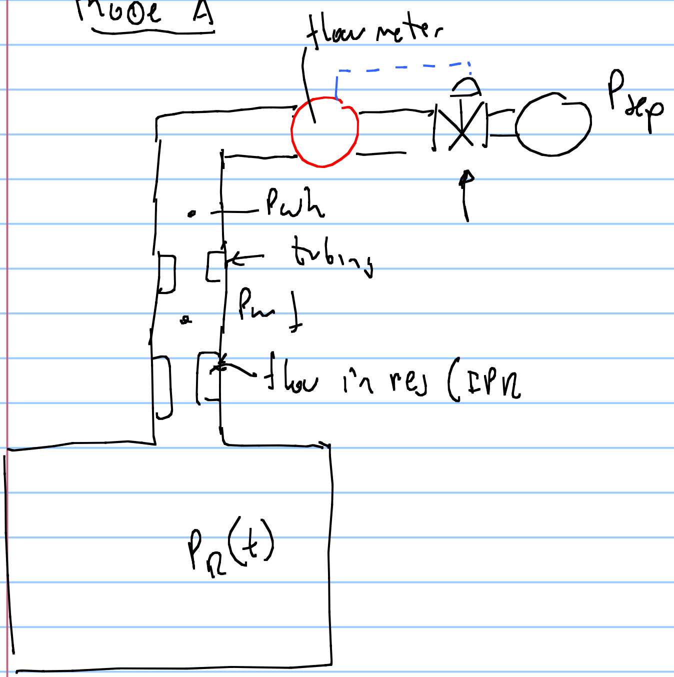
# Week 2 - Day 6:

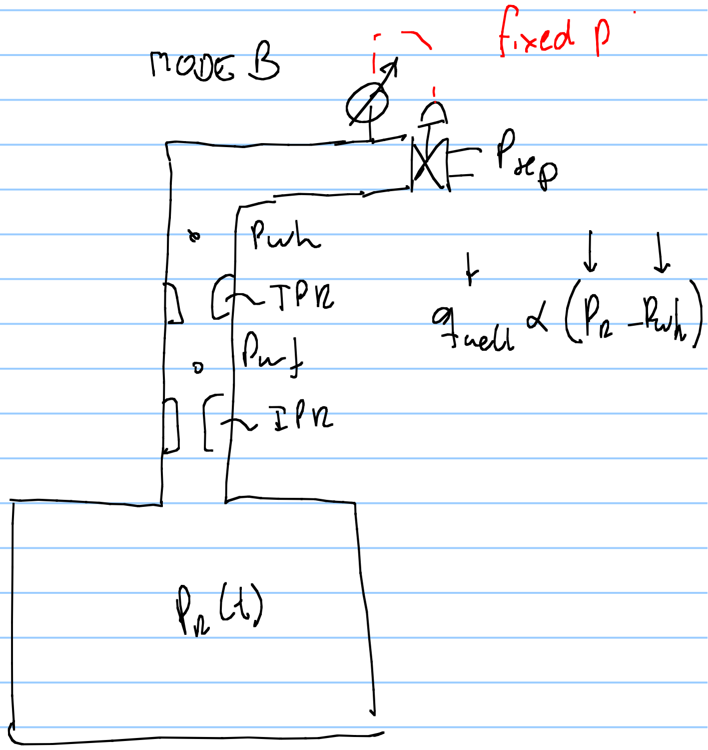
## Production modes of wells and field

MODE A

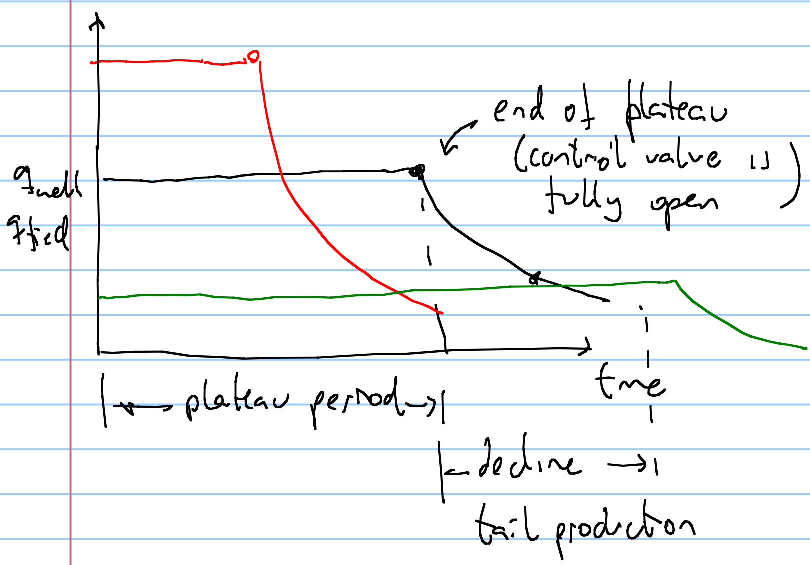


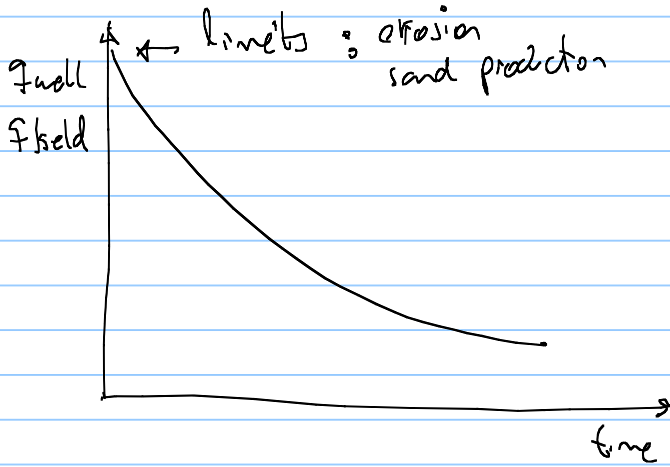

Constant production mode

MODE B




constant pressure mode




- New development with standalone processing facilities
- Big size
- typically for gas (offshore), LNG
  predefined delivery contract
  long term

- Produce as much as possible as early as possible
- Satellite fields (medium to small size)

the production is routed to existing processing facilities with spare capacity

Rule of thumb for defining plateau for oil reservoirs:

yearly outake = 0.1 . TRR (total recoverable reserve)

$TRR = R.F . G$ ← initial gas in place

$R.F . N$ ← initial oil in place

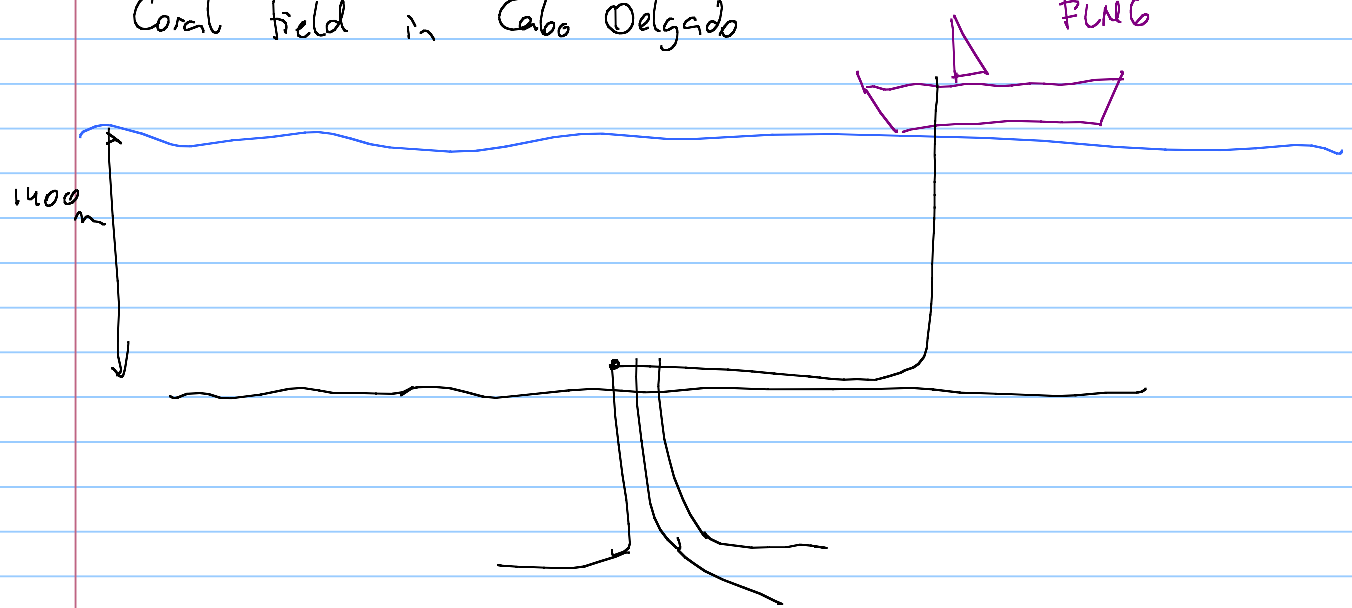
↑ recovery factor

$$q_{plateau} = \frac{0.1 \; TRR}{N_{operational\ days\ per\ year}}$$

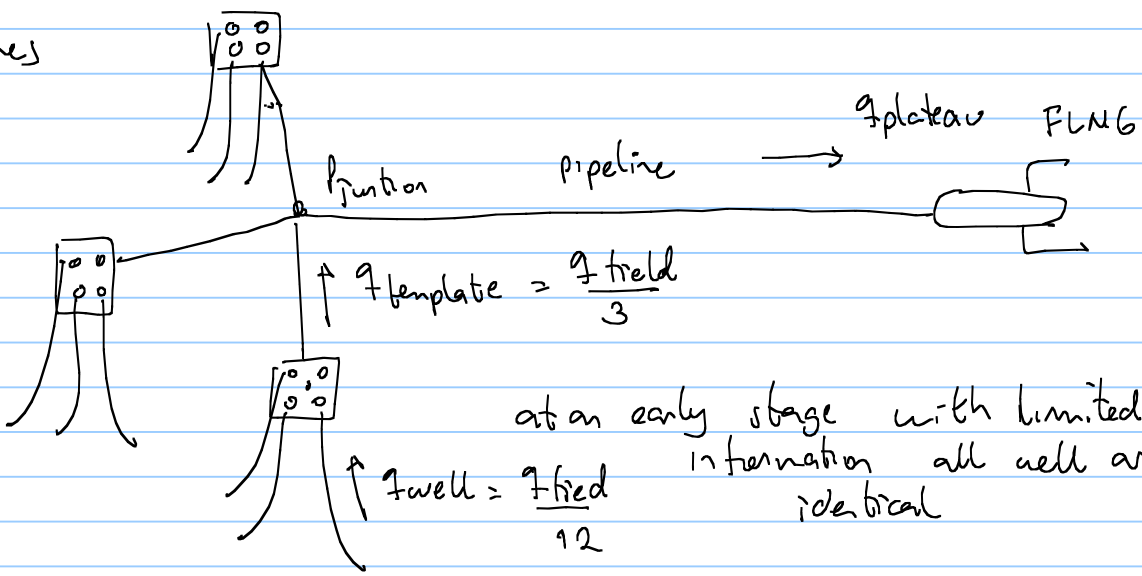
for gas

yearly outake = (0.03-0.05) TRR

Coral field in Cabo Delgado

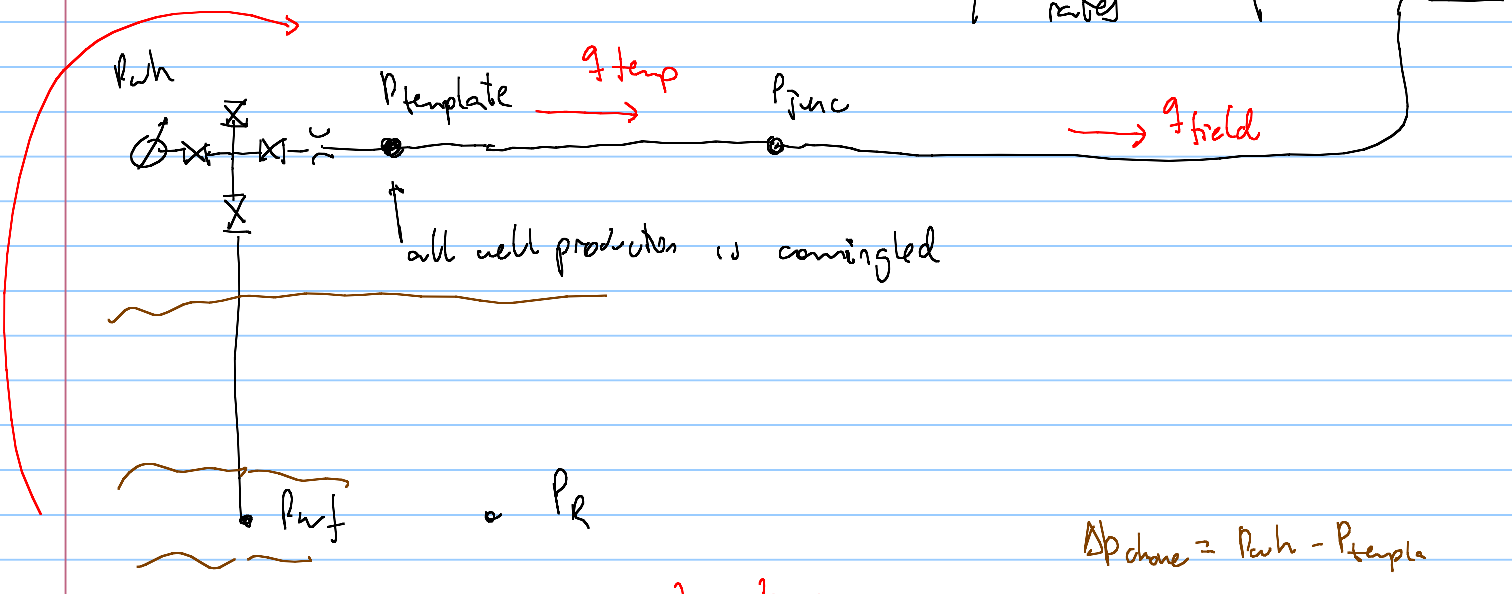



identical flowlines

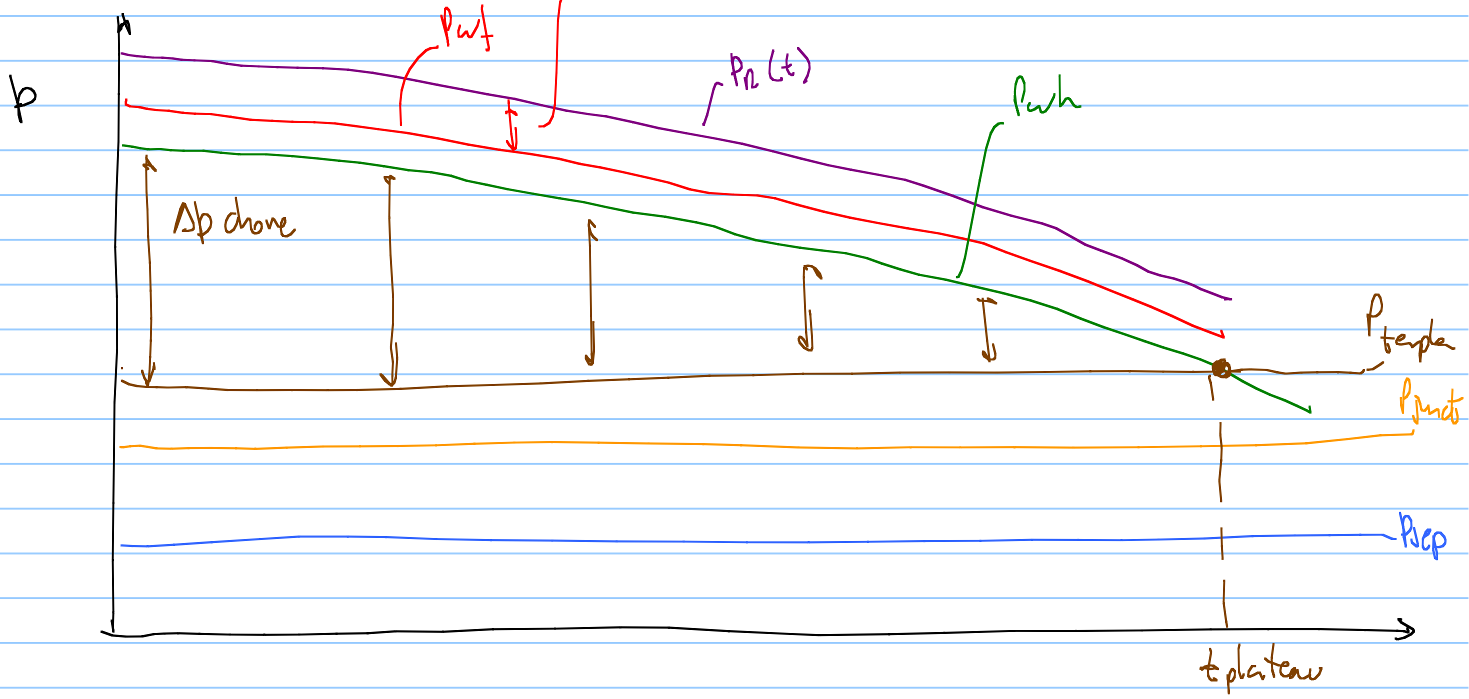


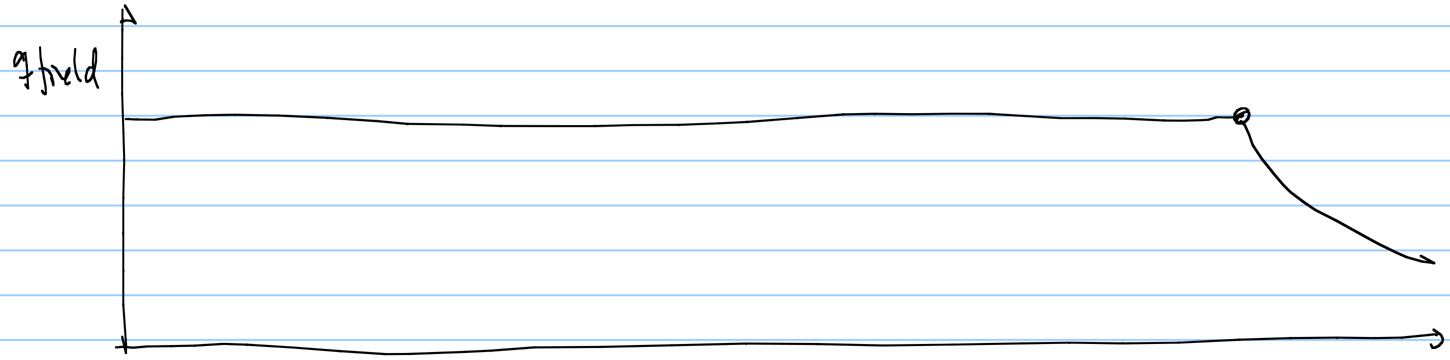

at an early stage with limited information all well are identical

Production scheduling {define the field and well rates}

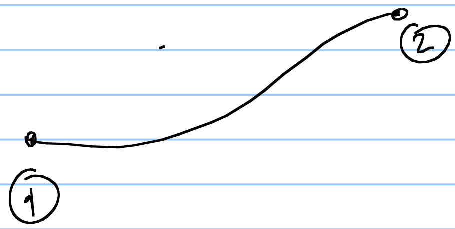



$\Delta p_{choke} = P_{wh} - P_{template}$



- **Pressure drop for liquids: undersaturated oil + water**

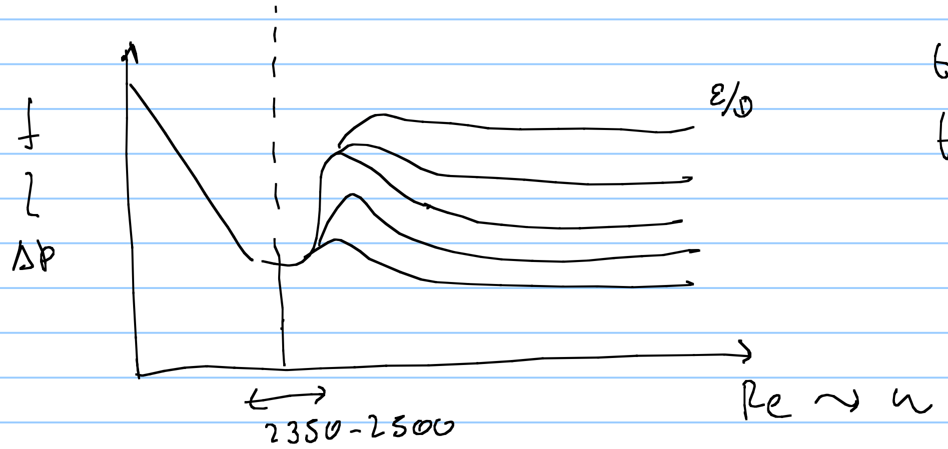



$$z_1 + \cancel{\frac{1}{2}\frac{v_1^2}{g}} + \frac{P_1}{\rho g} = \frac{P_2}{\rho g} + z_2 + \cancel{\frac{1}{2}\frac{v_2^2}{g}} + \frac{f\,L}{\Phi}\frac{v^2}{2g}$$

tubing $P_1 = f(P_2, q)$

tubing $P_2 = f(P_1, q)$

tubing $q = f(P_1, P_2)$

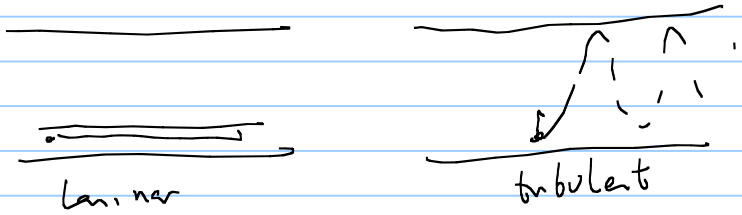



$$q = V \cdot A = \frac{\pi \Phi^2}{4} \cdot V$$

$$V = \left(\frac{q}{\pi \Phi^2} \cdot 4\right)$$

$$V^2 = \frac{q^2\, 16}{\pi \Phi^2}$$

laminar




$$f_{laminar} = \frac{64}{Re} \qquad f_{turbulent} =$$

Colebrook-White equation

implicit $\longrightarrow$ $$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7\,\Phi} + \frac{2.51}{Re\sqrt{f}}\right)$$

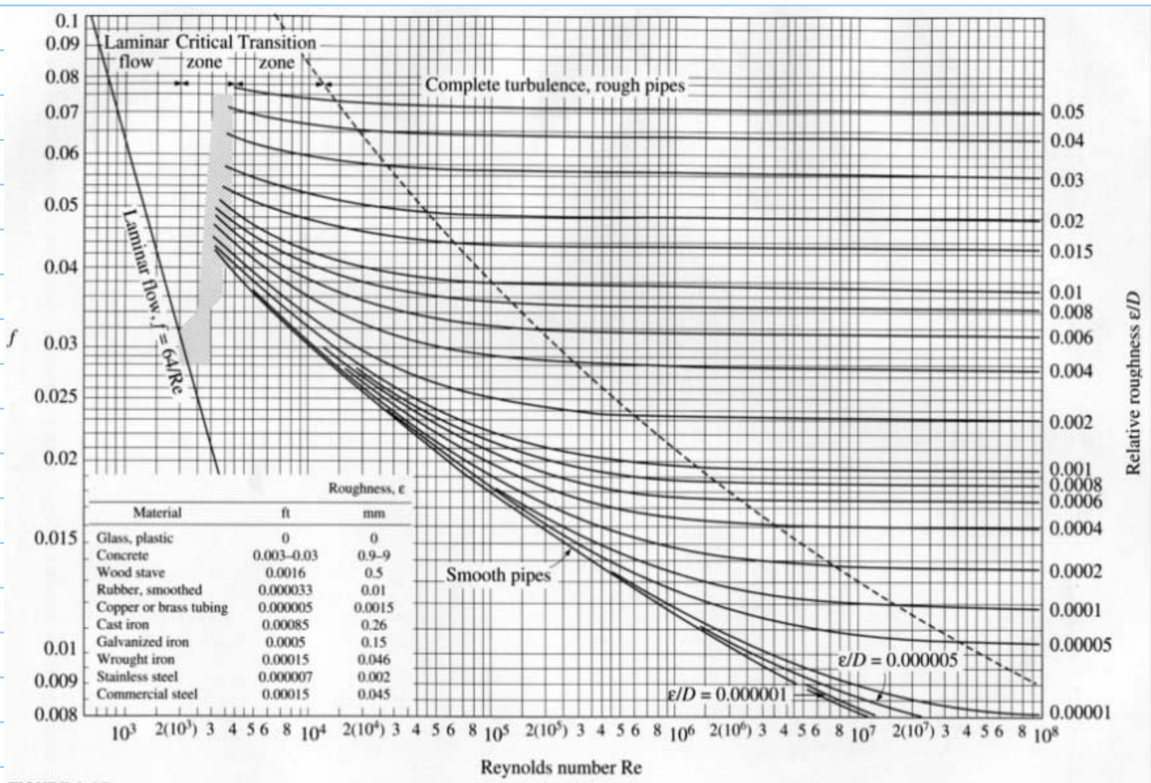



**FIGURE A-27**
The Moody chart for the friction factor for fully developed flow in circular tubes.

https://en.wikipedia.org/wiki/Darcy_friction_factor_formulae    all expressions for friction factor

Table of Colebrook equation approximations

| Equation | Author | Year | Range | Ref |
|---|---|---|---|---|
| $f = .0055\left[1+\left(2\times10^4\cdot\frac{\varepsilon}{D}+\frac{10^6}{\mathrm{Re}}\right)^{\frac{1}{3}}\right]$ | Moody | 1947 | $Re = 4000 - 5.10^8$ <br> $\varepsilon/D = 0 - 0.01$ | |
| $f = .094\left(\frac{\varepsilon}{D}\right)^{0.225}+0.53\left(\frac{\varepsilon}{D}\right)+88\left(\frac{\varepsilon}{D}\right)^{0.44}\cdot\mathrm{Re}^{-\Psi}$ <br> where <br> $\Psi = 1.62\left(\frac{\varepsilon}{D}\right)^{0.134}$ | Wood | 1966 | $Re = 4000 - 5.10^7$ <br> $\varepsilon/D = 0.00001 - 0.04$ | |
| $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.715}+\frac{15}{\mathrm{Re}}\right)$ | Eck | 1973 | | |
| $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{5.74}{\mathrm{Re}^{0.9}}\right)$ | Swamee and Jain | 1976 | $Re = 5000 - 10^8$ <br> $\varepsilon/D = 0.000001 - 0.05$ | |
| $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.71}+\left(\frac{7}{\mathrm{Re}}\right)^{0.9}\right)$ | Churchill | 1973 | Not specified | |
| $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.715}+\left(\frac{6.943}{\mathrm{Re}}\right)^{0.9}\right)$ | Jain | 1976 | | |
| $f = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12}+\frac{1}{(\Theta_1+\Theta_2)^{1.5}}\right]^{\frac{1}{12}}$ <br> where <br> $\Theta_1 = \left[-2.457\ln\left(\left(\frac{7}{\mathrm{Re}}\right)^{0.9}+0.27\frac{\varepsilon}{D}\right)\right]^{16}$ <br> $\Theta_2 = \left(\frac{37530}{\mathrm{Re}}\right)^{16}$ | Churchill | 1977 | | |
| $\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7065}-\frac{5.0452}{\mathrm{Re}}\log\left(\frac{1}{2.8257}\left(\frac{\varepsilon}{D}\right)^{1.1098}+\frac{5.8506}{\mathrm{Re}^{0.8981}}\right)\right]$ | Chen | 1979 | $Re = 4000 - 4.10^8$ | |
| $\frac{1}{\sqrt{f}} = 1.8\log\left[\frac{\mathrm{Re}}{0.135\mathrm{Re}(\varepsilon/D)+6.5}\right]$ | Round | 1980 | | |
| $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{4.518\log\left(\frac{\mathrm{Re}}{7}\right)}{\mathrm{Re}\left(1+\frac{\mathrm{Re}^{0.52}}{29}(\varepsilon/D)^{0.7}\right)}\right)$ | Barr | 1981 | | |
| $\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7}-\frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon/D}{3.7}-\frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon/D}{3.7}+\frac{13}{\mathrm{Re}}\right)\right)\right]$ <br> or <br> $\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7}-\frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon/D}{3.7}+\frac{13}{\mathrm{Re}}\right)\right]$ | Zigrang and Sylvester | 1982 | | |
| $\frac{1}{\sqrt{f}} = -1.8\log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11}+\frac{6.9}{\mathrm{Re}}\right]$ | Haaland[9] | 1983 | | |
| $\frac{1}{\sqrt{f}} = \Psi_1-\frac{(\Psi_2-\Psi_1)^2}{\Psi_3-2\Psi_2+\Psi_1}$ <br> or <br> $\frac{1}{\sqrt{f}} = 4.781-\frac{(\Psi_1-4.781)^2}{\Psi_2-2\Psi_1+4.781}$ <br> where <br> $\Psi_1 = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{12}{\mathrm{Re}}\right)$ | Serghides | 1984 | | |

| | | | | |
|---|---|---|---|---|
| $\Psi_2 = -2\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51\Psi_1}{\mathrm{Re}}\right)$ <br> $\Psi_3 = -2\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51\Psi_2}{\mathrm{Re}}\right)$ | | | | |
| $A = 0.11\left(\frac{68}{Re} + \varepsilon\right)^{0.25}$ <br> if $A \geq 0.018$ then $f = A$ and if $A < 0.018$ then $f = 0.0028 + 0.85A$ | Tsal | 1989 | | |
| $\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7} + \frac{95}{\mathrm{Re}^{0.983}} - \frac{96.82}{\mathrm{Re}}\right)$ | Manadilli | 1997 | $Re = 4000 - 10^8$ <br> $\varepsilon/D = 0 - 0.05$ | |
| $\frac{1}{\sqrt{f}} = -2\log\left\{\frac{\varepsilon/D}{3.7065} - \frac{5.0272}{\mathrm{Re}}\log\left[\frac{\varepsilon/D}{3.827} - \frac{4.657}{\mathrm{Re}}\log\left(\left(\frac{\varepsilon/D}{7.7918}\right)^{0.9924} + \left(\frac{5.3326}{208.815+\mathrm{Re}}\right)^{0.9345}\right)\right]\right\}$ | Monzon, Romeo, Royo | 2002 | | |
| $\frac{1}{\sqrt{f}} = 0.8686\ln\left[\frac{0.4587\mathrm{Re}}{(S-0.31)^{\frac{S}{(S+1)}}}\right]$ <br> where: <br> $S = 0.124\mathrm{Re}\frac{\varepsilon}{D} + \ln(0.4587\mathrm{Re})$ | Goudar, Sonnad | 2006 | | |
| $\frac{1}{\sqrt{f}} = 0.8686\ln\left[\frac{0.4587\mathrm{Re}}{(S-0.31)^{\frac{S}{(S-0.9633)}}}\right]$ <br> where: <br> $S = 0.124\mathrm{Re}\frac{\varepsilon}{D} + \ln(0.4587\mathrm{Re})$ | Vatankhah, Kouchakzadeh | 2008 | | |
| $\frac{1}{\sqrt{f}} = \alpha - \frac{\alpha + 2\log\left(\frac{\mathrm{B}}{\mathrm{Re}}\right)}{1 + \frac{2.18}{\mathrm{B}}}$ <br> where <br> $\alpha = \frac{0.744\ln(\mathrm{Re}) - 1.41}{1 + 1.32\sqrt{\varepsilon/D}}$ <br> $\mathrm{B} = \frac{\varepsilon/D}{3.7}\mathrm{Re} + 2.51\alpha$ | Buzzelli | 2008 | | |
| $f = \frac{6.4}{(\ln(\mathrm{Re}) - \ln(1 + .01\mathrm{Re}\frac{\varepsilon}{D}(1 + 10\sqrt{\frac{\varepsilon}{D}})))^{2.4}}$ | Avci, Kargoz | 2009 | | |
| $f = \frac{0.2479 - 0.0000947(7 - \log\mathrm{Re})^4}{(\log\left(\frac{\varepsilon/D}{3.615} + \frac{7.366}{\mathrm{Re}^{0.9142}}\right))^2}$ | Evangelides, Papaevangelou, Tzimopoulos | 2010 | | |
| $f = 1.613\left[\ln\left(0.234\varepsilon^{1.1007} - \frac{60.525}{Re^{1.1105}} + \frac{56.291}{Re^{1.0712}}\right)\right]^{-2}$ | Fang | 2011 | | |
| $f = \left[-2\log\left(\frac{2.18\beta}{Re} + \frac{\varepsilon}{3.71}\right)\right]^{-2}$, $\beta = \ln\frac{Re}{1.816\ln\left(\frac{1.1Re}{\ln(1+1.1Re)}\right)}$ | Brkić | 2011 | | |
| $f = 1.325474505\log_e\left(A - 0.8686068432B\log_e\left(A - 0.8784893582B\log_e\left(A + (1.665368035B)^{0.8373492157}\right)\right)\right)^{-2}$ <br> where <br> $A = \frac{\varepsilon/D}{3.7065}$ <br> $B = \frac{2.5226}{\mathrm{Re}}$ | Alashkar | 2012 | | |

Haaland

Prof @ NTNU

~ 1983

explicit

$$\frac{1}{\sqrt{f}} = -1.8\log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \left(\frac{6.9}{Re}\right)\right]$$

$$f = \left[-1.8\log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \left(\frac{6.9}{Re}\right)\right]\right]^{-2}$$

friction factor

Beware !

Darcy-weisbach $\qquad f = 4 \cdot f_{FANNING}$

Fanning (american) $\qquad f_{FANNING} = \frac{\tau}{\frac{1}{2}\rho v^2}$

$$f_{DARCY} = \frac{\tau}{\frac{1}{8}\rho v^2}$$

Class exercise IPR-TPR equilibrium for undersaturated oil well

(peregrino field, offshore Brazil).

| | | | | IPR | | TPR |
|---|---|---|---|---|---|---|
| $p_R$ | bara | 231 | | | | |
| J, for oil flow | Sm^3/d/bar | 70 | | | | |
| L, tubing length | m | 2340 | | | | |
| d, tubing diameter | m | 0.14 | | pwf | qo | pwf |
| e, tubing roughness | m | 0.00010 | | [bara] | [Sm^3/d] | [bara] |
| teta, tubing angle | [deg] | 90 | | 231 | | |
| muo, oil viscosity | [Pa s] | 0.1 | | 208 | | |
| rhoo, oil density | [kg/m^3] | 897 | | 185 | | |
| pwh, wellhead pressure | [bara] | 7 | | 162 | | |
| | | | | 139 | | |
| | | | | 116 | | |
| | | | | 92 | | |
| | | | | 69 | | |
| | | | | 46 | | |
| | | | | 23 | | |
| | | | | 0 | | |

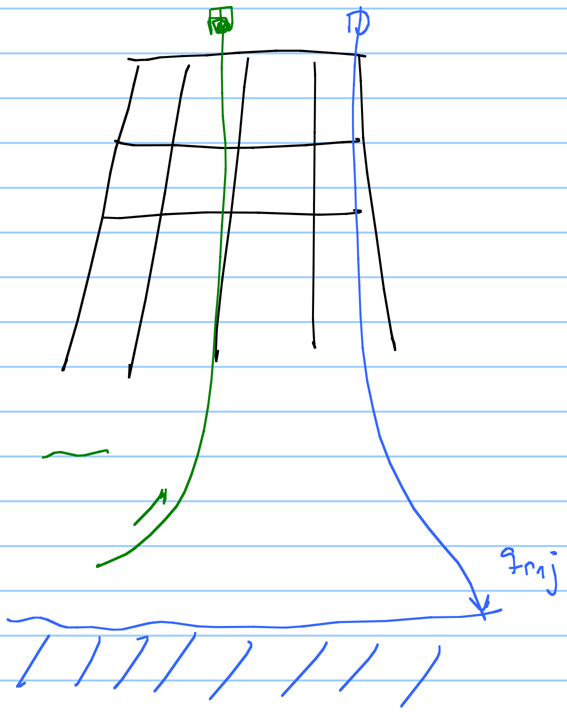
$q_o = J\,(P_R - P_{wf})$

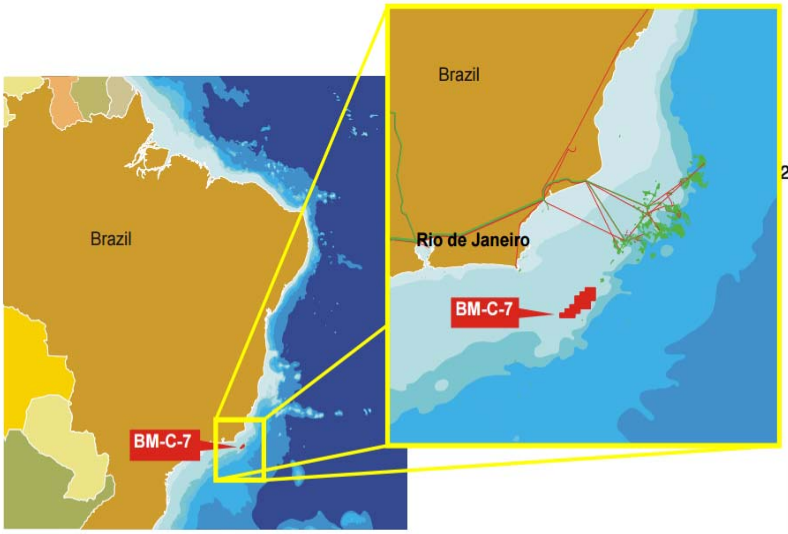
pressure required at well bottom to flow against 7 bara

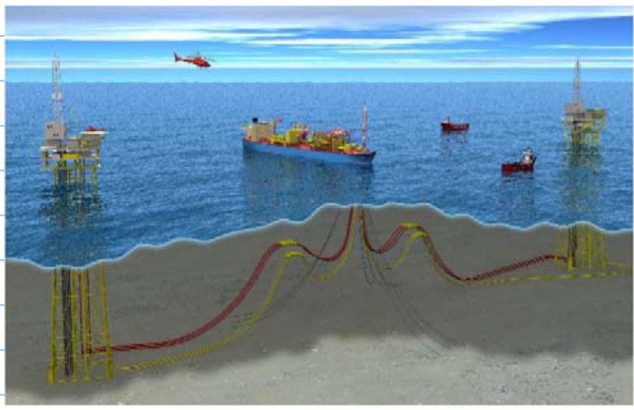
tubing $P_1$ ?

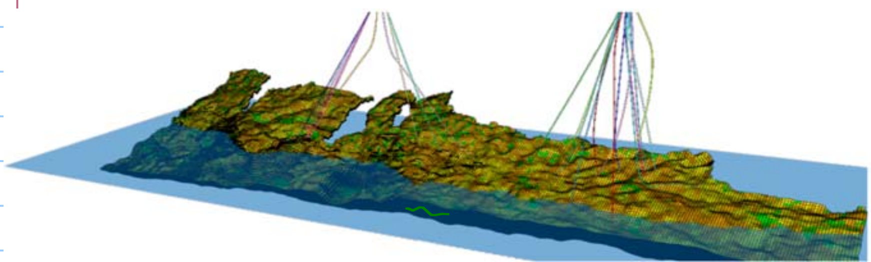
tubing $P_2$ ?

$P_{wh} = 7$ bara





- LQ
- Drilling module
- Movable drill rig
- Electrical plant
- Wellheads
- Booster pumps
- Water Injection
- Uptime 99% bracket

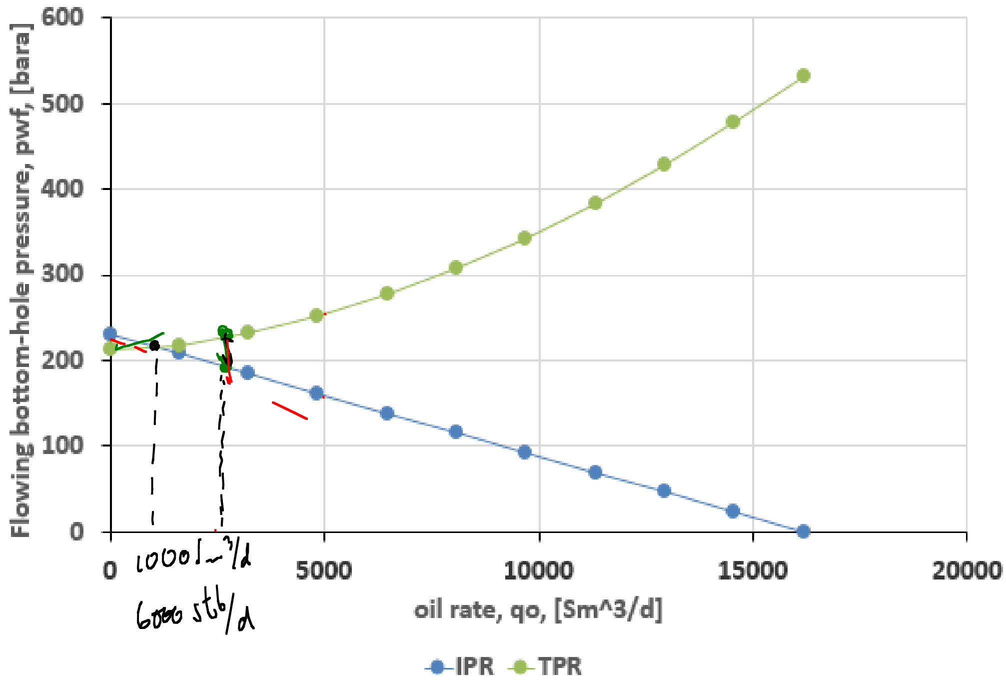
| | | |
|---|---|---|
| $p_R$ | bara | 231 |
| J, for oil flow | Sm^3/d/bar | 70 |
| L, tubing length | m | 2340 |
| d, tubing diameter | m | 0.14 |
| e, tubing roughness | m | 0.00010 |
| teta, tubing angle | [deg] | 90 |
| muo, oil viscosity | [Pa s] | 0.1 |
| rhoo, oil density | [kg/m^3] | 897 |
| pwh, wellhead pressure | [bara] | 7 |

| IPR | | TPR |
|---|---|---|
| pwf [bara] | qo [Sm^3/d] | pwf [bara] |
| 231 | 0 | 213 |
| 208 | 1618 | 218 |
| 185 | 3236 | 233 |
| 162 | 4853 | 252 |
| 139 | 6471 | 277 |
| 116 | 8089 | 307 |
| 92 | 9707 | 343 |
| 69 | 11325 | 383 |
| 46 | 12942 | 428 |
| 23 | 14560 | 477 |
| 0 | 16178 | 531 |

3236 Sm³/d

$\Delta p_{pump} = 233 - 185$

$\Delta p_{pump} = 48$ bar




Electric submersible pump (ESP) → as close as possible to formation

↳ installed as vertical as possible

↳ takes liquid ONLY !

↳ typical lifetime 2 years

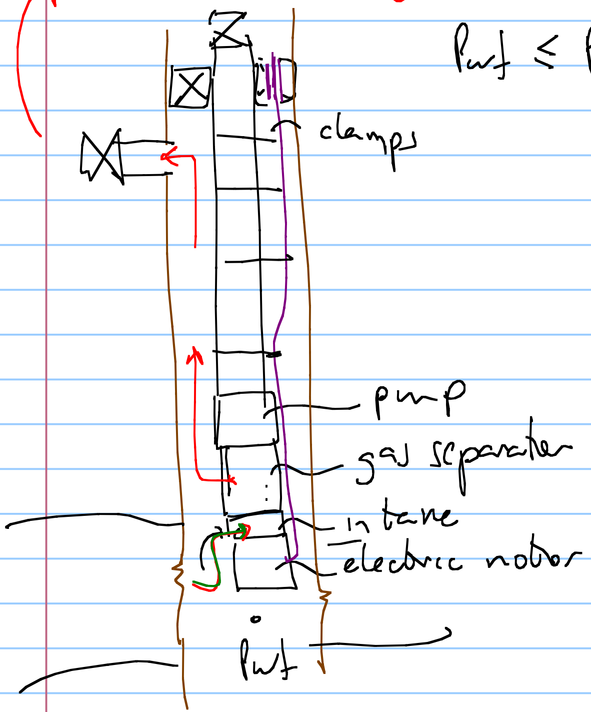
10% GVF high tolerance

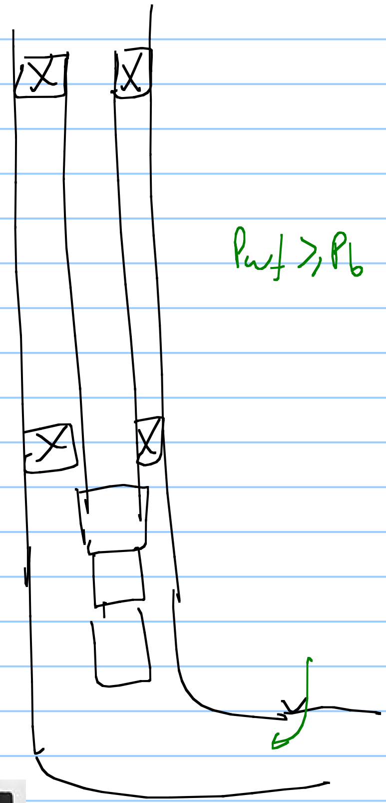
↳ gas volume fraction

producing gas through the annulus

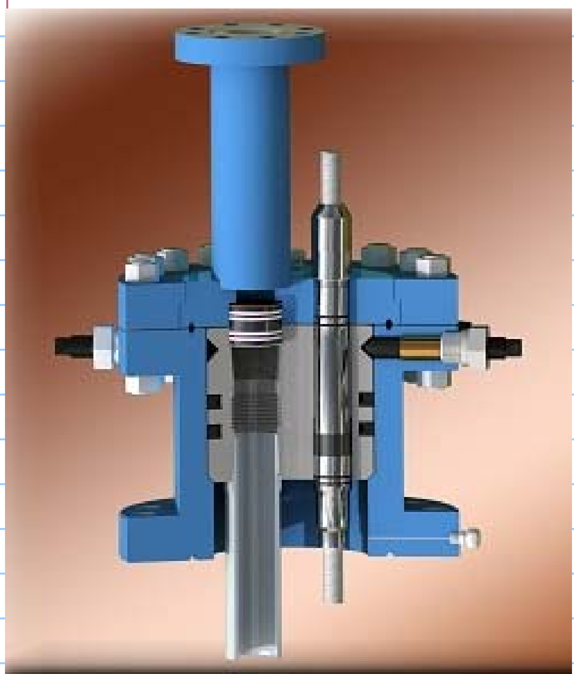
$P_{wf} \leq P_b(T_R)$

bubble point pressure



$P_{wf} \geq P_b$



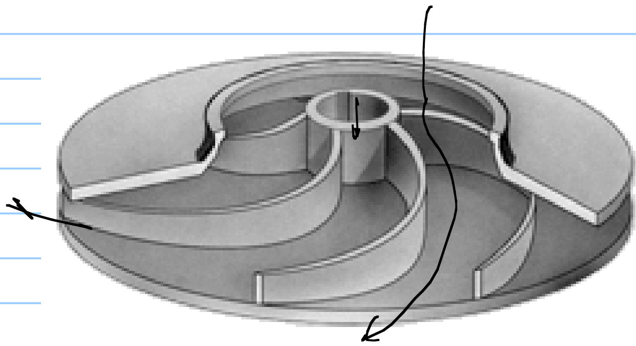
Armais

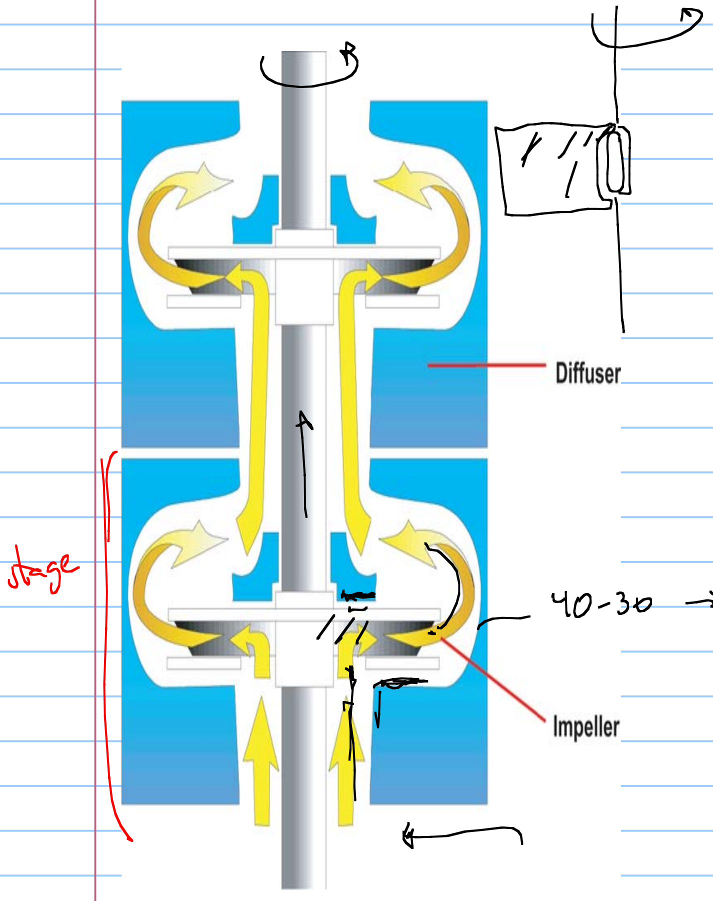
Arutunoff ≈1930

Oklahoma

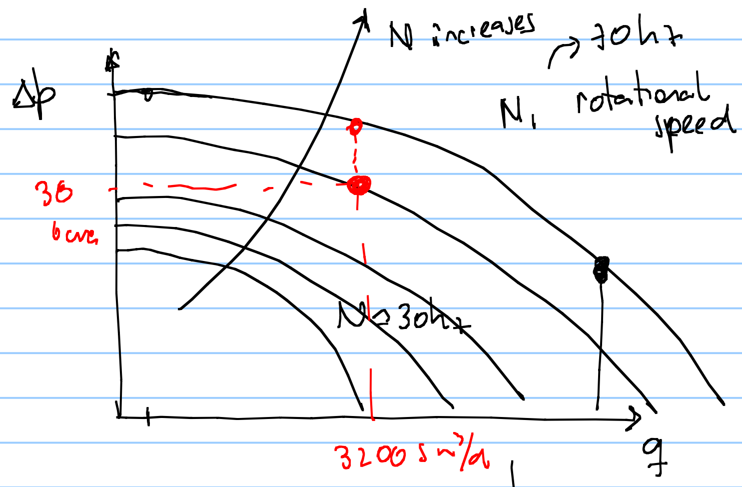
Reda pump

Schlumberger

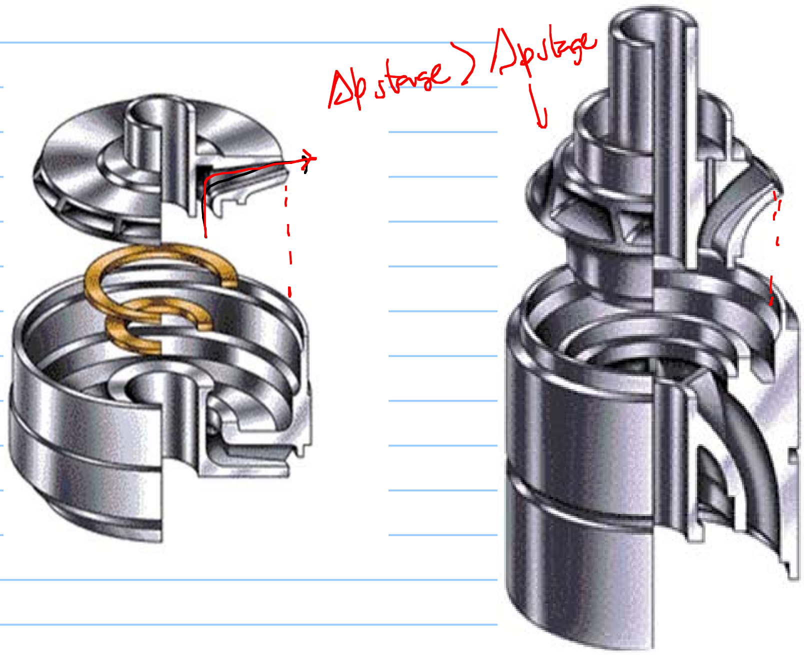


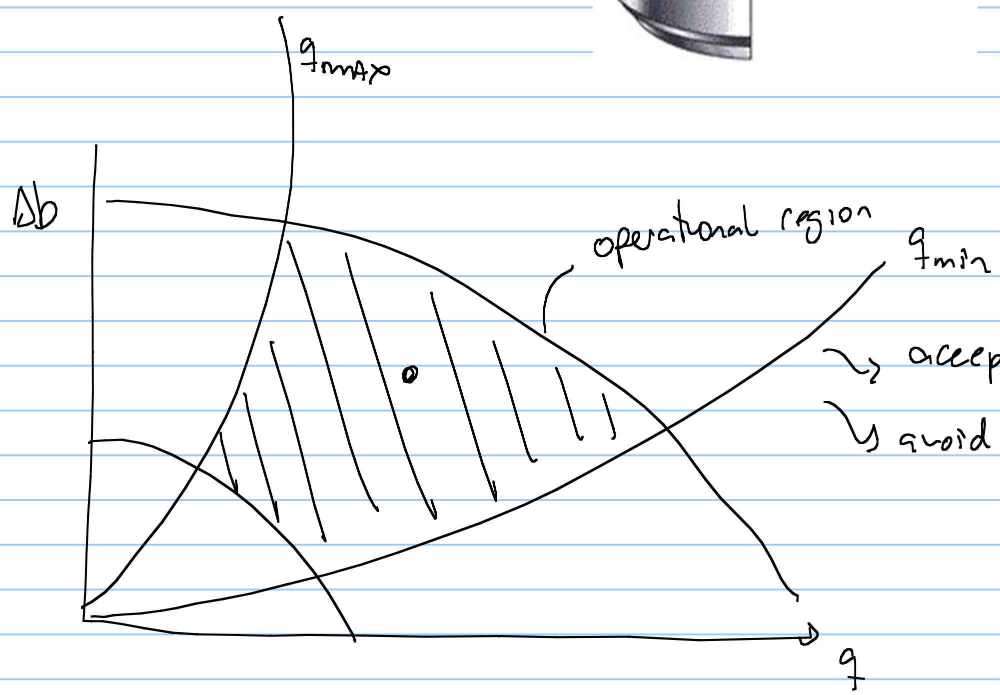



40-30 → 100 sti




Power = q Δp

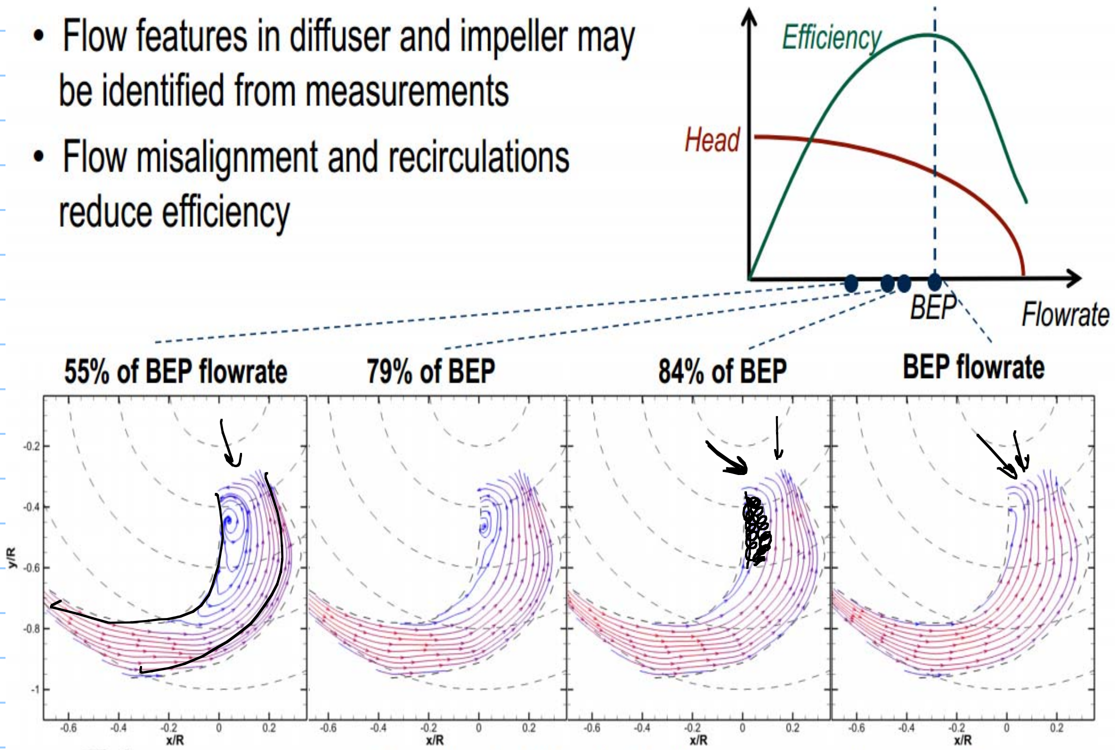



↳ acceptable efficiency
↳ avoid upthrust rotor
downthrust rotor

## PIV measurement in a radial flow stage

- Flow features in diffuser and impeller may be identified from measurements
- Flow misalignment and recirculations reduce efficiency

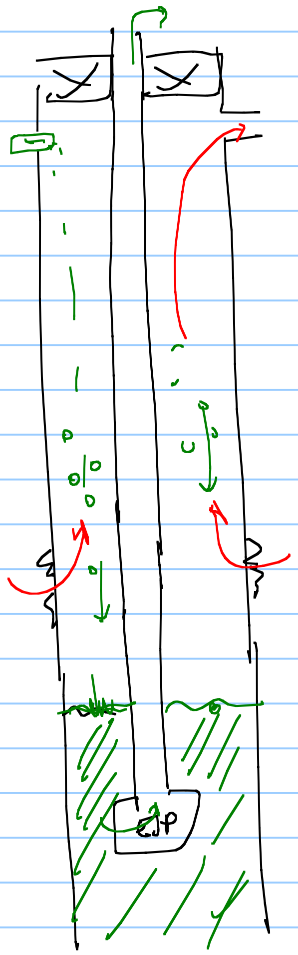



*Example of stall region in diffuser passage (measured)*

ARTIFICIAL LIFT SPE MIDDLE EAST CONFERENCE & EXHIBITION

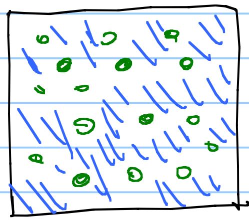
SPE-14MEAL-14017-PP-MS • Measurement and Unsteady Simulation of Internal Flows within Stages • J Dusting

ESP are also used to drain liquid accumulated in gas wellbores



Pressure drop expressions for liquid are also useful to deal with oil + water emulsions ⇝ stable dispersion ⇝ oil in water

water in oil

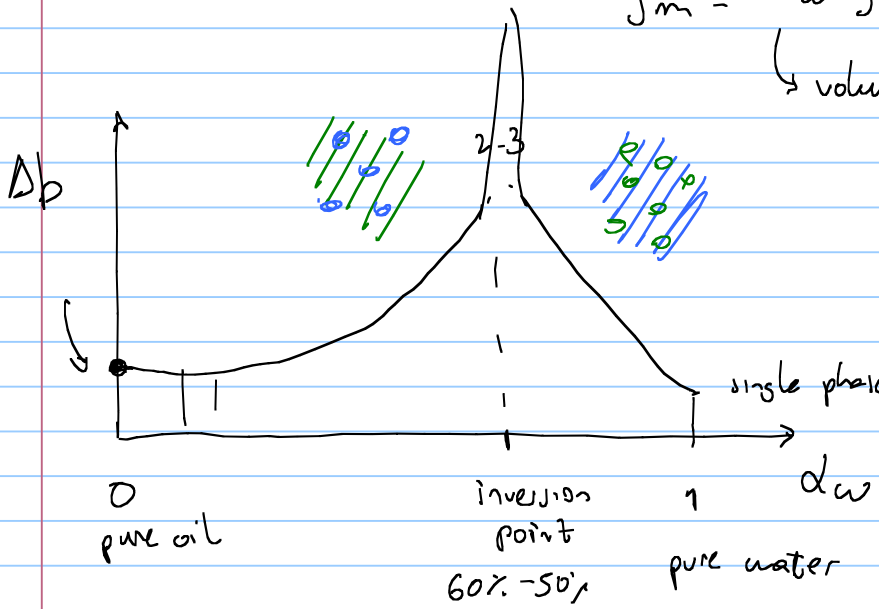


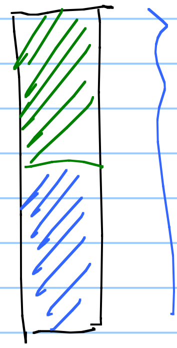
$$\frac{P_1}{\rho g} + z_1 + = \frac{P_2}{\rho g} + z_2 + f \frac{L}{D} \frac{v^2}{2g}$$

$\mu_{mixture}$

$$\rho_m = \alpha_w \rho_w + (1-\alpha_w) \rho_o$$

↳ volume fraction of water $\frac{q_w}{q_o + q_w}$ $\frac{10}{40} =$



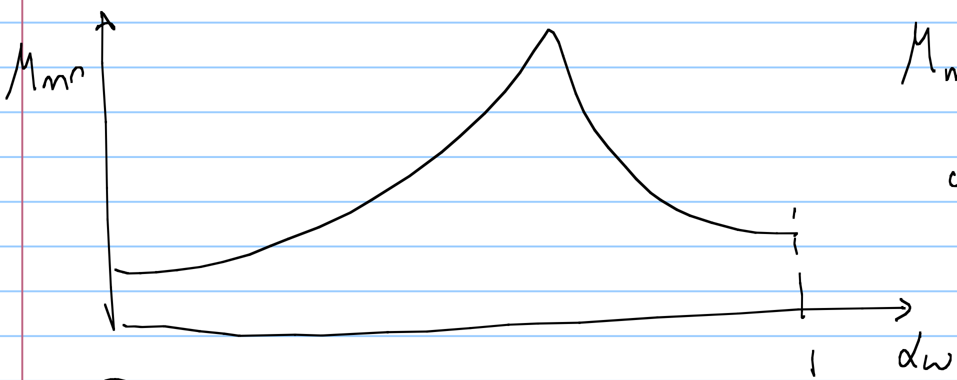



oil continuous

$$\mu_m = \mu_o e^{\alpha_w}$$

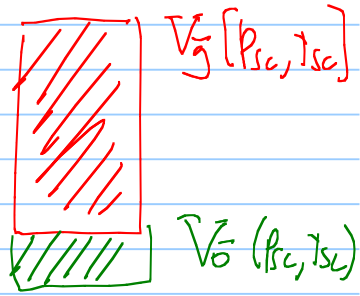
water continuous

$$\mu_m = \mu_w e^{\alpha_o}$$



$u_{fluid} = \frac{q}{\frac{\pi \phi^2}{4}}$ ← $m^3/d$  $q_{\bar{o}}$  $Sm^3/d$

$V_o(P,T)$




$B_g = \frac{q_g(P,T)}{q_{\bar{g}}(P_{sc},T_{sc})} \ll 1$

$GOR = \frac{V_{\bar{g}}}{V_{\bar{o}}}$

$B_o = \frac{q_o(P,T)}{q_{\bar{o}}(P_{sc},T_{sc})}$  oil volume factor

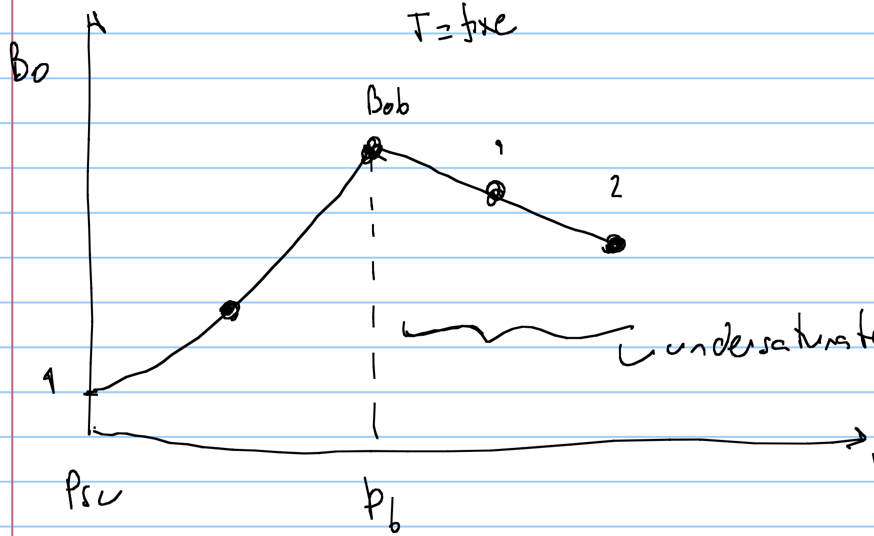
formation volume factor

oil

1.3-1.5  "Normal" → 600-900 scf/stb

1. → 1.05  "Low" → 5-150 scf/stb

1.7 → 2  "high" → 2500 →




undersaturated $B_o$

oil compressibility

$C_o = -\frac{1}{V_o}\frac{\partial V_o}{\partial p}$ thermodynamic definition

$V_o = B_o \cdot V_{sc}$

$C_o = -\frac{1}{\cancel{V_{sc}} B_o}\frac{\partial(B_o \cancel{V_{sc}})}{\partial p}$

$$C_o = -\frac{1}{B_o}\frac{\partial B_o}{\partial p}$$

$$\int_{p_b}^{p>p_b} C_o \, \partial p = \int_{B_{ob}}^{B_o} -\frac{\partial B_o}{B_o}$$

Vazquez Beggs

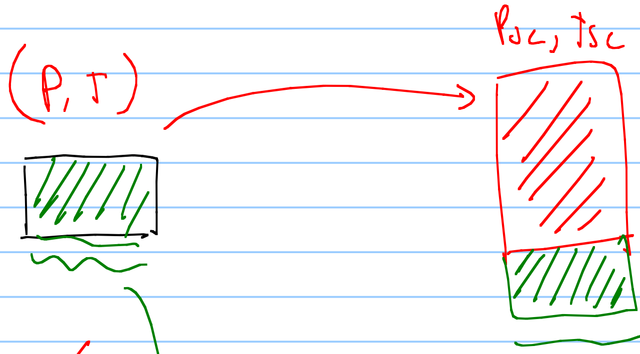
check ✓

$$B_o = B_{ob} \, e^{C_o(p_b - p)}$$

standing Standing

$f(\underbrace{SG_g, SG_o}, GOR, p, T)$

Black oil correlations




$\frac{q}{A}$ ✓ $B_o$

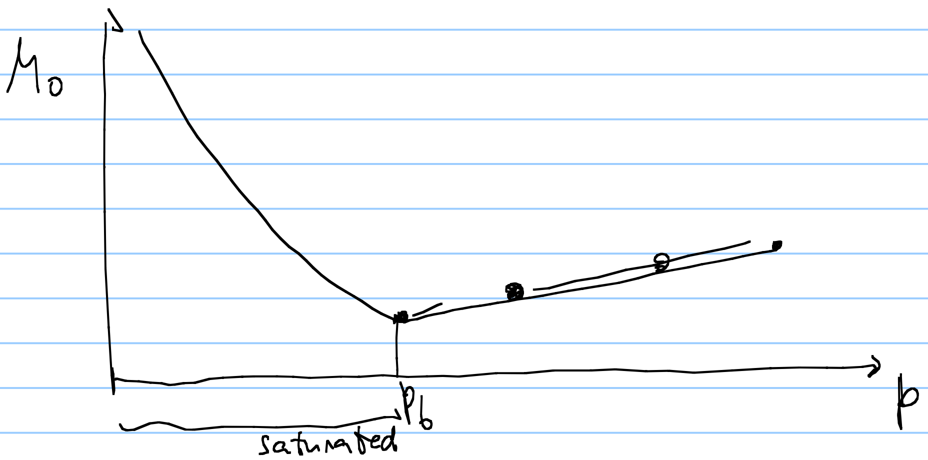
$$Re = \frac{v \cdot \Phi \cdot \rho}{\mu}$$

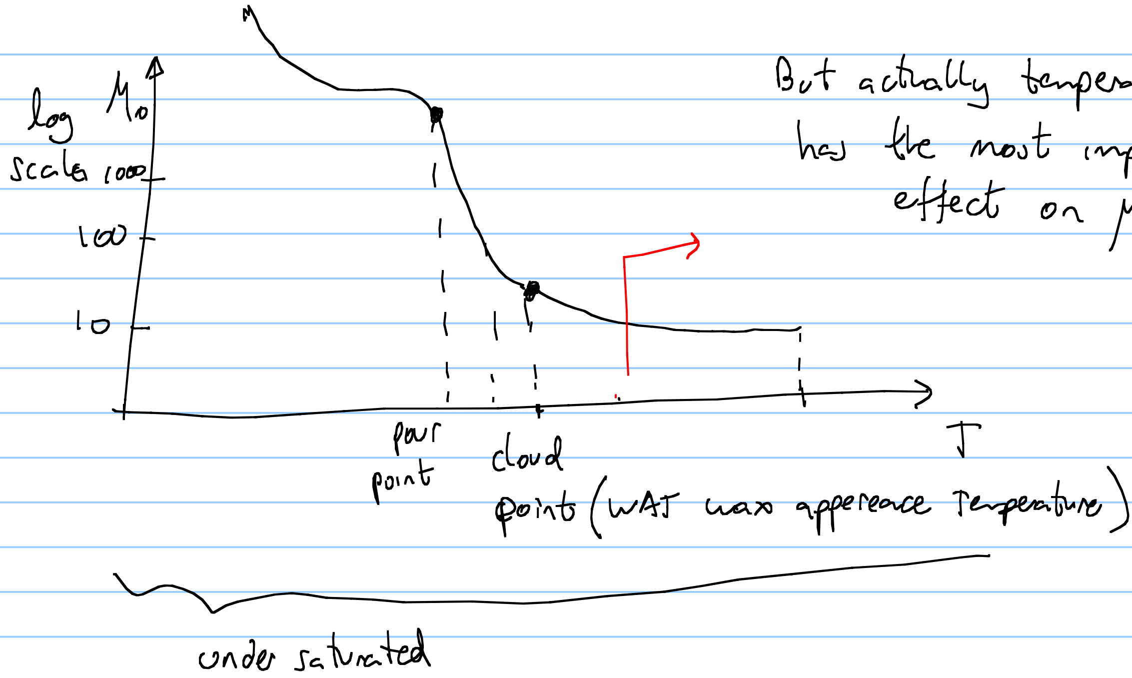
@ s.c

$$\rho_o = \frac{M_o}{V_o} = \frac{V_{\bar{g}} \cdot \rho_{\bar{g}} + V_{\bar{o}} \cdot \rho_{\bar{o}}}{V_o} \qquad V_{\bar{g}} = GOR \cdot V_{\bar{o}}$$

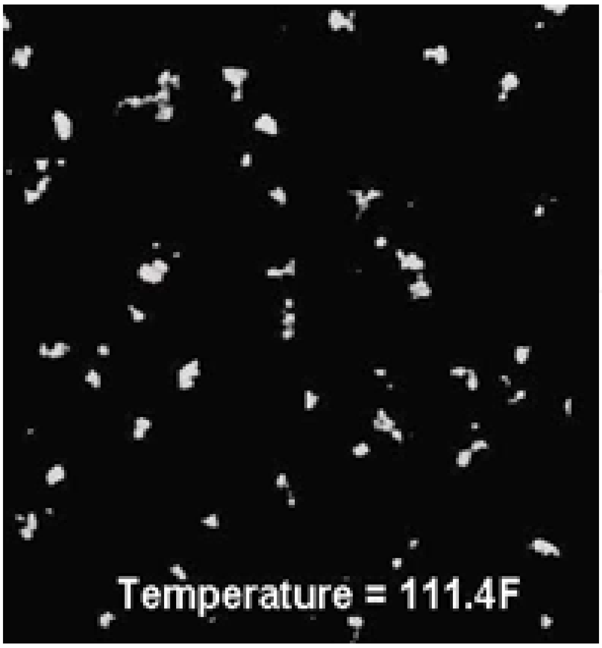
$$\rho_o = \frac{SG_g \cdot 1.224 \; GOR \cdot V_{\bar{o}} + V_{\bar{o}} \; SG_o \cdot 1000}{V_o}$$

$$\rho_o(p,T) = \frac{SG_g \cdot 1.224 \; GOR + SG_o \cdot 1000}{B_o}$$






But actually temperature has the most important effect on $\mu_o$ !




cloud point

pour point (no flow)