

PETE 324
Final Exam
May 8, 2006

Key

120 minutes, closed book except for 4 cheat sheets, calculator, and straight edge. Do not turn in your cheat sheets with your exam. Show your work. Include the units. Use symbols instead of values when necessary.

1. (10 points) Write the diffusivity equation for radial flow and indicate the units of each of the variables.

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial P}{\partial r} \right) = \frac{\phi \mu c_t}{0.00633 K} \frac{\partial P}{\partial t}$$

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} = \frac{\phi \mu c_t}{0.00633 K} \frac{\partial P}{\partial t}$$

$P = \text{psi}$

$t = \text{days}$

$\phi = \text{fraction}$

$\mu = \text{cp}$

$c_t = \text{psi}^{-1}$

$r = \text{ft}$

2. (10 points) We often make log-log plots to analyze data as a straight line on these plots.

(a) Write an explicit equation ($y = f(x)$) for such a straight line.

(b) Suppose you have two points on a log-log plot and assume a straight line relationship. The points are: $(x_1, y_1) = (125, 51.3)$ and $(x_2, y_2) = (343, 15.2)$. Calculate the value y at $x = 201$, assuming a straight line interpolation on the log-log plot.

(c) What is the log-log slope in part (b)?

a)

$$\log y = m \cdot \log x + c$$

$$\log y = \log x^m + c$$

$$y = 10^{(\log x^m + c)} = x^m \cdot 10^c$$

$$y = ax^b$$

b)

$$b = \frac{\log(y_2/y_1)}{\log(x_2/x_1)} = \frac{\log(15.2/51.3)}{\log(343/125)} = -1.205$$

$$y = ax^b$$

$$51.3 = a(125)^{-1.205}$$

$$a = 17254.16$$

$$y_{\text{at } x=201} = 17254.16(201)^{-1.205} = 28.94$$

c)

$$b = -1.205$$

3. (10 points) A well has the following data:

$p_i = 4,221$ psia	$\mu = 3.1$ cp	$h = 145$ ft
$q = 123$ stb/d	$\phi = 0.13$	$r_w = 0.24$ ft
$B_o = 1.12$ rb/stb	$c_t = 15 \times 10^{-6}$ psi ⁻¹	$S_w = 0.22$

Suppose the well has been producing at a constant rate for 420 days. The well has a productivity index of 0.44 stb/d/psi and a drainage area of $A = 1.55 \times 10^6$ ft².

- (a) Calculate the pore volume and original oil-in-place (OOIP).
 (b) Calculate the average reservoir pressure at 420 days (use the tank model approach).
 (c) Calculate p_{wf} at 420 days assuming that the well is in pseudo-steady state.

$$a) V_p = A \cdot h \cdot \phi = 1.55 \times 10^6 \text{ ft}^2 \cdot 145 \text{ ft} \cdot 0.13 = 29,217,500 \text{ ft}^3 = 5203.47 \text{ Mrb}$$

$$OOIP = \frac{V_p (1 - S_w)}{B_o} = \frac{5203.47 (1 - 0.22)}{1.12 \text{ rb/stb}} = 3623.8 \text{ MSTB}$$

$$b) \bar{p} = p_i - \Delta p$$

$$\frac{\Delta p}{\Delta t} = \frac{-qB}{V_p c_t} \Rightarrow \bar{p} = p_i - \frac{qB\Delta t}{V_p c_t}$$

$$\bar{p} = 4221 \text{ psi} - \frac{(123 \text{ stb/d}) (1.12 \text{ rb/stb}) (420 \text{ days})}{(5203.47 \text{ Mrb}) \cdot (15 \times 10^{-6} \text{ psi}^{-1})} = 3480 \text{ psi}$$

$$c) J = \frac{q}{\bar{p} - p_{wf}}$$

$$0.44 \text{ stb/d/psi} = \frac{123 \text{ stb/d}}{(3480 \text{ psi} - p_{wf})}$$

$$p_{wf} = 3200 \text{ psi}$$

4. (10 points) Suppose wells A and B are in an *infinite homogeneous reservoir* a distance of 350 ft apart. Well B has a skin factor of 3.5 and begins producing at 160 stb/d at $t = 0$. Well A has a skin factor of 4.9 and begins producing 600 hours later at 160 stb/d.

(a) Calculate the effect of well B on well A at $t = 2,500$ hours.

(b) Calculate the effect of well A on well A at $t = 2,500$ hours.

(c) Calculate the total effect of A and B to give p_{wf} in well A at $t = 2,500$ hours.

$p_i = 4,221$ psia	$\mu = 3.1$ cp	$h = 185$ ft	$k = 6.4$ md
$q = 123$ stb/d	$\phi = 0.16$	$r_w = 0.24$ ft	
$B_o = 1.12$ rb/stb	$c_t = 12 \times 10^{-6}$ psi ⁻¹	$S_w = 0.22$	

a) B on A :

$$t_{Dr} = \frac{0.000264 K}{\phi \mu c_t} \frac{t_{hs}}{r^2} = \frac{0.000264 (6.4) (2500)}{(0.16) (3.1) (12 \times 10^{-6}) (350^2)} = 5.79$$

$$P_D = 1.25 = \frac{K h \Delta P}{141.2 q B_o \mu}$$

(fig e.2)

$$\Delta P_{B/A} = \frac{1.25 (141.2) (160) (1.12) (3.1)}{(6.4) (185)} = 82.8 \text{ psi}$$

b) A on A

$$t_{Dr} = \frac{0.000264 (6.4) (2500 - 600)}{(0.16) (3.1) (12 \times 10^{-6}) (0.24)^2} = 9.36 \times 10^6$$

$$P_D = 8.3$$

(fig e.2)

$$\text{Add SKIN: } 8.3 + 4.9 = 13.2$$

$$\Delta P_{A/A} = \frac{(13.2) (141.2) (160) (1.12) (3.1)}{(6.4) (185)} = 874.5 \text{ psi}$$

$$c) P_{wf} = P_i - \Delta P_{B/A} - \Delta P_{A/A} = 4221 - 82.8 - 874.5 = 3263.7 \text{ psi}$$

5. (10 points) Attached is the Gassim data file for HW3 in which we modeled wellbore storage and skin for a radial oil well. We now have the following changes:

- It is now a gas well with 0.85 gas gravity and 155 °F temperature. $\rightarrow T(^{\circ}R) = 155 + 460 = 615^{\circ}R$.
- The skin factor is 9.4
- Wellbore storage is for 11,000 ft of 1.995" I.D. tubing.

Show your calculations below, then write on the data sheet to show the indicated changes in data:

$$S = \left(\frac{K}{K_s} - 1 \right) \ln \frac{r_s}{r_w}$$

$$9.4 = \left(\frac{12}{K_s} - 1 \right) \ln \left(\frac{0.8301}{0.25} \right)$$

$$K_s = 1.3586 \text{ md}$$

Field

$$V_w = 11000 \cdot \frac{\pi}{4} \cdot \left(\frac{1.995}{12} \right)^2 = 238.78 \text{ ft}^3$$

Model

$$P_{his} = \frac{238.78 \text{ ft}^3}{\pi \cdot (0.25^2) \cdot 130} = 9.355$$

CASE EXAM A
CMNT Homogeneous Cylindrical Reservoir
CMNT Radial Flow, Constant-rate production, Infinite-acting

CMNT Slightly Compressible Fluid
CMNT Wellbore is modeled by the first cell to show
CMNT Single Value Input Data

IMAX 27
JMAX 1
RWEL 0.001
CROC 0.000015
SWAT 0.25
CWAT 0.000004
PREF 3000
NEWT 1
BETA 0

CMNT Bo, rcf/scf viscosity cp
~~CMNT 1.2 0.82~~

GRAV	0.85
T	615

END
CMNT Grid Input Data
CMNT Geometrically spaced grid system
CMNT b = 1.49
CMNT The actual value of rw is assigned to the

RR -1 1.491895506
0.2500 0.3729 0.5564 0.8301 1.2384 1.8477 2.7565 4.1125 6.1354 13.65601
20.3733 30.394 45.346 67.651 100.92 150.57 224.64 335.14 550 600
650 700 750 800 850 900 950

DELY 130
KX 12
KY 12
PHI 0.21
POI 3000

WIND 1 1 1 1

PHIS 12.4 → 9.355

KX 1000000
KY 1000000

WIND 2 4 1 1

KX 0.15
KY 0.15 → 1.3586

END
CMNT Schedule Data
CMNT Well No. i - location j - location skin
NAME 1 1 1 0
CMNT Well No. scf/D
QG 1 720.0
ALPH 1.2
DELT 0.0001
DTMX 50
WELL 1
PMAP 2
TIME 1000
END

6. (10 points) Suppose you *did not know the productivity index* in problem 3, but can use all the other data. Use the Dietz shape factor tables. You estimate that the well is in the center of a 2 x 1 rectangle and that $k = 5.3$ md. S = 4.2

- (a) Calculate the productivity index (stb/d/psi).
 (b) When is the end of the SLSL?
 (c) When does pseudo-steady state begin?

↓
 $C_A = 21.8369$

a)
$$J = \frac{K h}{141.2 B \mu} \frac{1}{\left[\frac{1}{2} \ln \frac{10.06 A}{C_A r_w^2} - \frac{3}{4} + S \right]}$$

$$J = \frac{5.3 \cdot 145}{141.2 \cdot 1.12 \cdot 3.1} \frac{1}{\left[\frac{1}{2} \ln \frac{10.06 \cdot 1.55 \times 10^6}{21.8369 \cdot 0.24^2} - \frac{3}{4} + 4.2 \right]}$$

$J = 0.1349 \text{ STB/d/psi}$

b)
$$t_{DA} = \frac{0.00633 K t_{\text{days}}}{\phi \mu c_t A}$$

$t_{DA} \text{ end of SLSL} = 0.025$

$$0.025 = \frac{(0.00633) \cdot (5.3) \cdot t}{(0.13) \cdot (3.1) \cdot (15 \times 10^{-6}) \cdot (1.55 \times 10^6)}$$

$t = 6.98 \text{ days} = 167.57 \text{ hrs}$
end of SLSL

c) $t_{DA} \text{ begin of PSS} = 0.3$

$$0.3 = \frac{0.00633 (5.3) \cdot t}{(0.13) (3.1) (15 \times 10^{-6}) (1.55 \times 10^6)}$$

$t = 83.78 \text{ days} = 2010.85 \text{ hrs}$

pss begins

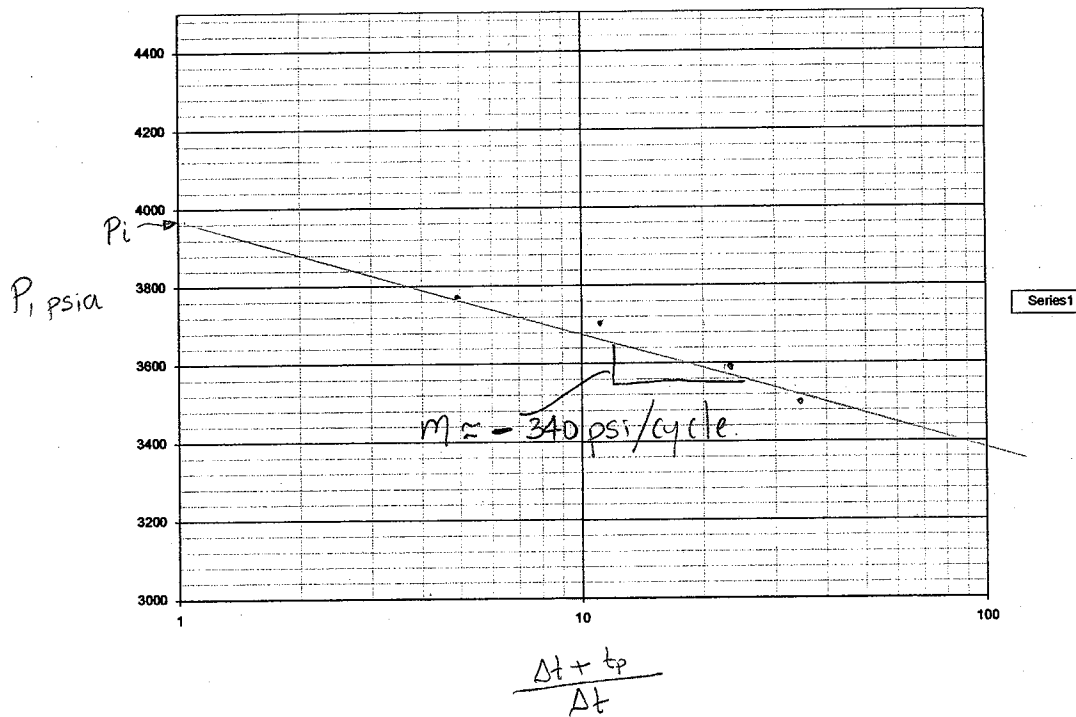
7. (10 points) We have a discovery well in a potentially large reservoir. We want to evaluate the well, so we produce it at constant rate of 310 stb/d for 220 hours and then shut it in. Below is the shut-in time and pressure data. Use the following data:

Shut-in time, hours	Shut-in pressure, psia	$\frac{t_p + \Delta t}{\Delta t}$	$B = 1.12 \text{ rb/stb}$ $\mu = 2.1 \text{ cp}$	$\phi = 0.16$ $c_t = 12 \times 10^{-6} \text{ psi}^{-1}$	$h = 85 \text{ ft}$ $r_w = 0.24 \text{ ft}$ $S_w = 0.22$
7	3490	32.43			
10	3590	23			
22	3710	11			
55	3770	5			

[Note: You can use only 3 of the following points to save time]

Analyze this as a build-up test.

- Calculate the plotting variables,
- Make a Horner plot
- Determine the initial reservoir pressure
- Determine permeability.



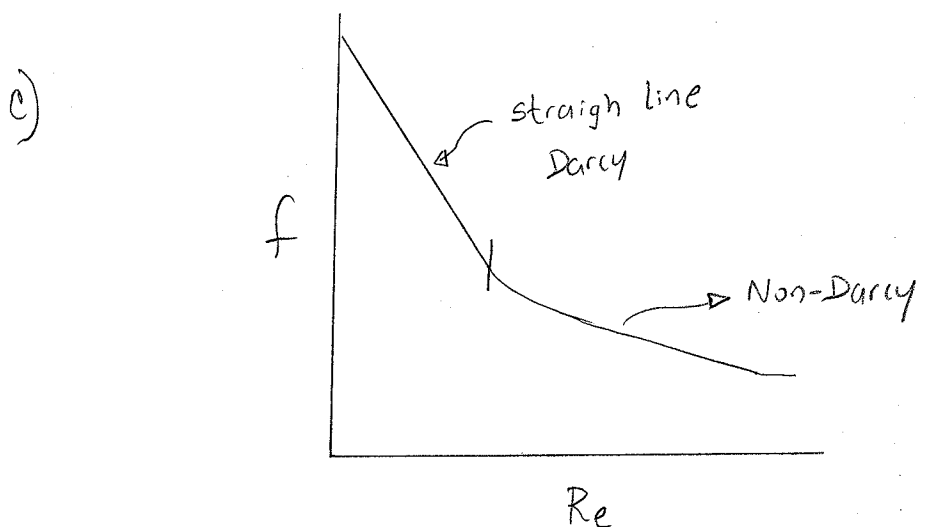
c) $P_i \approx 3970 \text{ psia}$

d) $m = 340 \text{ psi/cycle}$

$$K = \frac{162.6 q \cdot B \cdot \mu}{mh} = \frac{162.6 (310) (1.12) (2.1)}{(340) (85)} = 4.1 \text{ md}$$

8. (10 points) Forchheimer's equation is used for non-Darcy flow: $\left| \frac{dp}{dx} \right| = \frac{\mu}{k} u + \beta \rho u^2$, where u is the Darcy velocity.

- What *one word* describes the first term on the RHS. *Laminar or Darcy or viscous*
- What *one word* describes the second term on the RHS. *Turbulent or Inertial or non-Darcy*
- Sketch a plot of friction factor, f , vs. Reynolds number, Re , for gas flow through a porous rock.
- Is non-Darcy flow more likely in oil wells or gas wells? *Gas*
- Is non-Darcy flow more likely in high or low permeability wells? *High Permeability*



9. (10 points) Attached is a chart of the water vapor content of natural gas.

(a) Calculate the rate that water condenses in the wellbore (in STB/D) for the following well conditions, assuming that water does not flow out of the wellbore (below critical rate).

(b) Calculate the critical rate for the above well. Assume a value for any missing data and indicate your assumption.

(c) What is the maximum tubing pressure that will eliminate condensation of water in the tubing?

$q_g = 500$ Mscf/D
$S_w = 0.20$
$(\bar{p})_{reservoir} = 10,000$ psia
$(T)_{reservoir} = 300$ °F
$p_{tf} = 200$ psia (tubing pressure)
$T_{tf} = 80$ °F (tubing temperature)
Tubing I.D. = 1.995 inches

a) Condensing: $\frac{750}{-130} = 620 \text{ \# H}_2\text{O/MMscf}$

$q_w \text{ condensing} = 0.5 \text{ MMscf/D} * \frac{620 \text{ \# H}_2\text{O/MMscf}}{350 \text{ \#/STB}}$

$q_w \text{ condensing} = 0.886 \text{ STB/D}$

b) Assume $B_w = 1 \text{ RB/STB}$ $Z = 1$

$V_c \text{ water} = \frac{5.62 (67 - 0.0031 p)^{0.25}}{(0.0031 p)^{0.5}} = \frac{5.62 (67 - 0.0031 (200))^{0.25}}{(0.0031 \cdot 200)^{0.5}} = 20.37 \text{ ft/s}$

$q_c \text{ (Mscf/d)} = \frac{3060 P_{wh} V_c A}{T Z} = \frac{3060 (200) (20.37) \left(\frac{\pi}{4} \left(\frac{1.995}{12}\right)^2\right)}{(80 + 460)^\circ R (1)}$

$q_c = 501 \text{ Mscf/d}$

c) $P_{Tf} = 40$ psia
(graphically)

$\frac{(750 - X) \text{ lb/MMscf}}{(350) \text{ lb/bbl}} = 0$

$X = 400 \text{ lb/MMscf}$

For no water condensing the water content at tubing pressure and temperature must be lower than 750 lb/MMscf.

10. (10 points) Suppose an oil well is perforated 280 ft above the water-oil contact. Calculate the *critical coning rate*.

$\rho_o = 39 \text{ lb/ft}^3$ $\rho_w = 68 \text{ lb/ft}^3$ $B = 1.13 \text{ rb/stb}$	$\mu = 1.1 \text{ cp}$ $c_t = 15 \times 10^{-6} \text{ psi}^{-1}$ $\phi = 0.16$	$h = 200 \text{ ft}$ $S_w = 0.22$	$J = 30.3 \text{ b/d/psi}$ $r_w = 0.25 \text{ ft}$
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$$(P_i - P_{wf})_{crit} = \left(\frac{\rho_w - \rho_o}{144} \right) h_{bp}$$

$$\Delta p = \left(\frac{68 - 39 \text{ lb/ft}^3}{144 \text{ in}^2/\text{ft}^2} \right) \cdot 280$$











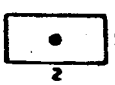
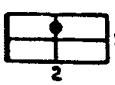
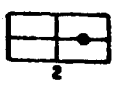


$$\Delta p = 56.3888 \text{ psi}$$

$$q_c = J (\bar{p} - P_{wf})$$

$$q_c = 30.3 \text{ b/d/psi} (56.3888 \text{ psi})$$

$$q_c = 1708.6 \text{ b/day}$$

TABLE 1.2 - SHAPE FACTORS FOR VARIOUS SINGLE-WELL DRAINAGE AREAS¹⁰

In Bounded Reservoirs	C_A	$\ln C_A$	$0.5 \ln \left(\frac{2.2458}{C_A} \right)$	Exact for $t_{DA} >$	Less Than 1% Error for $t_{DA} >$	Use Infinite System Solution With Less Than 1% Error for $t_{DA} <$
	31.62	3.4538	1.3224	0.1	0.06	0.10
	31.6	3.4532	-1.3220	0.1	0.06	0.10
	27.6	3.3178	-1.2544	0.2	0.07	0.09
	27.1	3.2985	-1.2452	0.2	0.07	0.09
	21.9	3.0885	-1.1387	0.4	0.12	0.08
	0.098	-2.3227	1.5659	0.9	0.60	0.015
	30.8828	3.4302	-1.3106	0.1	0.05	0.09
	12.9851	2.5638	-0.8774	0.7	0.25	0.03
	4.5132	1.5070	-0.3490	0.6	0.30	0.025
	3.3351	1.2045	-0.1977	0.7	0.25	0.01
	21.8369	3.0836	-1.1373	0.3	0.15	0.025
	10.8374	2.3830	-0.7870	0.4	0.15	0.025
	4.5141	1.5072	-0.3491	1.5	0.50	0.06
	2.0769	0.7309	0.0391	1.7	0.50	0.02
	3.1573	1.1497	-0.1703	0.4	0.15	0.005