



CT&F Ciencia, Tecnología y Futuro

ISSN: 0122-5383

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Colombia

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CT&F Ciencia, Tecnología y Futuro, vol. 4, núm. 1, junio, 2010, pp. 51-62

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DETERMINATION OF RESERVOIR DRAINAGE AREA FOR CONSTANT-PRESSURE SYSTEMS USING WELL TEST DATA

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(Received, Jan. 29, 2010; Accepted May 26, 2010)

In this work, the conventional cartesian straight-line pseudosteady-state solution and the Total Dissolved Solids (TDS) solution to estimate reservoir drainage area is applied to constant-pressure reservoirs to observe its accuracy. It was found that it performs very poorly in such systems, especially in those having rectangular shape. On the other hand, the pseudosteady-state solution of the TDS technique performs better in constant-pressure systems and may be applied only to regular square- or circular-shaped reservoirs with a resulting small deviation error. Therefore, new solutions for steady-state systems in circular, square and rectangular reservoir geometries having one or two constant-pressure boundaries are developed, compared and successfully verified with synthetic and real field cases. Automatic matching performed by commercial software sometimes are so time consuming and tedious which leads to another reason to use the proposed equations.

Keywords: reservoir, pressure, well testing, reservoir drainage area, pseudosteady state, TDS Technique.

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En este trabajo se aplica la solución convencional de análisis cartesiano para estimar el área de drenaje en yacimientos con fronteras a presión constante para verificar su exactitud. Se encontró que esta produce resultados muy pobres, especialmente en yacimientos con geometría rectangular. Por otro lado, la solución de estado pseudoestable de la técnica TDS trabaja mejor en sistemas a presión constante y se podría aplicar con un pequeño margen de error en sistemas regulares con geometría circular o cuadrada. Por tanto, se desarrollaron nuevas soluciones para sistemas en estado estable con geometría circular, cuadrada y rectangular que tienen una o más fronteras de presión constante. Estas se compararon y se probaron exitosamente en casos simulados y de campo. El ajuste automático efectuado por los paquetes comerciales algunas veces consumen mucho tiempo y son tediosos. Esto proporciona otra razón para usar las ecuaciones aquí propuestas.

Palabras clave: *yacimientos, presión, pruebas de presión, área de drenaje del yacimiento, estado pseudoestable, técnica TDS.*

INTRODUCTION

The first solution for the estimation of the reservoir drainage area was presented by Ramey & Cobb (1971) from the pseudosteady-state pressure solution case. The late-time pressure data during the pseudosteady-state period behave linearly with flowing pressure and, therefore, its slope leads to the estimation of the drainage area. Later on Tiab (1994), introduced a more practical and easy-to-use solution which uses the point of intersection between the late-time pseudosteady-state period with the extrapolation of the horizontal radial flow regime straight line as part of the TDS technique, Tiab (1993). This solution works perfectly in either circular, square or rectangular closed systems, but it fails to provide accurate results constant-pressure systems having a rectangular or elongated geometry, therefore, its application as currently done so far leads to severe mistakes in the estimation of the reservoir drainage area. Another solution presented by Chacón, Djebrouni, & Tiab (2004) uses any arbitrary time and pressure derivative point read during the late-time pseudosteady state period to easily and exactly provide an estimation of reservoir drainage area in closed systems. A great advantage of this solution is the fact that it does not involve the reservoir permeability in the calculations and can be usefully used whenever the radial flow data is highly noisy. However, care should be taken in designing and running the test long enough so the late-time pseudostate/steady state period is well developed.

MATHEMATICAL BACKGROUND

The dimensionless quantities used in this work are:

$$t_{DA} = \frac{0,0002637kt}{\phi\mu c_i A} \quad (1)$$

$$t_D = \frac{0,0002637kt}{\phi\mu c_i r_w^2} \quad (2)$$

$$W_D = \frac{Y_E}{r_w} \quad (3)$$

$$X_D = \frac{2b_x}{X_E} \quad (4)$$

$$Y_D = \frac{2b_y}{Y_E} \quad (5)$$

The general pseudosteady-state equation was proposed by Ramey & Cobb (1971) as:

$$P_D = 2\pi t_{DA} + \frac{1}{2} \ln \left(\frac{A}{r_w^2} \right) + \frac{1}{2} \ln \left(\frac{2,5458}{C_A} \right) \quad (6)$$

From this, the cartesian slope during the late pseudosteady-state period was defined as:

$$m^* = - \frac{0,23395qB}{\phi c_i Ah} \quad (7)$$

Which implies that the reservoir drainage area can be estimated from the slope of a cartesian plot of pressure versus time during late-time pseudosteady-state period.

Following the philosophy of the *Tiab's Direct Synthesis Technique* Tiab (1994), developed an equation to estimate reservoir area using the intercept of the pressure derivative of Equation 6 with the derivative during infinite-acting radial-flow regime, ($t_D^* P_D' = 0,5$):

$$A = \frac{kt_{rpsi}}{301,77\phi\mu c_i} \quad (8)$$

Also, reservoir drainage area can be estimated using any arbitrary point on the pressure derivative curve during the late-time pseudosteady-state period, t_{pss} and $(t^* \Delta P')_{pss}$, Chacon *et al.* (2004):

$$A = \frac{0,234qBt_{pss}}{\phi c_i h (t^* \Delta P')_{pss}} \quad (9)$$

For steady-state cases, the slope of the Cartesian plot of pressure versus time may be used so Equation 7 can be applied. On the other hand, Equations 8 and 9 may also be used if a negative unit slope is drawn tangentially to the pressure derivative curve during the steady-state period; then, the intercept with this line with the straight line of the radial-flow regime or a point touched by the tangential line are, respectively, used in the mentioned equations. We should be aware that pressure and pressure derivative behaves differently for constant-pressure case systems; then, application

of the above equations should lead to unaccurate area estimations. Therefore, the following section deals with this situation in order to overcome the problem.

Square or Circular Reservoirs

The negative unit-slope straight-line tangential to the pressure derivative curve during the steady-state period (Figure 2) is given by the following approximation:

$$t_D * P_D' \approx \frac{\pi}{84 t_{DA}} \quad (10)$$

During the infinite-acting radial-flow regime, the dimensionless pressure derivative is governed by:

$$t_D * P_D' = \frac{1}{2} \quad (11)$$

An equation for the drainage area is obtained from the intersection of the steady-state and the radial-flow regime lines. After plugging the dimensionless time quantity in the resulting equation will provide:

$$A = \frac{kt_{ssri}}{283,66 \phi \mu c_t} \quad (12)$$

Suffix *ssri* stands for the intersection between the negative unit-slope line drawn tangentially to the pressure derivative curve with the radial line. It should be clarified that *Equation 8* applies to any closed reservoir geometry, but *Equation 12* only applies to either circular or square shape drainage area as indicated in Table 1.

Rectangular systems

Equations 7 to 9 work well for elongated closed systems but do not apply to long reservoirs with either one or both extreme boundaries subjected to constant-pressure conditions. The reservoir configuration is given in Figure 1. For such systems the governing equation depends upon several conditions:

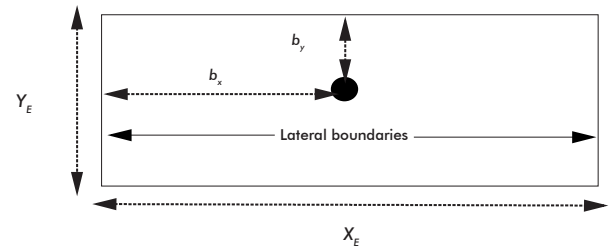


Figure 1. Reservoir configuration

Table 1. Summary of equations

Constant, Ξ	Equation	Reservoir Geometries
301,77	$A = \frac{kt_{rpssi}}{\Xi \phi \mu c_t}$	
283,66		
4066	$A = \sqrt[3]{\frac{kt_{ssri} Y_E^4}{\Xi \phi \mu c_t}}$	
482,84		
7584,2		
2173,52	$A = \left(\frac{kt_{ss1ri,ss2ri}}{\Xi \phi \mu c_t} \right)^{2/3} \frac{Y_E^{5/3}}{b_x}$	
6828,34		
41,82	$X_E = \frac{1}{\Xi} \left(\frac{kt_x}{\phi \mu c_t} \right)^{0,5}$	
20,91		

Well centered (Figure 3)

One constant-pressure boundary

Both constant-pressure boundaries

Well off-centered

Well near a constant pressure boundary – closed-far boundary (Figure 4)

Well near a constant pressure boundary – constant-pressure far boundary (Figure 4)

Well near a no-flow boundary – constant-pressure far boundary (Figure 5)

Well Centered

The governing equation of the negative-unit slope tangential to the pressure derivative curve for a well centered inside a rectangular reservoir with one constant-pressure boundary (Figure 3) is given here as:

$$t_D * P_D' = \frac{32W_D^2}{19\pi} \left(\frac{X_E}{Y_E} \right)^3 t_D^{-1} \quad (13)$$

The equation for drainage area is derived from manipulation of *Equations 11 and 13*, assuming $A=X_E Y_E$ and replacing the dimensionless expressions, *Equations 2 to 4*, in the resulting equation, to yield:

$$A = \sqrt[3]{\frac{kt_{ssr} Y_E^4}{4066\phi\mu c_i}} \quad (14)$$

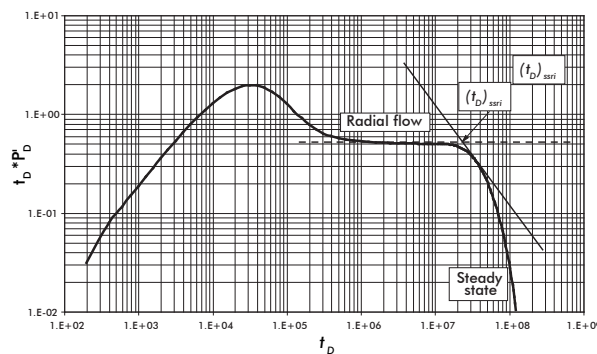


Figure 2. Dimensionless pressure derivative behavior for a well inside a constant-pressure circular/square area

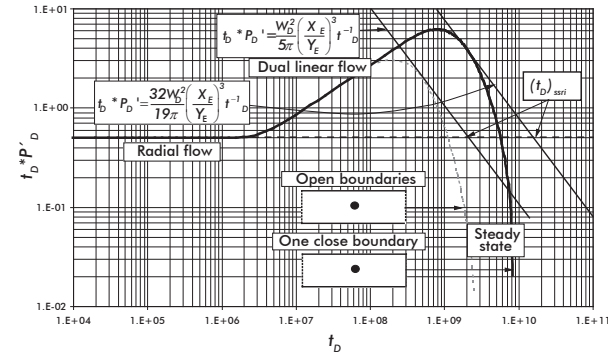


Figure 3. Dimensionless pressure derivative behavior for a well centered inside no-flow and constant-pressure boundaries

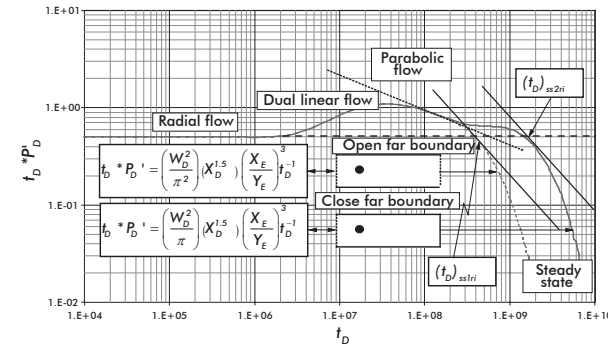


Figure 4. Dimensionless pressure derivative behavior when a well is near a constant-pressure boundary

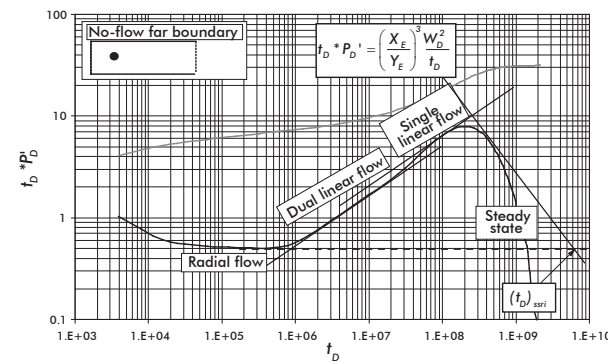


Figure 5. Dimensionless pressure derivative behavior when a well is far from a constant-pressure boundary

When both lateral boundaries are subjected to constant pressure, the governing equation of the negative-unit slope tangential to the pressure derivative curve, Figure 3, is given as:

$$t_D * P_D' = \frac{W_D^2}{5\pi} \left(\frac{X_E}{Y_E} \right)^3 t_D^{-1} \quad (15)$$

And the reservoir drainage area is found from the intercept of the above equation with *Equation 11* as described above, then:

$$A = \sqrt[3]{\frac{kt_{ssri}Y_E^4}{482,84\phi\mu c_i}} \quad (16)$$

The maximum point for the case of one constant-pressure boundary is governed by the following expression:

$$\frac{X_E}{Y_E} = \frac{15}{32} \pi \left(\frac{1}{W_D} \right) t_{Dx}^{0,5} \quad (17)$$

And for the case of both constant-pressure boundaries:

$$\frac{X_E}{Y_E} = \frac{15}{16} \pi \left(\frac{1}{W_D} \right) t_{Dx}^{0,5} \quad (18)$$

Expressions for determination of the reservoir length and area, assuming $A = X_E Y_E$, is found from *Equations 17* and *18*, respectively:

$$X_E = \frac{1}{41,82} \left(\frac{kt_x}{\phi\mu c_i} \right)^{0,5} \quad (19.a)$$

$$A = \frac{Y_E}{41,82} \left(\frac{kt_x}{\phi\mu c_i} \right)^{0,5} \quad (19.b)$$

$$X_E = \frac{1}{20,91} \left(\frac{kt_x}{\phi\mu c_i} \right)^{0,5} \quad (20.a)$$

$$A = \frac{Y_E}{20,91} \left(\frac{kt_x}{\phi\mu c_i} \right)^{0,5} \quad (20.b)$$

Well off-Centered

Escobar, F. H., & Montealegre, M. (2007) presented the governing equation for the unit-slope line drawn tangentially to the pressure derivative curve for constant-pressure lateral boundaries, (Figure 4):

$$t_D * P_D' = \left(\frac{W_D^2}{\pi} \right) (X_D^{1,5}) \left(\frac{X_E}{Y_E} \right)^3 t_D^{-1} \quad (21)$$

The equation for drainage area is derived from manipulation of *Equations 11* and *21*, assuming $A = X_E Y_E$ and replacing the dimensionless expressions, *Equations 2-4*, in the resulting equation, then:

$$A = \left(\frac{kt_{ssri}}{2173,52\phi\mu c_i} \right)^{2/3} \frac{Y_E^{5/3}}{b_x} \quad (22)$$

For the mixed boundary case (Figure 4) the governing equation was also presented by Escobar, Hernández & Hernández (2007) as:

$$t_D * P_D' = \left(\frac{W_D^2}{\pi^2} \right) (X_D^{1,5}) \left(\frac{X_E}{Y_E} \right)^3 \frac{1}{t_D} \quad (23)$$

By the same token:

$$A = \left(\frac{kt_{ssri}}{6828,34\phi\mu c_i} \right)^{2/3} \frac{Y_E^{5/3}}{b_x} \quad (24)$$

When dual-linear and linear flow regimes are exhibited, (Figure 5), then the governing equation is:

$$t_D * P_D' = \left(\frac{X_E}{Y_E} \right)^3 \frac{W_D^2}{t_D} \quad (25)$$

Which leads to the following equation for estimation of the reservoir drainage area:

$$A = \sqrt[3]{\frac{kt_{ssri}Y_E^4}{7584,2\phi\mu c_i}} \quad (26)$$

The maximum point in Figure 5 is governed by the following expression presented by Escobar *et al.* (2007).

$$\frac{X_E}{Y_E} = \frac{\pi^{1,5}}{4} \left(\frac{1}{W_D} \right) t_{Dx3}^{0,5} \quad (27)$$

From which the following expression area obtained:

$$X_E = \frac{1}{44,24} \left(\frac{kt_{x3}}{\phi\mu c_i} \right)^{0,5} \quad (28)$$

$$A = \frac{Y_E}{44,24} \left(\frac{kt_{x3}}{\phi\mu c_i} \right)^{0,5} \quad (29)$$

b_x and Y_E in Equations 22 and 24 can be obtained from the equation presented by Escobar *et al.* (2007) using the TDS technique:

$$b_x = \sqrt{\left(\frac{Y_E}{246,32}\right) \sqrt{\frac{kt_{RPBi}}{\phi\mu c_t}}} \quad (30)$$

$$Y_E = 0,05756 \sqrt{\frac{kt_{RDLi}}{\phi\mu c_t}} \quad (31)$$

Or from the conventional straight-line method, Escobar & Montealegre (2007):

$$b_x = \sqrt{-\frac{m_{PB} h Y_E}{34780,8 q B \sqrt{\phi c_t}} \left(\frac{k}{\mu}\right)^{1,5}} \quad (32)$$

$$Y_E = 8,1282 \frac{qB}{m_{DLF} h} \left[\frac{\mu}{k \phi c_t} \right]^{0,5} \quad (33)$$

The just mentioned references contain some other expression to estimate well position and reservoir width along with the estimation of the geometric skin factors.

A practical summary of the drainage area equations is provided in Table 1.

EXAMPLES

Synthetic Example 1

A drawdown test was generated for a circular ($r_e=1000$ ft) constant-pressure reservoir with the information given in Table 1. Figure 6 contains the pressure and pressure derivative data for this synthetic test. Find reservoir drainage area.

Solution. For this reservoir, the drainage area is $(\pi \times 1000^2) = 3\,141\,593$ ft². From Figure 6, the intercept, t_{ssri} , of the minus-one slope straight with the radial flow regime line takes place at 43,6 hr. Using this value in Equation 12 the obtained area is 3 074 103 ft² which is a reasonable value for this case. Other estimations are reported in Table 3, including that from Equation 7. For this case, the cartesian slope was found using the latest points in the test.

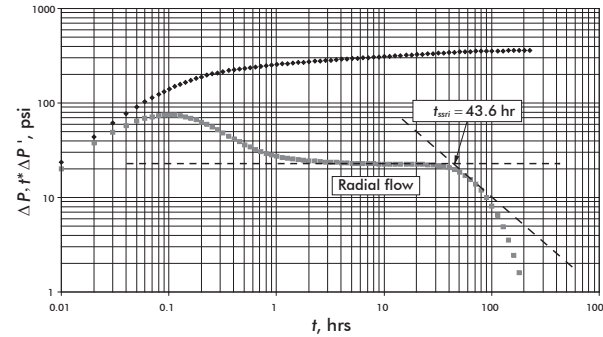


Figure 6. Pressure and pressure derivative plot for synthetic example 1

Synthetic Example 2

Figure 7 shows the pressure and pressure derivative plot for a well centered inside a rectangular reservoir with a no-flow lateral boundary and a constant-pressure boundary. Data used for the simulation are given in the Table 2. Find reservoir drainage area.

Solution. From Figure 7, $t_{ssri} = 29,957$ hr. The resulting area value from Equation 14 along with others is reported in Table 2.

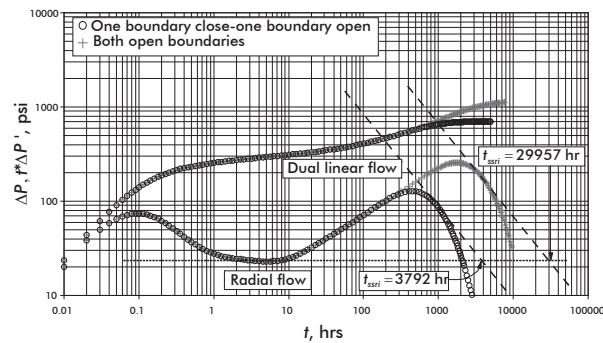


Figure 7. Pressure and pressure derivative plot for synthetic examples 2 and 3

Synthetic Example 3

Figure 7 also shows the pressure and pressure derivative plot for a well centered inside a rectangular reservoir with constant-pressure lateral boundaries. This simulation was attained using data from the third column of Table 2. Find reservoir drainage area.

Solution. From Figure 7, $t_{ssri} = 3,792$ hr and the maximum point, $t_x = 501$ hr. The results from Equations 16 and 20b are reported in Table 3, along with some others.

Table 2. Data for simulated and field examples

Parameter	Synthetic examples			Field examples		
	1	2, 3, 4	5, 6	1	2	3
k , md	100	100	100	440,7	252,1	6,74
r_w , ft	0,3	0,3	0,3	0,51	0,3541	0,359
h , ft	100	100	100	14	40	22
ϕ , %	10	10	10	24	20	13
B , rb/STB	1,25	1,25	1,25	1,07	1,04	1,22
μ , cp	5	5	5	3,5	5	1,137
c_r , 1/psi	1×10^{-5}	1×10^{-5}	1×10^{-5}	9×10^{-6}	$7,6 \times 10^{-6}$	$9,84 \times 10^{-6}$
q , BPD	500	500	500	1400	150	123
Y_{Er} , ft		800	800	360		360
X_{Er} , ft		5000	5000	1318		1318
b_x , ft			1000	286		286

Synthetic Example 4

A drawdown test was generated for a well centered inside a rectangular-shaped reservoir with one constant-pressure boundary and one no-flow boundary, using the information given in Table 1. Figure 8 contains the pressure and pressure derivative data for this synthetic test. Find reservoir drainage area.

Solution. From Figure 8, $t_{ss2ri} = 5,600$ hr and $t_x = 2001$ hr. The results from *Equations 24, 19b, 7 and 8* are also reported in Table 3.

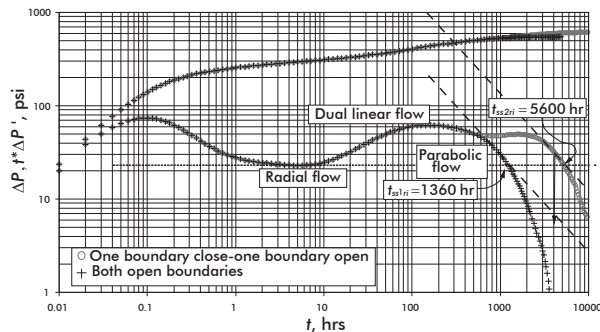


Figure 8. Pressure and pressure derivative plot for synthetic examples 4 and 5

Synthetic Example 5

Contrary to Example 4, in this example the reservoir has both constant-pressure lateral boundaries. Needless to say that the simulation was performed with data from

Table 1. The pressure and pressure derivative plot is given in Figure 8. Find reservoir drainage area.

Solution. From Figure 8, $t_{ss1ri} = 1,360$ hr. The result from *Equation 22* along with others is reported in Table 3.

Synthetic Example 6

A simulation with the information from Table 1 was run for a well inside a long reservoir, near a no-flow boundary and far from the constant-pressure boundary is presented in Figure 9. Find reservoir drainage area.

Solution. Since the well is off-centered in a rectangular reservoir and the open boundary is far from the well, then, both dual-linear and single-linear flow regimes are observed. From Figure 9, $t_{ssri} = 54,000$ hr, then the

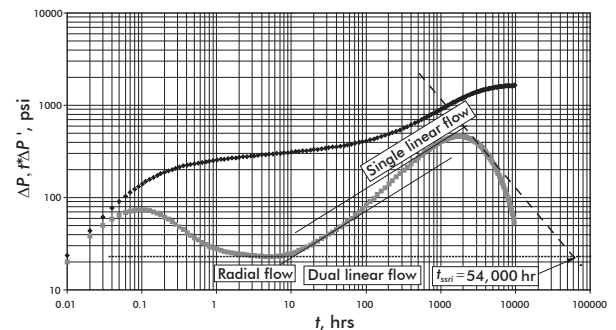


Figure 9. Pressure and pressure derivative plot for synthetic example 6

reservoir drainage area estimated from *Equation 26* is 3 878 150 ft². Other results are provided in Table 3.

Field Example 1

Escobar *et al.* (2007) reported a drawdown test run in a channelized reservoir in the Colombian Eastern Planes basin. Reservoir and well parameters are given in Table 2. Dimension parameters in Table 2 were obtained from the reference. The initial pressure is 1326,28 *psi* and the pressure and pressure derivative data are reported in Figure 11. Estimate reservoir drainage area.

Solution. From Figure 10, $t_{ssri} = 24$ hr. A reservoir drainage area of 474 880,2 ft² was obtained from *Equation 22*. A reservoir width of 355 ft was also obtained

from a commercial software since it was not practical to obtained an acceptable match for this test.

Field Example 2

Figure 11 presents the pressure and pressure derivative plot for a test run in a well in the Colombian Eastern Planes basin. The well-flowing pressure for this test is 1527,36 *psi*. Other information pertinent to this pressure tests is given in Table 2. Find reservoir drainage area.

Solution. From Figure 11, $t_{ssri} = 3,5$ hr is used in *Equation 12* to provide an area of 335 164 ft² and 314 984 ft² from *Equation 8*. The reservoir geometry looks to be slightly rectangular (although a faulted reservoir may be considered). For this test was difficult to obtain a reason-

Table 3. Comparative drainage area estimation for the synthetic examples

Example	Eq. No.	A, ft ²	Absolute Error, %	m*, psi/hr
1	Actual	3 141 593		
	12	3 074 103	2,15	
	8	2 889 618	8,02	
	7	91 961 478	2827,3	-0,0159
2	Actual	4 000 000		
	14	3 922 597	1,94	
	8	1985,42x10 ⁶	49 535,5	
	7	221,55x10 ⁶	5438,8	-0,0066
3	Actual	4 000 000		
	16	4 069 901	1,75	
	7	251,32x10 ⁶	6,183	-1
	8	1 462 188	63,5	
	20.b	3 829 745	4,25	
4	Actual	4 000 000		
	24	3 717 096	7,1	
	8	90,14x10 ⁶	2153,5	
	7	10 260,97x10 ⁶	256 424,3	-0,000143
	19.b	3 826 877	4,32	
5	22	4 450 600	11,3	
	8	371,15x10 ⁶	9178,8	
	7	1313,1x10 ⁶	32 727,5	-0,00111
6	Actual	4 000 000		
	26	3 878 150	3,05	
	8	3578,9x10 ⁶	83 372,5	
	7	140,4x10 ⁶	3410,1	-0,0104

able match using a rectangular geometry. The best match was obtained for a circular reservoir with a radius of 278 ft which gives an area of 242 696 ft².

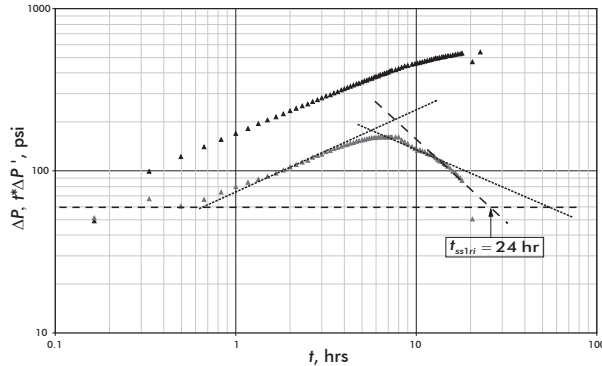


Figure 10. Pressure and pressure derivative plot for field example 1

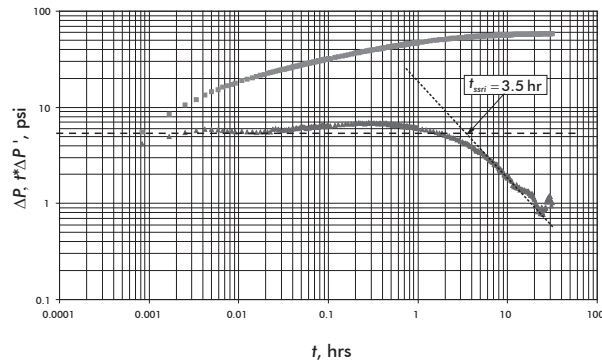


Figure 11. Pressure and pressure derivative plot for field example 2

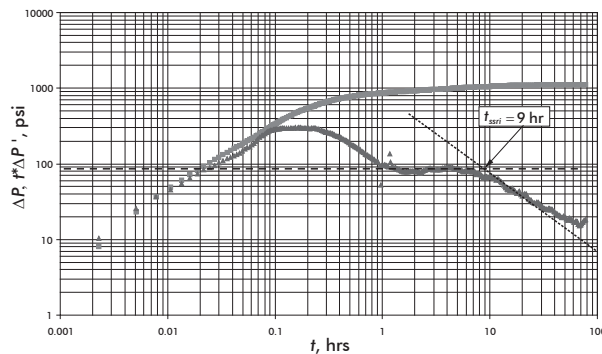


Figure 12. Pressure and pressure derivative plot for field example 3

Field Example 3

Pressure and pressure derivative from a DST data run in a well located in the High Magdalena River Val-

ley basin in Colombia are reported in Figure 12. The well-flowing pressure for this well is 429,08 *psi*. Other important data related to this test is given in Table 2. Find reservoir drainage area.

Solution. A value of t_{ssr} of 9 hr is read from Figure 12 and used in Equation 12 to estimate an area of 147 030 ft². The best match obtained for this test was for a circular reservoir model with a radius of 210 ft. This gives an area of 136 544 ft² using a commercial simulation which closely agrees with the equation proposed here.

ANALYSIS OF RESULTS

From the worked examples, especially the simulated ones, is observed that the late-time pseudosteady-state equation for conventional cartesian analysis performs poorly for rectangular- shaped reservoirs having one or both lateral boundaries subject to constant pressure. The TDS technique solution for pseudosteady-state provide approximated area estimations in circular/ square constant-pressure reservoirs.

In the worst case, the introduced equations provided an absolute error of 11,3% in the estimation of the reservoir area. However, care should be taken in the selection of the appropriate equation which are easily summarized in Table 1. Of course, the proposed equations which are based upon the TDS technique are dependant on the quality of the pressure derivative curve.

CONCLUSIONS

- New equations for estimating reservoir drainage area in steady-state systems have been presented and successfully tested with synthetic and field examples. It was found that the pseudosteady-state cartesian solution fails to provide accurate results of the reservoir drainage area, especially in rectangular-shaped reservoirs. The pseudosteady-state solution of the TDS technique performs better and may be applied in either square- or circular-shaped reservoirs.

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NOMENCLATURE

A	Area, ft ²
B	Oil formation factor, bbl/STB
b_x	Distance from well the to the near lateral boundary in the x-axis, ft
b_y	Distance from well the to the near boundary in the y-axis, ft
CA	Shape factor
c_t	Compressibility, 1/psi
h	Formation thickness, ft
k	Permeability, md
m	Slope
m^*	Conventional cartesian slope
P	Pressure, psi
P_D	Dimensionless pressure
P_i	Initial reservoir pressure, psia
P_{wf}	Well flowing pressure, psi
q	Flow rate, bbl/D
r_e	Drainage radius, ft
r_w	Well radius, ft
t	Time, hr
t_D	Dimensionless time based on well radius
t_{DA}	Dimensionless time based on reservoir drainage area
$t_D^*P_D'$	Dimensionless pressure derivative
X_E	Reservoir length, ft
X_D	Dimensionless reservoir length
Y_E	Reservoir width, ft
Y_D	Dimensionless reservoir width
W_D	Dimensionless reservoir width

SUFFICES

Δ	Change, drop
Δt	Flow time, hr
ϕ	Porosity, fraction
μ	Viscosity, cp

GREEK

D	Dimensionless
DLF	Dual-linear flow
i	Intersection or initial conditions
L	Linear
PB	Parabolic
pss	Pseudosteady
psi	Pounds per Square Inch
SS	Steady
$DLPSSi$	Intersection of pseudosteady-state line with dual- linear line
$LPSSi$	Intersection of pseudosteady-state line with lineal line
$rpssi$	Intersection of pseudosteady-state line with radial line
$RDLi$	Intersection of radial line with dual lineal line
RLi	Intersection of radial line with lineal line
$RPBi$	Intersection of radial line with with the parabolic flow line
$ss1ri$	Intersection between the radial line and the -1-slope line
$ss2ri$	Intersection of radial line with -1-slope line ($SS2$)
$ssri$	Intersection of radial line with -1-slope line ($SS2$)
r	radial flow
w	Well
x	Maximum point (peak) after dual linear flow is vanished and steady state begins