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Optimizing oil recovery using new inflow-control devices (ICDs) skin equation

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Inflow-control devices (ICDs) were developed to avoid coning problems in long horizontal wells mainly in heterogenous formations, but cause some additional drawdown which does not contribute to rate increase. This rate reduction is seen to be impairment to the productivity of horizontal wells. Therefore, horizontal wells that are equipped with ICDs require a pre-quantification of their productivity by determining skin caused by each ICD nozzle size. This will help prevent additional expenditure that will be spent for a corrective horizontal well intervention. Many authors have proposed equations that can be used to estimate skin due to damage, partial completion, slanted well and perforation. No author has provided a skin equation that can be used to estimate recoverable and productivity loss that may result from the use of inflow control devices. In this work, a 3D numerical model which includes inflow control devices along horizontal wells was used to investigate reservoir and production performances of various ICD nozzle sizes. Different productivity losses from different nozzle sizes were seen as skin and a 0.002ft^2 ICD nozzle flow area estimated to have a zero skin. Consequently, a simple equation for calculating this skin due to restricted fluid entry through ICD nozzles was derived. The derived equation which shows insignificant deviation from skin equation is then used for selecting the right nozzle size for production and recovery optimization from horizontal wells.

Key words: Inflow control device

INTRODUCTION

Horizontal wells have superior production and recovery performance compared to vertical wells because they have more contact with the reservoir. This advantage in terms of fluid production rates, actually becomes a disadvantage when water breaks through into the wellbore causing a very rapid increase in water cut (Inikori, 2002). Rate of fluid into a horizontal well normally varies along the horizontal well length due to either frictional pressure losses (the heel–toe effect) or reservoir permeability heterogeneity. Such variations usually negatively affect the oil sweep efficiency and the ultimate recovery.

Denney (2010) reported that Inflow-control devices (ICDs) were developed to avoid water-coning problems in long horizontal wells. Figure 1 shows the advantage of using an inflow control device; the horizontal heel to toe effects is reduced. Daneshy et al. (2012) reported that inflow control devices were developed in response to early water breakthrough from the heel of prolific horizontal wells. They said that these tools are often installed along the entire length of a horizontal well with the logic that because choking level is proportional to

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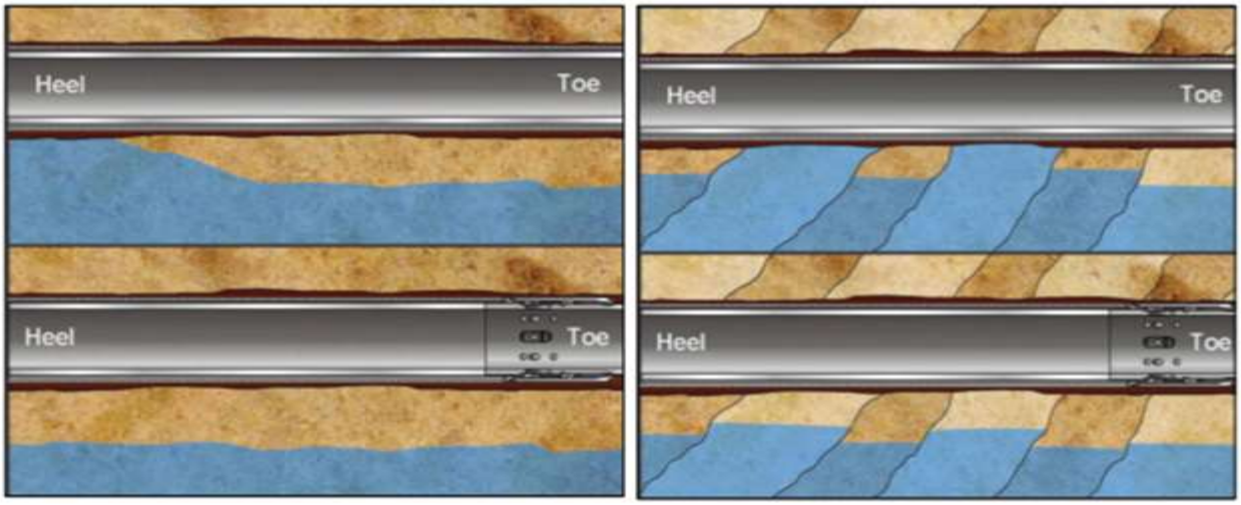

Figure 1. Water coning due to pressure drop in the tubing.
Source: Halliburton (2008).

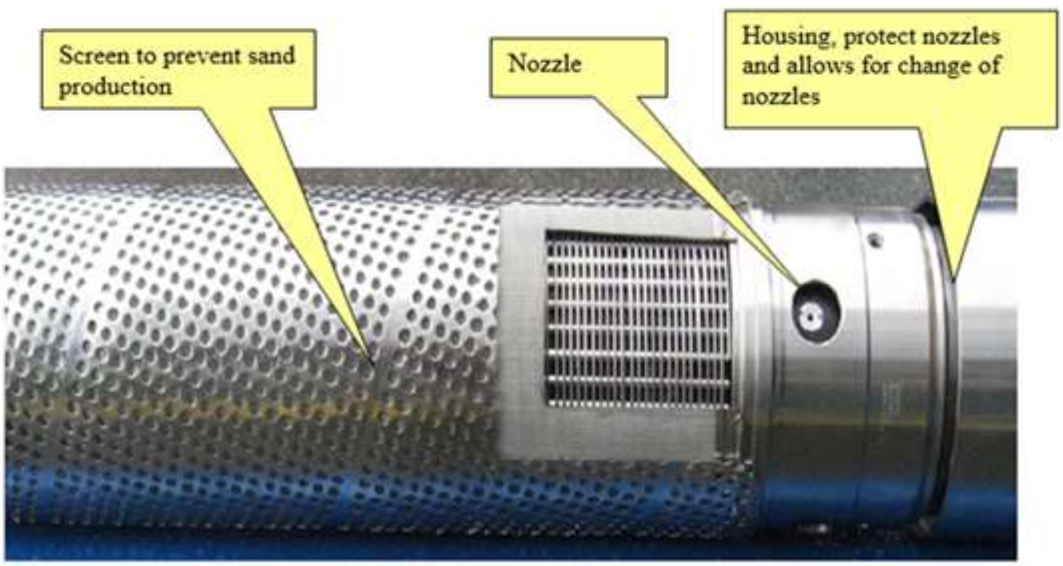

Figure 2. Nozzle type ICD.
Source: Schlumberger (2010).

flow, the tool will automatically produce a more uniform flow profile. Abd Elfattah et al. (2013) indicated that there are various types of ICDs which are tube, helical, orifice and nozzle types. Figure 2 shows a typical representation of the essential parts in an inflow control device; the screen, the housing and the nozzle where the fluid makes entrance into the completion

Li et al. (2011) said that the pressure drop created by ICD is considered impairment to the productivity of wells. To make the problem simple they illustrated the impact of ICD on well production since the frictional pressure drop of flow can be expressed explicitly as a function of flow rate. Since frictional pressure drop is proportional to squared flow rate (q^2), Li et al. (2011) used a general equation for ICD pressure drop, Δp_{ICD}, calculation.

$$\Delta p_{ICD} = Cq^2 \rho_m \tag{1}$$

They said that for an ICD to work appropriately, two conditions have to exist. First, the pressure drop inside the wellbore needs to be at a relevant level to reservoir drawdown, and secondly, the ICDs can create corresponding pressures at a meaningful level (certain

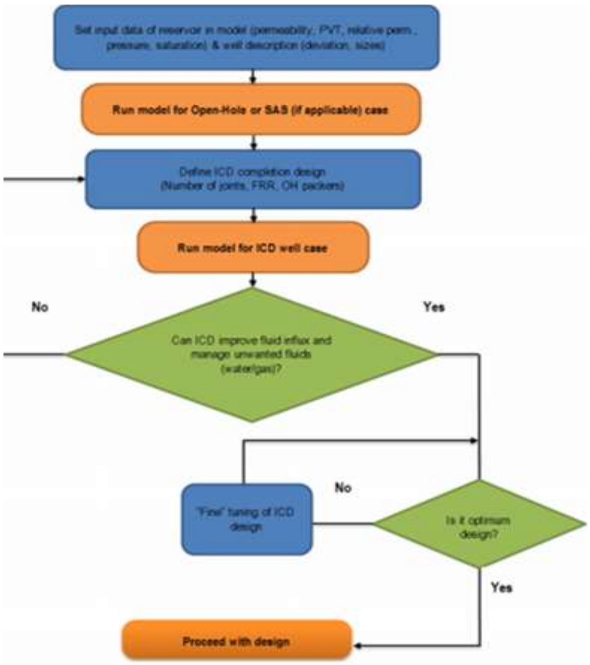

Figure 3. Typical ICD modeling approach.
Source: Awad et al. (2015).

flow rate is required). Zhu and Hill (2006) showed that the ratio *K* of pressure drop in the wellbore to the reservoir can be used to evaluate if an inflow control device will impair the productivity of a horizontal well. The ratio is defined as follows:

$$K = \frac{\Delta p_f}{\Delta p_r} \quad (2)$$

Zhu and Hill (2006) using the K ratio said if K is beyond 70%, using ICDs or other flow control devices can balance the flow along the wellbore, improve well performance, and increase recovery, but if K is less than 10%, adding ICDs to the completion for wellbore flow distribution may cause productivity losses. Zhu and Hill (2006) finally said that for each individual well, K should be examined before deciding to use an ICD in a completion.

Wang et al. (2014) said ICDs will lower startup production which goes a long way delaying early breakthrough of unwanted fluids. Al-Jasmi et al. (2013) said that any misunderstanding in the reservoir parameters will lead to wrong decisions which will affect the cumulative production of oil. This would finally result in low value realization of the technology and its disapproval for large scale implementation.

According to Li et al. (2011), ICDs can be either beneficial or detrimental to production, strongly depending on the reservoir condition, well structure and ICD design. To Lee et al. (2017), the additional pressure loss in an ICD completion will cause reduction of effective productivity of horizontal wells; in other words it will require lower flowing bottom-hole pressure for a well with ICD completion to produce the same liquid rate compared to a well without an ICD. They therefore said that the pressure of a reservoir where an ICD well is installed will require to be managed properly as part of a field development strategy since the well with an ICD will require a lower flowing bottomhole pressure to produce a desired off take rate. Li et al. (2011) noted that ICDs are not adjustable; once installed in the well, the location of the device and the relationship between rate and pressure drop are fixed and this makes the design of a well completion and ICDs extremely critical for production.

Cao et al. (2016) explained that because of risk involved in ICD including the money invested especially in offshore fields, it is essential to design ICDs (number, location, type, size, etc.) effectively in order to improve production and net present value (NPV), otherwise the ICDs even would be overlooked.

Awad et al. (2015) showed a typical flow diagram that should be used in a proper modeling and designing of ICD. This is presented in Figure 3. Mojaddam et al. (2012), in their paper titled “optimal inflow control devices configurations for oil rim reservoirs” indicated that the primary objective in every ICD modeling is to maximize oil production from the whole completion interval and that effective design process should be put in place to avoid losses in production and recovery. Skin is defined as a drawdown which is not accounted for in terms of barrels. (Li et al. (2011) illustrated that the pressure losses caused by ICD may therefore be seen as a skin which may result in reduction in productivity of a horizontal well. To illustrate this, they conducted an experiment using the channel-type ICD to show the impact of ICDs to horizontal wells. Daneshy (1995) said that with the focus on getting best return on investment it is no more enough to just be profitable. Optimum well productivity will enhance the economic value of any reservoir. From works done by many in ICD design, it is obvious that ICDs create skin in most horizontal wells. The level of skin is dependent on ICD design. Total skin can be divided into skin due to damage, skin due to completion, skin due to perforation and skin due to slanted well. To avoid misuse of skin due to ICD to other skin, there is the need to derive skin due to restricted fluid entry into ICD nozzles for use in horizontal wells evaluation. More so, a predetermination of skin due to ICD of the nozzle sizes which has to be installed is required for effective ICD designing and recovery optimization.

METHODOLOGY

In this study, objectives were accomplished using Eclipse (E300) which is a compositional three-dimension reservoir simulator. The major objective of using the numerical model which includes the

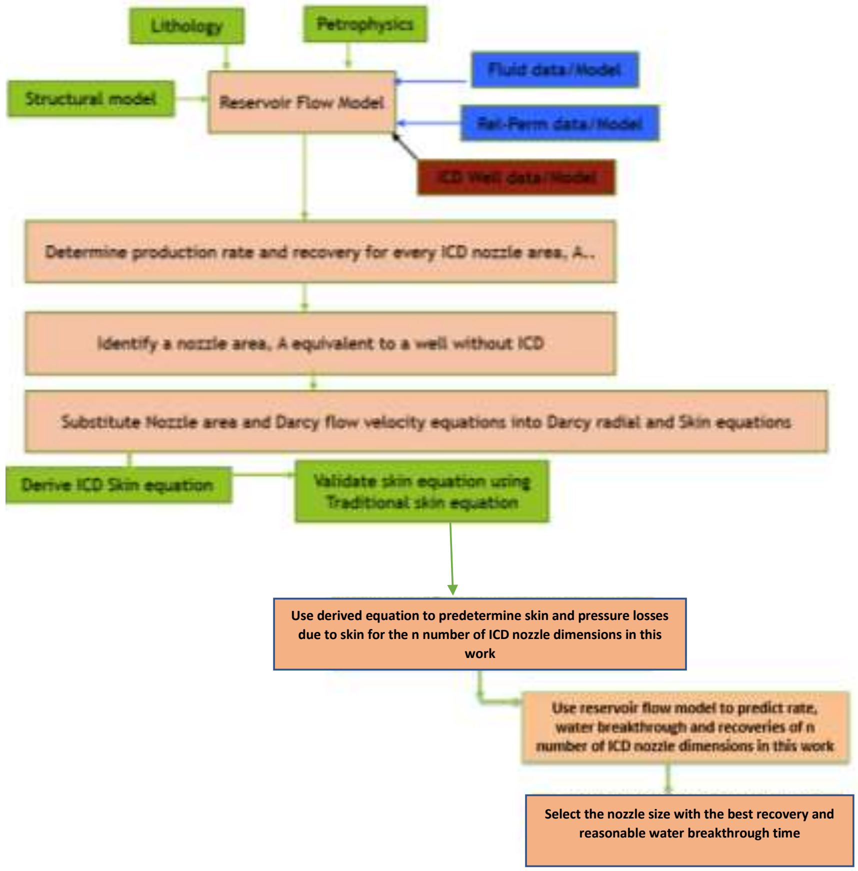

Figure 4. Chart representing approach used in the study.

ICD model is to first of all identify rate changes with changing ICD nozzle flow area and secondly, identify the ICD nozzle flow area which represents little or no frictional pressure losses, and which has its rate equivalent to the rate of a well without an ICD. An equation of skin was derived from first principle. The model result and the derived equation were used to determine the best ICD nozzle size to improve oil recovery.

MODEL DESCRIPTION

The geological model (Figure 5) of reservoir is described by a model with dimensions 40ft x 40ft x 4ft in the X*Y*Z dimensions respectively. The model is divided in terms of grid cells (reservoir gridding) to generate 10 cells in x direction, 10 cells in Y direction and 20 simulation cells in Z direction in order to get rid of all numerical dispersion problems. The reservoir model contains one well to produce the oil as shown in Figure 5. The production well was located at cell (6,4). The top of the reservoir is located at 2300 ft in terms of reservoir depth and the initial reservoir pressure at 2380 ft is set to be 1100 psi. The production started in January 2015. The reservoir was depleted at maximum drawdown of 305 psi. This constraint was applied mainly to observe any reduction in rate with changing ICD nozzle size. The model was run for 15 years. An average effective porosity value of 0.3 is used across the reservoir. The reservoir, fluid and well data used for the model are illustrated in Tables 1 and 2. The flow diagram in Figure 4 illustrates the step taken in selecting the best nozzle size during ICD design. In the study, two case wells enumerated below are used in the process study.

Case A: A horizontal well without an ICD

In this case, the reservoir fluid flows from near the reservoir boundary towards the horizontal well with flow area, A. The flow area, A is determined from simulation. In this case, there is no restriction to fluid flow into the horizontal well and skin is zero.

Case B: A horizontal well with an ICD

In this case, the reservoir fluid flows from near reservoir boundary towards the horizontal well. The reduction in rate is caused by reduced ICD flow area *As,* and the region where the backlog of fluid gathers is seen as S. The reduction in rate is caused by pressure losses/energy loss. The long lateral section of the well is divided into 31 ICD joints/segments with each ICD in each segment having different flow area dependent on design and formation permeability, K open to flow into that ICD joint/segment (Figure 6).

ICD selection criteria

The selection of best ICD for horizontal well completions is based on few criteria listed below:

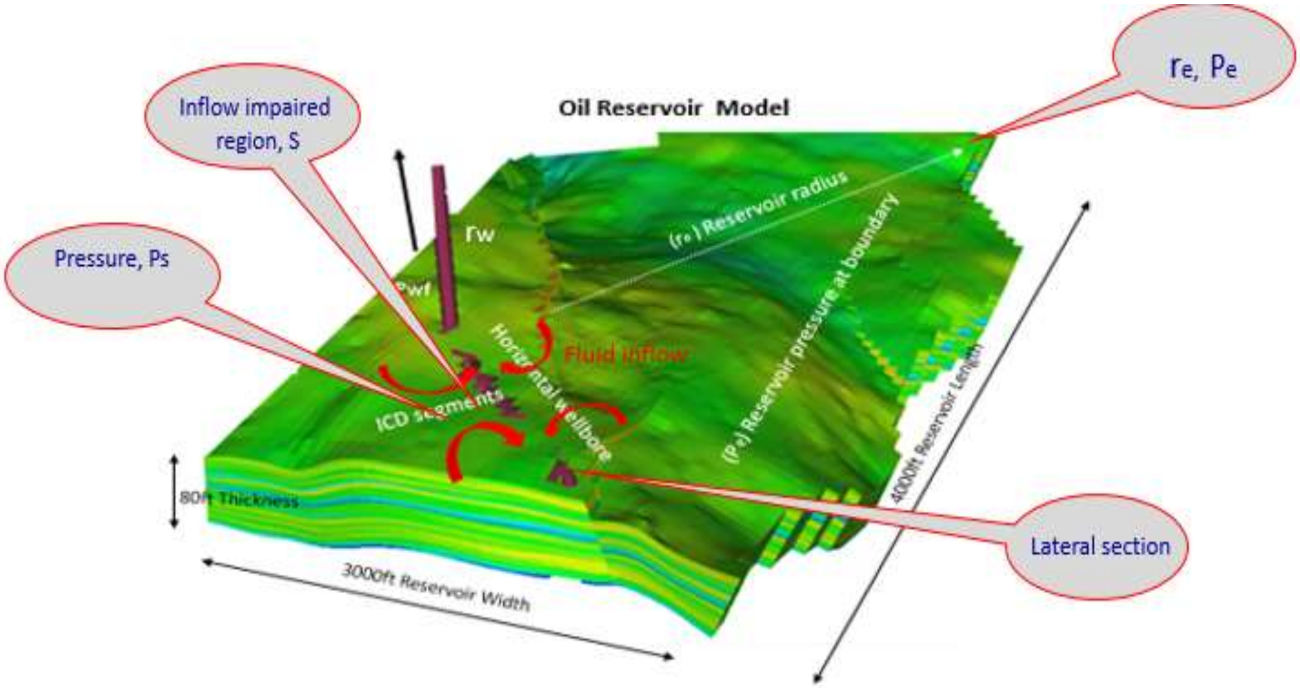

Figure 5. Well and reservoir model for skin evaluation.

Table 1. Fluid Densities at surface conditions.

Property	Value	Unit
Oil density	58.862	Lb/ft^3
Water density	62.4	Lb/ft^3
Gas density	0.053	Lb/ft^3

Table 2. ICD design/Well data.

Parameter	Value	Unit
Well length	1172	ft
ICD nozzle diameter	1.6, 2.5, 4.0	mm
Segment length	36.25	ft
Blank pipes	4	number
Average permeability	1700	md
Average deviation through zone	90.0	degrees
Packers and valves	None	NTR
Offtake rate constraint	3000	Bopd
Maximum drawdown	300	psi
Cemented blank pipe	1	number

Selecting ICD nozzle size with an optimal pressure loss across completion

Because of Bernoulli's principle, it is believed that fluid flow through constrictions has energy loss which in this case is pressure loss; but it is the responsibility of the ICD designer to conduct a sensitivity to select the best nozzle size with a pressure loss which does not compromise the well performance.

Figure 6. showing lateral surface area of each cylindrical shape ICD nozzle in each segment of a horizontal well.

Selecting an ICD nozzle size with an optimal water breakthrough time and best recovery

Including an ICD in a horizontal well completion and reducing the nozzle size for fluid inflow automatically reduces fluid off take rate and delays the time when water enters the completion. Therefore, it becomes an important thing to determine the best nozzle size that will delay water breakthrough time without compromising well performance. More so, reduction in field offtake rate due to skin automatically reduces recovery for an ICD well. The major focus is therefore to find an ICD nozzle size that delays water breakthrough, gives best offtake rate and gives the best ultimate recovery

Selecting an ICD nozzle size with minimal skin

For effective ICD design and to ensure that the included ICD completion does not compromise production and effective recovery, a new equation which computes skin due to fluid entrance into ICD completions will be formulated to ease the ICD design process.

RESULTS AND DISCUSSION

The modeling result helped in deriving equation of skin due to restricted fluid entry through ICD nozzles; the approach used is to assume radial flow into small nozzles of an ICD equipped horizontal well in order to derive an approximate formula for calculating the skin or productivity loss due to restricted fluid movement into the horizontal well.

Using the model in Figure 5, the fluid is bounded by the reservoir with boundary radius, re having an average reservoir pressure, Pe. The fluid flows into the horizontal well as shown in Figure 5. For the establishment of this equation, Darcy radial flow into two regions is considered; (a) radial flow from the reservoir boundary into the flow impaired region (S) represented by Darcy in (3),

$$p_e - p_s = \frac{qB\mu}{2\pi kh}\ln\left(\frac{r_e}{r_s}\right) \quad (3)$$

And (b) radial flow from the impaired region (S) into the wellbore as represented Darcy in (4)

$$p_s - p_w = \frac{qB\mu}{2\pi k_s h}\ln\left(\frac{r_s}{r_w}\right) \quad (4)$$

The fluid flow through an ICD constriction/nozzle with radius r has a Darcy velocity represented by Darcy in the equation below.

$$v = \frac{q}{A} = \frac{q}{2\pi rh} \quad (5)$$

A in Equation 5 is the nozzle flow area which is lateral surface area of a cylinder $= 2\pi rh$.

"Since the interest is in determining the reduction in rate between flow through A and As in a horizontal well, h is assumed to be radius, r." Equation 5 is substituted into Equation 3 and 4 and transformed into Equation 6 and 7

$$p_s - p_w = \frac{qB\mu}{2\pi k_s r h}\ln\left(\frac{r_s}{r_w}\right) \quad (6)$$

$$p_e - p_s = \frac{qB\mu}{2\pi k r h}\ln\left(\frac{r_e}{r_s}\right) \quad (7)$$

Substituting for flow area of the nozzle A = πr^2 into equations 6 and 7, the equations become,

$$p_s - p_w = \frac{qB\mu}{2\,K\,A_s} \ln(\frac{r_s}{r_w}) \qquad (8)$$

$$p_e - p_s = \frac{qB\mu}{2K\,A} \ln(\frac{r_e}{r_s}) \qquad (9)$$

Adding Equation 8 and 9 transforms the equation to,

$$p_e - p_w = \frac{qB\mu}{2K}\left[\frac{\ln(\frac{r_s}{r_w})}{A_s} + \frac{\ln(\frac{r_e}{r_s})}{A}\right] \qquad (10)$$

According to Darcy skin model,

$$p_e - p_w = \frac{q\mu B}{2\pi kh}\left[\ln(\frac{r_e}{r_w}) + S\right] \qquad (11)$$

According to skin model,

In a horizontal well with inflow control device, skin model can be regenerated into

$$= \; p_e - p_w = \frac{q\mu B}{2KA}\left[\ln(\frac{r_e}{r_w}) + S\right] \qquad (12)$$

Elimination of total pressure drop, Pe-Pw between equations 10 and 12 and further simplification of Equation 12 degenerates into

$$S = \left(\frac{A}{A_s} - 1\right) \ln(\frac{r_s}{r_w}) \qquad (13)$$

Where S = the pseudoskin due to restricted fluid entry into ICD nozzles. A = equivalent nozzle area of an ICDless horizontal well which is 0.002ft^2 from analysis conducted.A_s = average nozzle area for all ICD joints in a horizontal well.

r_s = (1-average nozzle radius of all ICD joints)/2
r_w= wellbore radius

VALIDATION OF EQUATION

For high confidence in skin result obtained using this new equation, the traditional Darcy total skin existing equation results are compared with results from the new skin equation and the plot is presented in Figure 7. Generally, the difference between both is not up to 10%. The new equation generally predicts lower skin compared to the existing traditional skin equation because the new equation predicts strictly skin due to restricted fluid entry into ICD nozzles which is a subset of total measured skin.

3-D model analysis result

The modeling results of Figure 6 which included an ICD model are presented in Figure 8. The plot shows that there is no rate reduction with ICD flow area of between 0.0006 and 0.002ft2. The rate reduction is seen mainly in ICD nozzle flow area from 0.0002ft2 downwards. More so, because for an ICD to optimize production by delaying the breakthrough of water inflow into the completions, the flow area has to be reduced and because of this reason the optimum ICD flow area to create a balance between the completion being watered out early and impairment of well productivity. The optimum ICD flow area is 0.0025ft2, but this also depends on the reservoir environment. Ultimately, an analysis has been conducted with the use of derived equation to complement with other existing methods with the goal of optimizing recovery from ICD completions. These results are shared hence.

Selecting ICD nozzle size with optimal pressure loss

Results of this calculation are illustrated in Figure 9. In the figure, the targeted flowing bottom hole pressure is 700psi at point A. with reduction in the nozzle flow area, the flowing bottom hole pressure which accounts for an increase in rate shifts to point B. The difference between point A and point B for every ICD nozzle flow area is the pressure loss due to skin which did not account for any increase in oil rate. If skin can be predetermined for every ICD flow area before installation and the pressure losses and associated oil loss estimated then there will be ultimate oil gain for every ICD installation decision.

$$P_s \triangle = \frac{141.2QBu\,S}{KL} \qquad (14)$$

Where: $\triangle P_s$ = Pressure loss due to restricted fluid entry through ICD nozzles; Q = Offtake rate, STB/D; B = Oil formation volume factor; U = oil viscosity, Cp; S= Skin due to restricted fluid entry into ICD nozzles and determined with equation (5); K = Reservoir permeability, Md.L = Horizontal well length, Ft.

Selecting an ICD nozzle size with an optimal water breakthrough time and best recovery

Figures 10 to 13 show the recovery and water breakthrough time for every nozzle size studied here. Most facilities in oil fields have limited capacity to handle produced water; and, in that case, their major objective is to find technologies that deliver zero to minimal water production from the producer wells and they prefer their production profiles to look like Figures 11 and 12. Finally, focusing on delaying water breakthrough or limiting water

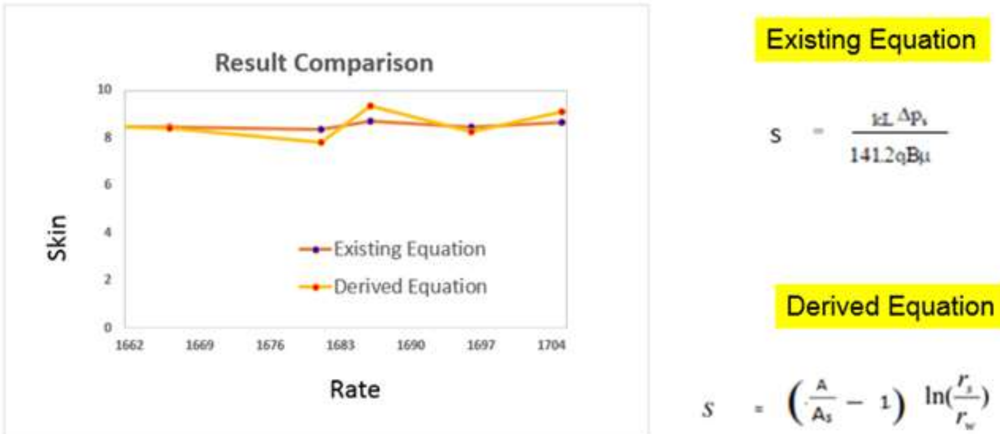

Figure 7. Derived equation validation.

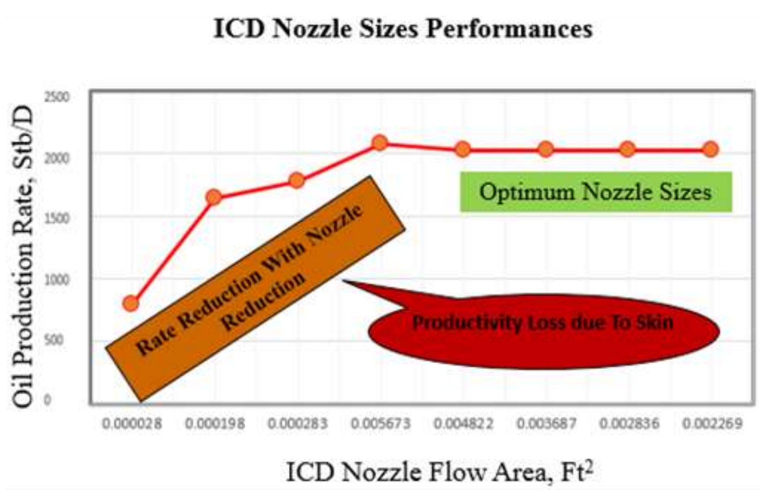

Figure 8. ICD Nozzle sizes performance plot.

Figure 9. Pressure loss plot for 2.8E-5ft2 nozzle flow area: The targeted bottom hole pressure is 700psia but increases to 900psia as the skin increases.

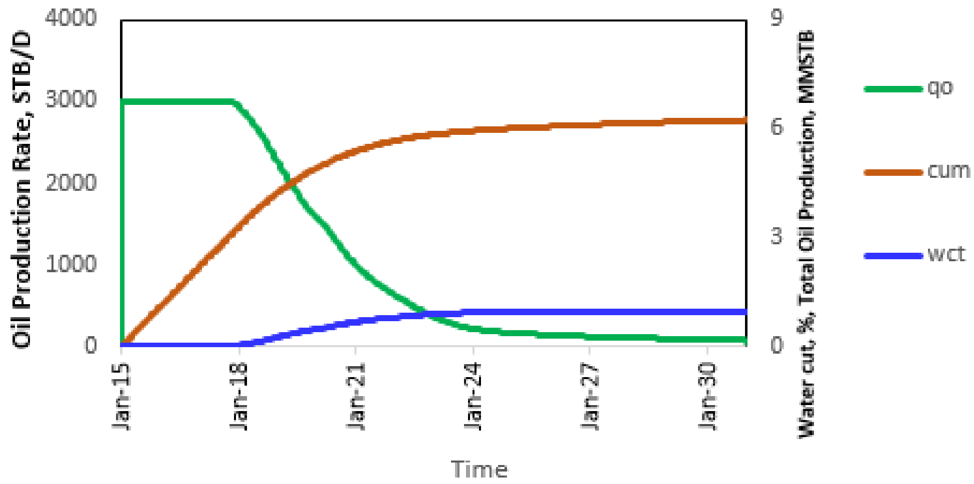

Figure 10. Production profile for 1.98E-3ft2 nozzle flow area.

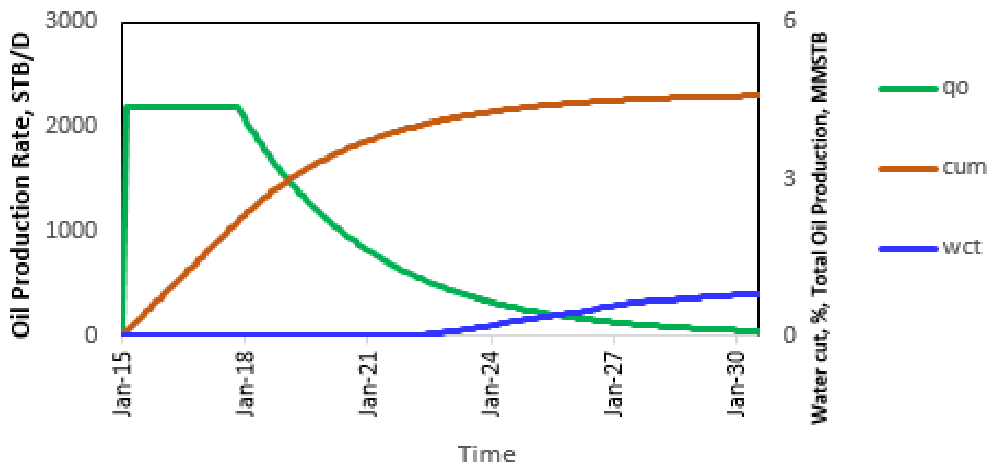

Figure 11. Production profile for 2.8E-4ft2 nozzle flow area.

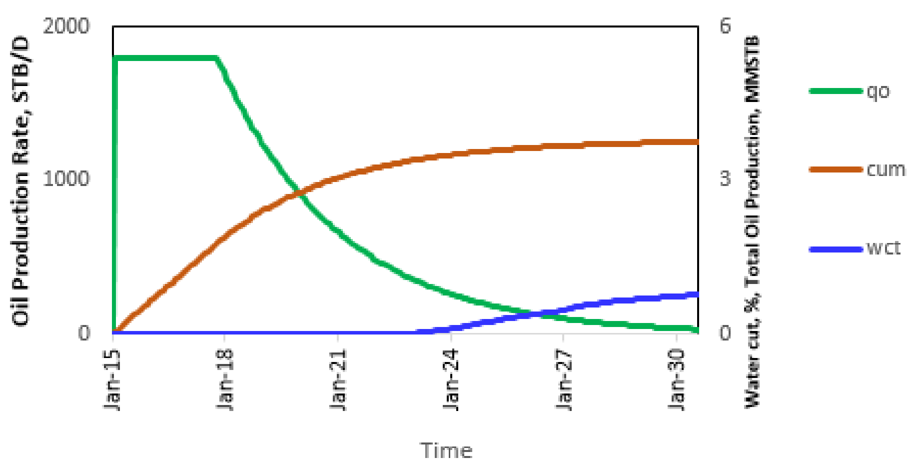

Figure 12. Production profile for 1.98E-4ft2 nozzle flow area.

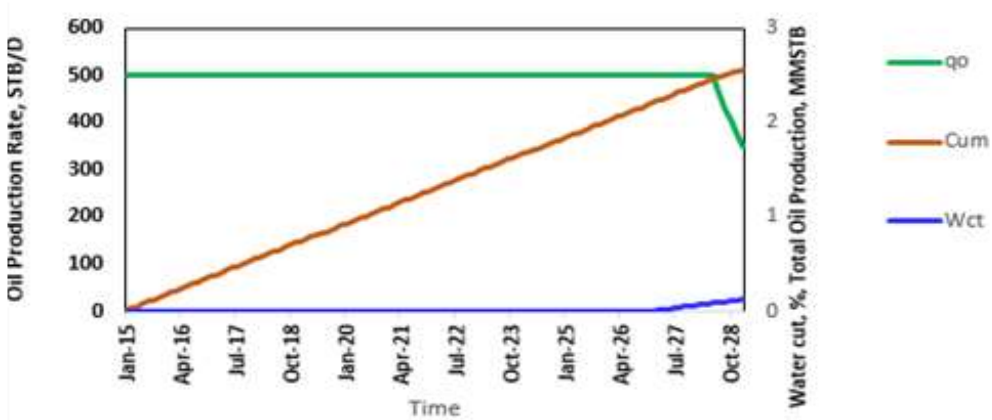

Figure 13. Production profile for 2.8E-5ft2 nozzle flow area.

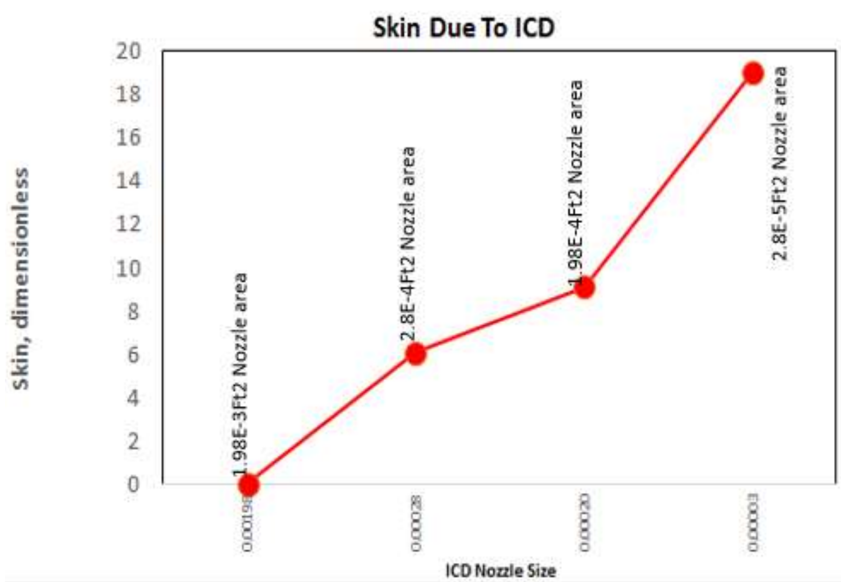

Figure 14. Skin values for all nozzle flow area in this study

production wells can cause a loss of over one million barrels of oil which is equivalent to a minimum of fifty million US dollars.

Selecting an ICD nozzle size with minimal skin

The skin estimates for four nozzle sizes are presented in Figure 14. The bigger the nozzle flow area the lower the skin value and the wells producibility; the lower the ICD flow area, the higher the skin value. From the study conducted, it is safer to design each ICD segment flow area to be averagely 2.5E-3ft2, but this may vary in different reservoir environment. As the flow area reduces the skin value begins to increase which will have a negative effect to productivity of any ICD completion.

Finally, these three methods complements each other in choosing the right size of nozzles for improved production performance and optimum recovery. From figure 9 to figure 12, it is obvious that nozzle flow area of 1.98E-3Ft2 gave the best production, best recovery and no skin, but water broke into the completion at an early stage. Therefore, further efforts will be embarked on to discard every other nozzle size and focus on adjusting 1.98E-3ft2 nozzle flow area in such a way that production and recovery are not compromised, and water breakthrough is delayed. In that way, 6.30E-4ft^2 flow area nozzle is chosen with a skin of 2 and the production profile illustrated in figure 14. These methods explained above are summarized in table 4 below. From summary table 3 above, the recoverable losses associated with each of the nozzle flow area is illustrated.

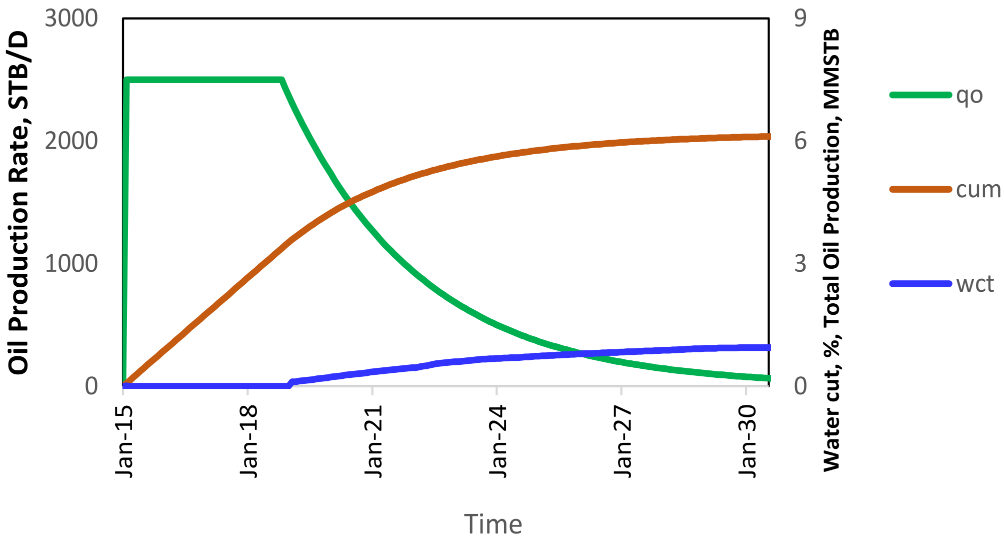

Figure 15. Production profile for 6.3E-4ft^2 nozzle flow area.

Table 3. Summary table of ICD selection criteria.

Case	Nozzle flow area (Ft^2)	Water breakthrough time	Skin/Pressure losses	Np (MMSTB)	Oil rate (Q)	Remarks
1	1.98E-3	1/1/2018	0/0	6.1	3000stb/D	Water production almost immediately after well was opened up.
2	2.84E-4	1/8/2022	6/43	4.5	2200stb/D	A loss of about 1.5MMstb for close to four years water production delay.
3	1.98E-4	1/11/2023	9/63	4	1800stb/D	2MMstb compromised in trying to delay water production till late 2023
4	2.8E-5	1/6/2027	18/188	2.5	500stb/D	Worst Production and recovery compromise for a zero-water production
5	6.30E-4ft^2	1/4/2018	2/11	6	2500stb/d	Water production was delayed 3 months later than base case. This serves as the best optimal ICD nozzle design to maintain recovery which is just about 0.1MMstb less than the base case.

About 1.5MMstb loss is associated with choosing a 2.84E-4ft2 flow area over a 1.98E-3ft2 nozzle flow area. The decision in choosing a 1.98E-4ft2 or 2.8E-5ft2 is one of living with a loss of 2 to 3.5 MMstb oil. Looking at water breakthrough time, there is about nine years delay compared with case A. With these analysis illustrated in Table 3, it is easy to choose a nozzle flow area between 1.98E-3ft2 and 2.8E-4ft2 knowing that case B gave a skin of 6, water breakthrough time of over three years and ICD pressure losses of 43psi which led to the choice in Figure 14 with a skin of 2.

Conclusion

(1) Inflow control devices can be used in horizontal wells to delay water breakthrough into completions by creating a uniform flux along the lateral. This is achieved by

constrictions in the ICD which causes additional pressure losses across the completion.

(2) Reduction in the constriction sizes of the ICD increases pressure loss across the completions and this causes production and recovery losses.

(3) An equation was derived to help in evaluating every ICD nozzle size. This equation complements the other two methods explained in this paper in choosing the right nozzle size for horizontal well completions.

(4) The major focus for every ICD design and optimization should be to optimize recovery. A very late water breakthrough time may simply mean a compromise of well performance. Therefore, determining skin and pressure losses caused by restricted fluid entry into ICD nozzles should be evaluated before finally choosing the right nozzle size.

NOMENCLATURE

A = equivalent nozzle area of an ICDless horizontal well which is 0.002ft2 from analysis conducted. As = Average nozzle area for all ICD joints in a horizontal well, ft2; B = formation volume factor, RB/STB; C = ICD configuration coefficient, dimensionless; h = formation thickness, ft K = permeability, md; Pe = Pressure at reservoir boundary, psia; Ps = Pressure around the inflow control device (damaged zone), psi; Pw = Wellbore flowing pressure, psi Pm = density of the mixture, g/cm^3; q = total flow rate, STB/D; r Δp_r adius of ICD nozzle, ft; r e = drainage radius, ft ; r w = wellbore radius, ft; rs = (1-average nozzle radius of all ICD joints), ft; S = pseudoskin due to restricted fluid entry into ICD nozzles. St = Total skin; U = viscosity, cp; Δp_{ICD} = Pressure loss across an ICD, psi; Δp_f = Pressure loss due to friction across a horizontal well, psi.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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APPENDIX

The fluid flow through the nozzles of the ICD joints in terms of darcy velocity is represented as v below.

$$v = \frac{q}{A} = \frac{q}{2\pi rh}$$

a1

Where

q = volumetric flow rate into the nozzles of each joint

A = the nozzle flow area which is same as lateral surface area of a cylinder.

A is the major focus here which is dependent on nozzle size chosen. In a flow impaired region, S which is an effect of delayed fluid entry is caused by reduced nozzle fluid throughput. The pressure in the impaired region is Ps, and pressure downstream of this region is Pwf which is in the wellbore. The flow in each of these regions is governed by darcy radial flow equations below.

$$p_s - p_w = \frac{qB\mu}{2\pi k_s h} \ln(\frac{r_s}{r_w})$$

a2

and

$$p_e - p_s = \frac{qB\mu}{2\pi kh} \ln(\frac{r_e}{r_s})$$

a3

Because the flow considered in this study is radial flow into the ICD nozzle sizes along a horizontal well and not into a perforation along a vertical well, a volumetric flow can be considered by substituting a1 into a2 and a3 above which is then transformed into a4 and a5 below.

$$p_s - p_w = \frac{qB\mu}{2\pi k_s r h} \ln(\frac{r_s}{r_w})$$

a4

$$p_e - p_s = \frac{qB\mu}{2\pi k r h} \ln(\frac{r_e}{r_s})$$

a5

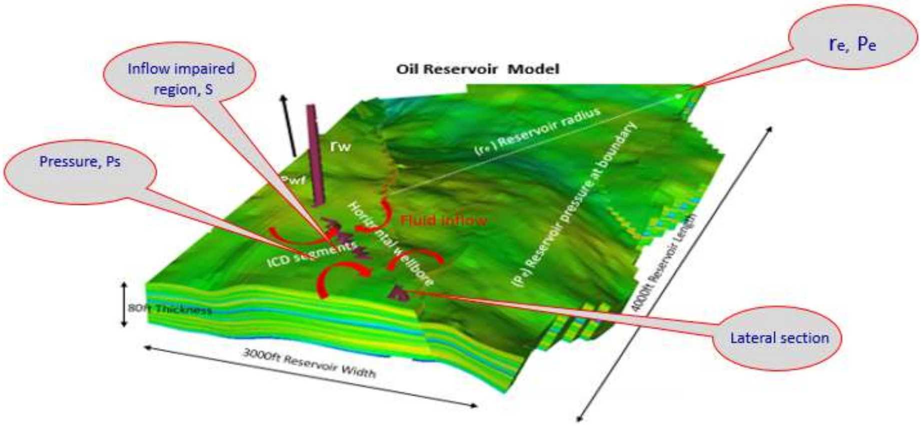
Substituting for flow area of the nozzle A = i πr^2 uations a4 and a5 The Equations become

$$p_s - p_w = \frac{qB\mu}{2 K A_s} \ln(\frac{r_s}{r_w})$$

a6

$$p_e - p_s = \frac{qB\mu}{2K A} \ln(\frac{r_e}{r_s})$$

a7



Adding equations a6 and a7 yields:

$$p_e - p_w = \frac{qB\mu}{2K}\left[\frac{\ln(\frac{r_s}{r_w})}{A_s} + \frac{\ln(\frac{r_e}{r_s})}{A}\right] \quad \text{a8}$$

According to the skin model,

$$p_e - p_w = \frac{q\mu B}{2\pi kh}\left[\ln(\frac{r_e}{r_w}) + S\right] \quad \text{a9}$$

In a horizontal well with inflow contol device, skin model can be regenerated to

$$= p_e - p_w = \frac{q\mu B}{2KA}\left[\ln(\frac{r_e}{r_w}) + S\right] \quad \text{a10}$$

Elimination of the total presure drop, Pe-Pw, between eqn a8 and a10 becomes

a11

$$= \frac{q\mu B}{2kA_s}\ln(\frac{r_s}{r_w}) + \frac{q\mu B}{2KA}\ln(\frac{r_e}{r_s}) - \frac{q\mu B}{2KA}\ln(\frac{r_e}{r_w}) - \frac{q\mu B}{2KA}S \quad \text{a12}$$

$$= \frac{q\mu B}{2kA_s}\ln(\frac{r_s}{r_w}) + \frac{q\mu B}{2KA}\left[\ln(\frac{r_e}{r_s}) - \ln(\frac{r_e}{r_w}) - s\right]$$

$$\frac{}{2kA_s}\quad r_w \quad \frac{}{2KA}\left[\quad r_e + \ln r_w - s\right] \quad \text{a13}$$

$$\frac{q\mu B}{2kA_s}\ln(\frac{r_s}{r_w}) + \frac{q\mu B}{2KA}\left[\ln r_w - \ln r_s - s\right] \quad \text{a14}$$

$$= \frac{q\mu B}{2kA_s}\ln(\frac{r_s}{r_w}) + \frac{q\mu B}{2KA}\left[\ln(\frac{r_w}{r_s}) - s\right] \quad \text{a15}$$

$$= \frac{q\mu B}{2k}\left[\frac{\ln(\frac{r_s}{r_w})}{As} + \left(\ln(\frac{r_w}{r_s}) - s\right)\frac{1}{A}\right] \quad a16$$

$$= \frac{q\mu B}{2k}\left[\frac{\ln(\frac{r_s}{r_w})}{As} + \frac{\ln(\frac{r_w}{r_s}) - s}{A}\right] \quad a17$$

Equation a17 becomes

Because $\ln(\frac{r_s}{r_w})$ is same as $-\ln(\frac{r_w}{r_s})$

$$= \frac{q\mu B}{2k}\left[\frac{-\ln(\frac{r_w}{r_s})}{As} + \frac{\ln(\frac{r_w}{r_s}) - s}{A}\right] \quad a18$$

$$= \frac{q\mu B}{2k}\left[\frac{\ln(\frac{r_w}{r_s})}{A} - SA_s - \frac{\ln(\frac{r_w}{r_s})}{As}\right] \quad a19$$

$$= \frac{q\mu B}{2K}\left[\frac{\ln(\frac{r_w}{r_s})^{As} - \ln(\frac{r_w}{r_s})^{A} - SA_s}{A\,As}\right] \quad a20$$

For reasons of simplification, let $(\frac{r_w}{r_s})$ be a.

Therefore $\frac{q\mu B}{2K}\left[\frac{\ln a^{As} - \ln a^{A} - SA_s}{A\,As}\right] = 0$ a21

$$\frac{q\mu B}{2K}\left[\frac{\ln(a^{As-A}) - SA_s}{A\,As}\right] = 0 \quad a22$$

Therefore

$$\frac{q\mu B}{2K}\left[\frac{\ln(\frac{r_w}{r_s})^{As-A}}{A\,As} - \frac{SA_s}{A}\right] = 0 \quad a23$$

$$\frac{q\mu B}{2K}\left[\frac{\ln(\frac{r_w}{r_s})^{As-A}}{As} - S\right] = 0 \quad a24$$

Therefore,

$$\frac{\ln(\frac{r_w}{r_s})^{As-A}}{As} - S = 0 \quad a25$$

and

$$\frac{\ln(\frac{r_w}{r_s})^{As-A}}{As} = S \quad a26$$

Equation 4.26 becomes

a27

and

$$(A_s - A)\ln\left(\frac{r_w}{r_s}\right) = S\,A_s$$ a28

$$\ln\left(\frac{\;}{r_s}\right) = \ldots A_s$$

A_s A_s (r_s) a29

Therefore,

$$S = \left(1 - \frac{A}{A_s}\right)\ln\left(\frac{r_w}{r_s}\right)$$ a30

$$\ln\left(\frac{r_s}{r_w}\right) = -\ln\left(\frac{r_w}{r_s}\right)$$

Recall that

Therefore,

$$S = \left(1 - \frac{A}{A_s}\right) - \left(\ln\left(\frac{r_s}{r_w}\right)\right)$$ a31

Therefore, by these simplifications of darcys equations of fluid flow, the skin in a horizontal well equipped with an inflow control device can be measured by equation a32 below.

$$S = \left(\frac{A}{A_s} - 1\right)\ln\left(\frac{r_s}{r_w}\right)$$ a32

Where:

S is the pseudoskin due to restricted fluid entry into ICD nozzles.

A is the equivalent nozzle area of an ICDless horizontal well which is 0.002ft^2 from analysis conducted.

A_s is the average nozzle area for all ICD joints in a horizontal well.

r_s is = (1-average nozzle radius of all ICD joints)

r_w is the wellbore radius.

As is the cross-sectional area of each nozzle multiplied by the number of segments. The value of A which considers a lateral without an ICD was derived by first determining the rate obtainable from a horizontal well which is not equipped with an inflow control device and secondly running a sensitivity to determine the equivalent nozzle size which does not serve as a constriction to fluid inflow and has an equivalent rate with that rate obtainable from same well without an ICD.

$$S = \frac{kL\,\Delta p_s}{141.2qB\mu}$$ a33

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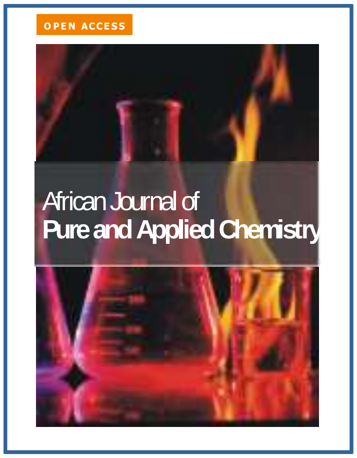

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