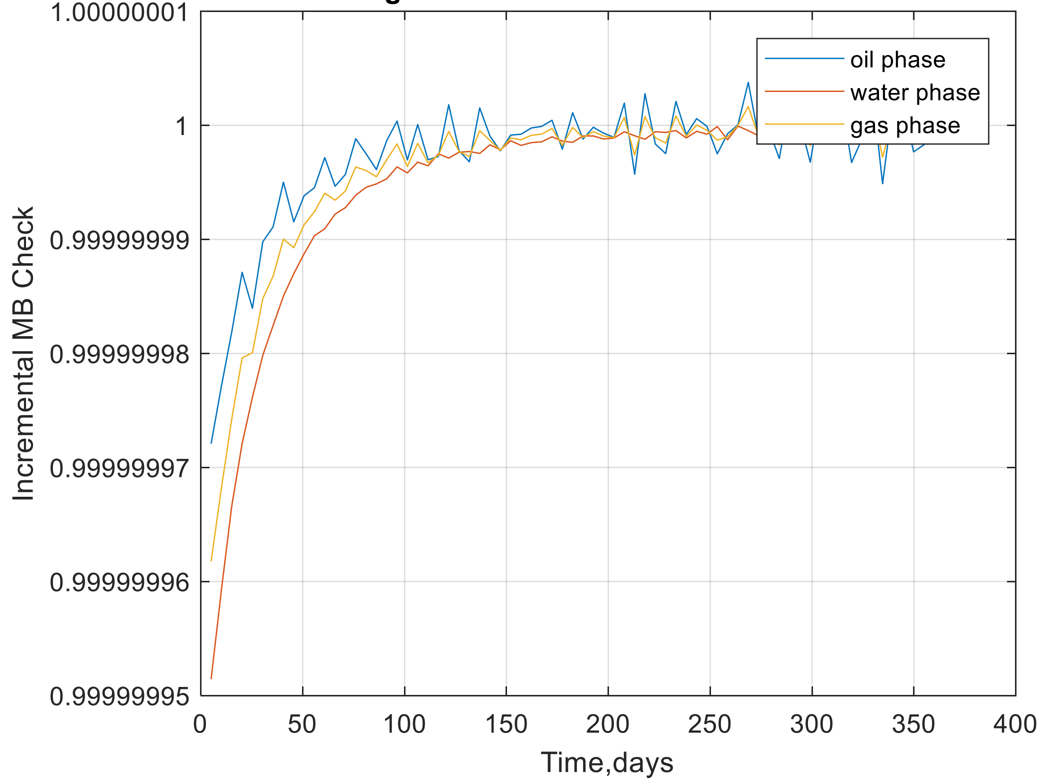
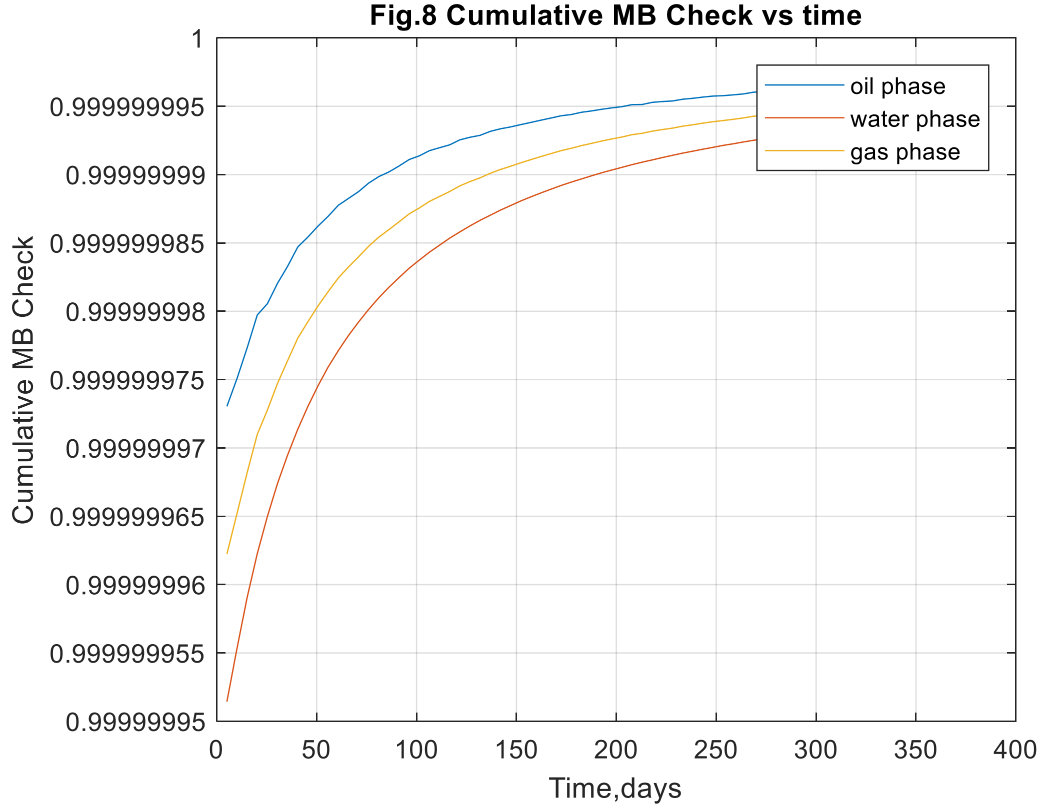
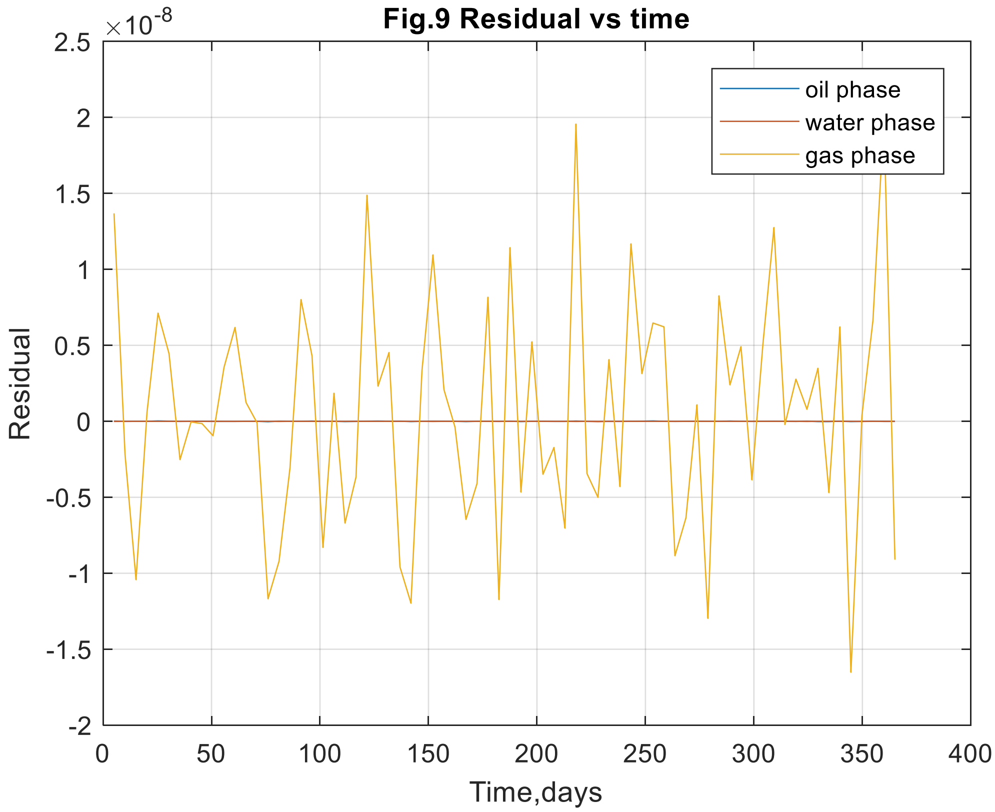


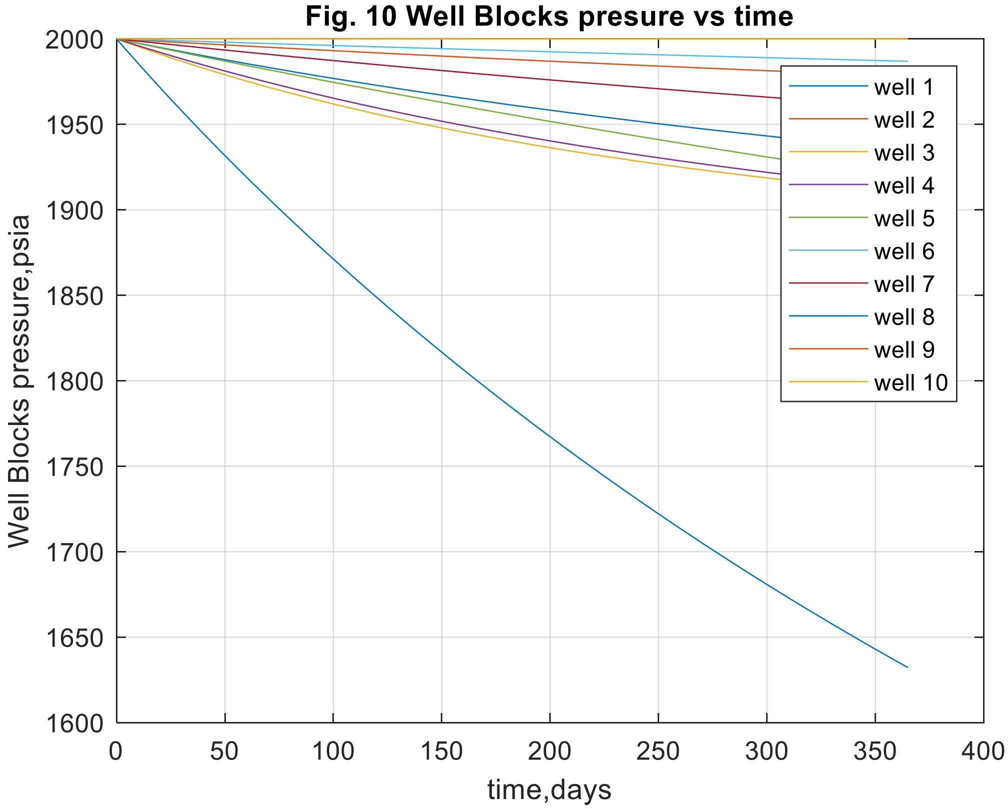
Fig.8 Cumulative MB Check vs time



Also, with smaller MB check convergence difference, which means the convergence efficiency increases.

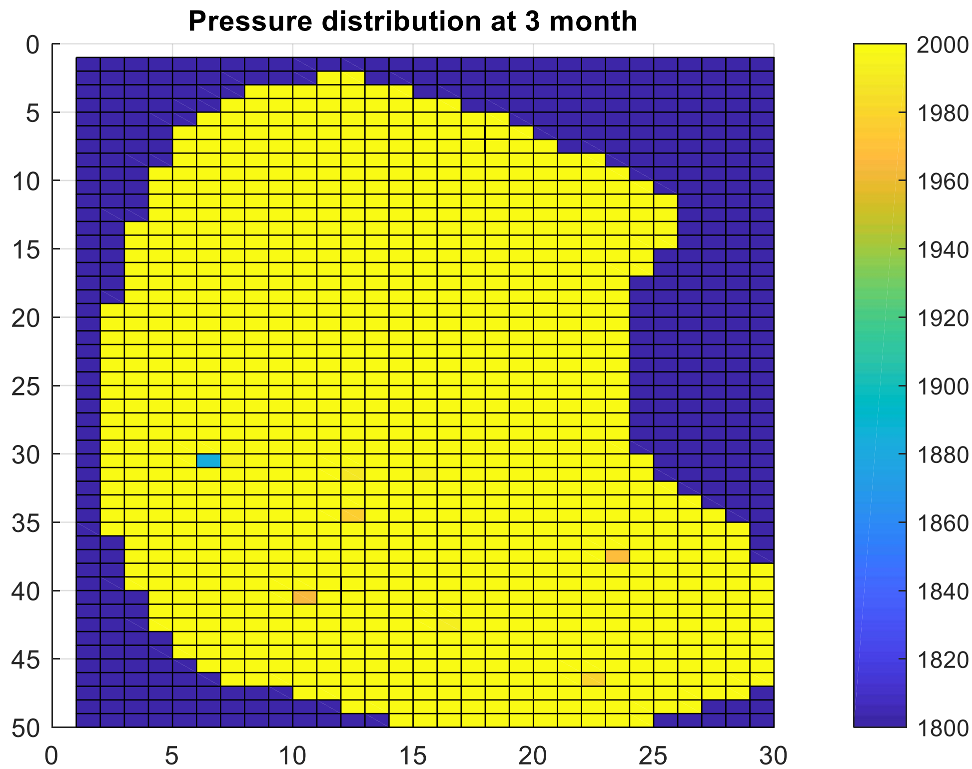


This residual is at the last grid block at (49,24), grid No.941.

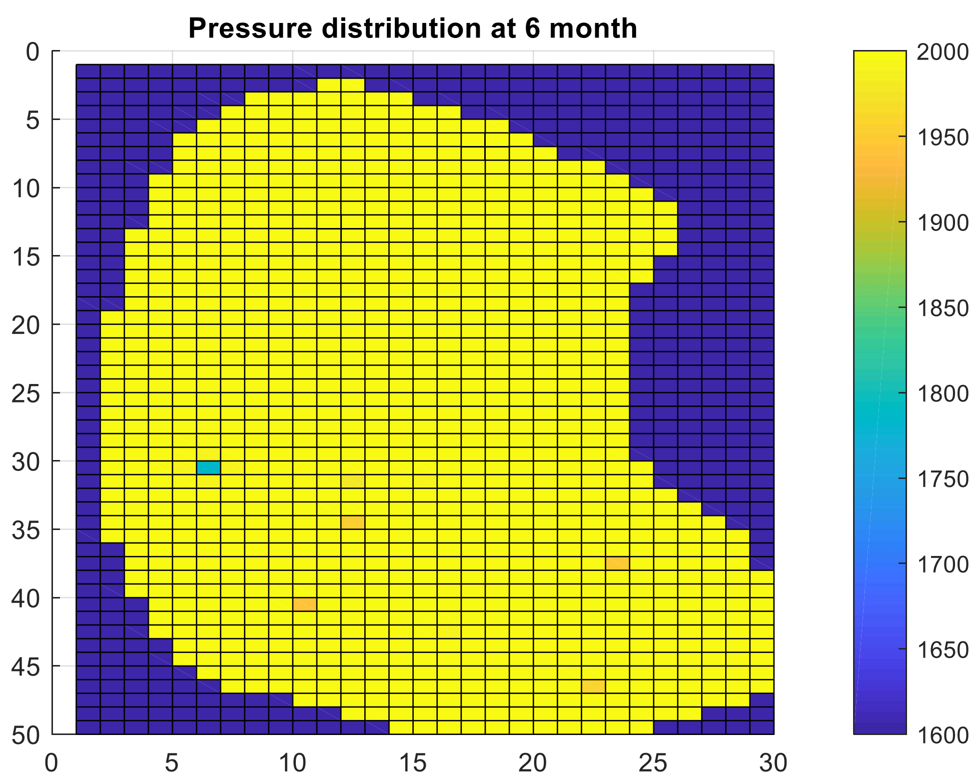


For well number 8 due high specified gas flow rates, the pressure drops trespasses other wells. And other wells show flatter pressure drop and stable production through the whole production period.

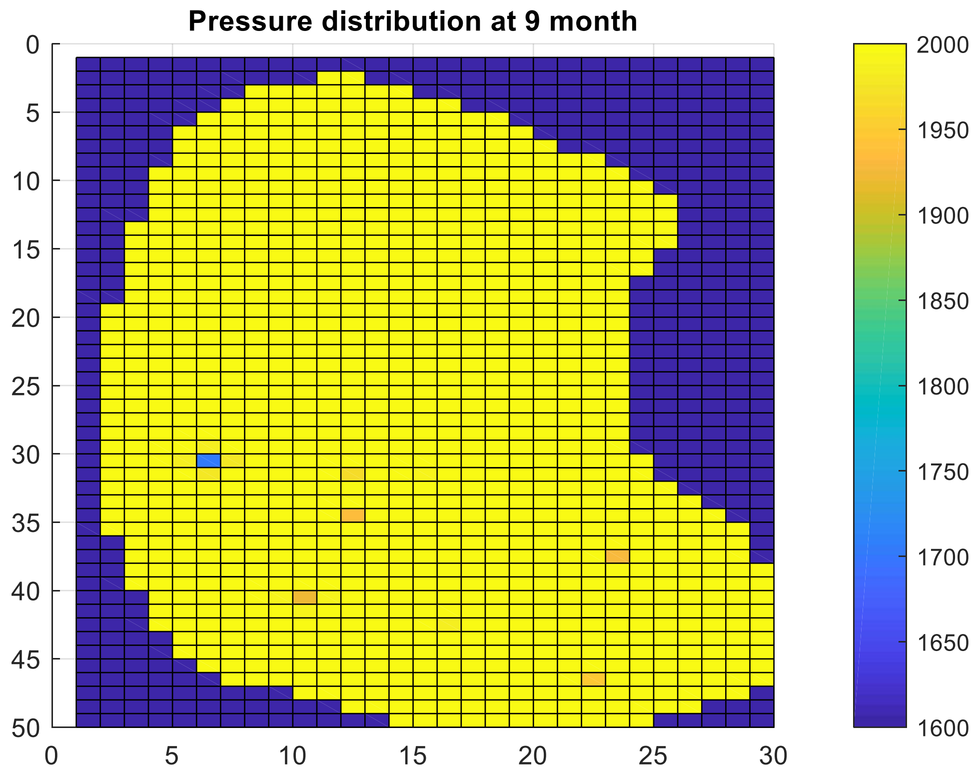
The following 4 figures are pressure distribution from the beginning to the end of the 1 year. Due to long simulation time, the results are truncated and only the first-year section is demonstrated. If needed, the simulation could continue to display the following years.

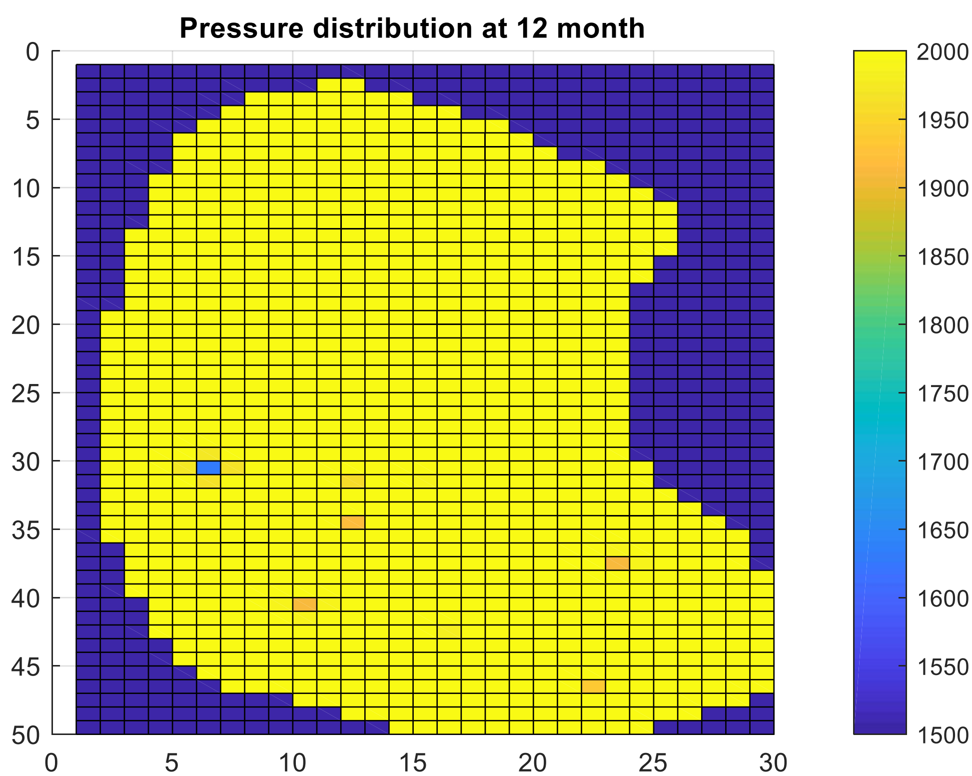


Pressure distribution at 3 month
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25
30
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
1800



Pressure distribution at 6 month
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25
30
2000
1950
1900
1850
1800
1750
1700
1650
1600


Pressure distribution at 9 month
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25
30
2000
1950
1900
1850
1800
1750
1700
1650
1600


Pressure distribution at 12 month
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25
30
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500

Based on the simulation results, we could easily discover that the average pressure drop is not severe due to short production time and nearly all the pressure is still around the initial pressure which means the pressure drop has not reached the most reservoir. And the reservoir has great potential to produce.

- Reference

1. Basic Applied Reservoir Simulation, Turgay Ertekin, et al, 2001, SPE textbook series vol.7