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Development of a Semi-Analytical Type Curve of Transient Pressure Response in Complex Well-Reservoir Architectures

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Abstract

The objective of the conventional well testing technique is to evaluate well- reservoir interaction through determining the flow capacity and well potential on a short-term basis by relying on the transient pressure response methodology. The well testing analysis is a major input to the reservoir simulation model to validate the near wellbore characteristics and update the variables that are normally function of time such as skin, permeability and productivity multipliers.

Well test analysis models are normally built on analytical approaches with fundamental physical of homogenous media with line source solution. Many developments in the last decade were made to increase the resolution of transient response derivation to meet the complexity of well and flow media.

Semi-analytical modeling for the pressure transient response in complex well architecture and complex reservoirs were adopted in this research. The semi analytical solution was based on coupling the boundary condition of source function to the well segment. Coupling well-reservoir on sliced based technique was used to re-produce homogenous isotropic media from several source functions of different properties. The approach can model different well geometries penetrated complex reservoirs. A computer package was prepared to model the pressure transient response of horizontal, dual-lateral, multi-lateral wells in complex anisotropic reservoirs, multilayered, compartmentalized, system of various boundary conditions such as: bottom support aquifers, edge supported, gas caps, interference of injection. The validity of the proposed model was successfully checked by using the commercial simulator.

Keywords: Semi-Analytical, Pressure transient, multilateral wells.

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1- Introduction

Both analytical and numerical approaches were implemented in a new technique to step away from the approximation in the finite difference and from the long calculations of Green's function [1] in the solution of BEM (Boundary Element Method) [2] multi-function domain response.

The propose methodology is to proceed with solution of three dimensional partial differential equation in Laplace space. The Laplace space equation is solved by applying the Stehfest algorithm [3].

The solution is for point source [4], integrate the solution over the wellbore length to estimate the transient well index over time [5], [6], [7].

The boundary condition was modeled in the finite element method of a single domain with boundary conditions that identified in a three-dimensional perspective. Hence, the solution comes to be similar to an infinite conductivity solution with mixed boundary conditions [8].

Ouyang [9] and Kabir [10] solutions were used in this study for modeling the finite conductive wells to estimate pressure drop in pipes.

The pressure drop for the wellbore segments was estimated [11], which simultaneously integrated with the boundary conditions and with the infinite conductive solution to determine the influx rate per segment and the pressure drop from the toe to the junction point with the main bore.

The newly proposed technique in this study is similar to that discussed by Yildiz [12], Ouyang [9], and Archer [6].

However, this technique does not take into account the lateral heterogeneity resolution across the drilled sections. This limitation is considered an advantage when modeling drainage area effective properties using the pressure transient response.

In pressure transient analysis, the analytical and semi analytical analyses are normally taking into consideration the effective permeability and the effective well length as compensative parameters for the heterogeneity.

However, it is not possible to determine the permeability profile across the drilled sections. It is convenient to use the finite difference simulators to determine the permeability profile where petrophysical information are usually integrated with well testing data for upgrading the model and with the fine grid distribution across the well to reduce the uncertainty.

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The objective of this work:

1- Generate a simple algorithm for determining pressure response for the following conditions:
   a. Complex wells of multiple drain holes that have different properties
   b. Model boundary conditions of different types and its effect on the lateral productivity over time for instance; bottom support aquifers (strong and weak support), Gas cap energy (strong and weak support), Edge water drive (strong and weak) for different sides, Wells interference including injection support. Compartmentalized reservoirs of different characteristics and different pressure baffles, and Multi layered reservoir with different pressure gradients
   c. Modeling and identification of drain holes cross flow phenomena
   d. Design and optimize laterals deviation and length to maximize the well potential
   e. Create a tool that can have great support on finite difference simulators history matching by identifying the drain holes main parameters from the pressure response model.
2- Validate the model approach across commercial computer packages (semi-analytical and finite difference)
3- Develop a computer package program with Python language to simulate and produce pressure response
4- Extend the solution to perform rate transient analysis as well as the pressure transient analysis

2- Mathematical Work

A new approach has been used in this study to determine the transient pressure drop which can be categorized into three solution stages

   A. Fluid flow towards the well segments : this part covers numerical inversion of point source Laplace space solution of diffusivity equation
   B. formulation of the boundary type: this part covers the type of boundary conditions supporting the drainage region which is solved with a finite difference.
   C. pressure drop across the wellbore: this part is to determine the pressure drop among adjacent point source functions in the borehole and connect them up to the multilateral junction point.

The first section of the mathematical development of the approach considers a small slab of the horizontal sink (Fig. **1**) as line source coupled with several numbers of similar conditions towards the main bore.

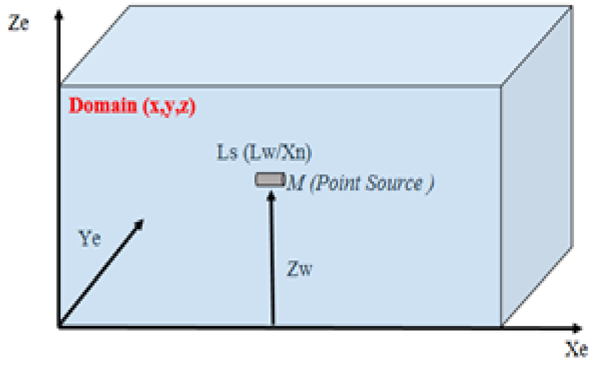

Fig. 1. Schematic unit porous system [12]

The source function as illustrated above is for a segment of the total inflow length where its sink in permeable media. The solution of the diffusivity equation for this body, that representing the three-dimensional diffusivity equation, which will be solved for a single-phase slightly compressible fluid. The flow is converged to the unit length of the pipe as line source. The dimensions (Xe, Ye, Ze) represent the drainage area dimensions (Domain x, y, z) of the inflow segment. The reason is to model a homogenous representation of the effective well drainage area.

The boundary type formulation represents the forces applied on the drainage domain in (x, y, and z) as shown in Fig. **2**.

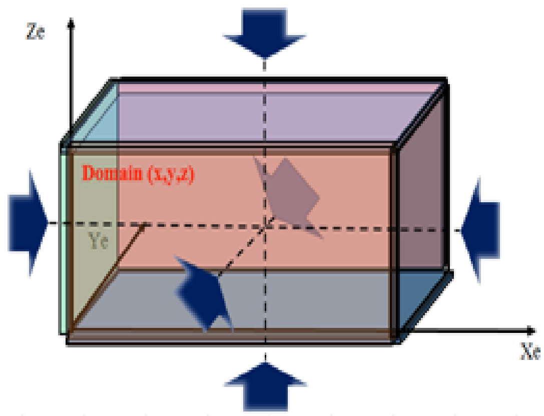

Fig. 2. Schematic boundary condition [12]

The boundary type represented the type of forces that applied on each side of the domain. The various types such as water drive, gas cap, or injection influence can be represented through the definition of the initial boundary pressure support per side, such as: volumetric, constant, or gradients.

The third part is to control the influx per inflow segment. The finite conductive approach is to integrate the pressure drop of entire segments for determining the influx rate per unit length. Additionally, it used to cooperate the multilateral segments into an operating point to revolve the fluid flow dynamics on the network. Fig. **3**.

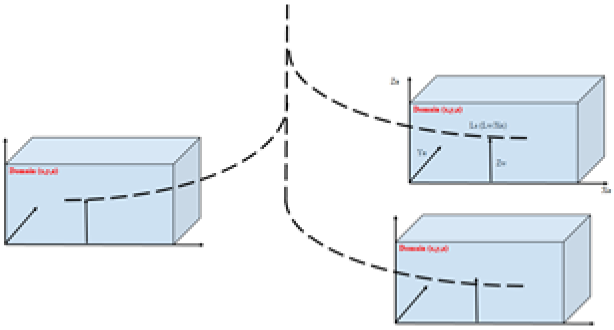

Fig. 3. Schematic multilateral well

A. Fluid Flow to Source Function

The diffusivity equation normally governs the fluid flow in permeable media. The diffusivity equation is derived from the Darcy equation and the mass balance equation. The general form of the diffusivity is [12]

$$\underset{K}{\rightarrow} . \nabla p = \varphi \mu Ct . \frac{dp}{dt} \tag{1}$$

The general solution for the infinite conductive segment in the infinite reservoir is represented below in Laplace space to resolve the short and long-term approximation of pressure [6] [7] [9].

$$Source\ function = \overline{P_D}(|x_D| \le 1, y_D = 0, z_D = z_{wD} + r_{wD}) = \frac{1}{2s\sqrt{u}}\left[\int_0^{\sqrt{u}(1-x_D)} K_0(z)dz + \int_0^{\sqrt{u}(1+x_D)} K_0(z)dz\right] + \frac{1}{2L_D s}\sum_{n=-\infty}^{+\infty}\left[K_0\left(\frac{|z_D - z_{wD} - 2n|\sqrt{u}}{L_D}\right) + K_0\left(\frac{|z_D + z_{wD} - 2n|\sqrt{u}}{L_D}\right)\right] - \frac{\pi}{2s\sqrt{u}} - \frac{1}{s}\sum_{n=1}^{\infty}\frac{\cos n\pi z_D \cos n\pi z_{wD}}{\sqrt{u + n^2\pi^2 {L_D}^2}}\left\{K_{i1}\left[\sqrt{u + n^2\pi^2 {L_D}^2}(1 - x_D)\right] + K_{i1}\left[\sqrt{u + n^2\pi^2 {L_D}^2}(1 + x_D)\right]\right\} \tag{2}$$

The main advantage of having the solution in Laplace space is that it is easy to obtain the solutions in the time domain at any period regardless of the flow regime. In other words, the short and long time approximation of the pressure response can be determined using the same equation for short and long time functions.

The primary objective of the solutions reported by Medeiros et al [13] is to define the source function of flow in Laplace space as a general solution that can be inversely transformed at all times (short and long) to determine the pressure values over time.

In summary, the approach adopted is to [13], [14]:

1- Define the main flow equation in Laplace space
2- Solve the flow equation with Stehfest numerical Laplace inversion at long and short times,
3- Compare the results with the reported asymptotic formulas
4- Validate the Laplace numerical inversion outputs at short and long times
5- Perform pressure solution at given times to determine flowing pressure at the well segments (source function) for infinite acting reservoirs with no inner and outer boundary conditions.

B. Reservoir Fluid Flow Model

The source function that defined previously represents the fluid flow from an infinite acting reservoir to the infinite conductive horizontal segment. The boundary type that affects the reservoir pressure over time of production requires separate modeling to adjust the depletion rate on the productivity of the well [5].

The determination of boundary pressure was calculated using the finite difference approximation for a single grid block with homogenous anisotropic properties at each time step. This approach is efficient in well testing data interpretation due to the complexity of multi-well multi-reservoir characteristic and with adding the heterogeneity.

The derivative match can be misleading. In such a case, the variable will be consistent per each well that penetrates specific layer properties.

The finite difference approximation can be expressed as [7]:

$$A_{i,j,k}P^{n+1}_{i,j,k-1} + B_{i,j,k}P^{n+1}_{i,j-1,k} + D_{i,j,k}P^{n+1}_{i-1,j,k} + E_{i,j,k}P^{n+1}_{i,j,k} + F_{i,j,k}P^{n+1}_{i+1,j,k} + H_{i,j,k}P^{n+1}_{i,j+1,k} + L_{i,j,k}P^{n+1}_{i,j,k+1} + WI_{i,j,k}P^{n}_{well_{i,j,k}} = R_{i,j,k} \tag{3}$$

From the derivation above [7], the dimensions (Δx, Δy, Δz) represents the same dimensions that defined for the source function derivation, which is the drainage volume. The reservoir pressure P(i,j,k) is the variable that represents the output of the calculations for each time step and then feeds into the source functions to determine P (x,y,z). The adjacent grids pressures are represented in terms of the boundary support. In the case of volumetric reservoir; their values are zeros. If a constant pressure boundary is supplied, their values will be fixed. If the boundary is supportive, the gradient pressure value will be used to represent the side and the magnitude of the pressure support.

The well index in the finite difference approximation equation is the output of the solution of source function where it is [7], [15]:

$$\left[P_D(x_D, y_D, z_D, z_{wD}, L_D, t_D)\frac{141.2B\mu}{kh}\right] = \left[\frac{[Po - P(x,y,z,zw,L,t)]}{q}\right] = TWI \tag{4}$$

Where PD is the output of the solution of the source function after the numerical inverse of Laplace equation, B, μ, k, h are input parameters.

TWI is the transient well index, which is fed to the finite difference equation to determine reservoir pressure at time step n-1, TWI is used at time step n

In summary, the procedure used for determining the boundary pressure used is [7]:

1- The dimensionless pressure values are defined for each time step.
2- The transient well index is calculated from the dimensionless pressure group
3- The reservoir pressure, influx rate, and borehole pressure are key parameters to estimate the reservoir pressure at each using the finite difference approximation with the appropriate boundary type.

4- The well index is used to determine the reservoir pressure at time step n in order to calculate the reservoir pressure at time step n-1
5- The remaining variables to be determined are the borehole pressure and rate. This will be resolved simultaneously with boundary pressure subject to the effect of reservoir pressure and well index per each time step keeping constant Junction pressure.

C. Pressure and Rate Solution

A reservoir-well coupling model needs to be developed to link the reservoir pressure with the source function inflow index to wellbore pressure drop at each time step. Many researchers have been investigated the impact of inflow on pressure drop in addition to pipe flow gradient. Ouyang and Aziz [9] presented a general equation to determine the pressure drop in inflow borehole, which was validated by the Stanford laboratory experiment [11].

The pressure drop along the inflow section with the mass transfer is

$$\frac{dp}{dL} = -\frac{4\tau_w}{D} - \rho g \sin\theta - \frac{2\rho}{A} q_I U + \frac{n\rho A_I}{2A} U_I^2 \sin 2\gamma \tag{5}$$

Where τ is the shear friction, θ is the pipe inclination, Al is the cross sectional area in the inflow segments, and ql is the segment inflow volumetric flow rate, U is the velocity, and γ is the inflow angle that represents the inclination between pipe and inflow direction.

The equation (5) defines four different pressure drop components: friction, gravity, accelerations due to inflow, and inflow direction.

The pressure drop in the inflow segment can be represented by the equation

$$\frac{dpw}{dx} = R_w q_w(x)^{2-\alpha} \tag{6}$$

Where Rw is the flow resistance in the wellbore segment and qw(x) is the flow rate at point x in the well segment

The interdependent mechanisms for the wellbore segment flow are [16], [9]:

- Boundary Layer effect: it is the change of thevelocity profile near borehole wall due to the inflow
- Kinetic energy effect: it is the additional acceleration added to the flow in the pipe due to inflow segments
- Inflow directional effect: it is the energy loss or increment due to the relation of the inflow direction to the axial pipe flow angle and direction.

The dynamics of friction factor due to inflow have been studied previously where the no-flow pipe fanning friction factor does not represent the many forces that cause friction and pressure losses in inflow segments. The inflow causes an increment of dynamic friction component when laminar flows exist. In contrast, the inflow causes a reduction of friction when the flow is turbulent.

The friction forces changes compared to flow dynamics. Therefore, the friction factor calculations cannot be used for pipe flow without inflow.

The procedure to determine the reservoir inflow by knowing the transient productivity index and the reservoir pressure at each time step is as follow:

1- For a specific heel pressure. Assume the pressure at the well toe
2- Divide the well into segments of specific resolution ratio
3- Determine the flow for the first segment from the assumed pressure at toe

$$\left[\frac{[Po - Ptoe]}{q}\right] = TWI \tag{7}$$

4- Determine the friction component for the specified rate. Calculate the axial velocity, Reynold number and dynamic friction factors as per the flow pattern
5- Determine pressure drop per segment for specified flow rate, move to the next inflow segment, with starting pressure as the assumed pressure at well toe subtracted from the pressure drop of the first segment.
6- Calculate the flow rate for the second segment and sum with the previous rate to have cumulative rate flow part of mass transfer.
7- Complete the process to reach the pressure at the heel of the well
8- Perform iterative calculation to determine the actual pressure at toe that matches the gradient to pressure at the well heel.
9- The output will be the pressure profile from the toe to heel with the production profile of the well.
10- For multi-lateral, wells, matrix solution to the junction pressure in the iterative procedure (Newton-Raphson method) to resolve the production rate per each lateral for each inflow zone up to the well junction.
11- The rate calculation using such procedure was implemented on purpose to determine the operative junction pressure with maximum production without cross flow depicted between lateral.

Fig. **4** illustrates the points mentioned above.

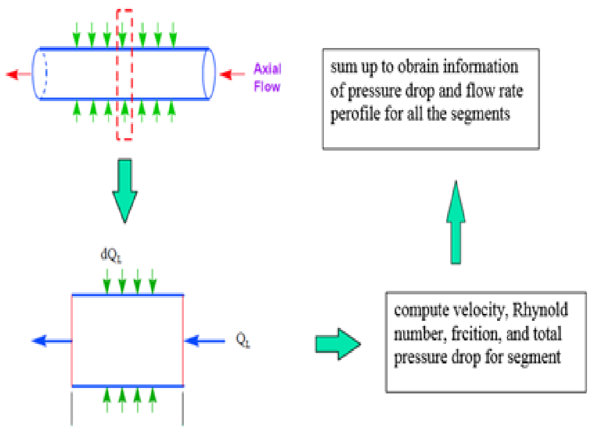

Fig. 4. Illustration of the iterative pressure drop computation [9]

Python code was developed in this study to solve the series of steps explained. Figure 5 represents the software architecture

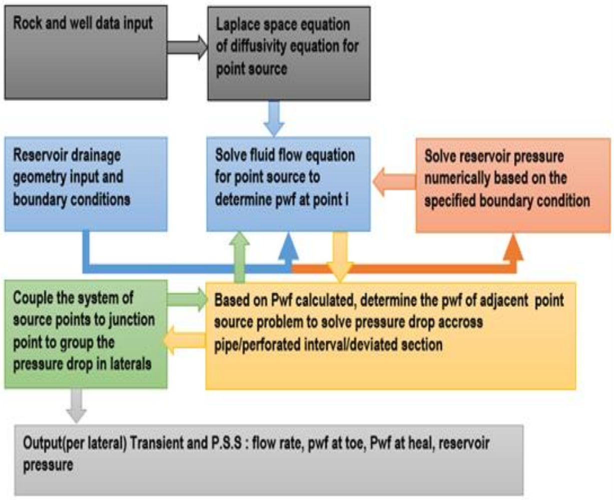

Fig. 5. Conceptual schematic of Python code

3- Results and Discussion

Three main cases have been conducted in this study to illustrate the capabilities of the proposed model.
These cases are:

A. Case 1 Dual lateral well in anisotropic homogenous reservoirs with a volumetric boundary type

The first case is a short radius dual lateral in a single layer of homogenous anisotropic properties. The input data is illustrated in figure 6 and tabulated in Table **1**.

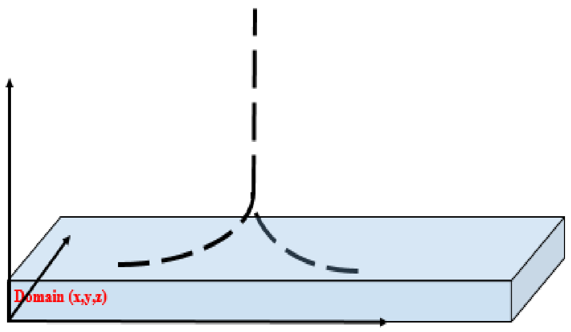

Fig. 6. Case 1 schematic

Table 1. Case 1 input data

	Lateral 1	Lateral 2	unit
rw	0.1	0.1	ft
h	100		ft
phi	0.2		
B	1		
Eccentricity	0.5		
mu	1		
ct	5.00E-05		1/psi
Pi	5000		psi
kx	10		mD
ky	10		mD
kz	1		mD
skin	0	0	
Inflow section length	100	100	ft
total horizontal section	1000	1000	ft
deviated section	100	100	ft
cureture angle	40	40	degree
vertical section to junction	50	50	ft

The performance capacity of the proposed model in predicting the pressure response has also been checked with commercial computer simulator.

The pressure response and the pressure log-log plot are shown in Fig. **7** and Fig. **8**.

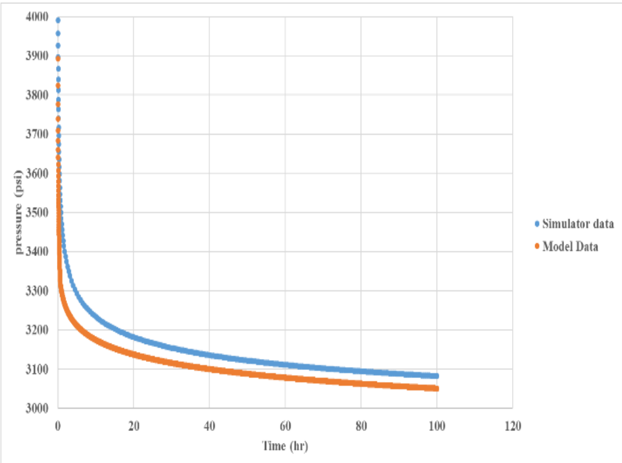

Fig. 7. Bottom hole pressure calculation against simulator results

The separation in pressure values is constant, around 30 psi on average, the difference is justified by the well-reservoir coupling as the commercial software model assume infinite conductive drain holes while the proposed model takes into account the extra pressure drop happens that in the wellbore which is most significant in the early transient time.

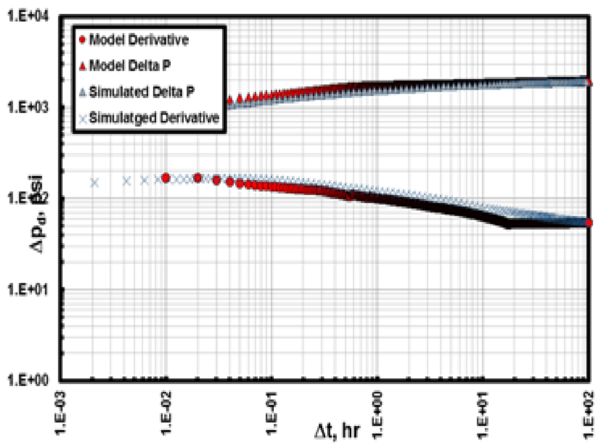

Fig. 8. Pressure drop and derivative log -log plot in comparison with simulated data

The pressure derivative is a function to reservoir response regardless of the wellbore pressure as the plot takes the pressure difference but not the absolute values.

The radial flow stabilization in late time in the model data can be attributed to the data-smoothing algorithm in the commercial software, which is not taken into consideration in the proposed model.

B. Case 2 Multi-layer reservoir anisotropic heterogeneous penetrated by dual lateral of different drain hole information. The reservoir lower layer has the bottom water drive boundary type.

The second case is more complicated dual lateral than the first case. A multi-layer system has been introduced with the stacked dual lateral of different elevation for the junction point.

The reservoir characteristics are different. The upper layer is closed with the lower layer has a bottom water drive. The well schematic displayed in Fig. **9** and information of inputs is grouped in Table **2**.

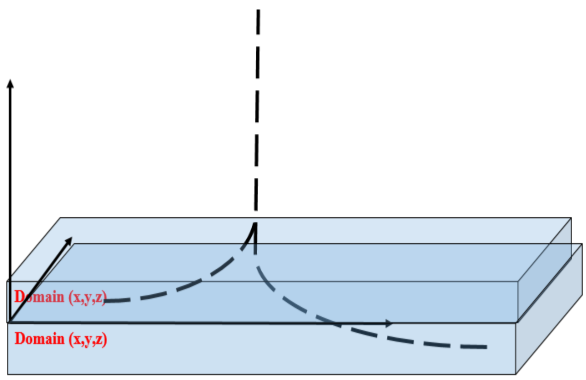

Fig. 9. Case 2 schematic

Table 2. Case 2 input data

	Lateral 1	Lateral 2	unit
rw	0.1	0.1	ft
h	30	70	ft
phi	0.25	0.15	
B	1.2	1.2	
Eccentricity	0.3	0.7	
mu	3	3	
ct	1.00E-06	1.00E-06	1/psi
Pi	5000	5000	psi
kx	100	70	mD
ky	50	20	mD
kz	10	1	mD
skin	0	0	
Inflow section length	500	1000	ft
total horizontal section	1000	1500	ft
deviated section	200	400	ft
cureture angle	40	40	degree
vertical section to junction	50	150	ft

The pressure drop in each lateral section is not equal which causes different rate contribution per lateral, the pressure response as shown in Fig. **10**.

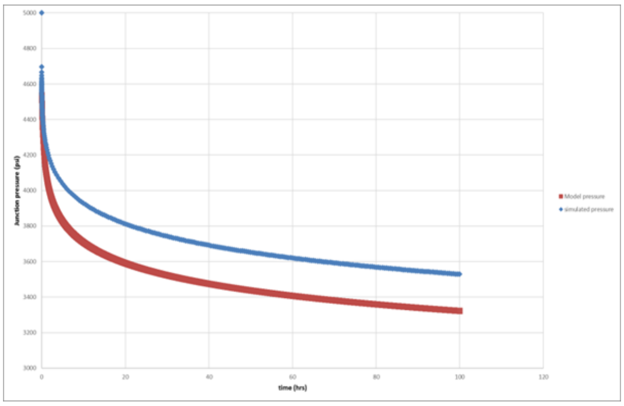

Fig. 10. Bottom hole pressure calculation against simulator results

The deviation in the bottom hole pressure is only 20 psi compared with the commercial simulator. The pressure log-log plot for the model data and the simulator data is shown in Fig. **11**.

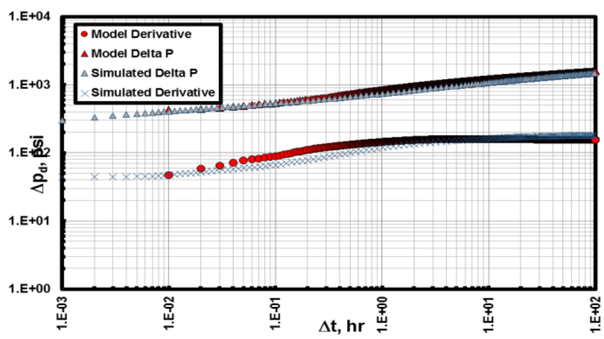

Fig. 11. Pressure drop and derivative log log plot in comparison with simulated data

The slight mismatch in the intermediate linear flow in figure (11) is due to the extra pressure drop representation of the wellbore as a pseudo skin, which is the main difference between finite and infinite conductive wells.

C. Case 3 Quadrilateral well drilled in four different heterogamous layers of different boundary conditions, two layers under the gas cap, one layer with edge water drive and the fourth is volumetric

The case is a multi-layer system with four branched well of different lengths and elevations from the junction point. The reservoirs characteristics are different in terms of porosity, permeability, and fluid properties. Four layers with the different boundary conditions, all relevant information of the third case displayed in Table **3**. The well schematic is shown in Fig. **12**.

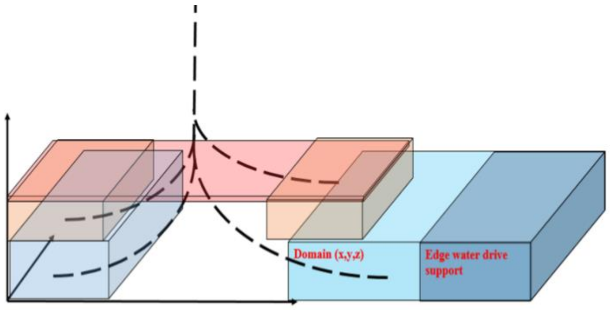

Fig. 12. Schematic of case 3

Table 3. Case 3 input data

	Lateral 1	Lateral 2	Lateral 3	Lateral 4	unit
rw	0.3	0.3	0.3	0.3	ft
h	10	30	15	45	ft
DX	5000	7000	3000	100000	
DY	5000	70000	100000	100000	
phi	0.2	0.25	0.1	0.2	
B	1	1	1	1	
Eccentricity	0.5	0.8	0.1	0.5	
mu	1	1	1	1	
ct	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1/psi
Pi	3500	3800	4200	5000	psi
kx	200	50	300	10	mD
ky	200	50	300	10	mD
kz	200	0.5	60	5	mD
skin	-2	-4	2	-3	
Inflow section length	500	1000	300	1500	ft
total horizontal section	500	1000	300	1500	ft
deviated section	200	200	200	200	ft
cureture angle	40	40	40	40	degree
vertical section to junction	50	50	50	50	ft
Boundary conditions	Gas cap	Gas cap	volumetric	edge water drive	

The pressure response as below:

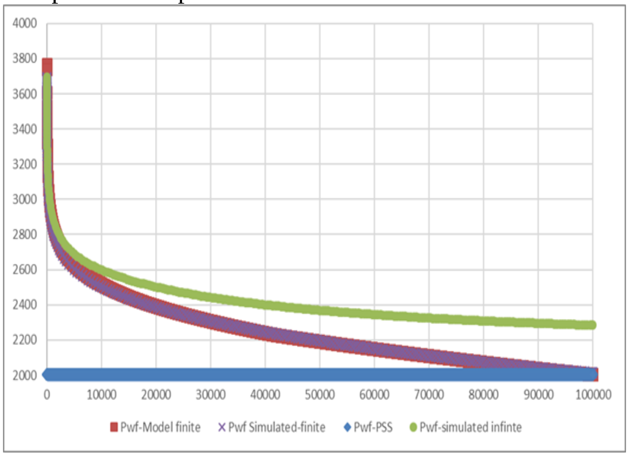

Fig. 13. Comparison of pressure drop between simulator and model

The deviation in the bottom hole pressure is only 350 psi compared with the commercial simulator, while by comparing model results with the finite difference model for segmented wellbore coupling the difference is less than 50 psi. The pressure log-log plot for the model data and the simulator data is below.

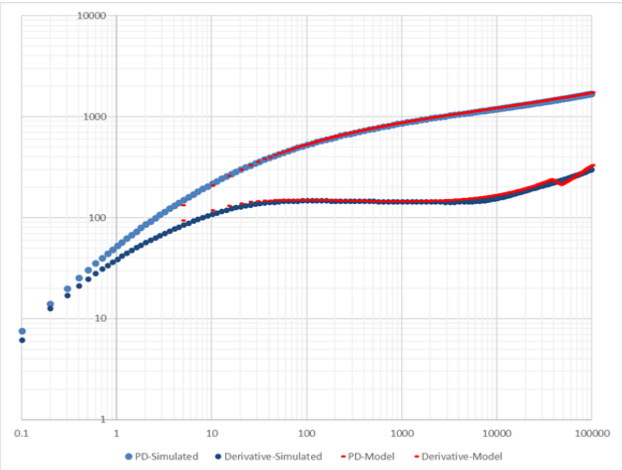

Fig. 14. Log –Log plot comparing model results versus simulator data

4- Conclusions

The conclusions with regards the semi-analytical solution that has been done in this study are listed below:

1- Due to the analytical nature of the solution, more resolution and accuracy are expected if they are compared with the full numerical approach.
2- The results were in good agreement with the commercial simulators in predicting the pressure drop of a reservoir and through the borehole (for the finite conductive approximation).
3- When modeling the wells as infinite conductive, the error in pressure drop is less than 10%. However, the

error percent is subjected to the ratio of pressure drop in the reservoir to pressure drops in the well.

4- The pressure derivative response was very well matching the laterals and layers response, i.e, the transient state was well captured to determine the effective system properties (skin components, effective layers permeabilities, and pressure baffles)

5- Productivity indices per lateral were adequately matching the commercial simulator modeled inputs.

Recommendations

The following are the limitations of the current study, which can be discussed, in future work

1- Multiphase was not included in the calculation and all flows in the reservoir and well is single phase.

2- Injection frontal advance was not included in calculation and injector support considered by pressure rate influx of it produced phase.

3- Instead of using Stehfest algorithm for Laplace numerical inversion, Fourier numerical inversion can be used in future researches.

4- The pressure drop effect in pipes does not take into account the acceleration component in the horizontal section, which is assumed fully horizontal with no change in elevation.

Multilayer production from single wellbore was not taken into consideration and each lateral in single layer model, however, internal multilayer cross flow was studied

Nomenclature

$\vec{K}$:	Permeability Tensor (three dimensional Matrix value)
∇P :	Pressure gradient in three dimensions
φ :	Porosity
μ :	Viscosity
Ct :	Compressibility
ki :	Directional Permeability (i=x,y,z)
tD :	Dimensionless time
XD :	Dimensionless x direction drainage region length
YD :	Dimensionless y direction drainage region length
ZD :	Dimensionless z direction drainage region length
LD :	Dimensionless well length
K :	effective permeability (geometrical or horizontal based on vertical permeability effect on flow regime)
Po :	Reservoir pressure
$P(x,y,z,zw,L,t)$:	pressure at any point and time in borehole.
ZwD :	Dimensionless borehole elevation in the reservoir
$PD(xD,yD,zD,zwD,LD,$:	dimensionless pressure drop at any point and time
$\overline{PD}$:	Dimensionless pressure drop in Laplace domain
β :	Constant
rwD :	Dimensionless wellbore radius
$Ko, K1$:	Bessel function roots
ZD :	Dimensionless z direction drainage region length
LD :	Dimensionless well length
$\sigma(x_D, y_D) =$	Pressure drop due to flow convergence – convergence skin
$F(x_D, y_D, z_D, z_{wD}, L_D)$:	Horizontal well radial pseudo skin factor

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تطوير موديل شبه تحليلي لاستجابة الضغط العابر في الآبار والمكامن المعقدة

الخلاصة

الهدف من فحوصات الضغط الانتقالي التقليديه للابار هو لتقييم التوصيليه بين البئر والمكمن عن طريق استحصال معامل التوصيليه المعرف بالسمك الفعال للطبقه والنفاذيه الفعاله للمكمن بالاضافه لحساب القابليه الانتاجيه للبئر. حسابات فحوصات الضغط الانتقالي هو خطوه مهمه لتقييم المكامن النفطيه والغازيه وكذلك ادائيه الابار المنتجه وابار الحقن, وتعتبر نتائجه مدخل مهم للمحاكاه المكمنيه للتنبؤ بهبوط الضغط والانتاج المستقبليه.

الهدف من هذه البحث هو أخذ مقاربة نموذج شبه تحليلي لاستجابة الضغط العابر في بنية البئر المعقدة والخزانات المعقدة. الحل شبه التحليلي يعتمد على اقتران الشرط الحدودي لداله المصدر بجزء البئر. مبدأ ربط البئر بالمكمن يعتمد على داله المصدر النقطي بأخذ مقطع من المكمن والبئر وتحليله ثم ربطه بالمقطع الاخر عدديا بأخذ بنظر الاعتبار هبوط الضغط بالبئر بين مقطعين وهبوط ضغط المكمن. التقنية تستند إلى إعادة إنتاج الوسائط مجزئه متجانسة من عدة دوال مصدريه من خصائص مختلفة. يمكن محاكاه من هذا الموديل نماذج هندسية مختلفة مخترقه المكامن المعقدة.

تم صياغه برنامج محاكاه باستخدام لغه البرمجه بايثون أعدت للتنبأ لاستجابة الضغط للآبار الأفقية والثنائية والمتعددة الأطراف في مكامن متباينة الخواص ومتعددة الطبقات ومجزأة وأنظمة ظروف حدودية مختلفة مثل: طبقات المياه الجوفية الداعمة للأسفل والحافة المدعومة وأغطية الغاز وتداخل الحقن . تم التحقق من النموذج بالمقارنه مع برنامج محاكاه تجاري

الكلمات الدالة : شبه تحليلية ، الضغط الانتقالي ، آبار متعددة الأطراف.