Calculation of The Linear Flow Rate of a Compressible Fluid (Gas) in a Reservoir

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Abstract. Derivation of the equation for the linear flow rate of a compressible fluid or gas in a reservoir has been carried out, the derivation of the gas equation is quite complicated and many factors must be taken into account. Calculations were carried out manually and numerically by using the Fortran 95 program. Numerical calculations were carried out because the calculations were quite complicated and easier when used for repeated calculations. In the middle of the program the price of the pseudo-reduce variable from temperature and pressure has been calculated, then from the data obtained the compressibility factor for natural gas from the Standing Kart Chart, then the calculation is continued again. So that the value of the linear flow rate of the compressible fluid is obtained.

Keywords: linear flow rate, compressible fluid, reservoir.

INTRODUCTION

There are several types of flow in the reservoir, including linear, radial, spherical and semi-spherical flows. Likewise with fluids, there are several kinds of fluids, namely compressible, slightly compressible and uncompressible. This research is a continuation of previous research on the derivation of Darcy's equation for linear flow of slightly compressible and uncompressible fluids (Satiawati & Yulia, 2019) & (Satiawati, 2022). This research is continued for compressible fluids which include gaseous fluids. In the derivation of the gas flow equation in this reservoir, first, gas is categorized as real gas in standard conditions P_{sc} is 14.7 psi and T_{sc} is 520° Rankine and the Darcy equation is used for linear flow and the unit used is standard cubic foot per day or scf/day. While the viscosity of natural gas is calculated using the Lee Gonzales Eakin method or the LGE Method and the viscosity value is considered constant for the observed pressure interval. For the natural gas system the value of pseudo critical temperature, T_{pc} (°R) and pseudo-critical pressure, P_{pc} (psia) is obtained from reference no. (Ahmed & Meehan, 2012) & (Ahmed, 2011). The molecular weight of the gas is obtained from the specific gravity data and the gas density is obtained from the real gas equation.

FORMULA

Darcy's equation is an equation that is commonly used to calculate discharge, and the velocity of linear flow and radial flow. Initially Darcy's equation was obtained from the results of the cylindrical tube experiment conducted by Darcy, further analysis of the Darcy equation was derived from the Navier Stokes equation to find a more general case solution (Satiawati & Yulia, 2019) Therefore, Darcy's equation is widely used in the calculation of fluid flow in the reservoir and the results are quite valid because it is supported by analysis and experimentation. For a flat reservoir, the Darcy equation is:

$$v = \frac{q}{A} = -0.001127 \; \frac{k \, dP}{\mu \, dx}$$

v is the flow velocity, q is the volumetric flow rate or discharge, A is the cross-sectional area of the rock, μ is the viscosity of the fluid, $\frac{dP}{dx}$ is the pressure gradient in the same direction as v and q, and k is the rock constant or permeability. The negative sign (-) is because the pressure gradient is negative or not in the direction of the flow.

For linear flow of a compressible fluids or gas. The equation of state for real gases is used

$$P\,V = Z\,n\,R\,T \quad \text{or} \quad n = \frac{PV}{ZRT}$$

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Where
n is the number of moles of gas
P is pressure
T is temperature
V is the volume, and
Z is the compressibility factor of the gas

Under standard conditions (sc)

$$n = \frac{P\,V}{Z\,R\,T} = \frac{P_{sc}\,V_{sc}}{Z_{sc}\,R\,T_{sc}}$$

And with the approach of the gas compressibility factor under standard conditions the price is close to 1,

$$\frac{PV}{ZT} = \frac{P_{sc}\,V_{sc}}{T_{sc}}$$

and equality (Boas, 1983) & (Hugh D. Young, 2012),

$$V\ (ft^3) \sim 5{,}615\ q\ (bbl/day)$$

$$V_{sc}\ (ft^3) \sim Q_{sc}\ (scf/day),$$

Then get

$$\frac{P(5.615\ q)}{ZT} = \frac{P_{sc}\,V_{sc}}{Q_{sc}}$$

$$q = \left(\frac{P_{sc}}{T_{sc}}\right)\left(\frac{ZT}{P}\right)\left(\frac{Q_{sc}}{5.615}\right)$$

$$\frac{q}{A} = \left(\frac{P_{sc}}{T_{sc}}\right)\left(\frac{ZT}{P}\right)\left(\frac{Q_{sc}}{5.615}\right)\left(\frac{1}{A}\right) = 0.001127\frac{k}{\mu}\frac{dP}{dx}$$

$$\left(\frac{Q_{sc}P_{sc}T}{0.006328\ kT_{sc}A}\right)\int_0^L dx = -\int_{P_1}^{P_2}\frac{P\,dP}{Z\,\mu_g}$$

Assuming $Z\ \mu_g$ is constant for the range $P_1 - P_2$

$$\left(\frac{Q_{sc}P_{sc}T}{0.006328\ kT_{sc}A}\right)\int_0^L dx = -\frac{1}{Z\ \mu g}\int_{P_1}^{P_2} P\,dP$$

$$\left(\frac{Q_{sc}P_{sc}T}{0.006328\ kT_{sc}A}\right)(L-0) = -\frac{1}{2\,Z\ \mu g}(P_2^2 - P_1^2)$$

$$Q_{sc} = \frac{0.003164\ T_{sc}Ak\ (P_1^2 - P_2^2)}{P_{sc}T\,(Z\ \mu_g)L}$$

Set prices $P_{sc} = 14{,}7$ psi and $T_{sc} = 520°$ Rankine

$$Q_{sc} = \frac{0.111924\ Ak\ (P_1^2 - P_2^2)}{T\ L\,(Z\ \mu_g)}$$

Where, T is the temperature in Rankine. P is the upstream and downstream pressure in psi. A is the cross-sectional area in ft^2. L is the length of the reservoir in ft. k is the absolute permeability in md. Z is the compression factor found on the Standing-Katz chart. And μ_g is the gas viscosity searched by the LGE Method (Lee Gonzales Eakin Method)

RESULTS AND DISCUSSION

Field data

An ideal gas flows in a linear porous medium with the following data:

- Specific grafity 0.72
- Temperature 140°F
- Upstream pressure 2100 psi
- Downstream pressure 1894.73 psi
- Cross-sectional area 4500 ft^2
- Total length 2500 ft
- Absolute permeability 60 mD
- Temperature at standard condition 520°R
- Pressure at standard conditions 14.7 psi

The gas flow rate in units of scf/day is:

Derivation of equations for fluid flow in a reservoir with specific gravity data, temperature, upstream and downstream pressures, cross-sectional area, length and absolute permeability. Followed by the calculation of the average pressure, pseudo-critical temperature and pressure, pseudo-reduce of temperature and pressure, then obtained the gas compressibility factor from the Standing Kart Chart. Followed by the calculation of the molecular weight, density and viscosity of the gas, the gas flow rate can be obtained in units of scf/day. The manual calculations are quite complicated, so numerical calculations using the Fortran 99 soft program (Mourik, 2005) are used for calculations with large and repetitive data.

Flowchart

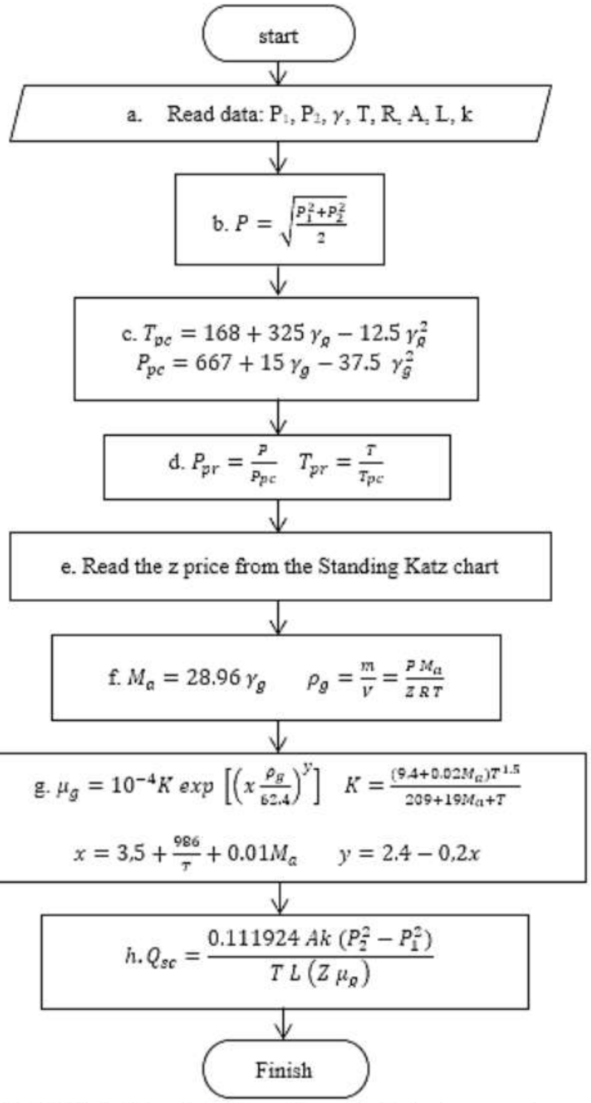

FIGURE 1. Flowchart of gas flow calculation in reservoir

Caption FIGURE 1
a. Read data
b. Calculating average pressure
c. Calculating pseudo critical temperature and pressure
d. Calculating pseudo reduce temperature and pressure
e. With pseudo reduce temperature and pressure data, the Z value is obtained from the Standing Kart Chart
f. Calculate the molecular weight and density of gas from the specific values of gravity and gas density from the real gas equation
g. Calculating gas viscosity using LGE method
h. Calculate the gas flow rate in the reservoir

Calculations using the Fortran 95 soft program

a. Pressure up: pup = 2100 (psia)
   Pressure down: pdown =1894.73 (psia)
   Specific gravity of gas: ggas =0.72
   Temperature: T=t =600 (oRankien / oR)
   General gas constant: R= r =10.73 (psia ft^3/(lb-mole R)
   Cross-sectional area: A= a =4500 (ft^2)
   Reservoir length: L= l =2500 (ft)
   Permeability: k= kk =60 (ft^2)

b.
```
pave=dsqrt((pup**2.0d0+pdown**2.0d0)/2.0d0)
```

c.
```
tpc=168.0d0+328.0d0*ggas-12.5d0*ggas**2.0d0
ppc=677.0d0+15.0d0*ggas-37.5d0*ggas**2.0d0
```

d.
```
pr=t/tpc
ppr=pave/ppc
```

e. Followed by reading the compressibility factor for natural gas z using the Standing Kart Chart, obtained z = 0.78. See Figure 2

f.
```
ma=ggas*28.96d0
rhog=(pave*ma)/(z*r*t)
```

g.
```
x=3.5d0+986.0d0/t+0.01d0*ma
y=2.4d0-0.2d0*x
k=((9.4d0+0.02d0*ma)*t**1.5d0)/(209.0d0+19.0d0*ma+t)
mug=10.0d0**(-4.0d0)*k*dexp(x*(rhog/62.4d0)**y)
```

h.
```
qsc=(0.111924d0*a*kk*(pup**2.0d0-pdown**2.0d0))/(t*l*z*mug)
```
   Gas flow rate calculation result = Qsc (scf/day) = qsc = 1.226433E+06

Manual flow rate calculation

- Calculation of average pressure

$$\bar{P} = \sqrt{\frac{{P_{up}}^2 + {P_{down}}^2}{2}} = \sqrt{\frac{2100^2 + 1894.73^2}{2}} = 2000\ psi$$

- Calculation of pseudo critical temperature and pressure

$$T_{pc} = 168 + 325\gamma_g - 12.5\gamma_g^2 = 168 + 325\ .0{,}72 - 12.5 0{,}72^2 = 395.5\ °R$$

$$P_{pc} = 677 + 15.0\gamma_g - 37.5\gamma_g^2 = 677 + 15.0\ \ 0.72 - 37.5\ 0.72^2$$
$$= 668{,}4\ psia$$

- Calculation of temperature 140°F = 140 + 459.67 = 600 °R
- Calculation of pseudo reduce temperature and pressure

$$P_{pr} = \frac{\bar{P}}{P_{PC}} = \frac{2000}{668{,}4} = 2.99$$
$$T_{pr} = \frac{T}{T_{pc}} = \frac{600}{395.5} = 1.52$$

- Followed by reading the compressibility factor for natural gas z using the Standing Kart Chart, obtained z = 0.78. See Figure 2

- Calculation of Natural Gas Viscosity Using the Lee Gonzales Eakin Method or LGE Method

$$\gamma_g = \frac{M_a}{28.96}$$

Then the molecular weight of the gas is

$$M_a = \gamma_g\ 28.96 = 0.72\ \ 28.96 = 20.85\ gram/mol$$

$$x = 3.5 + \frac{986}{T} + 0.01 M_a = 3.5 + \frac{986}{600} + 0.01\ 20.85 = 5.35$$

$$y = 2.4 + 0.2\ x = 2.4 - 0.2\ \ 5.35 = 1.33$$

$$K = \frac{(9.4 + 0.02\ M_a) T^{1,5}}{209 + 19 M_a + T} = \frac{(9.4 + 0.02\ \ 20.85) 600^{1.5}}{209 + 19\ 20.85 + 600} = 119{,}72$$

- Calculation of gas density

$$\rho_g = \frac{m}{V} = \frac{P M_a}{ZRT} = \frac{2000\ \ 20.85}{0.78\ \ 10.73\ 600} = 8.3\ \frac{lb}{ft^3}$$

so the value of viscosity is

$$\mu_g = 10^{-4} K\ exp\left[x\left(\frac{\rho_g}{62.4}\right)^y\right] = 10^{-4}.119.72\ exp\left[5.35\left(\frac{8{,}3}{62.4}\right)^{1{,}33}\right] = 0.0173\ cp$$

- Then the gas flow rate is

$$Q_{sc} = \frac{0.111924\ A\ k\ (P_{up}^2 - P_{down}^2)}{T\ L\ Z\ \mu_g} = \frac{0.111924\ .4500\ .60\ (2100^2 - 1894.73^2)}{600\ .\ 2500.\ 0.78\ .\ 0.0173}$$
$$= 1{,}224{,}243.9\ scf/day$$

CONCLUSIONS AND RECOMMENDATIONS

1. The derived equation can be used to calculate the linear flow rate of a compressible fluid or gas in a reservoir
2. The calculation of the flow rate manually has been done the results are: 1,224,243.9 scf/day
3. Numerical flow rate calculation has been done the result is: 1.226433E+06 scf/day
4. Numerical calculations with the Fortran computer program can be used because they have been validated by manual calculations and to facilitate repeated calculations.

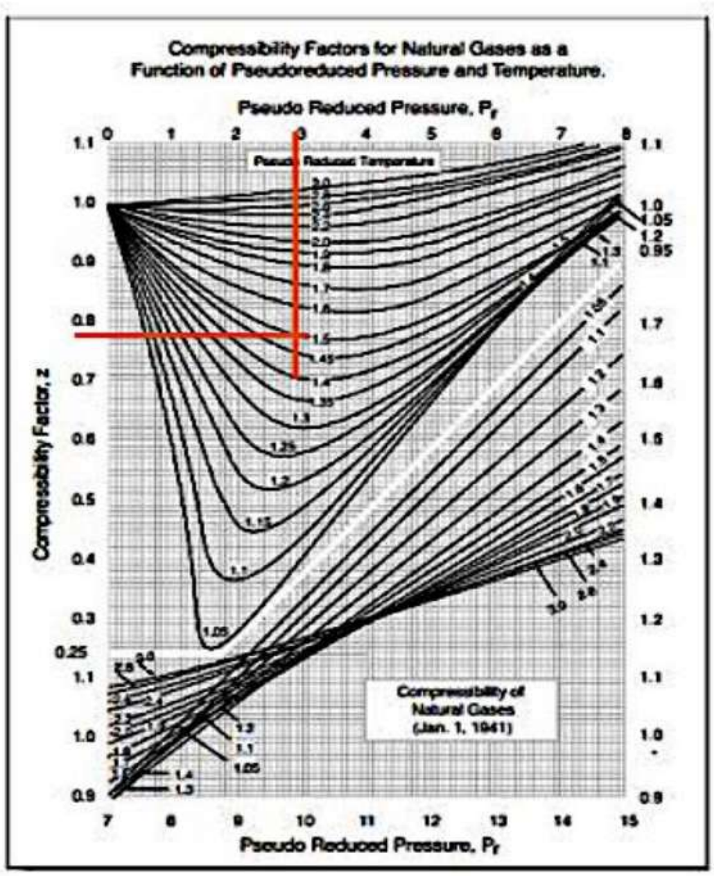

FIGURE 2. Reading of the compressibility factor for natural gas z using a Standing Kart Chart

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