**Exercises Reservoir Engineering II**

**PVT analysis**

**Exercise 1**

|  |  |
| --- | --- |
| a) | Describe a typical pressure-temperature diagram of a multi component hydrocarbon system. Use the diagram to distinguish between the following three types of gas reservoirs   1. Dry Gas 2. Wet gas 3. Gas condensate (Retrograde gas) |
| b) | Perform the derivation of the following material balance equation for a closed dry gas reservoir:  =  - Gp    where: Pic = reservoir pressure at initial conditions  Pres = reservoir pressure during production  Psc = pressure at standard conditions  Zic = compressibility factor at initial conditions  Zres = compressibility factor at Pres  Vic = volume of gas in the reservoir at initial conditions  Tic = reservoir temperature at initial conditions |
| c) | The following production history is known for a gas reservoir: |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Column 1** | **Column 2** | **Column 3** | **Column 4** | **Column 5** |
| **Pres (psia)** | **Zres** | **Cumulative separator gas (∙106 SCF)** | **Cumulative stock tank oil (SBL)** | **Cumulative water**  **(SBL)** |
| 5392 | 1.0530 | 0 | 0 | 0 |
| 5368 | 1.0516 | 661.272 | 12314 | 3 |
| 5301 | 1.0470 | 2883.114 | 47674 | 762 |
| 5245 | 1.0442 | 5073.370 | 83132 | 2054 |
| 5182 | 1.0404 | 6957.608 | 112902 | 3300 |
| 5147 | 1.0383 | 8070.262 | 144035 | 4644 |

|  |  |
| --- | --- |
|  | First neglect the produced liquid, and estimate the volume of gas originally in place at standard conditions (IGIP). |
| d) | Assume that all produced liquid exists as gas in the reservoir. Perform another estimate of total well stream volume as gas (hydrocarbons + water vapour) initially present, given the following information:  γSTO = 0.72, MSTO = 72 and the standard conditions are Psc = 15 psia and Tsc = 60ºF |

**Exercise 2**

Calculate Pb for the following hydrocarbon system at 180°F:

|  |  |
| --- | --- |
| **Component** | **zi** |
| C1  C2  C3  n-C4  n-C5  C6  C7+ | 0.3396  0.0646  0.0987  0.0434  0.0320  0.0300  0.3917 |

K-values are determined using maps with a convergence pressure of 5000 psia. The K-value for decane is used for C7+.

A table of K-values is given below (K-values from the GPSA-handbook):

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Component** | **2500 psia** | **2000 psia** | **1900 psia** | **1800 psia** |
| C1  C2  C3  n-C4  n-C5  C6  C7+ | 1.8  1.0  0.66  0.44  0.26  0.16  0.015 | 2.4  1.05  0.61  0.38  0.21  0.12  0.009 | 2.5  1.07  0.61  0.36  0.20  0.11  0.008 | 2.6  1.1  0.60  0.35  0.19  0.11  0.0075 |

**Exercise 3**

A stream of hydrocarbons, with known composition, passes through a two-step separator system:

1. step: T = 40°F, P = 35 psia

2. step: T = 40°F, P = 15 psia

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Component** | **zi** | **Ki 1. Step** | **Ki 2. Step** | **Mi** |
| C1  C2  C3  n-C4  n-C5  C6  C7+ | 0.3396  0.0646  0.0987  0.0434  0.0320  0.0300  0.3917 | 61.0  9.0  2.2  0.61  0.151  0.035  0.0032 | 145  20.5  5.1  1.4  0.375  0.075  0.003 | 16.04  30.06  44.09  58.12  72.14  86.17  263.0 |

Further it is given that:

ρC7+ = 55.28 lb/ft3 (at sc)

(ρo)res = 46.6 lb/ft3

(Mo)res = 122.17

Vm = 380.69 SCF/lb-mole (molar volume of gas at sc)

(Note that Vm is 380.69 since the temperature at sc is 40°F).

1. Calculate the mole fraction of liquid and gas from step 1, together with the composition of the liquid. (First assume L = 0.5).
2. Calculate the mole fraction of liquid and gas from step 2, together with the composition of the liquid. (First assume L = 0.95).
3. Determine: GORsep, GORtank and GORtot. Given: ρSTO = 53.5 lb/ft3
4. Assume Pres > Pb and calculate Bo.

**Exercise 5**

Calculate volumetric depletion parameters (data in Table 2) for a retrograde gas condensate reservoir based on a reservoir volume of 1 acft (acre-foot) = 43560 ft3. The following data are given:

Reservoir data Experimental data

Pic = Pd = 2960 psia Vcell = 947.5 cm3

Pa = 500 psia MC7+ = 114

Tres = 195ºF = 655ºR γC7+ = 0.755

Swr = 0.3 Vm = 379.5 SCF/lb-mole

Φ (porosity) = 0.25 sc = 14.7 psia; 60ºF

Liquid recovery factors Conversion of gas volume

from wellstream to liquid volume

C4 = 0.25 C4 = 32.04 Gal/kSCF

C5 = 0.50 C5  = 36.32 Gal/kSCF

C6 = 0.75 C6  = 41.03 Gal/kSCF

C7+ = 1.00 C7+ = 47.71 Gal/kSCF

CVD analysis of the fluid is performed. Compositions of well-stream, volumetric data and Z-factors are given in table 1 below.

**Table 1: Data needed**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| **Pres**  **(psia)** | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** | **C7+** | **ΔV**  **(cm3)** | **Vl**  **(cm3)** | **Vl**  **(%)** | **Z** |
| 2960 | 0.752 | 0.077 | 0.044 | 0.031 | 0.022 | 0.022 | 0.052 | 0 | 0 | 0 | 0.771 |
| 2500 | 0.783 | 0.077 | 0.043 | 0.028 | 0.019 | 0.016 | 0.034 | 175.3 | 62.5 | 6.6 | 0.794 |
| 2000 | 0.795 | 0.078 | 0.042 | 0.027 | 0.017 | 0.014 | 0.027 | 227.0 | 77.7 | 8.2 | 0.805 |
| 1500 | 0.796 | 0.079 | 0.042 | 0.027 | 0.016 | 0.013 | 0.025 | 340.4 | 75.0 | 7.9 | 0.835 |
| 1000 | 0.793 | 0.080 | 0.043 | 0.028 | 0.017 | 0.013 | 0.025 | 544.7 | 67.2 | 7.1 | 0.875 |
| 500 | 0.768 | 0.082 | 0.048 | 0.033 | 0.021 | 0.015 | 0.033 | 1080.7 | 56.9 | 6.0 | 0.945 |

ΔV = produced volume of gas at given pressure and Tres

Vl = volume of retrograde liquid (cm3 and %) at given P and Tres.

Z = compressibility factor at given P and Tres.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| **Pres**  **(psia)** | **(ΔGp)i**  **(kSCF)** | **∑(ΔGp)i**  **(kSCF)** | **(ΔVg)i**  **(kSCF)** | **∑(ΔVg)i**  **(kSCF)** | **(ΔVo)i**  **(SBL)** | **∑(ΔVo)i**  **(SBL)** | **GOR**  **(SCF/SBL)** | **%ΔGp**  **(cumulative)** | **%ΔVg**  **(cumulative)** | **%ΔVo**  **(cumulative** |
| 2960 | 0 | 0 | 0 | 0 | 0 | 0 | 10600 | 0 | 0 | 0 |
| 2500 | 240.1 | 240.1 | 225.1 | 225.1 | 15.3 | 15.3 | 14700 | 15.2 | 15.6 | 10.7 |
| 2000 | 245.2 | 485.3 | 232.3 | 457.4 | 13.1 | 28.4 | 17730 | 30.7 | 31.7 | 19.8 |
| 1500 | 266.0 | 751.3 | 252.8 | 710.2 | 13.3 | 41.7 | 19010 | 47.6 | 49.3 | 29.1 |
| 1000 | 270.8 | 1022.1 | 256.9 | 967.1 | 14.0 | 55.7 | 18350 | 64.7 | 67.1 | 38.9 |
| 500 | 248.7 | 1270.8 | 233.0 | 1200.1 | 15.9 | 71.6 | 14650 | 80.4 | 83.3 | 50.0 |

**Table 2: Data to be calculated**

(ΔGp)i = well-stream volume at sc

∑(ΔGp)i = cumulative well-stream volume

(ΔVg)i = volume of separator gas

∑(ΔVg)i = cumulative volume of separator gas

(ΔVo)i = volume of STO

∑(ΔVo)i = cumulative volume of STO

GOR = average gas-oil-ratio.

%ΔGp = volume % of cumulative well-stream

%ΔVg = volume % of cumulative separator gas

%ΔVo = volume % of cumulative STO

All values are for given P (corresponding to pressure step i).

**Exercise 6**

The following data for a constant volume depletion analysis (CDV) are given:

Tres = 186ºF

Pres = Pd = 4000 psia

Psep = 300 psia

Tsep = 70ºF

Vcell = 3958.14 cm3

The table below contains the composition of the well-stream fluid, together with other relevant data, as a function of pressure:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Composition** | **4000 psia** | **3500 psia** | **2900 psia** | **2100 psia** | **1300 psia** | **605 psia** |
| **CO2** | 0.18 | 0.18 | 1.18 | 0.18 | 0.19 | 0.21 |
| **N2** | 0.13 | 0.13 | 0.14 | 0.15 | 0.15 | 0.14 |
| **C1** | 67.72 | 63.10 | 65.21 | 69.79 | 70.77 | 66.59 |
| **C2** | 14.10 | 14.27 | 14.10 | 14.12 | 14.63 | 16.06 |
| **C3** | 8.37 | 8.25 | 8.10 | 7.57 | 7.73 | 9.11 |
| **i-C4** | 0.98 | 0.91 | 0.95 | 0.81 | 0.79 | 1.01 |
| **n-C4** | 3.45 | 3.40 | 3.16 | 2.71 | 2.59 | 3.31 |
| **i-C5** | 0.91 | 0.86 | 0.84 | 0.67 | 0.55 | 0.68 |
| **n-C5** | 1.52 | 1.40 | 1.39 | 0.97 | 0.81 | 1.02 |
| **C6** | 1.79 | 1.60 | 1.52 | 1.03 | 0.73 | 0.80 |
| **C7+** | 6.85 | 5.90 | 4.41 | 2.00 | 1.06 | 1.07 |
| **Other data** |  |  |  |  |  |  |
| **M C7+** | 143 | 138 | 128 | 116 | 111 | 110 |
| **Zg** | 0.867 | 0.799 | 0.748 | 0.762 | 0.819 | 0.902 |
| **ΔVg (cm3)** | 0 | 224 | 474 | 1303 | 2600 | 5198 |
| **(GPM)well** | 5.254 | 4.578 | 3.347 | 1.553 | 0.835 | 0.895 |
| **GOR(SCF/SBL)** | 7127 | 8283 | 11621 | 26051 | 49312 | 45872 |
| **(Vl)cell (%)** | 0 | 3.32 | 19.36 | 23.91 | 22.46 | 18.07 |

ΔVg = gas volume removed from the cell for each step, at given P and Tres

GPM = liquid volume (gallon) for each 1000SCF of well-stream fluid

(Vl)cell = retrograde liquid volume in the cell at given P and Tres.

|  |  |
| --- | --- |
| a) | Based on an initial volume of reservoir fluid of 1.0 ∙ 106 SCF, calculate the volume of the well-stream fluid (SCF), separator gas (SCF) and STO (SBL) after pressure depletion for each interval. |
| b) | Calculate the volume of separator gas (SCF) and STO (SBL) initially in place in 1.0 ∙ 106 SCF well-stream fluid. |
| c) | Calculate cumulative recovery, and % recovery of well-stream fluid, separator gas and STO. |
| d) | Calculate the recovery (well-stream fluid, separator gas and STO) based on a termination pressure (Pt) of 605 psia, a reservoir volume of 1 acft = 43560 ft3, a porosity (Φ) of 0.10 and a connate water saturation (Swc) of 0.20. |
| e) | Evaluate the relevance of the calculations in d) if the retrograde fluid becomes mobile at a saturation of 15%. |
| f) | Calculate the additional recovery (well-stream fluid, separator gas and STO) resulting from a change in initial conditions to: Pi = 5713 psia and Pd = 4000 psia, given that Zg is 1.107 at Pi and Tres. |

**Immiscible displacement**

**Exercise 10**

A linear waterflood is conducted in a horizontal reservoir with the following properties:

qt = 2200 resbbl/D

A = 18000 ft2

L = 2200 ft

Φ = 0.21

k = 180 mD

μw = 0.5 cp

μo = 2.4 cp

Swr = 0.15

Sorw = 0.20

Bo = 1.2 resbbl/SBL

Bw = 1.0 resbbl/SBL

Relative permeability of oil and water as a function of water saturation is given by:

|  |  |  |
| --- | --- | --- |
| **Sw** | **krw** | **kro** |
| 0.15 | 0 | 0.920 |
| 0.25 | 0.020 | 0.725 |
| 0.35 | 0.050 | 0.470 |
| 0.45 | 0.095 | 0.290 |
| 0.55 | 0.150 | 0.150 |
| 0.65 | 0.225 | 0.060 |
| 0.75 | 0.335 | 0.015 |
| 0.80 | 0.410 | 0 |

Use the Buckley Leverett method, where a plane of constant saturation, moves with a constant rate:

Vsw = 

|  |  |
| --- | --- |
| a) | Calculate the time to water breakthrough (tbt), and find the average water saturation in the reservoir, produced oil volume and fractional flow of water at this time. |
| b) | Draw the water saturation profile at water breakthrough. It is sufficient to calculate two points between the injector and producer. |
| c) | The production has to be ended when WOR=20 (measured at standard conditions). What is the fractional flow of water? How much oil is produced, and what fraction is this of the oil that can be produced? |
| d) | What is the pressure drop between injector and producer at the start of production? Explain briefly how we can find the upper limit (at WOR = 20) and the lower limit (when fw = 1 and fo = 0) for the pressure drop at the end of production, and calculate these values. |

Darcy´s law for a linear reservoir in field units is given by:

qo = 7.081·10-3

**Coning**

**Exercise 8.**

A horizontal circular oil reservoir with a gas cap on the top and an impermeable layer on the bottom. The following reservoir data are given:

h = 30 ft (height of the oil zone)

re = 1820 ft

rw = 0.5 ft

ρg = 0.12 g/cm3

hc = 5 ft (height of perforation interval)

o = 0.8 g/cm3

o = 2.6 cP

ko = 0.078 darcy at Swr

Pe = 3480 psia

a.

Where must the perforation interval be placed. Give a reason for the answer.

b.

Show that the maximum gas-free oil production rate is given by:



Where C=1.535 system constant and should not be derived, ko (darcy), o (cP), (g/cm3), h (ft), qo (resbbl/D), D (ft) is the distance between gas oil contact, GOC, and the top of perforation (D=h-hc)

c.

In order to derive the formula above, some assumptions are made. Explain the assumptions. Discuss shortly how these assumptions are affecting the value of qo.

Suppose kv<<kh, what is the effect on qo ??

d.

Restrictions to the fluid flow close to the well can be described as a “skin-effect”.

Explain how, and derive the following formula:



By using the Darcy\s law. Make an illustration and explain the symbols.

e.

Calculate the maximum gas-free oil production rate for the reservoir. (Answer: 3.34 resbbl/D)

Calculate the pressure in the well, Pw, with a skin factor of S=0.8. (Answer: 3475 psia)