The impact of closed perforation zones and damaged sections on flow dynamics and pressure behaviors of horizontal wells

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Abstract:

Horizontal wells with multiple completion parts have become a common completion technique in the oil and gas industry. Sand and asphalt production problems, damaged zones and water cresting or gas coning are the main reasons for using this technique to sustain or improve oil and gas recovery. However, using such completion technique introduces negative effects on pressure behavior of horizontal wells.

This paper introduces new mathematical models for horizontal well containing several closed completed sections acting in finite and infinite reservoirs. These models can be used to evaluate the impact of the completion techniques on both pressure behaviors and flow regimes either in the vicinity of wellbore or at the outer boundary of reservoirs. They can be used also to investigate the change in productivity index that would result due to the usage of certain type of completion technique. In this research, the completed sections (cemented or isolated parts) and the places where packers are installed are considered as no-flow sections. These sections are expected to increase pressure drop required for flowing reservoir fluid toward wellbore. They are also expected to change flow regimes mainly in the vicinity of wellbore.

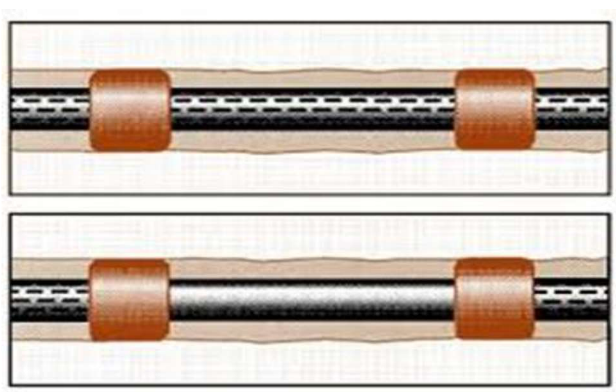
Several models have been developed and solved in this study for different completion techniques, wellbore conditions and reservoir configuration. It has been found that the great impact of completion techniques is observed on flow regimes that commonly develop in the drainage area close to wellbore. This impact shows similar trends to the skin factor. Several new flow regimes have been observed, one of them has been developed due to the existence of closed completed sections which is intermediate or second radial flow regime. This flow regime can be found for some cases of long wellbore having multi-short perforated sections. The study will introduce the mathematical models for known and newly developed flow regimes for horizontal well including the completion technique.

Keywords: Drilling engineering; Completion techniques; reservoir engineering; Pressure behaviour; flow regimes; well test analysis.

Introduction:

The main functions of oil and gas wells completion are to deliver the hydrocarbons from the sand face to the surface during production process and to deliver the injected fluid from the wellbore to the formation during the injection process. However, the completion techniques are designed for different primarily and important functions such as: protection production tubing from formation pressure, protection casing from the erosion might be caused by well fluids, controlling production rates for multi-layers formation, monitoring permanently the downhole pressure, and facilitate the future developing plans for the stimulation and enhancement process. It is well known that the selection of appropriate completion techniques undergoes several considerations such as reservoir consideration (production zones isolation, distance from fluid contacts, secondary target, minimum zone separation, and length interval), mechanical consideration, and safety consideration.

Up to the moment, three options of wellbore- reservoir interference are used to determine the selected type of single zone completion techniques. Open hole completion, often called "barefoot completion", is the first option in which the wellbore is left with no-casing in the production zone. This option is preferable for no-cost demand, but it does not provide the operators great opportunity for future reservoir management to reduced unwanted water production for example. The positive thing, it is possible to convert this completion technique in the future to a linear completion. The second option is the uncemented linear completion, shown in figure (1), where the slotted pipes, wire wrapped screens, and open hole gravel packs are typically installed. The formations in these completion techniques are supported by the slotted linear, wrapped sand screens or gravel packed. Third option is the perforated completion techniques which are most commonly used all over the world due to the high flexibility, considerable safety, and reasonable cost. Three groups are classified within the perforated completion techniques according to the application type: standard perforated casing or linear as shown in Fig. (2), fracture stimulation, and cased hole gravel pack.



(a)

(b)

Fig(1) (a) Uncemented slotted linear **(b) Slotted screen pipe**

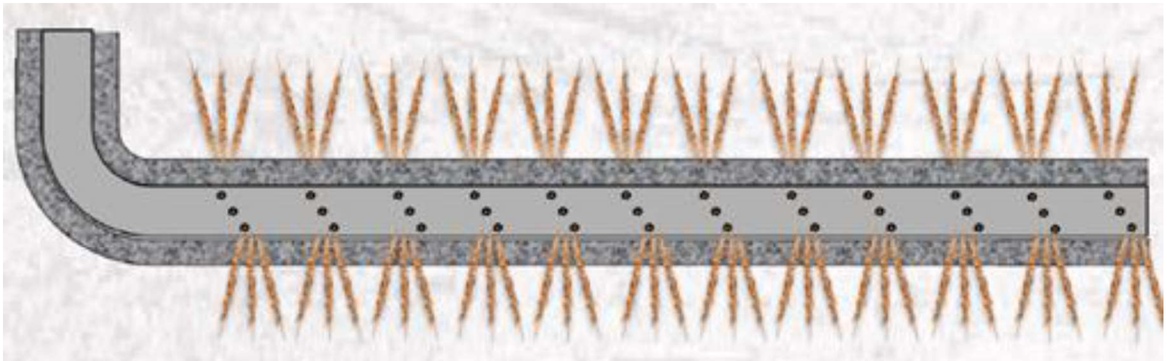


Fig.(2) Cemented perforated linear.

For multiple zones formation as shown in figure (3), four options of completion techniques are available. They are commingled production, sequential zonal production, single-string multi-zone segregated production, and multi-string multi-zone segregated production. Recently, as the horizontal wellbores are drilled for tens of thousands feet, the completion techniques become more complicated. Multi-segments completion techniques have been adopted for long and extra-long horizontal wells where the mechanical yield torque can be big challenge in addition to the production problems such as sand production. For example, three segments-completion techniques have been used for developing Nahr Umr sandstone formation in Qatar (Abbasy et al 2010).

Even though the completion techniques are common applications in petroleum industry as excellent remedies for several expected production problems, they have in the other hand significant impact on producing wells performance. This impact can be seen on pressure behaviors, flow regimes, and productivity index. For all types of completion technique except the open hole, there are closed sections along the wellbore represent real resistant for reservoir fluids to freely flow from the drainage area toward the wellbore. Therefore, the fluid may enter the wellbore at various section and different flow rate (Tang et al 2000) which is in turn leads to create non-symmetrical pressure behavior along the wellbore. Moreover, this would cause some changes in the flow regimes in the vicinity of the horizontal wellbore. Accordingly, well performance and productivity index are definitely negatively affected by changes in both pressure behavior and flow regime. Ouyang and Huang 2005 and Denney 2006 explained that mechanical skin factor is closely related to the completion technique. Additionally, turbulent flow resulted from narrowing the cross section area of flow may lead to increase the skin factor (Tang et al 2005).

Several papers have been presented in the last years showed the impact of the completion techniques of horizontal wells on the pressure behavior and flow regime. Furui et al 2005 presented a comprehensive skin –factor model of horizontal well completion performance. They concluded that the interaction among the damage and skin factor caused by the perforation or slots are shown to greatly affect horizontal well completion performance. This fact has been confirmed by Yildiz 2006 who investigated the impact of selectively perforated horizontal well on productivity. He showed that the productivity ratio of selectively completed wells increases with the increasing of the length of completed segments.

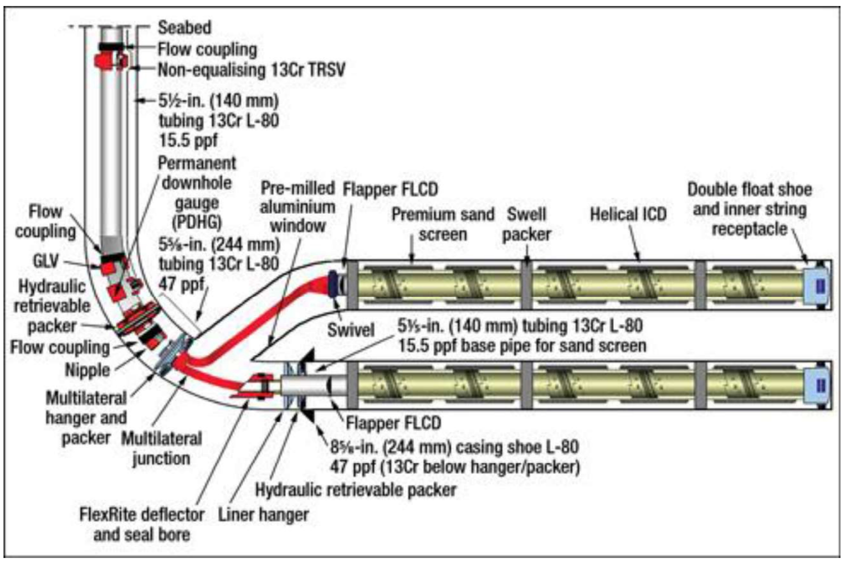


Fig.(3) Multilateral completion system.

Mathematical models:

The impact of the completion techniques on horizontal well performance can be reasonably expressed by investigating the changes that are typically occurred for pressure responses and flow regimes due to the existence of closed sections in completed segments of the wellbore. The closed sections in the slotted linear, uncemented segment linear, cased cemented and perforated linear in addition to the existence of packers, as shown in figure (4), may have great influences on fluid influx to the wellbore. The flow rate of reservoir fluid, entering the wellbore, depends on the surface contact area given by the wellbore circumference and length. For open hole completion, the maximum surface contact area is obtained, while this area is reduced for other completion techniques because of the closed sections in the completed segments. Al-Rbeawi and Tiab 2013, indicated the impact of the damaged sections and closed perforated zones on pressure behaviors and flow regimes for horizontal wellbores. They stated that the main impact can be observed when reservoir fluids reach closely to the wellbore. At this point, these fluids tend to move toward the small resistance sections of the completed zones .i.e. the open sections such as the slots and perforations.

Considering the closed sections of the completion system as no-flow zones, the horizontal wellbore can be divided into two zones. The first one is the open zones where reservoir fluids flow freely into the wellbore, while the second one is the closed zones where no fluids enter the wellbore. Therefore, the pressure response in this case can be simulated using some necessary assumptions such as: 1) the reservoir is homogenous and having constant and uniform thickness with two impermeable layers at the top and bottom of the formation. 2) Constant porosity in each direction, but the formation is anisotropic. 3) Gravitational and frictional effects are negligible, 4) Wellbore storage effect is not considered, and 5) There is no fluid flow at the boundaries. Accordingly, the pressure behavior, in dimensionless units, of horizontal well having wellbore length$(2L_W)$, shown in Figure (5), extends in finite reservoir having rectangular shape drainage area (Length$(2x_e)$, width$(2y_e)$) and the formation height is (h), can be written as:

Fig.(4) Horizontal well completion.

$P_D =$

$\frac{\pi y_{eD}}{4nL_{PD}} \int_0^{t_D} \left[\sum_{m=1}^{m=n} \sum_{N=1}^{N=\infty} \left\{ \left(erf\left(\frac{x_D - x_{WD} - (m-1)(L_{PD}+L_{CD}) - 2N/x_{eD}}{2\sqrt{\tau_D}} \right) - \right. \right. \right.$

$\left. erf\left(\frac{x_D - x_{WD} - mL_{PD} - (m-1)L_{CD} - 2N/x_{eD}}{2\sqrt{\tau_D}} \right) \right) +$

$\left. \left(erf\left(\frac{x_D + x_{WD} - (m-1)(L_{PD}+L_{CD}) - 2N/x_{eD}}{2\sqrt{\tau_D}} \right) - erf\left(\frac{x_D + x_{WD} - mL_{PD} - (m-1)L_{CD} - 2N/x_{eD}}{2\sqrt{\tau_D}} \right) \right) \right\} * \left\{ 1 + \right.$

$$2\sum_{N=1}^{N=\infty} e^{-N^2\pi^2 y_{eD}^2\tau_D}\cos(N\pi y_{WD}))\cos(N\pi(y_D y_{eD}+y_{WD})\Big\}*$$

$$\Big\{1+2\sum_{N=1}^{N=\infty} e^{-N^2\pi^2 L_D^2\tau_D}\cos(N\pi z_{WD}))\cos(N\pi(z_D L_D+y_{WD})\Big\}\Big]d\tau_D \quad (1)$$

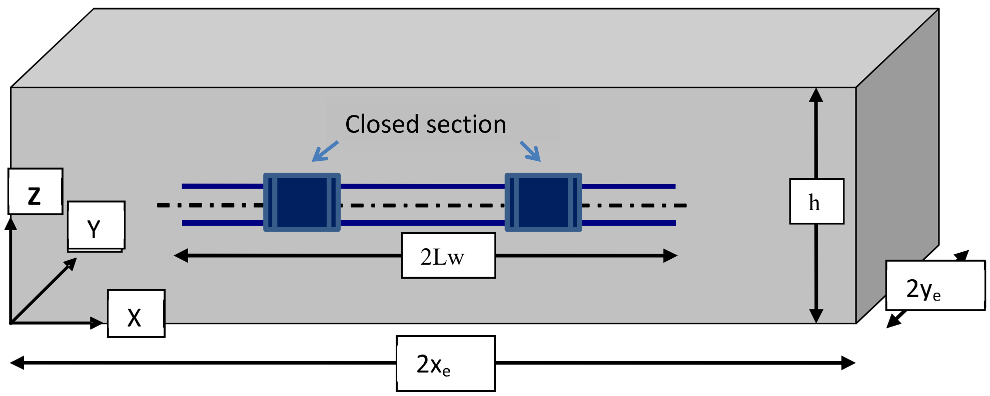


Fig.(5) Completion technique for horizontal well in finite reservoir.

While the impact of the closed sections in the completed segments on productivity index of horizontal wells can be represented by reducing the length of the wellbore and surface area of contact between wellbore and drainage area. The models for the productivity index are as follows (Owayed et al 2013):

$$J=\frac{C}{[C_{HF}+S_P+S_m]} \quad (2)$$

Where;

$$C=\frac{\sqrt{k_x k_z}(2y_e)}{141.2\,\mu B} \quad (3)$$

Mechanical skin factor in the Eq. (2) is represented by the term S_m , while the term S_P represents the pseudo-skin factor. Pseudo-skin factor represents the resistance to flow resulted from different resources such as the reduction of the wellbore length due to the completion techniques, horizontal wells partially penetrate the formation in the horizontal plan, and the eccentricity and assymetricity of the horizontal wells in the vertical plan. Pseudo-skin factor can be obtained as follows:

$$S_p = \pi x_{eD} L_D \left[\begin{array}{l} \frac{64}{\pi^3 y_{eD}} \sum_{n=1,m=1,l=1}^{\infty} \frac{1}{m(n^2 x_{eD}^2 + m^2 y_{eD}^2 + 4l^2 L_D^2)} \sin(m\pi \frac{y_{eD}}{2}) \cos(m\pi \frac{y_{wD}}{2}) \cos(\frac{m\pi}{2}(y_D y_{eD} + y_{wD})) \\ \qquad \cos(n\pi \frac{x_{wD}}{2}) \cos(\frac{n\pi}{2}(x_D x_{eD} + x_{wD})) \cos(l\pi z_{wD}) \cos(l\pi(z_D L_D + z_{wD})) \\ + \frac{32}{\pi^3 y_{eD}} \sum_{m=1,l=1}^{\infty} \frac{1}{m(m^2 y_{eD}^2 + 4l^2 L_D^2)} \sin(m\pi \frac{y_{eD}}{2}) \cos(m\pi \frac{y_{wD}}{2}) \cos(\frac{m\pi}{2}(y_D y_{eD} + y_{wD})) \\ \qquad \cos(l\pi z_{wD}) \cos(l\pi(z_D L_D + z_{wD})) \\ + \frac{16}{\pi^2} \sum_{n=1,l=1}^{\infty} \frac{1}{(n^2 x_{eD}^2 + 4l^2 L_D^2)} \cos(n\pi \frac{x_{wD}}{2}) \cos(\frac{n\pi}{2}(x_D x_{eD} + x_{wD})) \\ \qquad \cos(l\pi z_{wD}) \cos(l\pi(z_D L_D + z_{wD})) \\ + \frac{2}{\pi^2 L_D^2} \sum_{l=1}^{\infty} \frac{1}{l^2} \cos(n\pi z_{wD}) \cos(n\pi(z_D L_D + z_{wD})) \end{array} \right] \quad (4)$$

It is easy to infer from the above mentioned model that the pseudo-skin factor depends mainly on the effective length of the horizontal wellbore(L_D), the length of the open sections, for the same reservoir configuration. As the effective length increases, the pseudo-skin factor decreases which is in turn causes increasing in the productivity index of the horizontal wellsgiven in Eq. (2) knowing that the shape factor is unique value for specific reservoir configuration as shown below:

$$C_{HF} = \pi x_{eD} L_D \left[\begin{array}{l} \frac{32}{\pi^3 y_{eD}} \sum_{n=1,m=1}^{\infty} \frac{1}{m(n^2 x_{eD}^2 + m^2 y_{eD}^2)} \sin(m\pi \frac{y_{eD}}{2}) \cos(m\pi \frac{y_{wD}}{2}) \cos(\frac{m\pi}{2}(y_D y_{eD} + y_{wD})) \\ \cos(n\pi \frac{x_{wD}}{2}) \cos(\frac{n\pi}{2}(x_D x_{eD} + x_{wD})) + \frac{8}{\pi^2 x_{eD}^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \cos(n\pi \frac{x_{wD}}{2}) \cos(\frac{n\pi}{2}(x_D x_{eD} + x_{wD})) \\ + \frac{16}{\pi^3 y_{eD}^3} \sum_{m=1}^{\infty} \frac{1}{m^3} \sin(m\pi \frac{y_{eD}}{2}) \cos(m\pi \frac{y_{wD}}{2}) \cos(\frac{m\pi}{2}(y_D y_{eD} + y_{wD})) \end{array} \right] \quad (5)$$

Pressure Analysis:

The pressure behavior resulting from the depletion process with time represented by the mathematical model given in Eq. (1) is highly affected by the length of the wellbore. Therefore, the reduction in the effective length of the horizontal well or the length of open sections where reservoir fluids freely flow toward the wellbore causes reasonable change in the pressure. The effective length is shortened mainly by the existence of closed completed sections where no fluids can enter the wellbore from these sections.

For short horizontal wells fully penetrate the formation in the horizontal plan as shown in Fig. (6), the impact of completion techniques on pressure response can be noticed in both early time and late time production. This impact increases with increasing the length of closed sections because of increasing the pseudo-skin factor. Similar behaviors are observed for short horizontal wells that partially penetrate the formation in the horizontal plan as shown in Fig. (7). However, the impact of completion techniques in late time production is clearer in the partially penetrated formation rather than fully penetrated formation. Physically, for fully penetrated formation, pressure pulse does not need for long time to reach the boundary no matter the length of the perforated sections. While it takes some time for the pressure pulse to reach the boundary in partially penetrated formation.

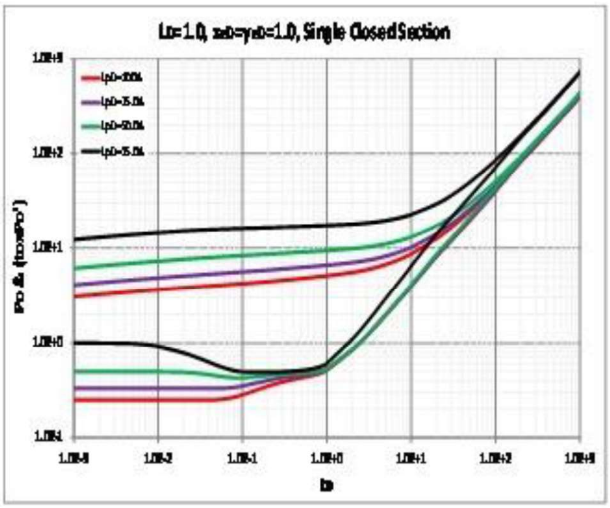


FIG.(6) Pressure response for short horizontal Wells fully penetrating the formation.

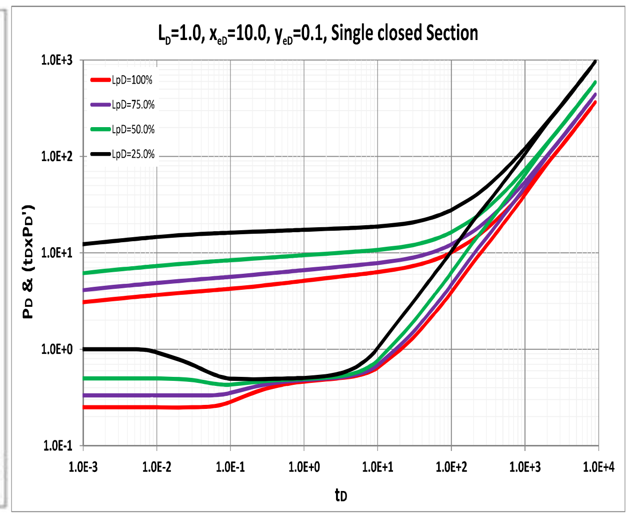


Fig.(7) Pressure response for short horizontal Wellspartially penetrating the formation.

For moderate and long horizontal wellbore, the impact of completion technique is mainly observed in the early time of production for both fully or partially penetrated formations. This is true as the boundary dominated flow can be developed in short time. Figure (8) shows the pressure response for fully penetrated formation by moderate length horizontal wells while Figure (9) represents the pressure response for moderate length horizontal wells partially penetrating the formations in the horizontal plan. For all cases, the change in pressure drop caused by the completion techniques in early time of production is proportional with the reduction percentage in wellbore length caused by closed completed sections. Mathematically, the effective length of the wellbore or the length of perorated sections can be represented by the ratio of the pressure derivative for the horizontal well with closed completed section and the well with no closed sections.

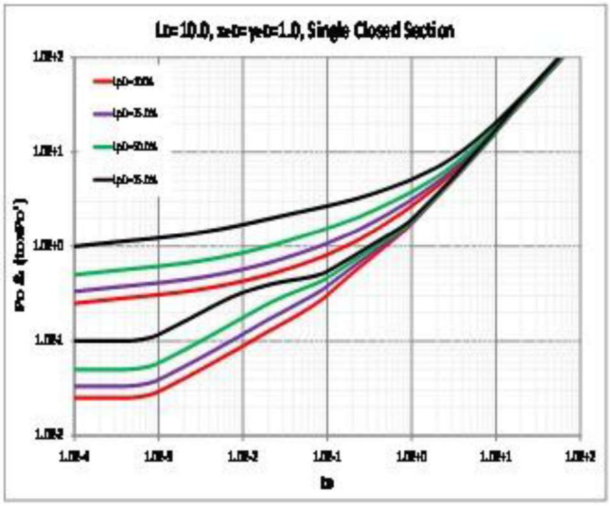


Fig.(8) Pressure response for moderate length Horizontal wells fully penetrating the formation

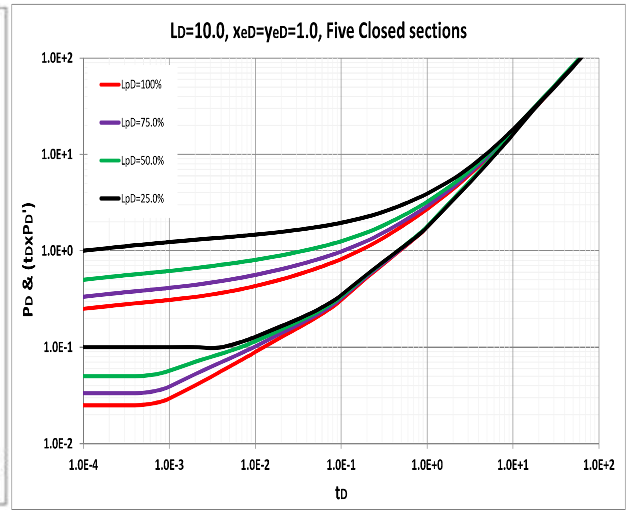


Fig.(9) Pressure response for moderate length horizontalwells partially penetrating the formation.

Impact od closed completed sectiona:

There is no significant impact for the number of closed completed sections on pressure response of horizontal wells as shown in Figures (10&11). This would be explained as the physical restriction for reservoir fluids to flow from the vicinity of the wellbore into the wellbore itself does not change with the number of closed completed section. The restriction is caused by the change in the length of perforated sections. However, for short horizontal wells as shown in Figre (10), the big number of perforated sections may need smaller pressure drop rather than small number. This is because of the fact that the spreading perforated sections along the wellbore may lead to similar behavior of the wellbore without closed completed sections.

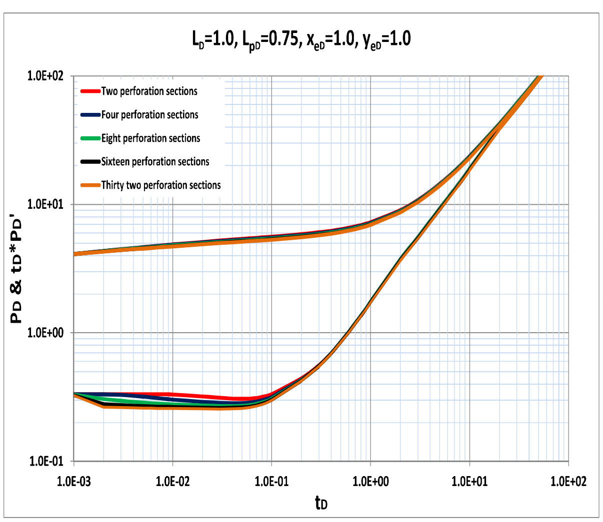


Fig.(10)Pressure response for short horizontal wells

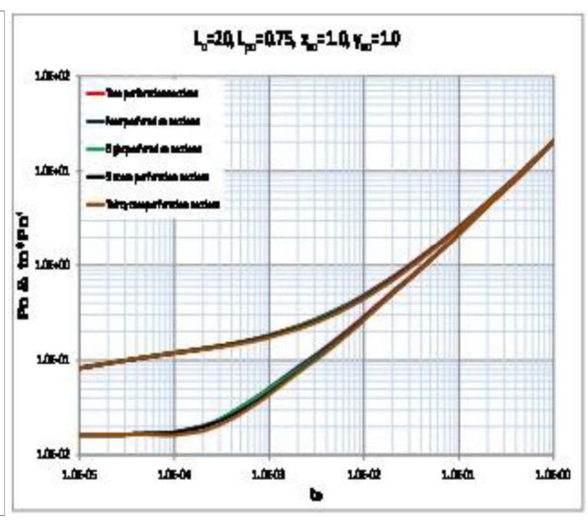


Fig. (11) Pressure response for long horizontal wells.

Flow regimes:

For open hole completion where there are no closed completed section, the expected flow regimes that can be developed during the entire production time are: early radial flow, linear flow, pseudo-radial flow and boundary dominated flow (late linear) if the wells extend in finite acting reservoirs. For infinite acting reservoirs, boundary dominated flow regime cannot be reached and only early radial flow, linear flow, and pseudo-radial flow are expected to occur as shown in Fig. (12). For both finite and infinite acting reservoirs, elliptical flow may develop through the transition from early linear flow to pseudo-radial flow. Intermediate or second radial flow regime may also develop for the cases of short perforation sections and long closed sections.

Early radial flow regimes:

This flow regime develops at early time when reservoir fluids flow radially toward the wellbore in the vertical plan normal to the horizontal well as shown in Fig. (13). It is characterized as a horizontal line having constant pressure derivative value on the log-log plot of dimensionless time and dimensionless pressure derivative. It can be written as follows:

$$(t_D * P'_D)_{ER} = \frac{0.5}{2n\, L_{PD} L_D} \quad (6)$$

Where (n) is the number of the open and perforated sections in the horizontal well. In field units:

$$(\Delta P)_{ER} = \frac{162.6 q\mu B}{\sqrt{k_z k_y} n L_P} \log(t) + C \quad (7)$$

Where (C) is taken as the pressure drop at the bottom hole after one hour of production (ΔP_{1hr}) . Then the following model is applicable:

$$\Delta P_{1hr} = \frac{162.6\, q\mu B}{2nL_p\sqrt{k_y k_z}}\left[\log\left(\frac{k_x}{\emptyset \mu c_t L_w^2}\right) - 3.227 + 0.868 s_R\right] \quad (8)$$

s_R Represents skin factor resulting from the early radial flow which most likely includes the mechanical skin factor and the impact of the completion techniques. This impact might be considered as a reduction in the free wellbore length opens to reservoir fluids or reduce the open perimeter of the wellbore.

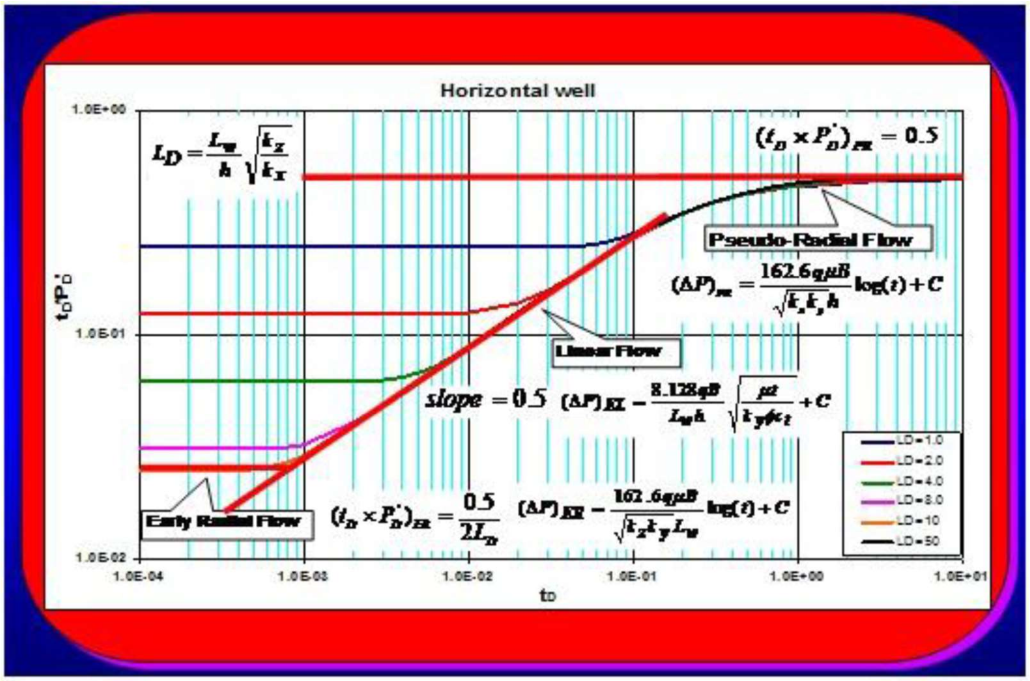


Fig.(12) Flow regimes for open hole completed horizontal wells in infinite acting reservoirs.

Early radial flow regime continues untill pressure pulse reaches the upper and lower impermeable bounadries. The elapsed time for early radial flow depends on the height of the formation and the permeability in the vertical direction. However, for long horizontal wells, this time is shorter than the time required to reach the boundary for short horizontal wells. Commonly for long and extra long hroizontal wells ($L_D \geq 20$) (Al-Rbeawi and Tiab 2013), early radial flow regime may not be seen and only early linear and pseudo-radial flow can be noticed for wells acting in infinite reservoirs.

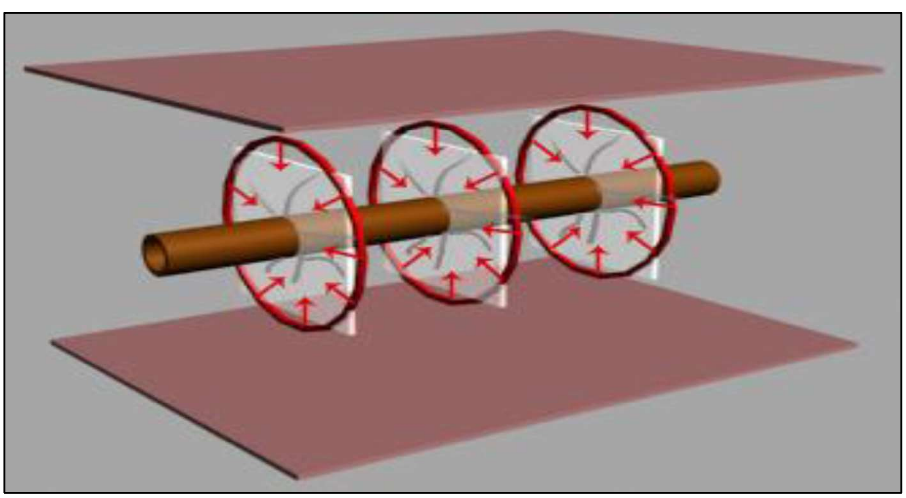


Fig.(13) Early radial flow regime.

Early linear flow regimes:

Early linear flow regime develops shortly after the pressure pulse reaches the upper and lower boundaries. In this flow regime, reservoir fluids move linearly in the horizontal plan from the two sides of the wells toward the wellbore as shown in Fig. (14). This flow is typically characterized by slope of (0.5) on pressure derivative curves. The governing equations are as follows:

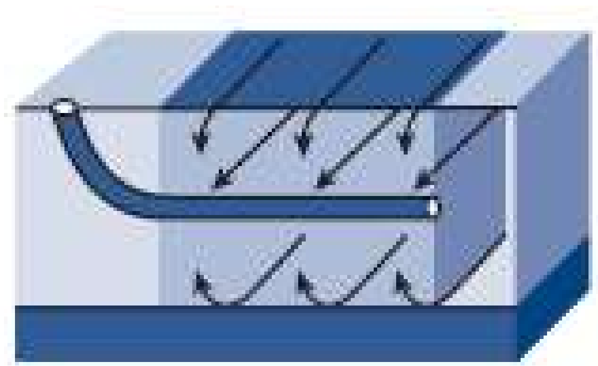


Fig.(14) Linear flow to horizontal well

$$(t_D * P'_D)_{LF} = \frac{\sqrt{\pi t_D}}{2nL_{PD}} \quad (9)$$

In field unit:

$$(\Delta P)_{LF} = \frac{2.032\, qB}{nL_p h}\sqrt{\frac{\mu t}{k_y \emptyset c_t}} + C \quad (10)$$

(C) Can be determined from the straight line of pressure derivative for linear flow intermediate time data at $(t = 1.0\ hr)$ as follows:

$$C = \frac{(nL_p)h}{4.064qB}\sqrt{\frac{k_y \emptyset c_t}{\mu}}\Delta P_{1hr}$$

(11)

Then:

$$s_L = C - log\left(\frac{h}{L_w}\right) - 0.25log\left(\frac{k_y}{k_z}\right) + 1.6 \quad (12)$$

Elliptical flow regime

Elliptical flow regime may develop for moderate and long length wellbores during the transition from early linear flow to pseudo-radially flow for the cases where the reservoir boundaries are long enough to create ellipsoid drainage area as shown in Fig. (15). This flow regime is characterized by slope of (0.36) on pressure derivative curves as shown in Fig. (16). It is described by the following model (Escobar and Montelegre, 2007):

$$(t_D * P'_D)_{ELF} = \frac{1}{54000}\left(\frac{(hx_e)}{(L_w r_w)}\right)^{0.72} t_D^{0.36}$$

(13)

In field units:

$$(\Delta P)_{ELF} = \frac{q\mu B}{2675\sqrt{k_y k_x}h}\left(\frac{k_x}{\emptyset\mu c_t}\right)^{0.36}\left(\frac{hx_e}{r_w L_w^2}\right)^{0.72} t_D^{0.36} + \frac{141.2q\mu B}{\sqrt{k_x k_y}h} s_{elf} (14)$$

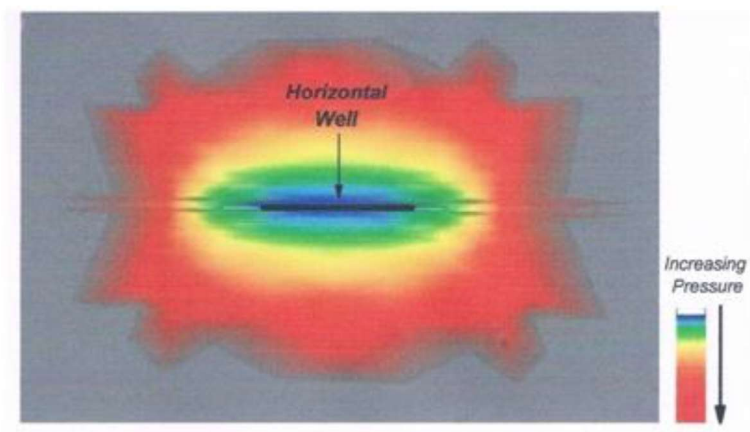


Fig.(15) Elliptical flow regime in horizontal well

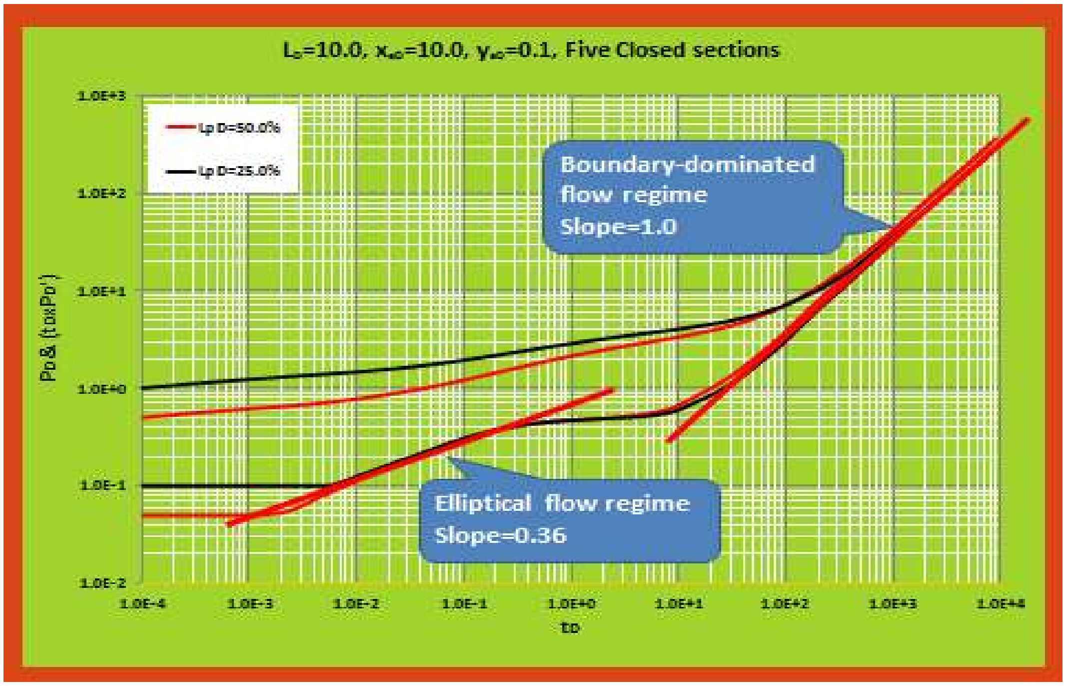


Fig.(16) Elliptical flow& Boundary-dominated regime in horizontal wells

Intermediate (second) radial flow regime

Intermediate or second radial flow regime represents fluid flow radially in the horizontal plan toward each perforated section as shown in Fig. (17). This flow regime develops for the cases of short perforation sections and long closed sections. It is characterized by horizontal line on pressure derivative curves equals to $(\frac{0.5}{n})$ as shown in Fig. (18). It is described by the following models:

$$(t_D * P_D')_{IRF} = \frac{0.5}{n} \quad (15)$$

In field units:

$$(t * \Delta P')_{IRF} = \frac{70.6\ q\mu B}{\sqrt{k_x k_y}h} \quad (16)$$

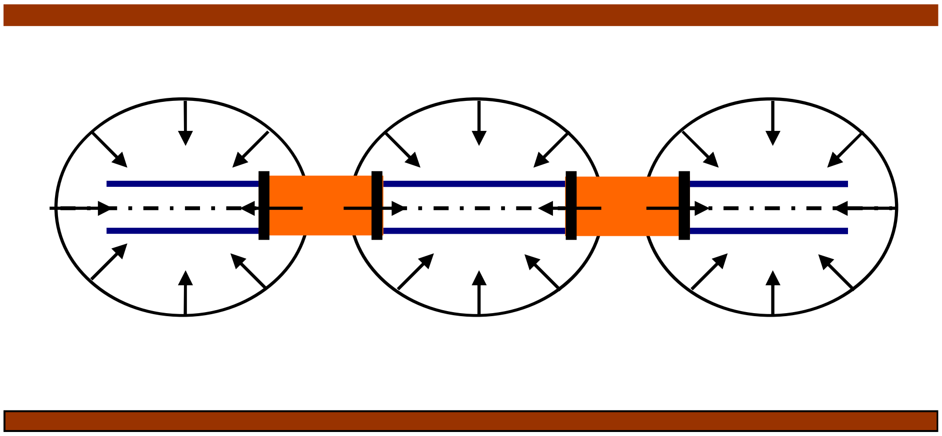


Fig. (17) Intermediate (second) radial flow regime

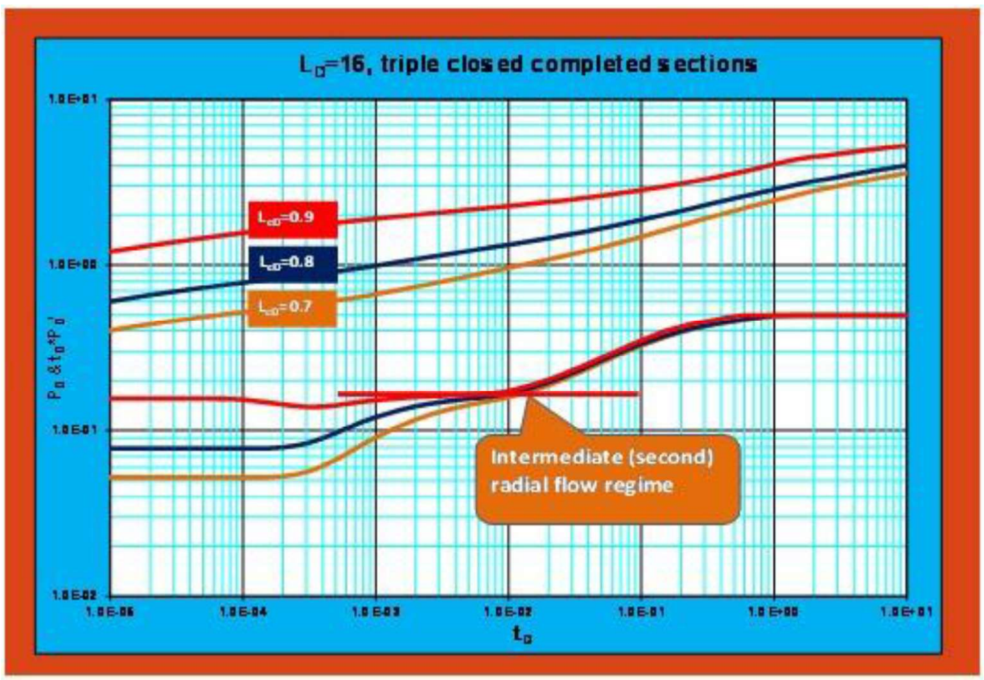


Fig.(18) Intermediate (second) radial flow regime for horizontal wells

Pseudo-radial flow regime

Late or pseudo-radial flow is the most common type of flow regimes takes place for infinite acting reservoirs and finite acting reservoirs with large drainage area. It is characterized by horizontal line of constant pressure derivative value equals to (0.5). This flow regime describes the radial flow in the horizontal plan toward the hole wellbore including perforated and closed sections as shown in Fig. (19). Mathematically, it is defined as:

$$(t_D * P'_D)_{PR} = 0.5 \quad (17)$$

In field units:

$$(t * \Delta P)_{PR} = \frac{70.6\ q\mu B}{\sqrt{k_x k_y}h} \quad (18)$$

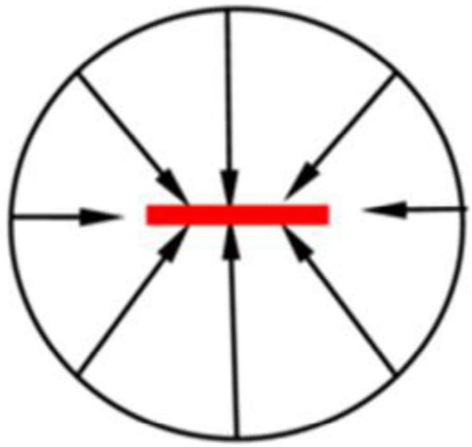


Fig.(19) Pseudo-radial flow regime

Boundary dominated (Late linear) flow regime

This flow develops when the pressure pulse reaches the outer boundaries of the reservoir. It is characterized by slope of (1.0) for both pressure and pressure derivative curve as shown in Fig. (15). It is described by the following models (Goode 1987):

$$(\Delta P)_{LL} = \frac{4.064\ qB}{hx_e}\sqrt{\frac{\mu t}{k_y \emptyset c_t}} + \frac{141.2\ q\mu B}{\sqrt{k_y k_z}L_w} s_t \quad (19)$$

Where: $(s_t)$is the total skin factor.

<u>Productivity Indx:</u>

Mathematically, the productivity index is defined as the production capacity of the sand face that can be obtained from (1.0) psi pressure drop. For a constant production rate, the pressure drop at any point in the formations depends on several parameters: permeability, homogeneity, isotropy, formation drainage area configuration, reservoir fluid properties, and wellbore length. The production rate and the pressure drop at the wellbore are the two items required for estimating the instantaneous productivity index using the model:

$$J = \frac{q}{\Delta P}$$
(20)

However, for pseudo-steady state, the productivity index of horizontal wells can be estimated using the model given in Eq. (2). Eq. (2) can be written as follows:

$$J = C * J_D$$
(21)

Where: J_D is the dimensionless productivity index obtained from.

From Figures. (20-23), it can be seen that the productivity index decreases as the length of closed section increases. This fact can be explained by increasing the pressure drop required for the same production rate because of increasing the restrictions to fluid flow due to the reduction in the wellbore length resulted from the existence of closed completed sections. The impact of the length of closed sections on productivity index can be noticed clearly on short length horizontal wells rather than moderate and long horizontal wells.

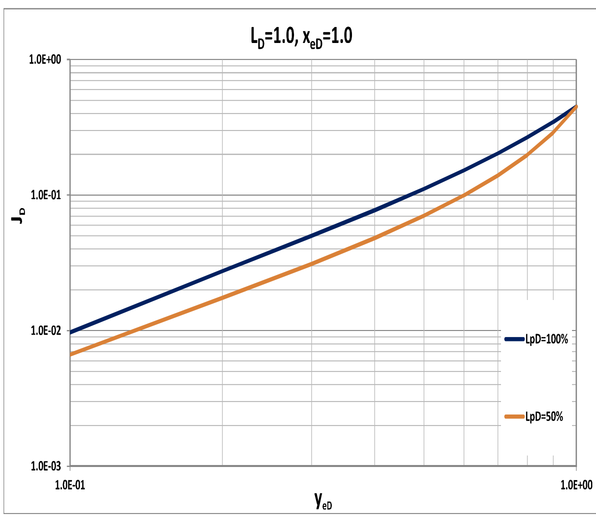


Fig.(20)Productivity index for short horizontal wells

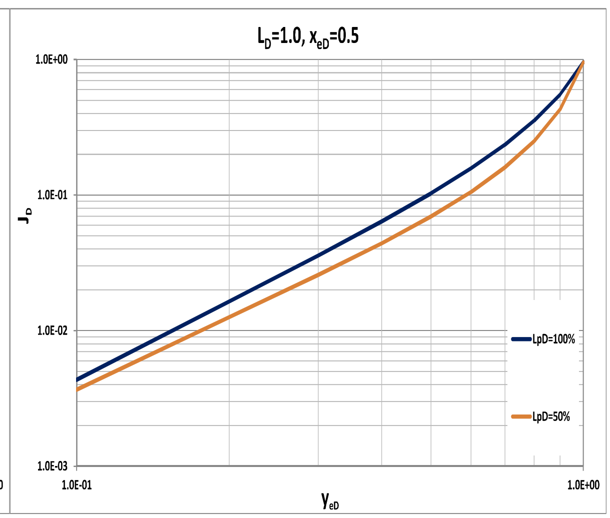


Fig. (21) Productivity index for short horizontalwells

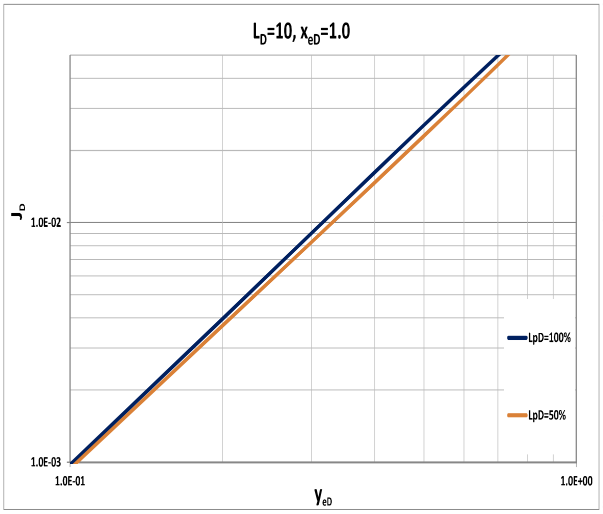


Fig.(22) Productivity index for moderate length Horizontal wells.

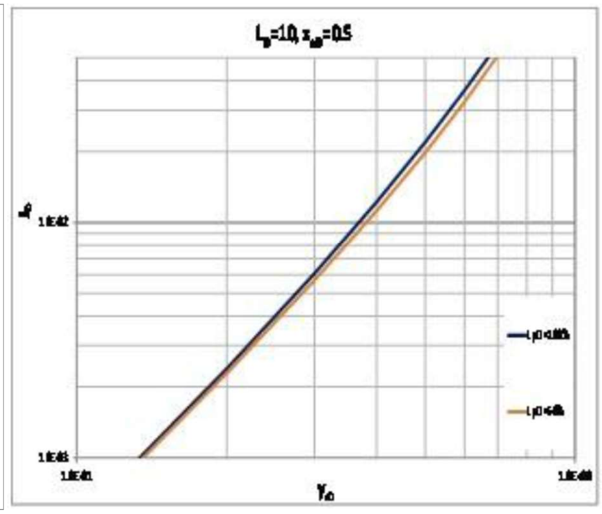


Fig.(23) Productivity index for moderate length Horizontal wells.

Well test analysis:

Well test analysis is typically used as an excellent tool for reservoir characterization. However, great attention should be given to the existence of the closed completed sections when the reservoir is characterized by well test analysis. The reason for that is the change in pressure behaviors and flow regimes due to these sections. The characterization process depends on the developed flow regimes in the test which is in turn depends on the time duration of the test. For short time well test, early radial flow regime may develop only after the wellbore-storage dominated flow regime. While pseudo-radial flow regime or boundary dominated flow regime may need for long time well test to be noticed.

Early radial flow regime:

From early radial flow regime data, the characterization procedure can be achieved as follows:

1- From the horizontal line of the pressure derivative obtained by the log-log plot of time and pressure derivative, the value of pressure derivative can be used to calculate the following permeability term:

$$\sqrt{k_z k_y} = \frac{35.3 q \mu B}{(nL_p)(t*\Delta P')_{ER}} \quad (23)$$

2- Using the slope (m) of the straight line obtained from the semi-log plot of time and pressure for early time data, the permeability term mentioned above can be checked as follows:

$$\sqrt{k_z k_y} = \frac{81.3q\mu B}{(nL_p)m} \quad (24)$$

3- From the intercept point (C) of the same plot mentioned above, the skin factor resulted from early linear flow can be obtained from the following model:

$$s_R = 1.1515\left[\frac{(nL_p)\sqrt{k_y k_z}}{161.2q\mu B}\Delta P_{1hr} - \log\left(\frac{k_x}{\emptyset\mu c_t L_w^2}\right) + 3.227\right] \quad (25)$$

Early linear flow regime:

Early linear flow regime data (intermediate time data) can be analyzed as follows:

1- Using the straight line obtained from the log-log plot of time and pressure derivative of linear flow data, the pressure drop corresponding to $(t = 1.0\ hr)$ can be determined.

2- The following model is applicable:

$$k_y = \left(\frac{2.032qB}{(nL_p)h\Delta P_{1hr}}\sqrt{\frac{\mu}{\emptyset c_t}}\right)^2 \quad (26)$$

Then (k_z) can be determined from the permeability term obtained by Eq. (23).

$$k_z = \frac{\left(\sqrt{k_z k_y}\right)^2}{k_y} \quad (27)$$

3- The permeability (k_y) can be determined also from the slope of the straight line obtained from the plot of $(\sqrt{t})$ vs. pressure drop as follows:

$$k_y = \left(\frac{4.064qB}{(nL_p)hm}\sqrt{\frac{\mu}{\emptyset c_t}}\right)^2 \quad (28)$$

While the intercept of the straight line with $(t = 1.0\ hr)$ can be used to check the permeability (k_y) as follows:

$$(\Delta P)_{LF} = \frac{4.064\ qB}{(nL_p)h}\sqrt{\frac{\mu t}{k_y \emptyset c_t}} + \frac{(nL_p)h}{4.064qB}\sqrt{\frac{k_y \emptyset c_t}{\mu}}\Delta P_{1hr} \quad (29)$$

The intersection time between early linear flow regime line and early radial flow regime line is useful in the interpretation process as follows:

$$k_z = \frac{302h^2\emptyset\mu c_t}{(t_{int})_{LF-ER}} \quad (30)$$

Similarly, the intersection point between early linear flow regime and pseudo-radial flow regime is used as follows:

$$k_x = \frac{1207(nL_p)^2 \emptyset \mu c_t}{(t_{int})_{LF-PR}} \quad (31)$$

and the intersection point between early linear flow regime and intermediate (second) radial flow regime is used as follows:

$$k_x = \frac{1207(L_p)^2 \emptyset \mu c_t}{(t_{int})_{LF-IR}} \quad (32)$$

Pseudo-radial flow regime:

The interpretation of pseudo-radial flow regime data can be used in checking the value of horizontal permeability as follows:

$$\sqrt{k_x k_y} = \frac{70.6 q \mu B}{h(t * \Delta P\prime)_{PR}} \quad (30)$$

Accordingly:

$$k_x = \frac{\left(\sqrt{k_x k_y}\right)^2}{k_y} \quad (31)$$

Intermediate (second) radial flow regime:

The data of this flow regime is used to calculate the number of closed completed section or perforated sections. This regime indicates the flow of fluid toward each individual perforated section in case of long horizontal well having long closed completed sections. The following model can be used for this purpose:

$$n = \frac{70.3 q \mu B}{\sqrt{k_x k_y} h(t * \Delta P\prime)_{IRF}} \quad (32)$$

Elliptical flow regime:

For the cases where the elliptical flow regime is observed, either the outer boundaries of the reservoir or the permeabilities can be checked using the data of this flow regime. Eq. (14) can be used for this purpose.

Boundary dominated (late linear) flow regime:

For finite acting reservoirs, the pressure pulsemay reachthe boundaries. Accordingly, boundary dominated flow or late linear flow characterized by slope of (1.0) for both pressure and pressure derivative curves is observed. The data of this flow regime can be used to estimate the boundaries using Eq. (19).

Example:

The following data are available:

$$L_w = 2000\,ft \qquad h = 125\,ft \qquad \mu = 0.5\,cp \qquad \emptyset = 0.05 \qquad c_t = 1 * 10^{-6} psi^{-1} \qquad q = 300 \frac{STB}{D} B_o = 1.15 \frac{bbl}{STB} P_e = 6{,}000\,psi$$

Pressure data have been recorded as shown in Table-1 in the Appendix. It is required to interpret the permeabilities and skin factors knowing that the length of the closed complete sections represents (90%) of the total wellbore length.

The interpretation procedures are started with plotting the pressure and pressure derivative with time (log-log) as shown in Fig. (24).

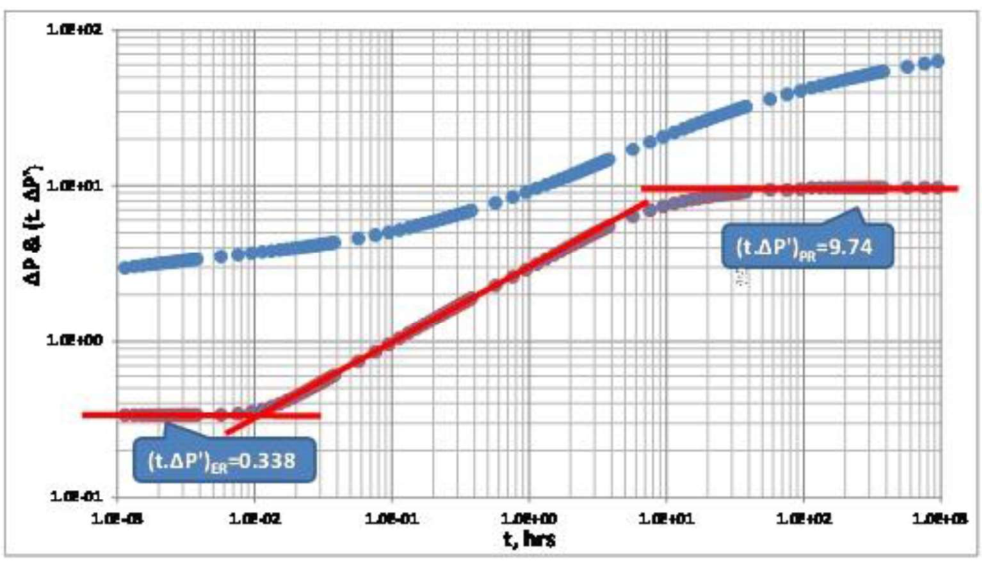


Fig.(24) Pressure and pressure derivative plot for example -1

It can be seen from the plot that three flow regimes have been developed: early radial, early linear and pseudo radial flow regimes where the well of interest is extending in infinite acting reservoir.

1- From early radial flow regime data (early time data $t \leq 0.01\,hr$), the value of pressure derivative is taken from Fig.(24):

$$(t * \Delta P')_{ER} = 0.338$$

Then the following permeability term is determined from Eq. (23):

$$\sqrt{k_z k_y} = \frac{35.3 * 300 * 0.5 * 1.15}{1800 * 0.338} = 10$$

2- From semi-log plot of time and pressure drop of early time data as shown in Fig. (25), the slope and intercept of the straight line are determined:

$m = 0.78$

$Intercept = 5.4$

Then, the above mentioned permeability term can be confirmed by Eq. (24):

$$\sqrt{k_z k_y} = \frac{81.3 q \mu V}{m(nL_p)} = \frac{81.3 * 300 * 0.5 * 1.15}{0.78 * 1800} = 9.99$$

3- From early linear flow regime data, the straight line of the pressure derivative curve characterized by slope (0.5), the following parameter can be determined:

$\Delta P_{1hr} = 3.1$

Then, the permeability in the Y-direction can be calculated using Eq. (26):

$$k_y = \left(\frac{2.032 qB}{(nL_p) h \, \Delta P_{1hr}} \sqrt{\frac{\mu}{\emptyset c_t}} \right)^2 = \left(\frac{2.032 * 300 * 1.15}{1800 * 125 * 3.1} \sqrt{\frac{0.5}{0.05 * 0.000001}} \right)^2 = 10 \, md$$

Thus:

$$k_z = 10 \, md$$

The above permeability result (k_y) can be checked using the slope of the straight line obtained from the plot of $(\sqrt{t}) vs \, \Delta P$ as shown in Fig. (26). Eq. (28) is used for this purpose. The following parameters have been obtained from Fig. (26):

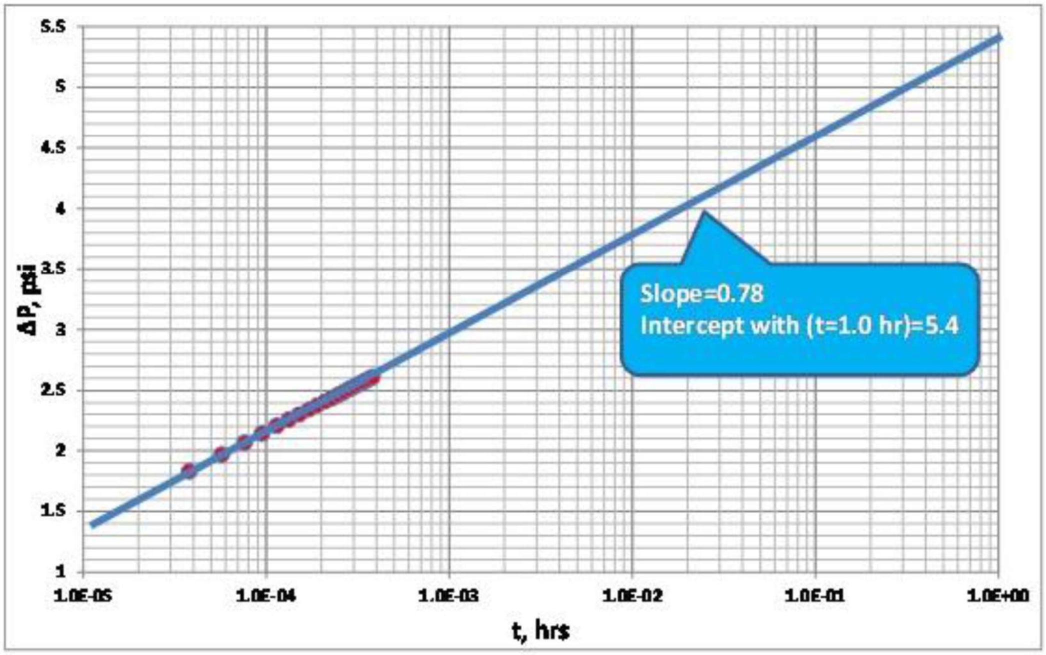


Fig.(25) Semi-log plot of pressure drop and time for early radial flow regime data

$$m = 6.045\Delta P_{1hr} = 9.2\ psi$$

Using Eq.(28): $k_y = 10\ md$

4- From pseudo-radial flow regime, the pressure derivative value is:

$$(t * \Delta P')_{PR} = 9.74$$

Then:

$$k_x = \left(\frac{70.6\ q\mu B}{h\ (t * \Delta P')_{PR}\sqrt{k_y}}\right)^2 = \left(\frac{70.6 * 300 * 0.5 * 1.15}{125 * 9.74 * \sqrt{10}}\right)^2 = 10\ md$$

5- The skin factor resulted from early radial flow regime is given by Eq. (24) as follows:

$$s_R = 1.1515\left[\frac{1800 * \sqrt{10 * 10}}{161.2 * 300 * 0.5 * 1.15} * 5.4 - \log\left(\frac{10}{0.05 * 0.5 * 0.000001 * 2000^2}\right) + 3.227\right] = 5.3$$

6- The skin factor resulted from early linear flow regime is given by Eq. (12) as follows:

$$s_L = \frac{1800 * 125}{4.064 * 300 * 1.15}\sqrt{\frac{10 * 0.05 * 0.000001}{0.5}} * 9.2 - \log\left(\frac{125}{2000}\right) - 0.25\log\left(\frac{10}{10}\right) + 1.6 = 4.28$$

7- The values of permeabilities can be checked using the intersection points. From Fig. (24):

$(t_{int})_{LF-ER} = 0.0118\ hrs$, $(t_{int})_{LF-PR} = 9.8\ hrs$

Using Eq. (30):

$$k_z = \frac{302 * (125)^2 * 0.05 * 0.5 * 0.000001}{0.0118} = 10\ md$$

Using Eq. (31):

$$k_x = \frac{1207 * (1800)^2 * 0.05 * 0.5 * 0.000001}{9.8} = 10\ md$$

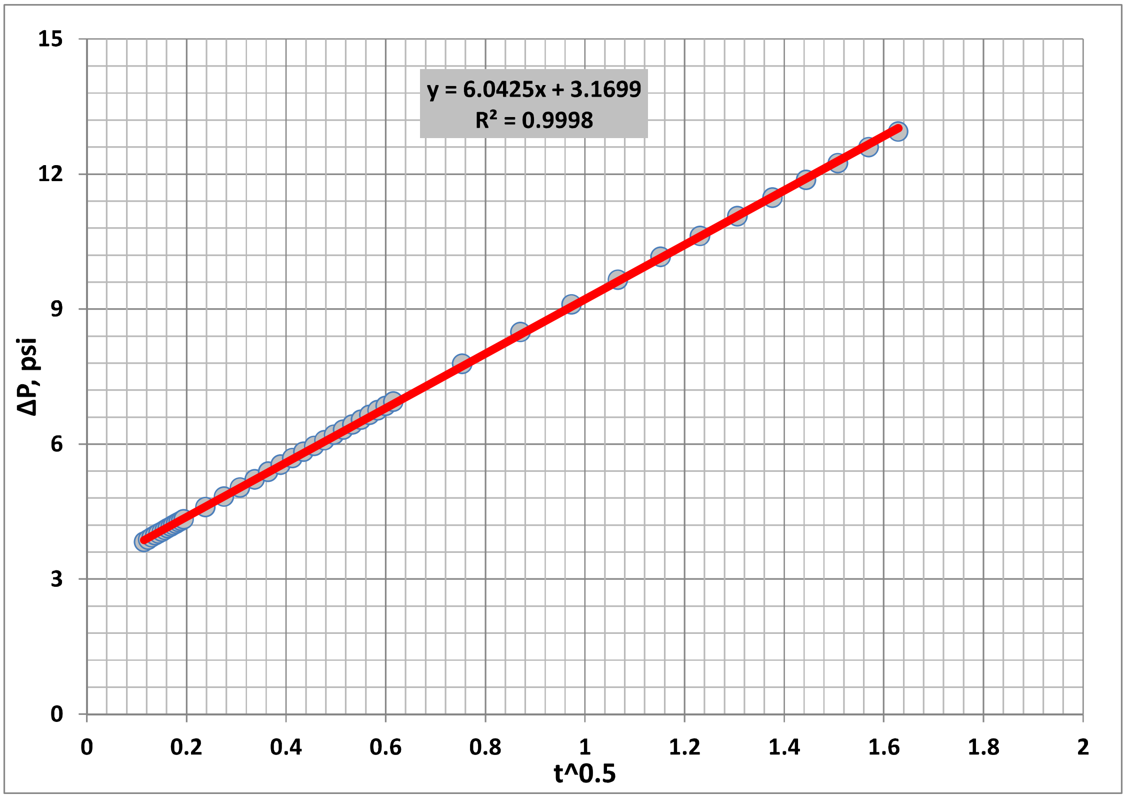


Fig.(26) Square root of time vs pressure drop for early linear flow regime

Conculsions:

1- Even though, the completion techniques are good practices for some of the prospective production problems, they have some impact on pressure behaviors, flow regimes, and productivity index of horizontal wells acting in finite and infinite reservoirs.

2- The impact of completion techniques is represented by the existence of closed completed section (cemented, isolated, and packers) along the horizontal wellbore that do not allow for reservoir fluids to enter in the wellbore.

3- The impact depends on the length of the closed completed sections. However, there is no significant impact for the number of closed completed sections.

4- Intermediate (second) radial flow has been noticed due to the existence of the closed sections.

Nomenclature:

B Formation volume factor, rbbl/STB

c_t Reservoirtotal compressibility, psi^{-1}

h Reservoir thickness, ft

kx Reservoir permeability in the X-direction, md

ky Reservoir permeability in the Y-direction, md

kz Reservoir permeability in the Z-direction, md

Lw Half wellbore length, ft

Lp Length of perforated section, ft

Lc Length of closed completed section, ft

n Number of perforated sections

P_D' Pressure derivative

ΔP Pressure drop, psi

q Flow rate, STB/D

s Skin factor

t Time, hrs

ϕ Porosity

μ Viscosity, cp

ER Early radial flow

IR Intermediate radial flow

PR Pseudo radial flow

LF Linear flow

LLF Boundary dominated or late linear flow

ELF Elliptical flow

List of Symbols:

$$x_D = \frac{x - x_w}{L_w}$$

$$y_D = \frac{y - y_w}{L_w}\sqrt{\frac{k_x}{k_y}}$$

$$z_D = \frac{z - z_w}{L_w}\sqrt{\frac{k_x}{k_z}}$$

$$z_{wD} = \frac{z_w}{h}$$

$$\bar{z_D} = \frac{z - z_w}{h} = z_D L_D$$

$$L_D = \frac{L_w}{h}\sqrt{\frac{k_z}{k_x}}$$

$$L_{pD} = \frac{L_p}{L_w}$$

$$L_{cD} = \frac{L_C}{L_W}$$

$$P_D = \frac{2\pi\sqrt{k_x k_y}\, h \Delta P}{q \ \mu}$$

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Appendex:

`	P, psi	t, hrs	P, psi	t, hrs	P, psi	t, hrs	P, psi	t, hrs	P, psi
3.79E-05	5998.168	0.001896	5996.845	0.03413	5995.737	1.516875	5989.379	30.3375	5969.7
5.69E-05	5998.031	0.002086	5996.813	0.036026	5995.706	1.706485	5988.941	32.2336	5969.2
7.58E-05	5997.934	0.002275	5996.783	0.037922	5995.675	1.896094	5988.528	34.12969	5968.7
9.48E-05	5997.858	0.002465	5996.756	0.056883	5995.402	2.085703	5988.136	36.02579	5968.2
0.000114	5997.797	0.002655	5996.731	0.075844	5995.173	2.275313	5987.763	37.92188	5967.7
0.000133	5997.745	0.002844	5996.708	0.094805	5994.97	2.464922	5987.406	56.88282	5963.9
0.000152	5997.699	0.003034	5996.686	0.113766	5994.787	2.654532	5987.064	75.84376	5961.2
0.000171	5997.66	0.003223	5996.665	0.132727	5994.619	2.844141	5986.735	94.8047	5959.1
0.00019	5997.624	0.003413	5996.646	0.151688	5994.462	3.03375	5986.418	113.7656	5957.4
0.000209	5997.592	0.003603	5996.628	0.170648	5994.315	3.22336	5986.112	132.7266	5955.8
0.000228	5997.562	0.003792	5996.611	0.189609	5994.176	3.412969	5985.816	151.6875	5954.5
0.000246	5997.535	0.005688	5996.473	0.20857	5994.044	3.602579	5985.53	170.6485	5953.4
0.000265	5997.51	0.007584	5996.376	0.227531	5993.918	3.792188	5985.252	189.6094	5952.4
0.000284	5997.487	0.00948	5996.298	0.246492	5993.797	5.688282	5982.849	208.5703	5951.4
0.000303	5997.465	0.011377	5996.233	0.265453	5993.681	7.584376	5980.928	227.5313	5950.6
0.000322	5997.444	0.013273	5996.176	0.284414	5993.569	9.48047	5979.325	246.4922	5949.8
0.000341	5997.425	0.015169	5996.124	0.303375	5993.461	11.37656	5977.949	265.4532	5949.1
0.00036	5997.407	0.017065	5996.076	0.322336	5993.356	13.27266	5976.742	284.4141	5948.4
0.000379	5997.389	0.018961	5996.032	0.341297	5993.255	15.16875	5975.667	303.375	5947.8
0.000569	5997.252	0.020857	5995.989	0.360258	5993.157	17.06485	5974.698	322.336	5947.2
0.000758	5997.155	0.022753	5995.949	0.379219	5993.061	18.96094	5973.816	341.2969	5946.6
0.000948	5997.079	0.024649	5995.91	0.568828	5992.218	20.85703	5973.006	360.2579	5946.1
0.001138	5997.018	0.026545	5995.873	0.758438	5991.516	22.75313	5972.258	379.2188	5945.6
0.001327	5996.966	0.028441	5995.838	0.948047	5990.902	24.64922	5971.563	568.8282	5941.7
0.001517	5996.92	0.030338	5995.803	1.137656	5990.351	26.54532	5970.913	758.4376	5938.9
0.001706	5996.881	0.032234	5995.77	1.327266	5989.847	28.44141	5970.302	948.047	5936.7