University of Stavanger

Faculty of Science and Technology

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Exam in : PET 540, Natural Gas Reservoir and Production Engineering
Duration : 4 hours
Supporting materials : Use of simple calculator is permitted
Content: 2 exercises on 4 pages
Course responsible : Prof. Jann Rune Ursin

Exercise 1

In strongly compartmentalized natural gas reservoirs, well location and sequence of well production are of great importance in order to optimize field production.

Faults of different kinds might be a reason for increased compartmentalization in gas fields.

1. Define what is meant by a fault and explain how a fault can reduce communication in a gas field.
2. Define the three cases of; a sealing fault, an open or sealing fault and an open fault.

In the Fault Block Model (FBM), the gas field is subdivided in various reservoirs or blocks based on known and to some degree unknown faults, restricting gas flow between the reservoirs. A cross-flow communication probability, $P_{i,j}$ is defining the likelihood for gas flow communication across the boundary between the adjacent block *i* and block *j*.

3. What is the relationship between the concepts of cross-flow communication probability and likelihood for gas flow across a particular fault?

In the FBM, natural gas contained in reservoirs or blocks in the field are grouped together to forme *Drainage compartments*, where wells located in a drainage compartment may produce gas contained in several neighbouring reservoirs. The estimation of drainage compartment volumes are sequentially organized, where the first step of calculating the drainage volumes is given by the following general formula,

$$^1V_i = \sum_{j=1}^{n} P_{i,j} \cdot V_j,$$

where V_j are the reservoir volumes, $P_{i,j}$ are the cross-flow communication probability and ^1V_i are the drainage volumes. n is the number of reservoirs in the field.

4. Based on the information of the drainage volumes, as presented above, how can we decide where to drill the first well ?

In a simplified example as shown in Figure 1, the gas field contains of 5 reservoirs, where the cross flow probability is 0.5 across the boarder lines between reservoirs 1, 2 and 3. Between all other borderlines the cross flow probability is 0.3.

The reservoir volumes are $(V_1, V_2, V_3, V_4, V_5) = (24, 8, 16, 8, 8)$ units of gas.

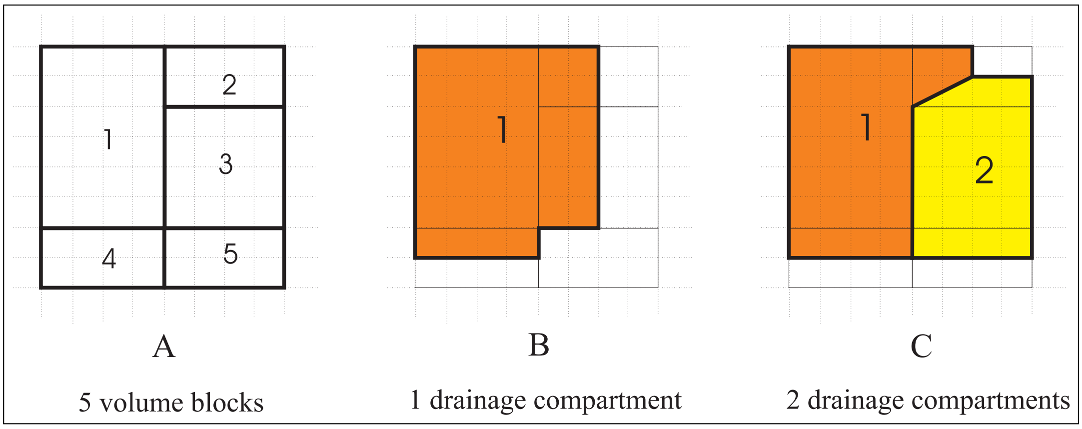

Figure 1: Formation of drainage-volumes for 2 wells in a compartmentalized field of 5 blocks.

5. Define the cross-flow communication matrix, containing all the elements $P_{i,j}$, where $i, j = 1, ..., 5$.

6. Calculate the volume of the five possible drainage compartments.

If the uncertainty in cross-flow communication probability $\Delta P_{i,j}$ and in reservoir gas volume ΔV_i are known, we may use *error propagation* techniques to determine the error in the drainage volume.

7. If a function, $f(x, y)$ have uncertainties defined by dx and dy, a differentiation of $f(x, y)$ will give the uncertainty in f by error propagation, i.e.

$$df = \frac{\delta f}{\delta x} dx + \frac{\delta f}{\delta y} dy$$

In dealing with differences instead of differentials and assuming x and y to be independent variables, - why can the equation above be written as:

$$(\Delta f)^2 = \left(\frac{\delta f}{\delta x}\Delta x\right)^2 + \left(\frac{\delta f}{\delta y}\Delta y\right)^2.$$

8. Using the above result of error propagation, show that the uncertainty in the drainage volumes $\Delta^1 V_i$ is written (Hint: use the formula ^1V_i on the previous page),

$$\Delta^1 V_i = \sqrt{\sum_{k=1}^{5} ([\Delta V_i P_{i,k}]^2 + [V_i \Delta P_{i,k}]^2}.$$

In Figure 2, the reservoir volumes in a gas condensate field containing 38 reservoir blocks are presented. The various reservoir volumes contain quite different volumes of gas.

9. Based on the reservoir volumes in Figure 2 and the assumption that 8 wells would sufficiently produce the gas from the field, suggest location of reservoirs where the wells should be located and the sequence of well production.

10. In the case of no cross-flow communication between reservoirs in the field ($P_{i,j} = 0$), what would then be the well gas coverage of the 8 wells?

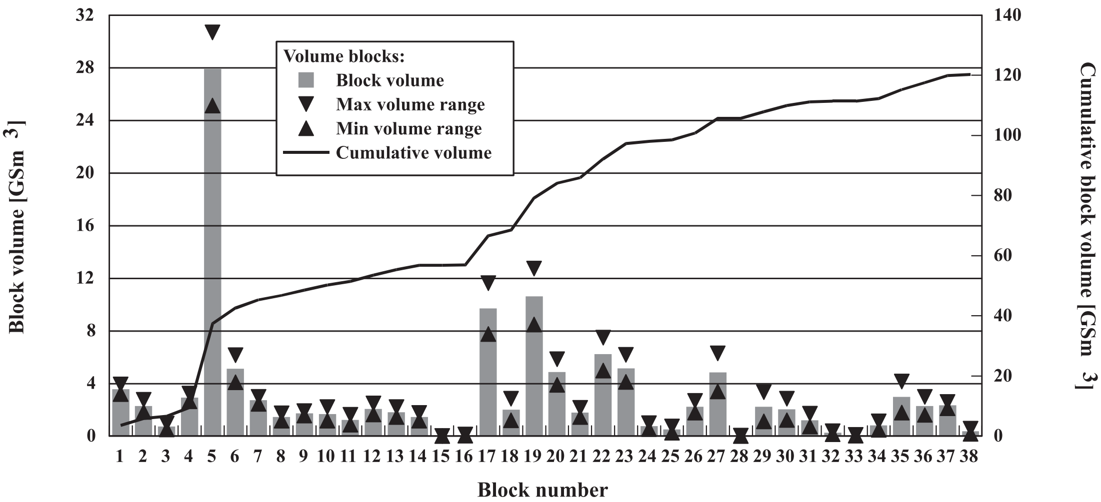

Figure 2: Gas in volume-blocks and uncertainty in gas volume.

Exercise 2

The Darcy Law without gravitational term is written on linear form (flow along the x-axis)

$$v_x = -\frac{k_x}{\mu}\frac{\partial p}{\partial x},$$

where v is the volumetric flow velocity ($v = q/A$, where q and A are the flow rate and flow cross section area, respectively), μ is the gas viscosity, k is the permeability and p is the pressure.

The mass conservation law on linear form is given

$$\frac{\partial}{\partial x}(\rho v_x) = 0,$$

where ρ is the gas density.

1. Show that the steady-state gas flow equation for linear flow can be written

$$\frac{\partial}{\partial x}\left(\frac{\rho}{\mu}\frac{\partial p}{\partial x}\right) = 0.$$

2. Explain why the above equation is not easily solved analytically.

The above steady-state flow equation can however be linearized using *Kirchhoff's transformation*.

$$m(p) = \frac{1}{(\rho/\mu)_r}\int_{p_r}^{p}\frac{\rho}{\mu}dp.$$

3. Define the pressure p_r and state a typical numeric value for this pressure.

4. The *pseudo pressure* given above is labeled a transformation. What does this transformation do?

5. Show that using Kirchhoff's transformation will reduce the above steady-state gas flow equation to the following form,

$$\frac{\partial^2}{\partial x^2}m = 0.$$

6. Use the ideal gas law at isothermal conditions and show that the pseudo pressure for an ideal gas is written,
$$m(p) = \frac{1}{2}\left(\frac{p^2}{p_r} - p_r\right).$$

7. What is the important assumption made about the viscosity μ in the deduction above?

8. Make a plot showing idealized behaviour of $m(p)$.

For a real gas the pseudo pressure, $m(p)$, is given by the equation
$$m(p) = \left(\frac{Z\mu}{p}\right)_r \int_{p_r}^{p} \frac{p}{Z\mu}dp,$$
where Z is the z-factor.

9. Based on Kirchhoff's transformation for real gases, as seen above, - sketch the pseudo pressure for real gases in the same plot as above and explain the difference.

10. What is the pseudo pressure deviation between the real-gas case and the ideal-gas case for low pressures?

A regular cylindrical core sample has a diameter of 5 cm and a length of 10 cm. The permeability is estimated to 200 mD and the inlet pressure (p_1) and outlet pressures (p_2) are 50 and 20 bars, respectively.

The flow rate at standard conditions can be approximated by the equation
$$q_{sc} = kA\frac{1}{(\mu B_g)_r}\frac{\Delta m}{L},$$
where $L = 10\,cm$ is the length of the core sample. Please notice that we here are using the gas-formation volume factor instead of the gas density. The reference pressure equal to 20 bar, the viscosity $\mu = 1.2 \cdot 10^{-2}\ mPa \cdot s$ and the formation volume factor $B_g = 6.88 \cdot 10^{-2}$ Rm^3/Sm^3.

11. Show that the flow rate at standard condition is,
$$q_{sc} = \frac{kA}{(\mu B_g)_r L}\frac{1}{2}\left(\frac{p_1^2 - p_2^2}{p_r}\right),$$
where $(\mu B_g)_r$ is evaluated at the reference pressure p_r.

12. Find the core flow rate q_{sc} in Sm^3/s, given the data above.

13. Why would it be appropriate to use the ideal gas pseudo pressure transformation in the example?

14. If we would have used the real gas pseudo pressure transformation, - would the calculated flow rate be less or higher than the rate found above? (Defend your conclusion.)

Best of luck!
JRU