TPG 4135 - Production technology - field processing and systems

https://www.ntnu.edu/studies/courses/TPG4135#tab=omEmnet

class notes, files, homeworks, videos
http://www.ipt.ntnu.no/~stanko/files/Courses/TPG4135/2019/

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blackboard

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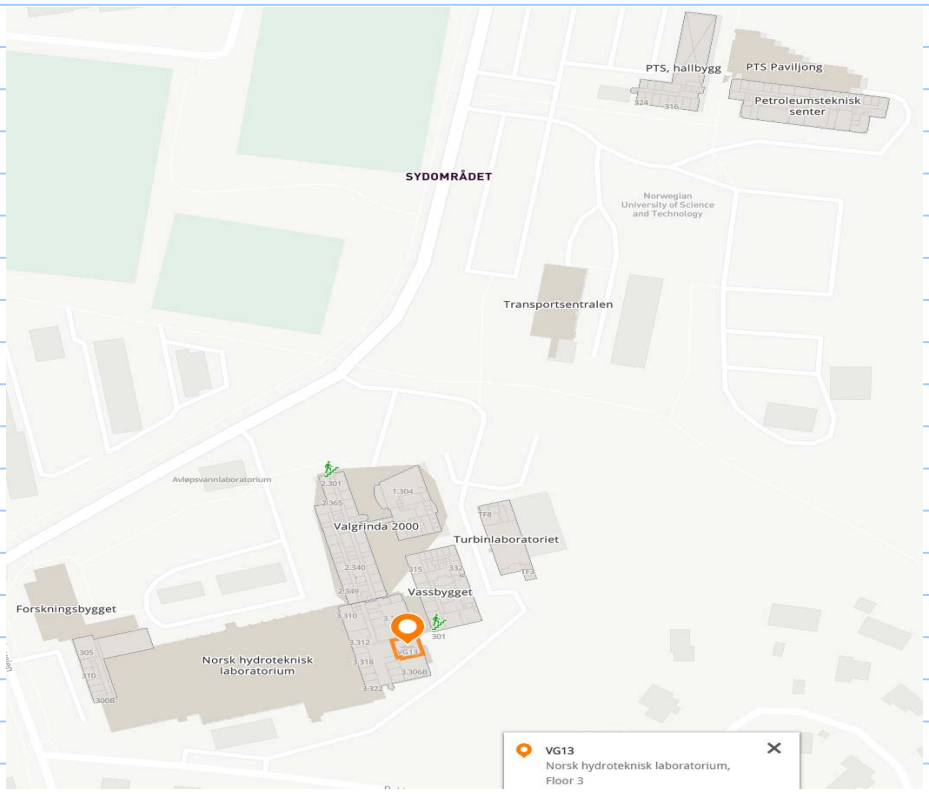
2019 VÅR

Day	Time	Weeks	Type	Planned for	Room
Monday	12:15 - 14:00	2-15	Forelesning	MIUVT, MTING, MTPETR	P12 PTS Paviljong
Tuesday	14:15 - 16:00	2-15	Forelesning	MIUVT, MTING, MTPETR	VG13 NHL Hall utvidelse
Tuesday	16:15 - 18:00	2-15	Øving	MIUVT, MTING, MTPETR	VG13 NHL Hall utvidelse



- Guest lectures from industry Mondays 14:15 - 15:00 P13

start 21.01.2019 stop 15.04.2019

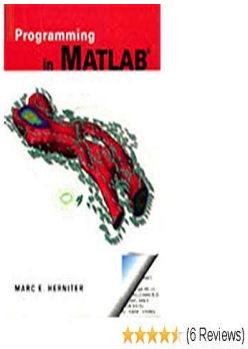
Evaluation:

Term	Statuskode	Evaluation form	Weighting	Examination aids	Date	Time	Room *
Spring	ORD	Written examination	100/100	D	2019-05-29	15:00	

Mandatory exercises to get access to exam

Software: Excel VBA Visual Basic for applications

Matlab



Marc Herniter

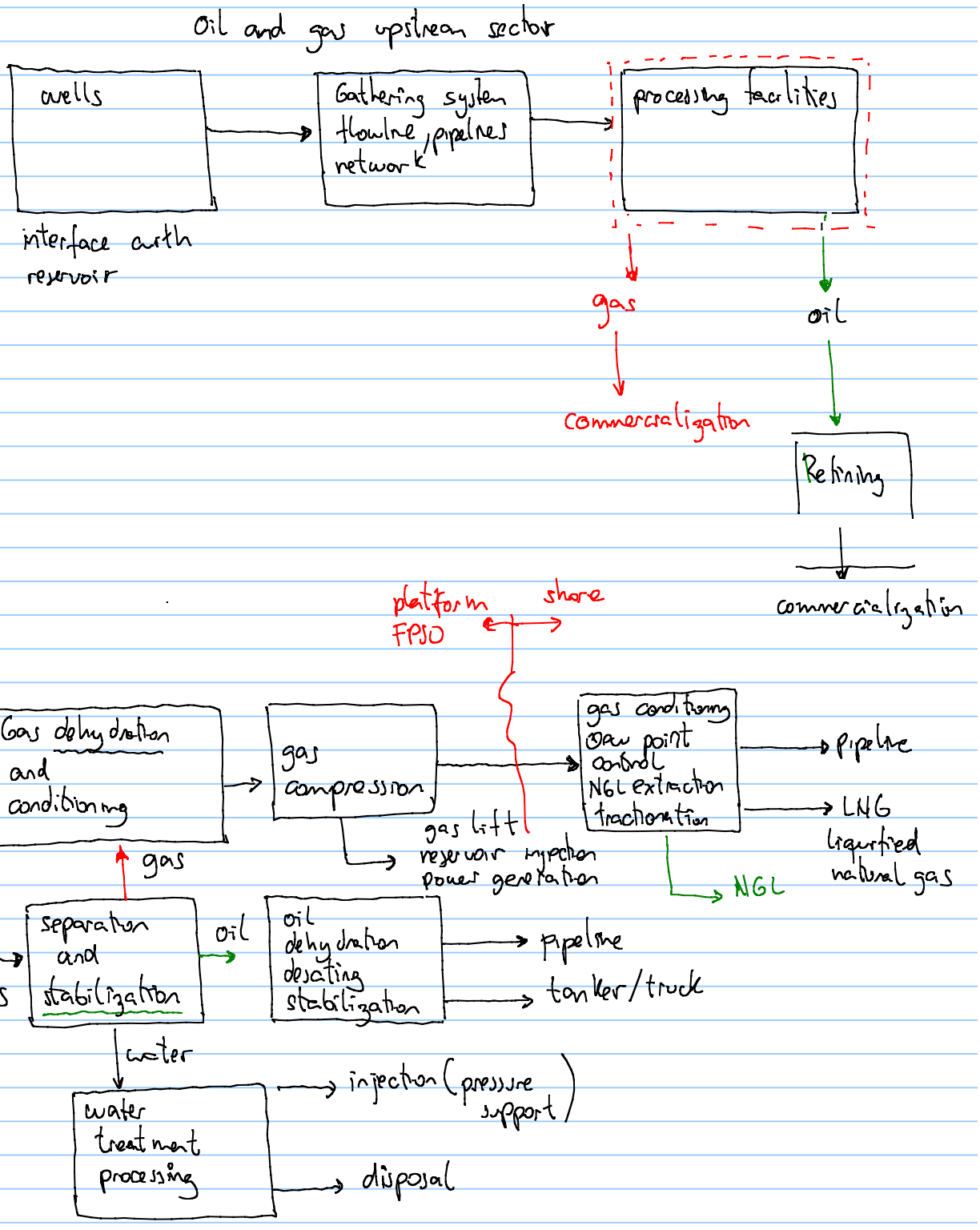
- Hysys Process simulator farm.ntnu.no

DWSim " " http://dwsim.inforside.com.br/wiki/index.php?

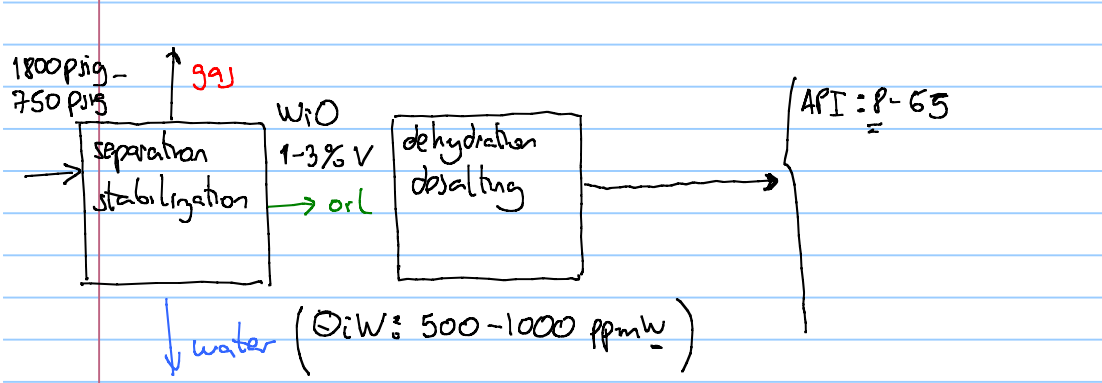
Reference group.

https://innsida.ntnu.no/wiki/-/wiki/English/Reference+groups+-+quality+assurance+of+educatio

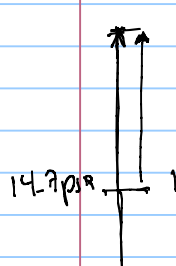
- Processing of oil and gas



gas destinations : • sell to power generation, heating, cement plant
: • Reinject for pressure support
EOR enhanced oil recovery
• power generation for field : gas turbine
• artificial lift (gas-lift)
• Remove "heavy" components → LPG Liquified petroleum gas
NGL Natural gas liquids



$\frac{V_o}{V_T} = 0.01 - 0.03$



psig? ppm = parts per million

$1\,ppm = \frac{1\,mg}{1\,kg} = \frac{1E{-}3\,g}{1E3\,g} = 1E{-}6$

$API = \frac{141.5}{\gamma_o} - 131.5$

$\gamma_{\bar{o}} = \frac{\rho_{\bar{o}}}{\rho_{\bar{w}}}$ ← 700-900 kg/m³ → 1000 kg/m³

specific gravity of oil

$\bar{o}$ @ standard conditions ↳ 1.01325 bar ↳ 15.56 °C

API

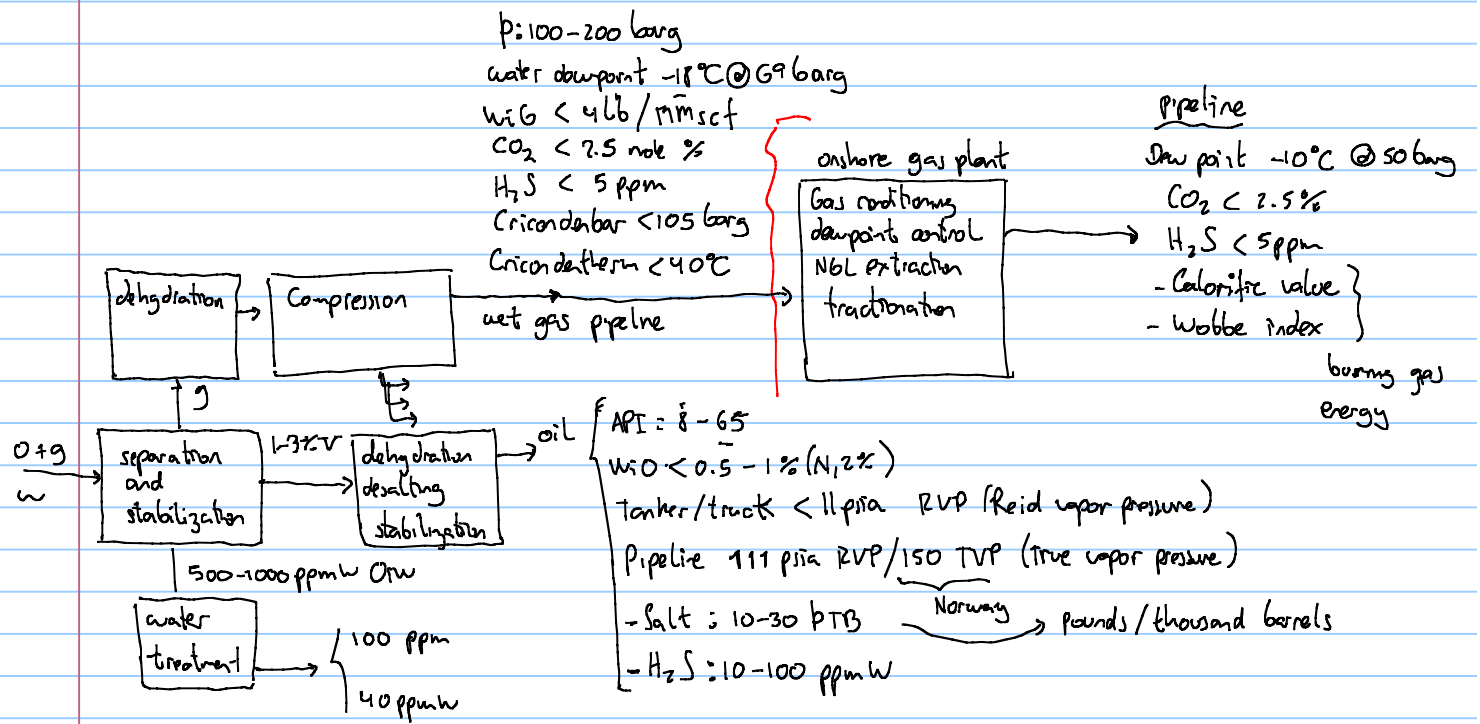
for an API = 10, what is γ_o ?

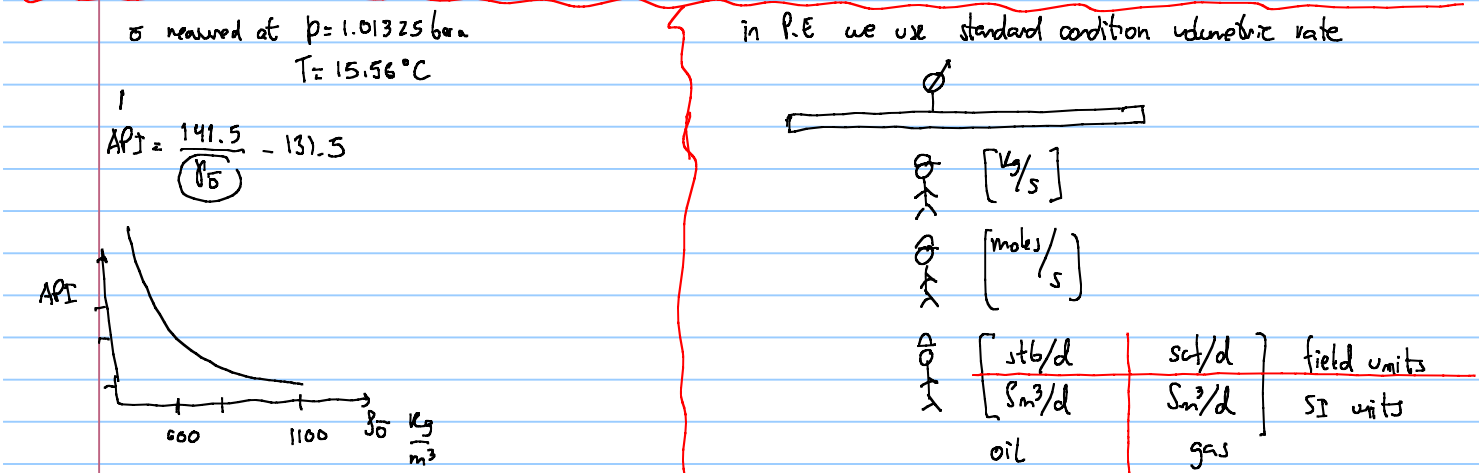
$$10 + 131.5 = \frac{141.5}{\gamma_o}$$

$$\gamma_o = 1$$

Class 2

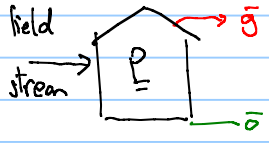
Course introduction. Overview of field processing. Product specs.	Milan
Oil-Gas sep (VLE), Rachford Rice, EOS calculations.	
Oil-Gas Separation . Introduction to process simulation (Hysys). —	Mariana
Oil-Gas Separation. Bubble and droplet dynamics. Separation capacity.	
Oil-water separation	
Water content in Natural gas. Gas dehydration (TEG)	Milan
Gas dehydration (TEG)	
Pressure calculations in pipe (single and two-phase)	Harald
Pressure calculations in pipe (single and two-phase)	
Heat transfer, pipe calculations, heat exchangers	
Heat transfer, pipe calculations, heat exchangers	
Pumping	Mariana
Compression	Harald
Compression	





- axis in black
- outer tick marks
- font (14-18), bold
- axis titles, name of variable, symbol, unit
- number of significant digits

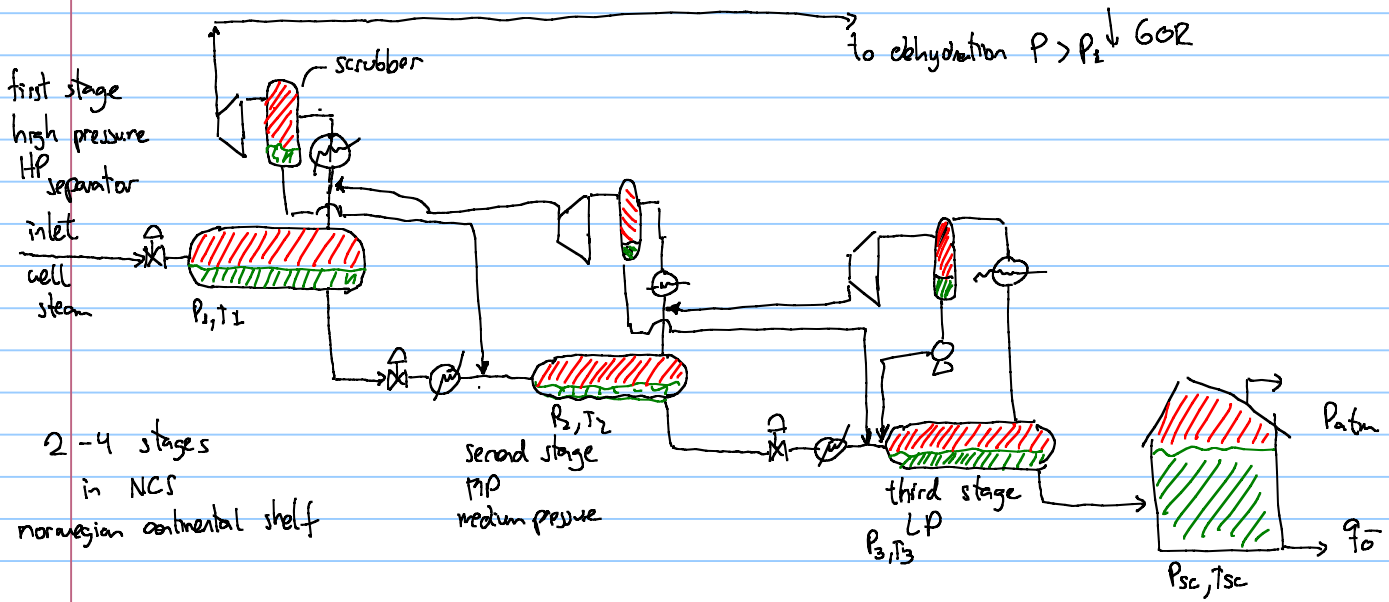
oil and gas separation and stabilization : functions
- mechanically separate oil-gas-water
- stabilize oil/gas
- increase the ratio between oil/gas

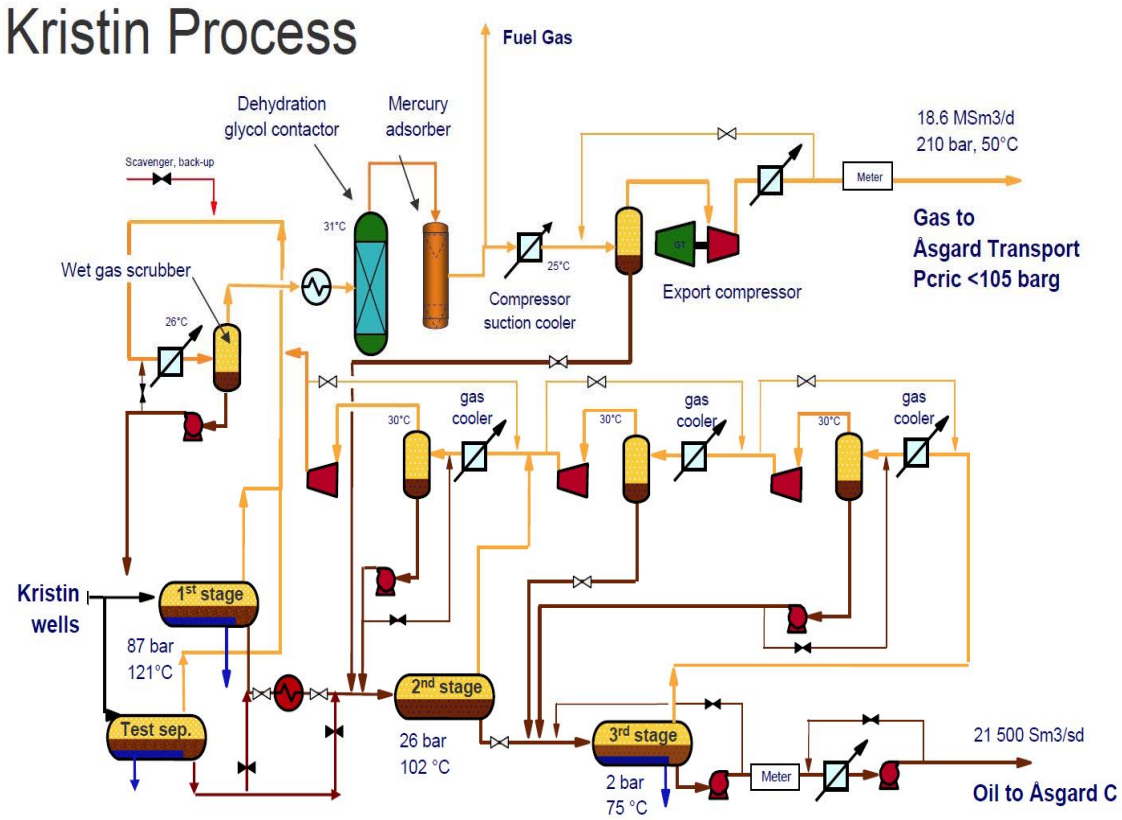


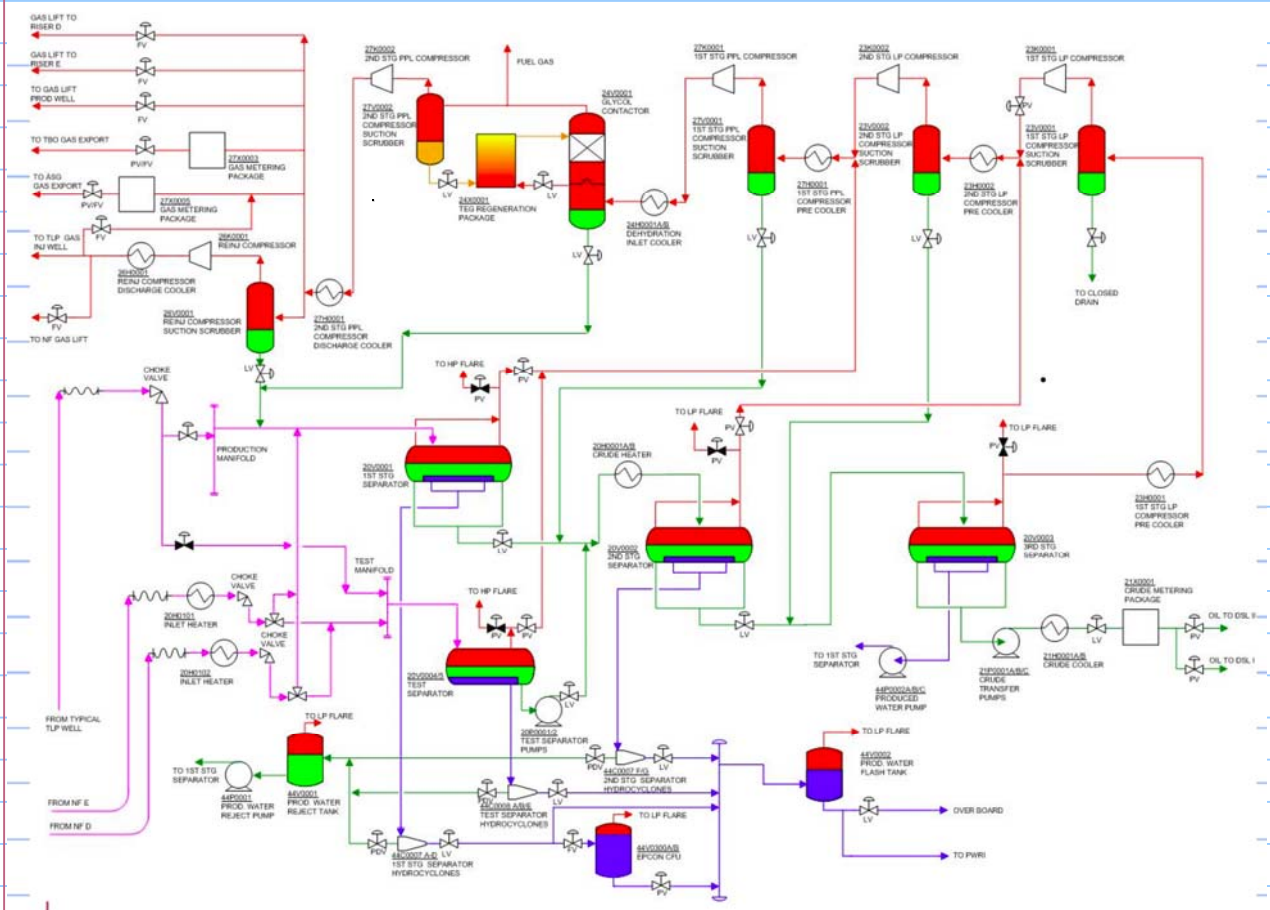
GOR gas-oil ratio

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

a processing train







How do we study separation processes? → thermodynamics of mixtures (HC) hydrocarbon

↳ fluid behavior
phase behavior
PVT behavior

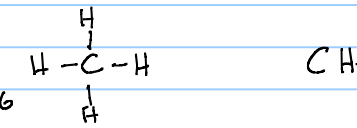
Pressure, volume, temperature

oil and gas consist of several pure components

Non HC { CO_2, N_2, H_2S

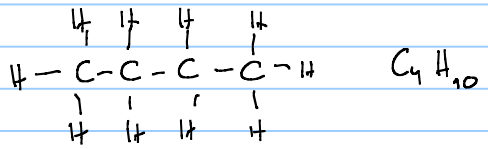
Hydrocarbons { Methane (C_1), C_2, C_3, C_4, $i\text{-}C_4$, C_5, $i\text{-}C_5$, C_6, C_7, C_8, ..., C_{50}

NGL: C_2 – C_5; LNG: C_1; LPG: C_3, C_4



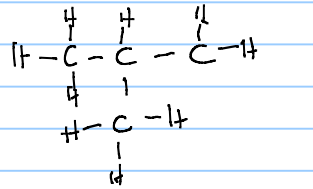
$C H_4$

alkanes $C_n H_{2n+2}$



$C_4 H_{10}$

isomer $i\text{-}C_4$ isobutane



the oil and gas are characterised by molecular composition

mole fraction $z_i = \frac{\text{number of moles of pure component "i"}}{\text{total number of moles}}$

	z_i	w_i
C_1	0.4	
C_3	0.3	
C_8	0.3	

mass fraction $w_i = \frac{\text{mass of component "i"}}{\text{total mass}}$

Molecular weight (pure component) $= \frac{\text{mass}}{\text{nr. moles}}$ $\left[\frac{kg}{kmol}\right], \left[\frac{g}{mol}\right]$

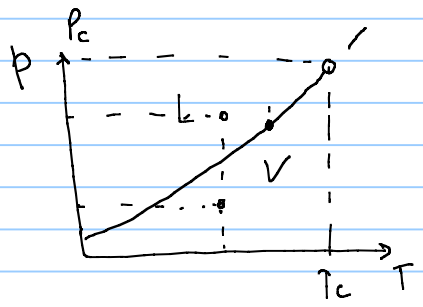
Molecular weight mixture $= \sum_{i=1}^{N} z_i MW_i$ (N = number compoes)

relationship between w_i, z_i ?

$$w_i = \frac{\text{mass of component } i}{\text{total mass}} = \frac{n_{\text{moles of } i} \cdot MW_i}{\text{total number of moles} \cdot MW_{\text{mixture}}} = z_i \frac{MW_i}{MW_{\text{mixture}}}$$

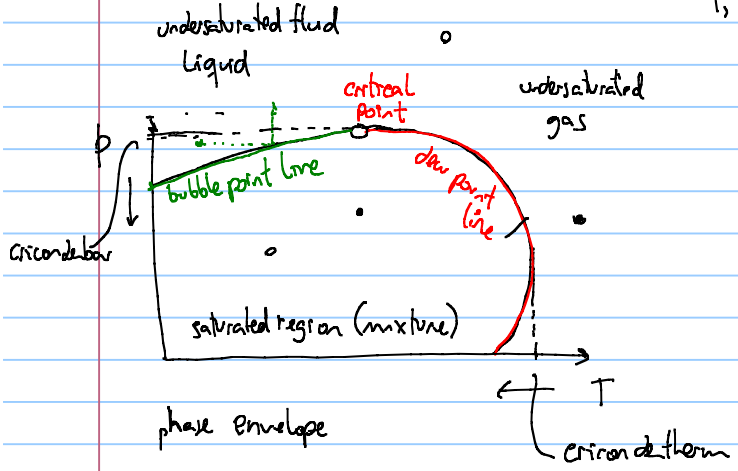
Class 3

Phase diagram
pure component
/single component

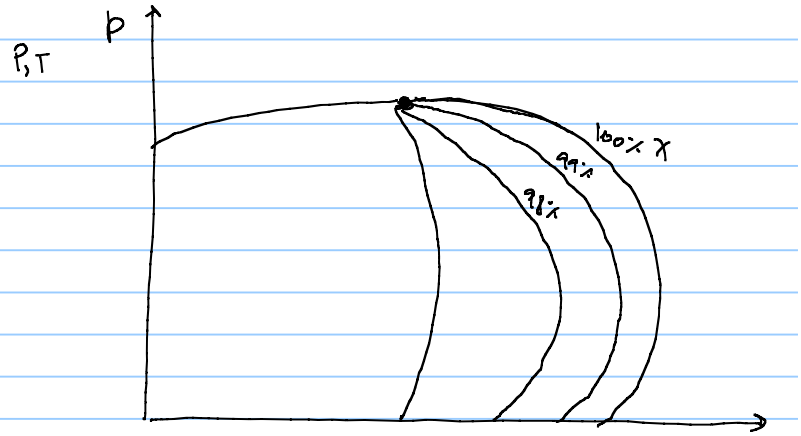


multicomponent
mixture

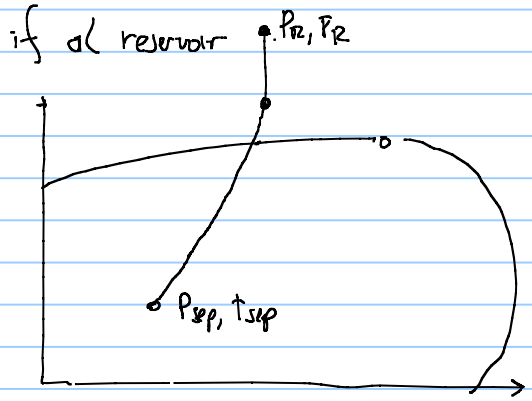
for a given composition

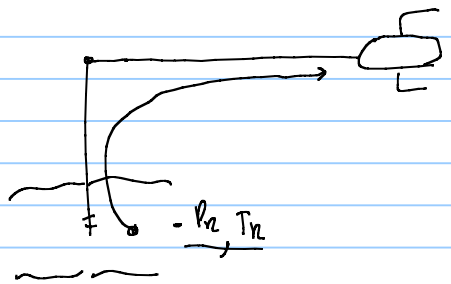


phase envelope

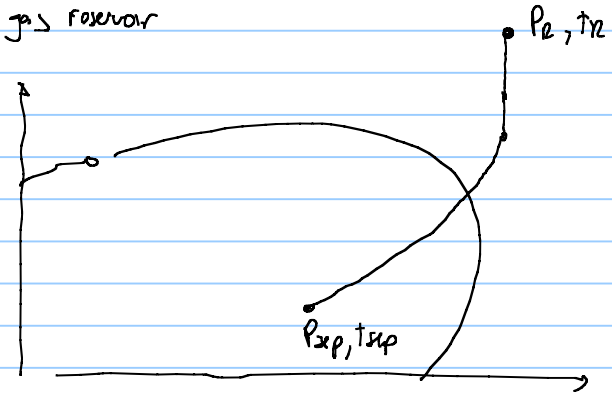


$$x = \frac{n_V}{n_T}$$





if gas reservoir



- Methods for performing flash calculations

equilibrium

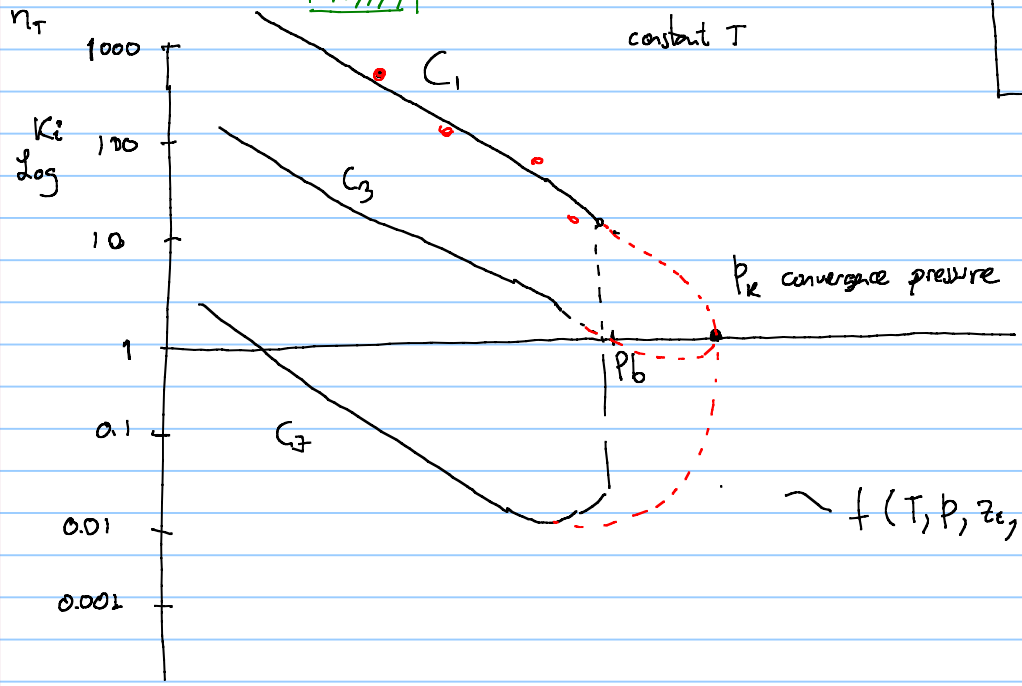
equilibrium ratio $K_i = \frac{y_i}{x_i}$

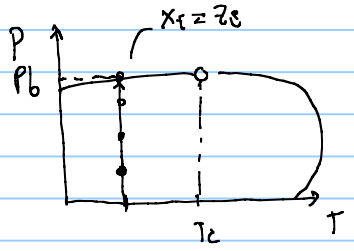
↑ for component "i"

z_i { $\frac{n_{c_1}}{n_v} = y_{c_1}$

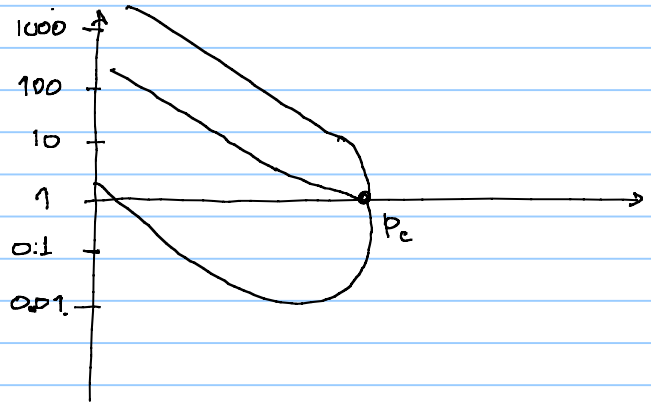
$\frac{n_{c_1}}{n_L} = x_{c_1}$

$z_{c_1} = \frac{n_{c_1}}{n_T}$





if the plot is made at T_c



Given $p, T \rightarrow K_i$. $\frac{x_i}{y_i}$ if N components $(2-N)$ unknowns

z_i

$K_i = \frac{y_i}{x_i}$ N equations

$\sum_{i=1}^{N} y_i = 1$ 1 eq

$\sum_{i=1}^{N} x_i = 1$ 1 eq

$z_i \quad y_i \quad x_i$

$n_i = n_{vi} + n_{Li}$

divide n_T $\frac{n_i}{n_T} = \frac{n_{vi}}{n_T} + \frac{n_{Li}}{n_T}$ vapor fraction $\frac{n_v}{n_T} = f_v \sim 0 -- 1$

$z_i = f_v \underbrace{\frac{n_{vi}}{n_v}}_{y_i} + \frac{n_{Li}}{n_L}(1-f_v)$

$n_T = \frac{n_v}{f_v}$

$\frac{n_L}{n_T} = (1-f_v)$

$z_i = f_v y_i + x_i (1-f_v)$

N eq

1 unknown

	Unknowns	equation
$K_i = \frac{y_i}{x_i}$	2-N	N
$\sum y_i = 1$	0	1
$z_i = f_v y_i + (1-f_v) x_i$	1	N
	(2-N+1)	2-N+1

Rachford-Rice

$$z_i = f_v y_i + (1-f_v) x_i \qquad K_i = \frac{y_i}{x_i} \qquad y_i = K_i x_i$$

$$z_i = f_v K_i x_i + (1-f_v) x_i$$

$$z_i = x_i \cdot (f_v K_i + 1 - f_v)$$

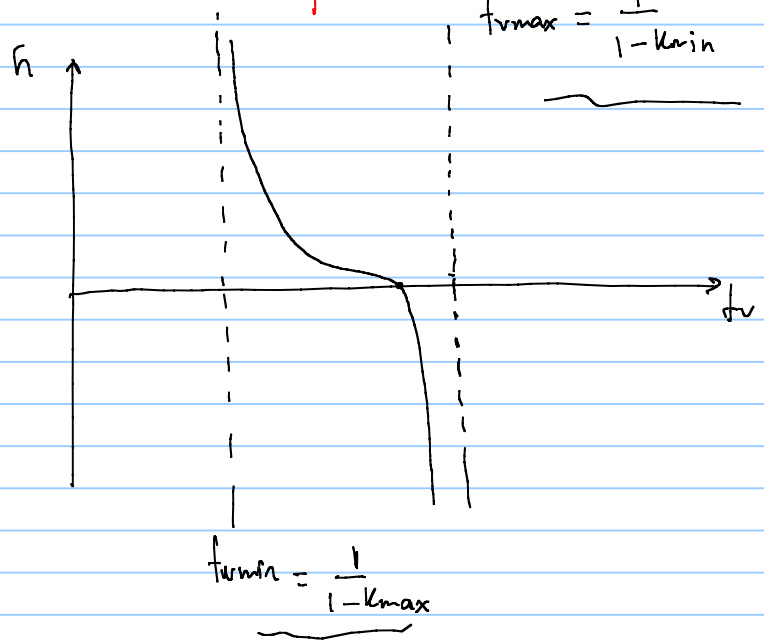
$$x_i = \frac{z_i}{f_v K_i + 1 - f_v}$$

$$\sum_{i=1}^{N} x_i = 1 \qquad \sum_{i=1}^{N} (y_i - x_i) = 0$$

$$\sum_{i=1}^{N} y_i = 1 \qquad y_i = K_i \cdot x_i$$

$$(K_i - 1) \cdot x_i = \frac{(K_i - 1) z_i}{f_v K_i + 1 - f_v}$$

$$\sum_{i=1}^{N} (K_i - 1) x_i = 0 = \sum_{i=1}^{N} \frac{(K_i - 1) z_i}{f_v K_i + 1 - f_v} \qquad h(f_v)$$



RR could give $0 < f_v < 1$ in mixture

$f_v = 0$ saturated liquid

$f_v = 1$ saturated gas

$f_v < 0$ liquid

$f_v > 1$ undersaturated gas

EX: MULTISTAGE SEPARATION FLASH. By Prof. Milan Stanko (NTNU)

SEPARATION PROCESS

Stage	p	T	z-C1	z-C3	z-N-C10	x-C1	x-C3	x-N-C10	y-C1	y-C3	y-N-C10	fv
[-]	bara	C	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
1-HP	50	70	0.5	0.2	0.3	0.07679	0.22803	0.69518	0.81955	0.17884	0.00162	0.56978
2-MP	35	50	0.07679	0.22803	0.69518							
3-LP	1.01325	15.56	0.00000	0.00000	0.00000							

COMPONENT PROPERTIES

Pk	[bara]	689	
Comp	**Tc**	**pc**	**AF (ω)**
	[K]	**[bara]**	
C1	190.6	46.1	0.0115
C3	369.8	42.5	0.1454
N-C10	617.7	21.0	0.4902

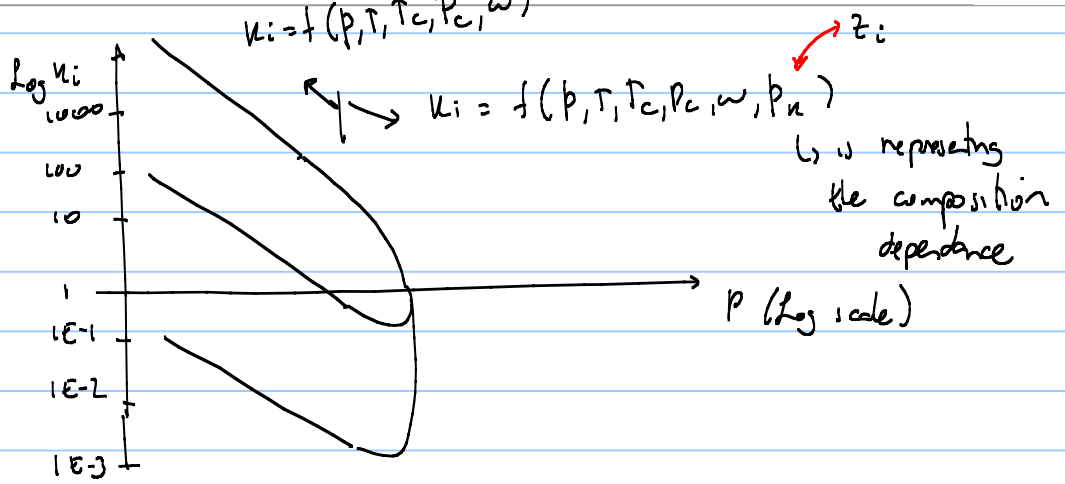
FLASH CALCULATIONS

p	[bara]	50	
T	[C]	70	
		fvmin	-0.103
		fvmax	1.002
		fv	0.5698

Comp	zi	Ki (T)	RR_term	xi	yi
C1	0.5	10.6723	7.43E-01	0.07679	0.81955
C3	0.2	0.7843	-4.92E-02	0.22803	0.17884
N-C10	0.3	0.0023	-6.94E-01	0.69518	0.00162
		SUM=	-7.40E-09	1.00000	1.00000

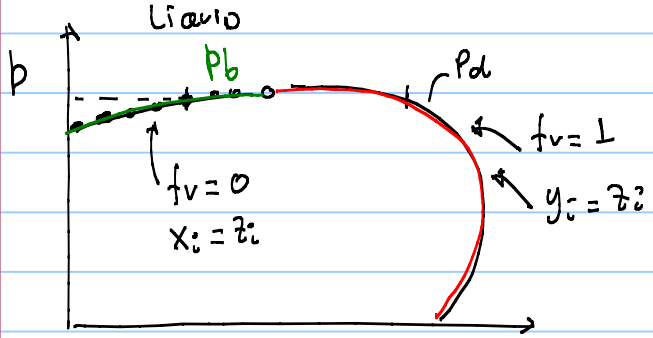
Note Title 15.01.2019

Class 4



K_i from correlation is not very accurate. Is more appropriate for low pressures

Equilibrium calculations can be used to estimate bubble point pressures and dew point pressures



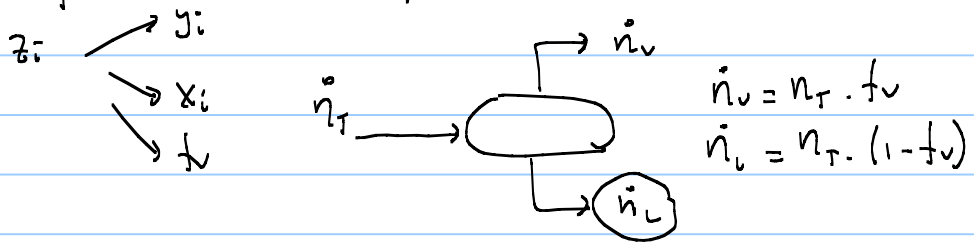
$$h(f_v) = \frac{z_i (K_i - 1)}{F_v (K_i) - F_v + 1}$$

to find $P_{b@T}$, $f_v = 0$, $x_i = z_i$ ⟶ find P such that $h(f_v) = 0$

to find $P_{d@T}$, $F_v = 1$, $y_i = z_i$ ⟶ find P such that $h(f_v) = 0$

//

for a mixture, with equilibrium calculations, I am able to estimate



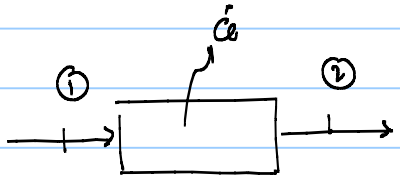
$\dot{n}$ (kmol/s) → $\dot{m}$ (kg/s) → q (Sm³/d) ?

$\dot{n} \cdot MW = \dot{m}$

$q = \frac{\dot{m}}{\rho} \left[\frac{3600 \cdot 24}{1\,d}\right]$ ← standard conditions

$MW_{mix} = \sum_{i=1}^{N} z_i \, MW_i$ (x_i, y_i)

How do we estimate fluid properties? ρ, h, s — analysis of components; heat exchanger, pump, compressor, pipe



$\dot{Q} = \dot{m}(h_2 - h_1)$

M, K ← thermal conductivity

thermodynamic properties → EOS (Equation of State)

thermophysical properties → correlation

Boyle

Hooke

Charles

Gay-Lussac

Avogadro

Ideal gas equation

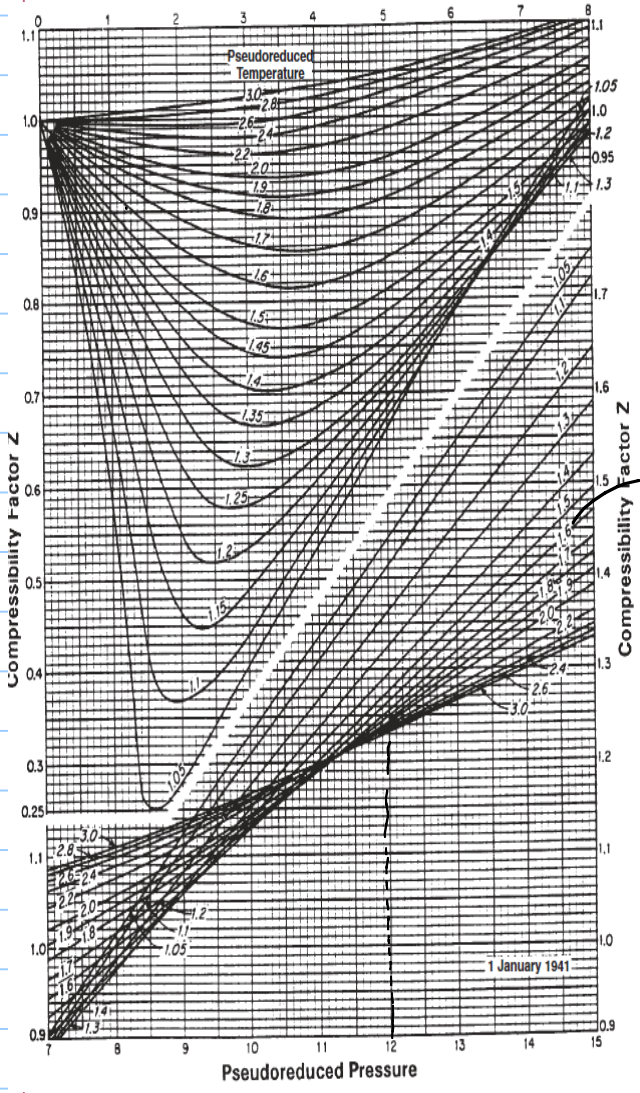
$pV = nRT$

p: Pa, bara; V: m^3; n: mol, kmol; R: K, °R

$$R = \frac{PV}{nT} = \left[\frac{Pa}{mol}\ \frac{m^3}{K}\right]$$

$$PV = nZRT \qquad v = \frac{V}{n} \quad \text{specific molar volume}$$

Real gas equation $pV = ZRT$ → gas deviation factor, gas compressibility factor



$v \rightarrow \rho$?

$\frac{m^3}{mol}$ $\frac{1}{MW}$ $\left[\frac{m^3}{kg}\right]$

$$\rho = \left(\frac{v}{MW}\right)^{-1}$$

$$T_r = \frac{T}{T_c}$$

$$P_r = \frac{p}{P_c}$$

when having a mixture how to estimate P_c T_c?

$$T_{pcHC} = 169.2 + 349.5\gamma_{gHC} - 74.0\gamma_{gHC}^2$$

and $p_{pcHC} = 756.8 - 131\gamma_{gHC} - 3.6\gamma_{gHC}^2$.

$$\gamma_{gHC} = \frac{\rho_{\bar{g}}}{\rho_{air}} = \frac{MW_{\bar{g}}}{MW_{air}} = \frac{MW_{\bar{g}}}{28.97}$$

EOS - Equation of state (PVT calculations)

(Van der Waals) (1873)

$$p = \underbrace{\frac{RT}{v-b}}_{\text{repulsion term}} \hookleftarrow \underbrace{\frac{a}{v^2}}_{\text{attraction term}} \quad \left[\frac{m^3}{mol}\right]$$

$$p = \frac{RT}{v}$$

$$p = \frac{RTv^2 - a(v-b)}{(v-b)v^2}$$

$$p(v-b)v^2 - RTv^2 + a(v-b) = 0$$

$pv = zRT$

$v = \frac{zRT}{p}$

$$Z^3 - (B+1)Z^2 + AZ - AB = 0,$$

where $A = a\frac{p}{(RT)^2} = \frac{27}{64}\frac{p_r}{T_r^2}$

and $B = b\frac{p}{RT} = \frac{1}{8}\frac{p_r}{T_r}$. .....

mixing rules are used to find constants for the EOS when there are multi components

Peng Robinson

Soave-Redlich Kwong (SRK)

$$p = \frac{RT}{v-b} - \frac{a}{v(v+b)+b(v-b)}$$

$pv = zRT$

$v = \frac{zRT}{p}$

$v \quad \frac{1}{mol} \left(\frac{1000\ mol}{1\ kmol}\right)$

R	8.31E-06	m^3 MPa/mol-K
T	343.15	[K]
p	5	[Mpa]

Compound	mole frac	Tc	pc	AF (ω)	MW	S	b	m	alpha	a	c	counter	Ai	fugacity
	[-]	[K]	[Mpa]	[-]	kg/kmol	[-]	m^3/mol	[-]	[-]	m^6 MPa/mol^2	m^3/mol		[-]	[Mpa]
C1	0.8196	190.6	4.6	0.0115	16.04	-0.1595	2.68E-05	0.3923	0.7497	1.87E-07	-4.27E-06	1	2.34E-07	3.88E+00
C3	0.1788	369.8	4.3	0.1454	44.09	-0.0863	5.63E-05	0.5932	1.0441	1.06E-06	-4.86E-06	2	5.55E-07	5.99E-01
N-C10	0.0016	617.7	2.1	0.4902	142.29	0.0655	1.91E-04	1.0700	1.6192	9.31E-06	1.25E-05	3	1.61E-06	1.90E-03

BINARY INTERACTION PARAMETERS

	C1	C3	N-C10
C1	0	0.014	0.04361
C3	0.014	0	0
N-C10	0.04361	0	0

PR equation coefficients

amix	2.93E-07	m^6 MPa/mol^2
bmix	3.23E-05	m^3/mol
Amix	1.80E-01	
Bmix	5.66E-02	
a1	-9.43E-01	
a2	5.74E-02	
a3	-0.00682	

Solving PR cubic equation

			if M<0 then			If M>0 then		
Q	0.080		teta	NA	fugacity	S'	0.334	
R	-0.025		z1	NA	NA	T'	0.239	
M	1.42E-04		z2	NA	NA	z	8.87E-01	
			z3	NA	NA			
MW	21.3	kg/kmol						
z	8.87E-01							
v	5.06E-01	m^3/kmol						
v_corrected	5.11E-01	m^3/kmol						
v	2.40E-02	m^3/kg						
den	41.64	kg/m^3						

with EOS one can calculate other properties, h, u, s

- definition of property $h = u + p \cdot v$
- first law $dU = dQ + dW$
- fundamental relationships between derivatives of properties

$$dU = C_v dT + \left[T\left(\frac{\partial P}{\partial T}\right)_V - P \right] dV$$

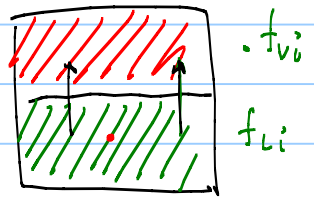
$$dU = C_v dT + \left[T\left(\frac{\partial p}{\partial T}\right)_V - p \right] d\bar{v}$$

$$\frac{\partial p}{\partial T} = \frac{RT}{v-b} - \frac{a}{v(v+b)+b(v-b)}$$

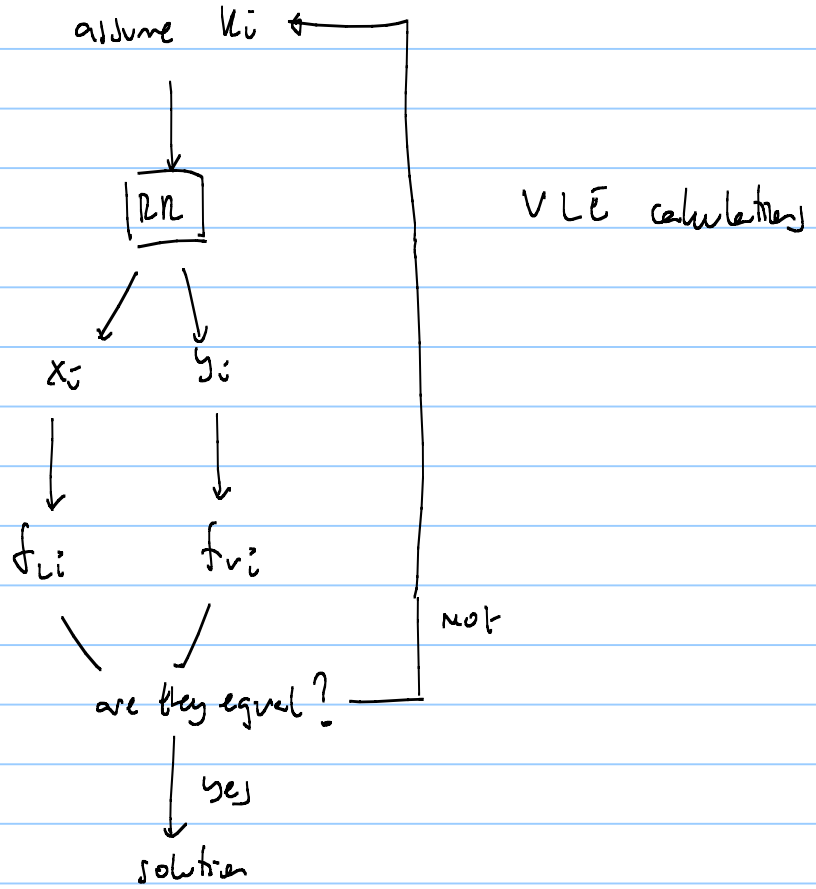
one can calculate a property called chemical energy f_i

$$\ln \frac{f_i}{y_i p} = \ln \phi_i = \frac{B_i}{B}(Z-1) - \ln(Z-B) + \frac{A}{2\sqrt{2}B}\left(\frac{B_i}{B} - \frac{2}{A}\sum_{j=1}^{N} y_j A_{ij}\right) \ln\left[\frac{Z+(1+\sqrt{2})B}{Z-(1-\sqrt{2})B}\right]$$

in a mixture $\boxed{f_{Li} = f_{Vi}}$

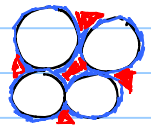


I can use EOS to find K_i


assume k_i
RR
x_i
y_i
f_{Li}
f_{vi}
are they equal?
not
yes
solution
VLE calculations

Water content in natural gas

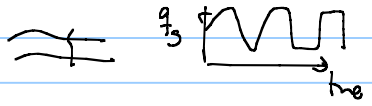
Gas is always saturated with water @ a given p, T

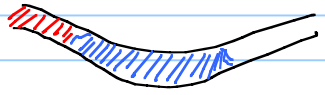


with p, T changes along the production system, water solubility in gas will change

typically with p↓, T↓ solubility is decreased ⇝ water comes out of solution (free water)

can cause some issues
- corrosion
- hydrates
- slugging (in transportation pipelines)



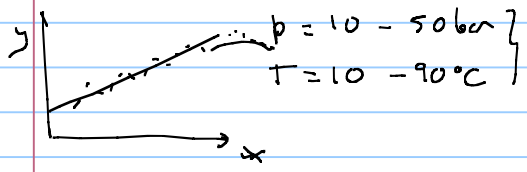


- scale

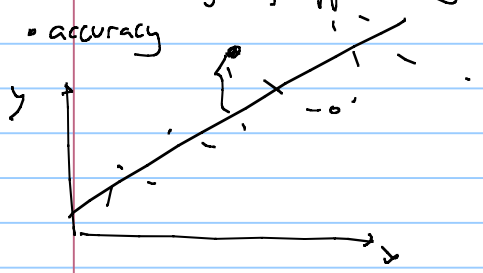
we need a way to estimate expected free water / water content in gas at any position of production system

Correlations

- mathematical expressions
- derived from measurements in lab / field
- often not based in physics



- advantages
  - easy to use
  - low computational expenses
- disadvantages
  - limited range of applicability
  - accuracy



EOS

equation of state

- ↳ not so accurate "out of the box"
- ↳ more general for wide range of conditions
- ↳ are usually customized with experimental data (by adjusting the default BIPs)

$$A = \sum_{i=1}^{N}\sum_{j=1}^{N} z_i \cdot z_j \cdot (1 - BIP_{ij}) \cdot \sqrt{A_i \cdot A_j}$$

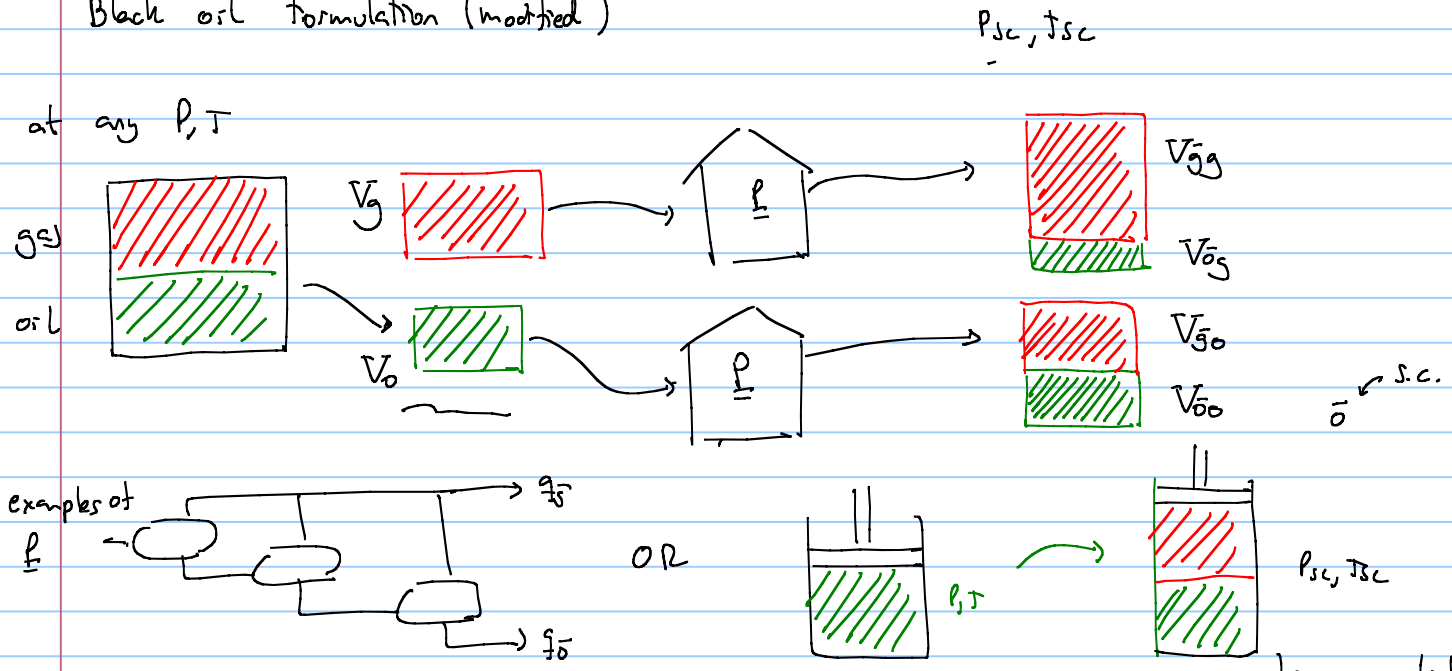
for more information read section 9.3 of chapter 9 whitson's monograph

- Review user manual for recommended EOS

Type of System	Recommended Property Method
TEG Dehydration	PR
Sour Water	PR, Sour PR
Cryogenic Gas Processing	PR, PRSV
Air Separation	PR, PRSV
Atm Crude Towers	PR, PR Options, GS
Vacuum Towers	PR, PR Options, GS (<10 mm Hg), Braun K10, Esso K
Ethylene Towers	Lee Kesler Plocker
High H2 Systems	PR, ZJ or GS (see T/P limits)
Reservoir Systems	PR, PR Options
Steam Systems	Steam Package, CS or GS
Hydrate Inhibition	PR
Chemical systems	Activity Models, PRSV
HF Alkylation	PRSV, NRTL (Contact Hyprotech)
TEG Dehydration with Aromatics	PR (Contact Hyprotech)
Hydrocarbon systems where H2O solubility in HC is important	Kabadi Danner
Systems with select gases and light hydrocarbons	MBWR

Correlations are built following the same principle as Black oil properties

Black oil formulation (modified)



oil volume factor $B_o = \frac{V_o}{V_{\bar{o}o}} = f(P,T)$ always > 1 { heavy 1.1 – 1.8 light crude }

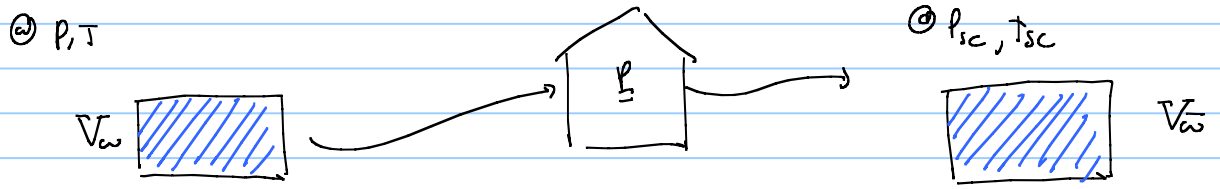
Solution gas-oil ratio $R_s = \frac{V_{\bar{g}o}}{V_{\bar{o}o}}$ typically { 80 → 1000 volatile crude }

gas volume factor $B_g = \frac{V_g}{V_{\bar{g}g}}$ { 1E-4 → 1E-2 }

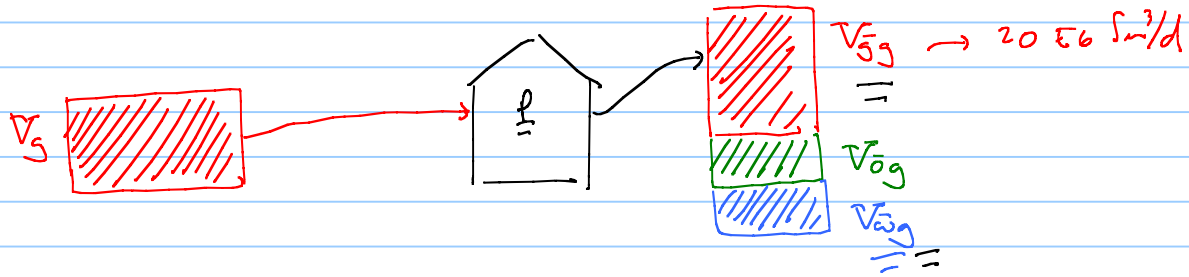
solution oil-gas ratio $r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}}$ (r_v)

BO properties are usually generated : • by lab measurements
• correlations (e.g. Glasø, Standing)
• use EOS simulator

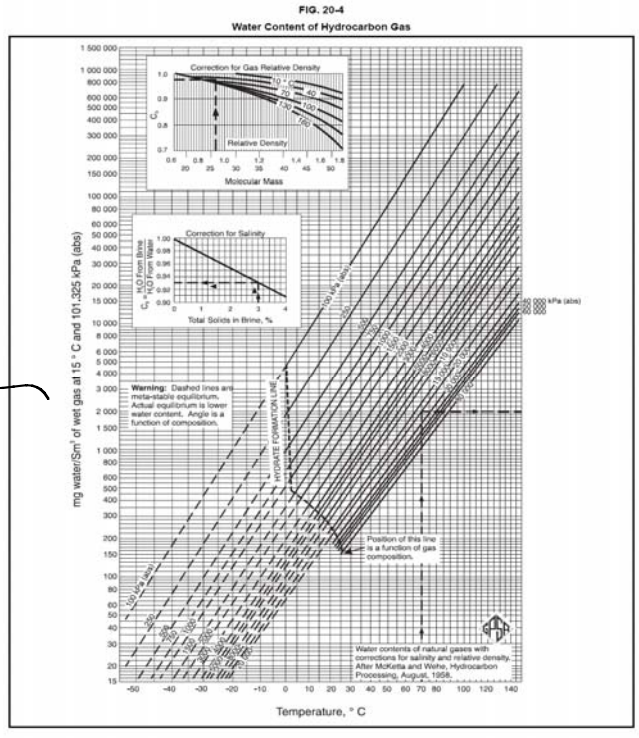
for water, a similar approach is used



water volume factor $B_w = \frac{V_w}{V_{\bar{w}}}$ due to compressibility of water $B_w > 1$



solution water-gas ratio $r_{sw} = \frac{V_{\bar{w}_g}}{V_{\bar{g}_g}}$



$r_{sw} \cdot \rho_{\bar{w}}$

$r_{sw} = \frac{Sm^3}{Sm^3} \rightarrow \frac{kg}{[Sm^3]}$

$r_{sw} \cdot \rho_{\bar{w}} \rightarrow \frac{kg}{[Sm^3]}$

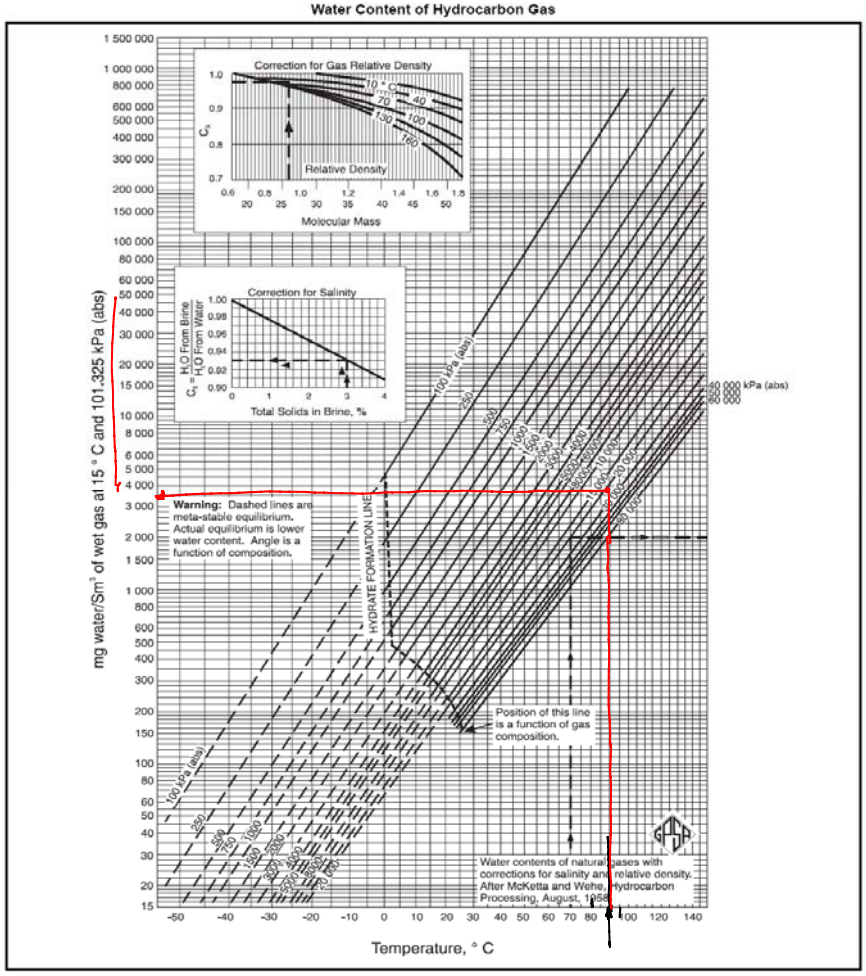
$\rho_{\bar{w}} = 1000\ kg/m^3$

Prof. Milan Stanko. TPG4135 - Water content in gas field

Gas MW	16	[Kg/Kmol]		
Gas gravity	0.552			
Water salinity	0.0	[ppm]		
CO2	0.0	[mole %]		
H2S	0.0	[mole %]		
Gas field rate	2.00E+07	[Sm^3/d]		
Nwells	8			
Well gas rate	2.50E+06			
Location	**p**	**T**	**rsw**	**qw**
[-]	[bara]	[C]	[Sm^3/1E06 Sm^3]	[m^3/d]
Reservoir	276	90		
Wellhead	160	70		
Choke downstream	120			
Separator	30	5		

@ P_R, T_R

FIG. 20-4
Water Content of Hydrocarbon Gas



20-5

$P_R = 276\,bara \sim 27600\ kPa$

$1\,bar = 165\,Pa$

$1\,bar = 100\,kPa$

$3500\ mg/Sm^3 = r_{sw} \cdot \rho_w$

$3.5\ kg/Sm^3 = r_{sw} \cdot \rho_w$

$r_{sw} = \frac{3.5\ kg}{1000\ \{kg/Sm^3\} \cdot m^3}$

$r_{sw} = 3.5E-3\ Sm^3/Sm^3$

r_{sw} is typically expressed in $Sm^3/1E06\ Sm^3$

$r_{sw} = 3.5E-3\ \frac{Sm^3}{Sm^3}\ \frac{1E6\ Sm^3}{[1\ Sm^3]}$

$r_{sw} = 3500\ \frac{Sm^3}{[1\ Sm^3]}$

↓ SI stands for Mega

$q_w = q_g \cdot r_{sw}$

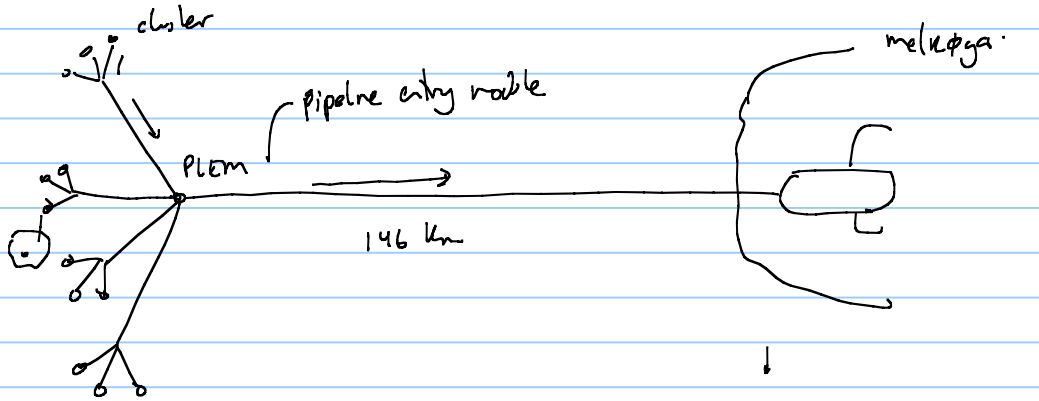
$q_w = 20\left[\frac{M\ Sm^3}{d}\right] \cdot 3500\left[\frac{Sm^3}{1\ Sm^3}\right] = 70000\ Sm^3/d$

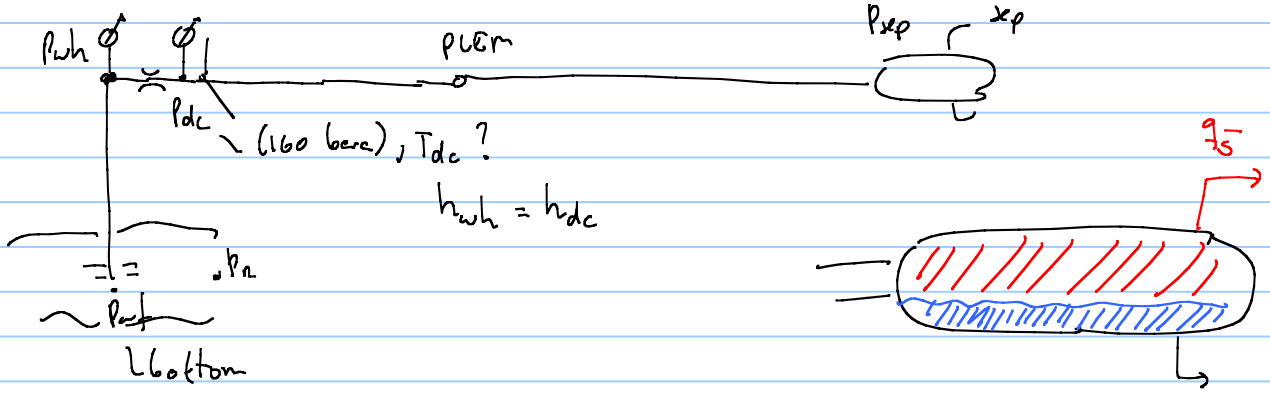
- VBA function for r_{sw}
- Class exercise
- Hydrates

$$\gamma_g = \frac{MW_g}{MW_{air}} = \frac{MW_g}{28.97}$$

Production system

- cell





water in gas wells can cause "liquid loading"

← slug flow (dP is higher)

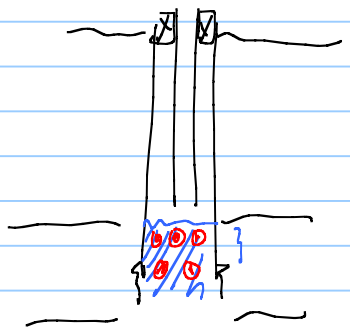
← annular flow

mist flow

single phase flow

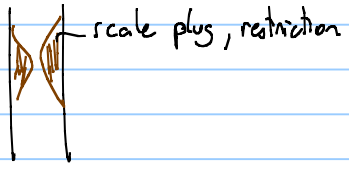
more water → higher viscosity, higher density → higher Δp

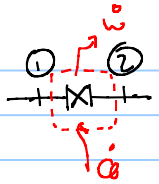
- reduce production rate
- liquid starts accumulating in well



for gas in a sudden expansion (e.g. choke, large and concentrated pressure drop)

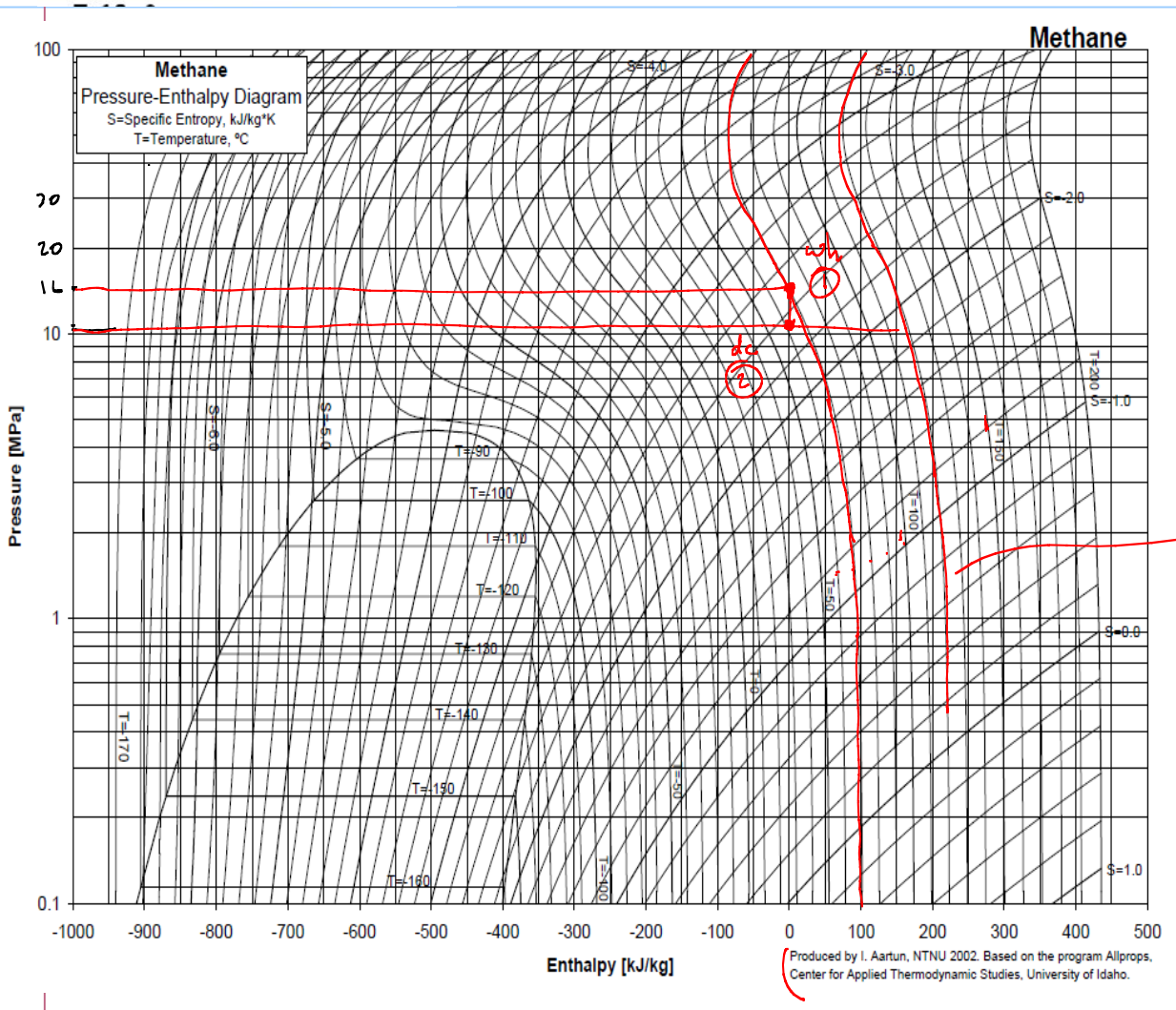
the temperature is also changing due to the pressure drop





isenthalpic

$h_1 = h_2$



$T_{dc} \simeq 60\,C$

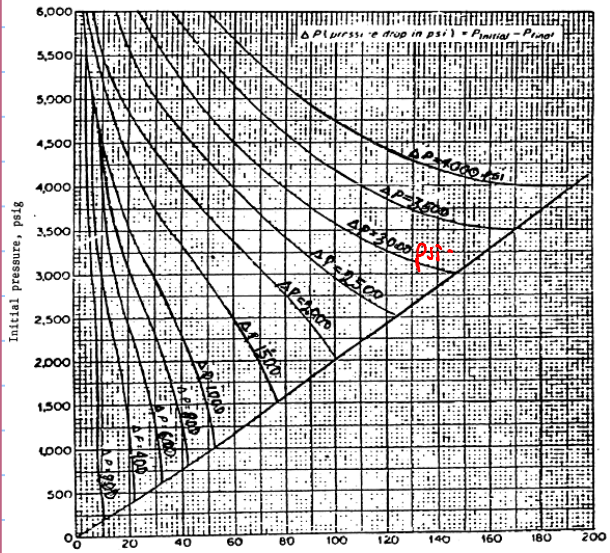
$T = 120\,C$

160 bar to MPa 1st Pa

$P_{dc} = 120$ bar

12 MPa

this cooling effect can be very significant, especially across choke



Temperature change due to pressure drop. (From Vondy et al.)

↝ charts like this are made for different γ_g to predict temperature across the choke.

Prof. Milan Stanko. TPG4135 - Water content in gas field					
Gas MW	16	[Kg/Kmol]			
Gas gravity	0.552				
Water salinity	0.0	[ppm]			
CO2	0.0	[mole %]			
H2S	0.0	[mole %]			
Gas field rate	2.00E+07	[Sm^3/d]			
Nwells	8				
Well gas rate	2.50E+06				
Location	**p**	**T**	**rsw**	**rsw**	**qw**
[-]	[bara]	[C]	[kg/1E06 Sm^3]	[Sm^3/1E06 Sm^3]	[Sm^3/d]
Reservoir	276	90	3360.4	3360.4	
Wellhead	160	70	2263.0	2263.0	
Choke downstream	120	60	1840.4	1840.4	
Separator	30	5	310.2	310.2	

$$q_{w_{TOTAL}} = q_g \cdot r_{sw}\Big|_{@P_R, T_R}$$

$$q_{w_{TOTAL}} = 20\ [m Sm^3/d] \cdot 3360\ \frac{Sm^3}{[m Sm^3]}$$

$$q_{w_{TOTAL}} = 67.2\ E03\ Sm^3/d$$

$$q_{w_{sep}}^{solution} = 20\ E06 \cdot r_{sw}\Big|_{@P_{sep}, T_{sep}}$$

$$q_{w_{sep}} = 20\ [m Sm^3/d] \cdot 310$$

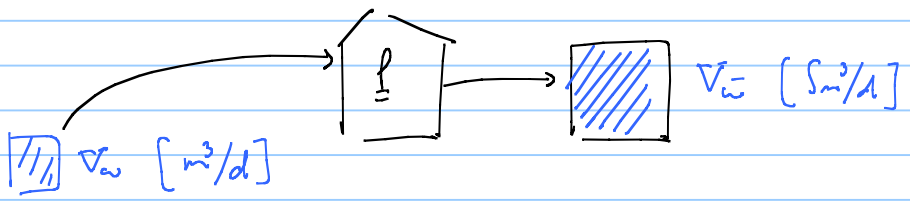
$$q_{w_{sep}} = 6200\ Sm^3/d$$

the free water at separator is the difference between the two

$$q_{w_{sep}}^{Free} = q_{w_{TOTAL}} - q_{w_{sep}}^{solution}$$

$$q_{w_{sep}}^{Free} = 67.2\ E03\ Sm^3/d - 6.2\ E03\ Sm^3/d$$

$$q_{w_{sep}}^{Free} = 61\ E03\ Sm^3/d$$



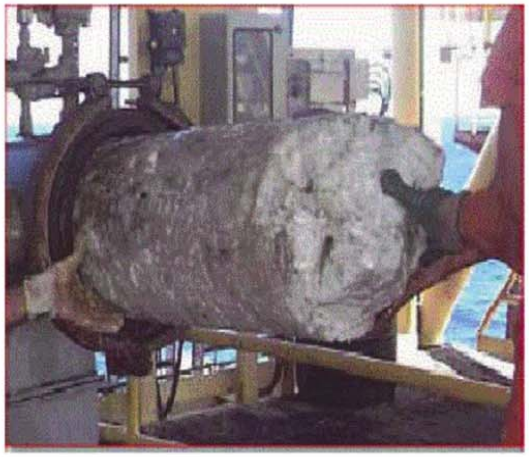
local free water rate at separator inlet

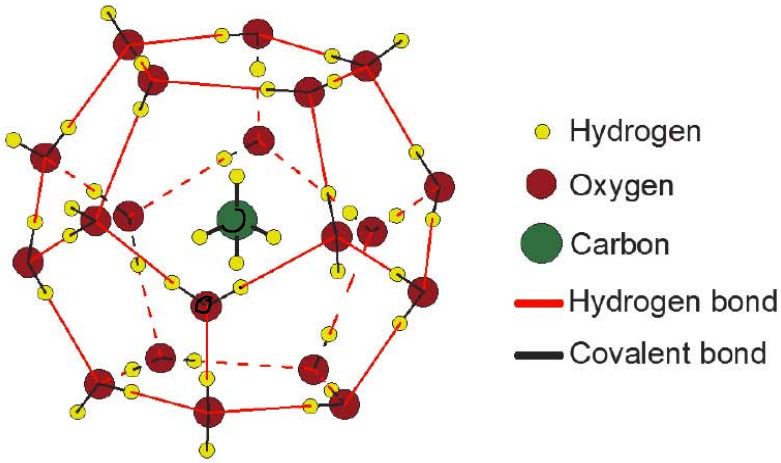
$$q_{w\,sep}^{Free} = q_{\bar{w}\,sep}^{Free} \cdot \underbrace{B_w(P_{sep}, t_{sep})}_{\approx 1}$$

knowing q_w is useful for
↳ local conditions.

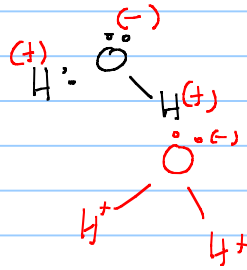
- pressure drop calculations
- to determine liquid loading problem
- to find adequate amount of chemical inhibitor for: corrosion
  hydrates

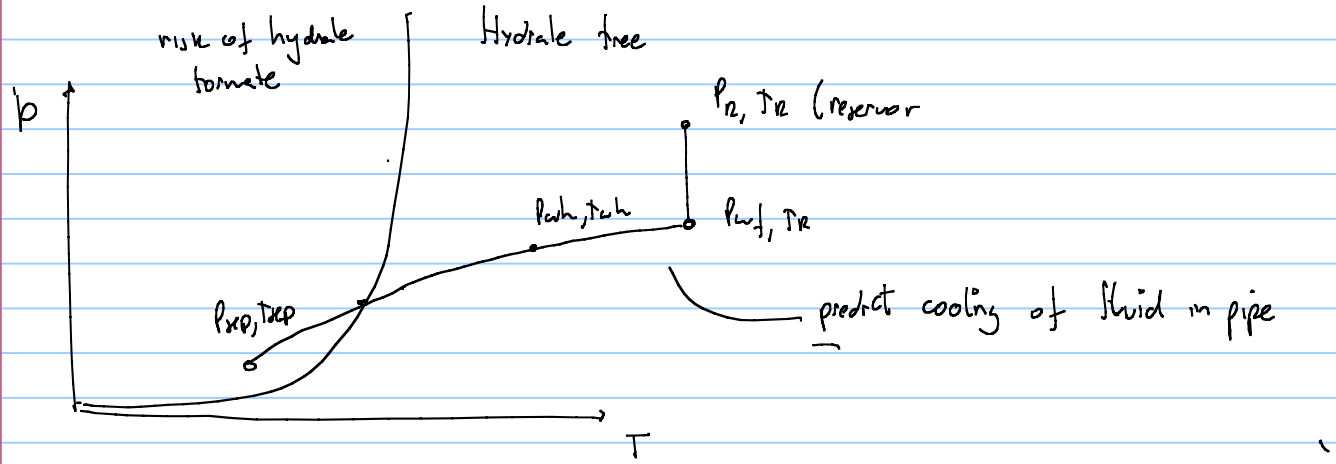
Hydrates



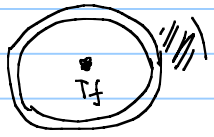


- free water } hydrogen
- small molecules CH_4 C_2H_6, C_3H_8, C_4H_{10}, CO_2, N_2 ~9 Å
- specific conditions of P, T
  low T,

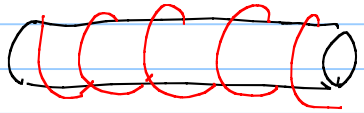




How to avoid hydrate formation? ○ "Slow-down" cooling in pipe { insulation

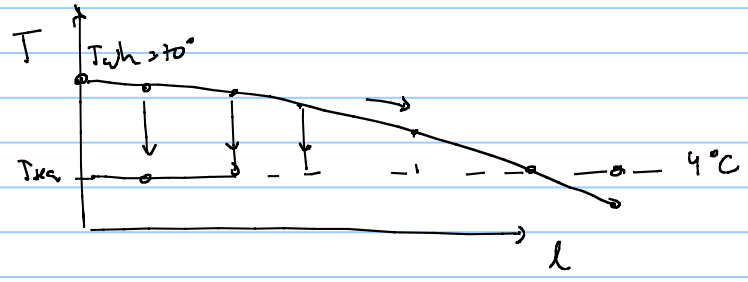


○ T_{sea}

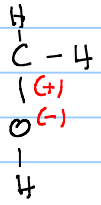


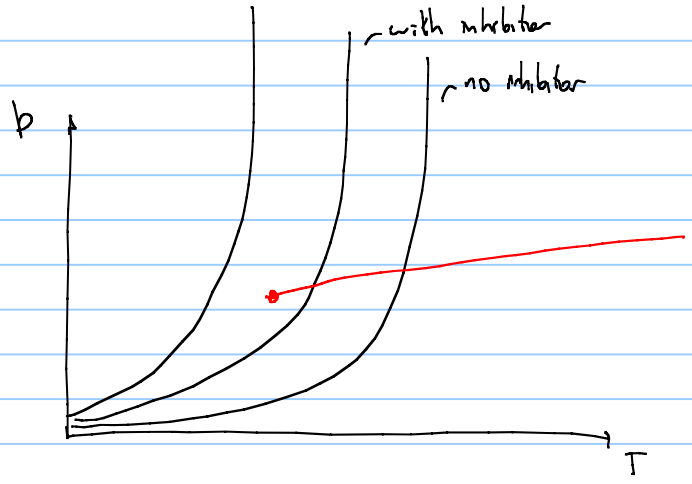
○ add heat to pipe { heat tracing

for the snowhite case



• chemical inhibitor { MeOH, MEG, TEG





Inhibitor quantities are typically given in weight %

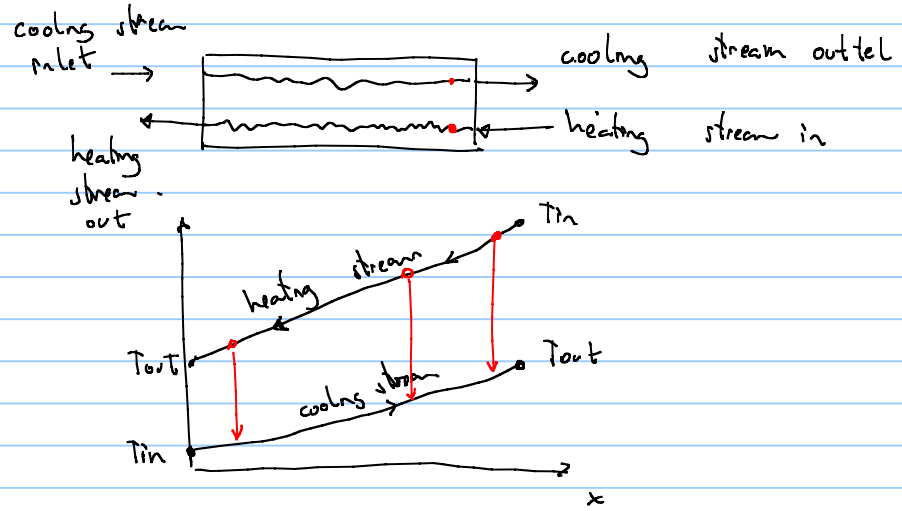
$$= \frac{\dot{m}_{inhibitor}\ [kg/s]}{\dot{m}_{inh} + \dot{m}_{water}} \cdot 100$$

[30 - 60] %

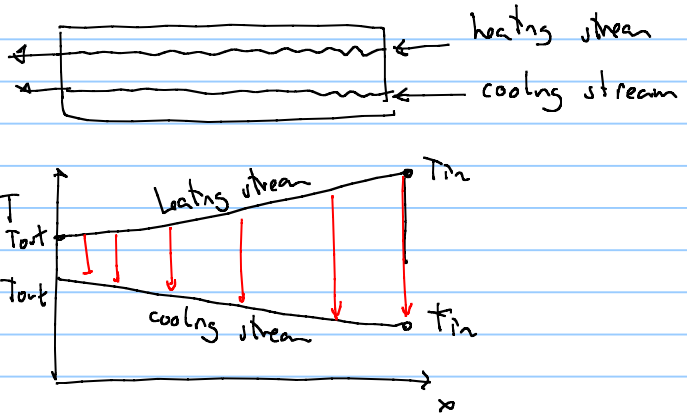
is injected typically at wellhead X-mas tree.

- Gas dehydration with TEG in absorber column (theory)
  ↳ triethylene glycol
- Class exercise

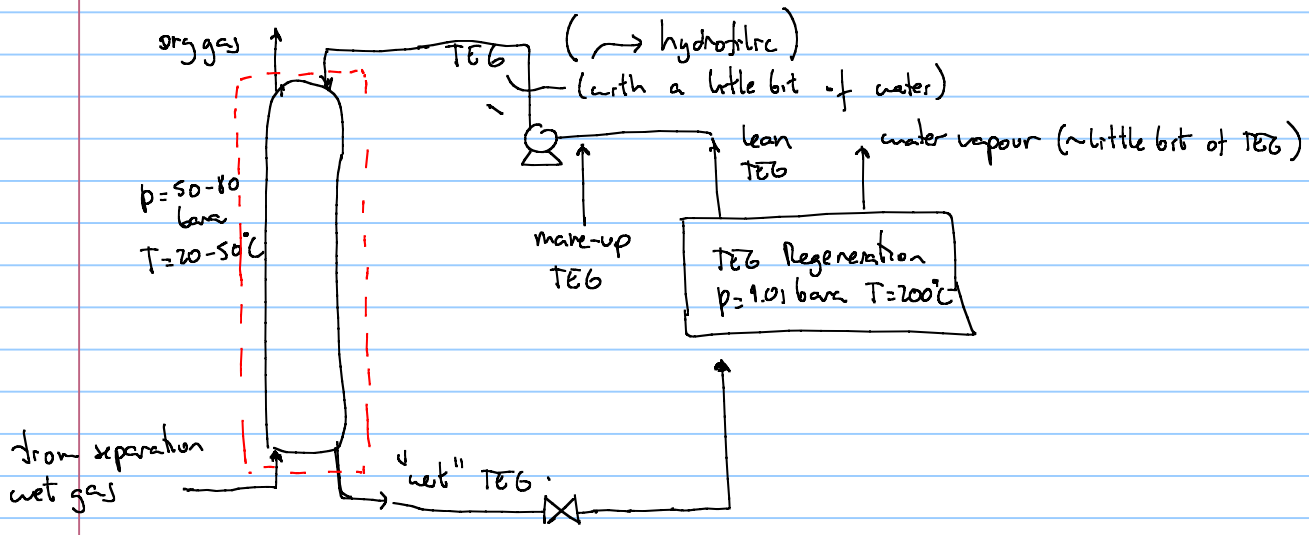
Similar to heat exchanger

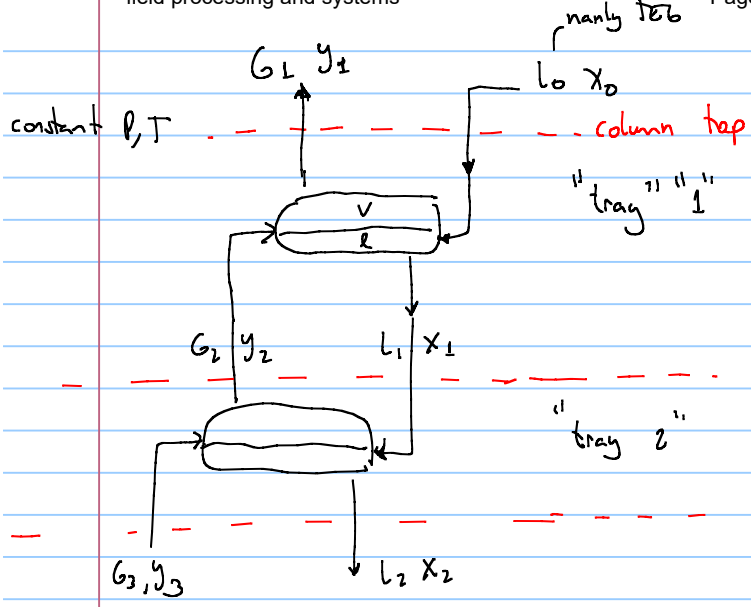


vs.



for gas dehydration (after separation - stabilization), before compression (wet gas transport) TEG columns are typically used





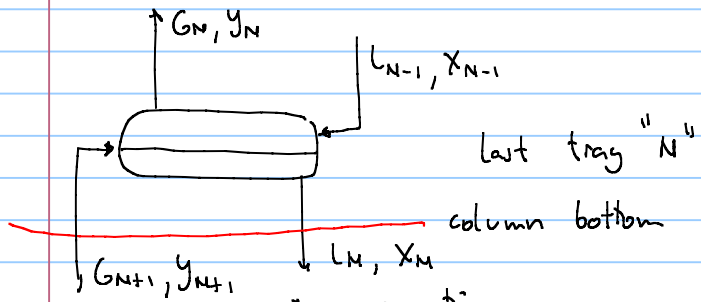
L liquid molar rate
G gas molar rate
x molar fraction of water in liquid stream
y molar fraction of water in vapor stream

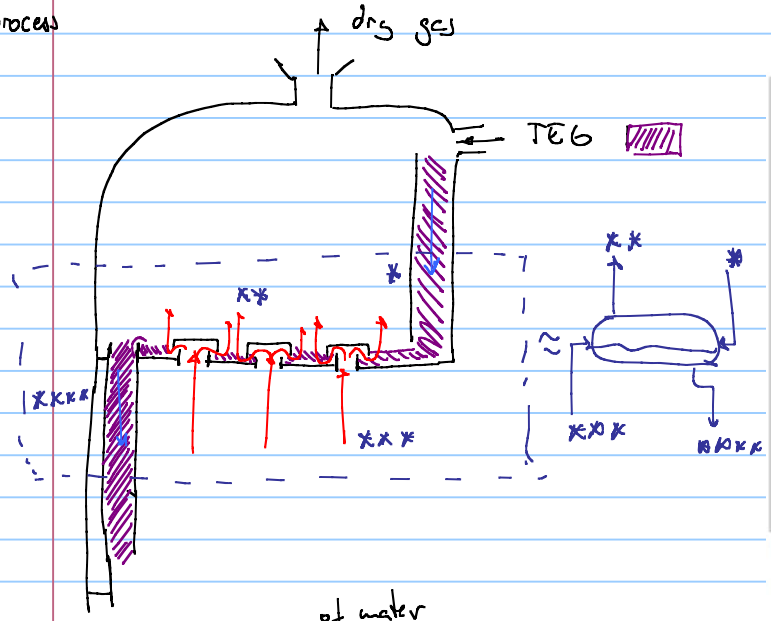
what happens in tray 1

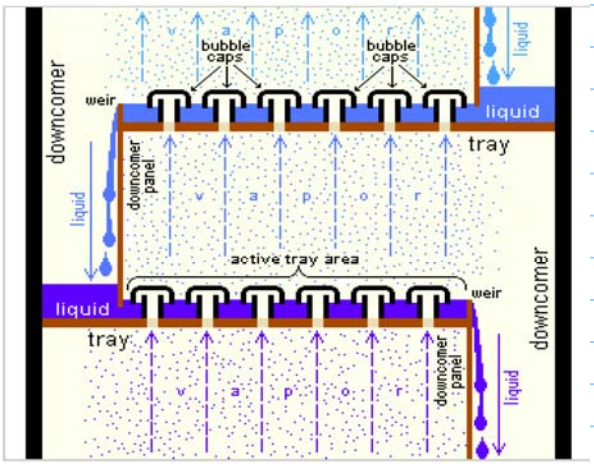
- L_0 and G_2 are mixed
- equilibrium rates G_1, L_1 are extracted.

G_1 is sent up, L_1 is sent down

G_1 and L_1 are in equilibrium, that mean $K_1 = \frac{y_1}{x_1}$

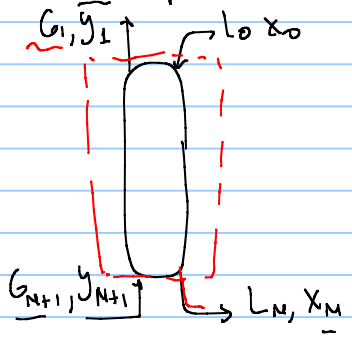






Typical bubble cap trays used in industrial distillation columns

- mass balance of water on the complete column



very low — desired water content

$$G_{N+1} \cdot y_{N+1} + L_0 x_0 = G_1 y_1 + L_N x_n$$

G_1 is usually $< G_{N+1}$ because water has been removed. However the amount of water is so small that

$$G_1 \simeq G_{N+1}$$

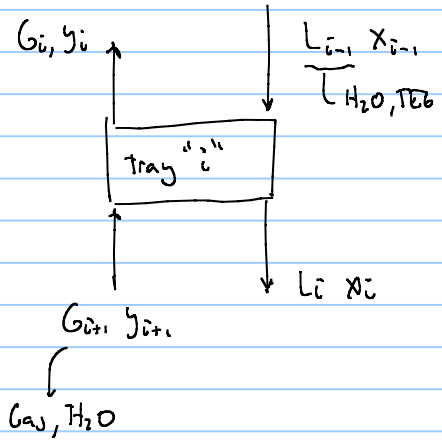
L_0, L_N and X_N are unknowns.

$L_N > L_0$ because it attracts water, however we can often have $L_0 \simeq L_N \simeq L$

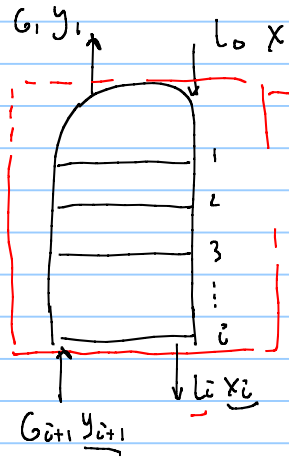
I can use the equation in two ways → ① provide L, calculate X_N (to be used in class.)

② provide X_N, calculate L

- mass balance of water in a tray "i"



$$G_i y_i + L_i x_i = L_{i-1} x_{i-1} + G_{i+1} y_{i+1}$$



- mole balance of water in control volume

$$G_1 y_1 + L_i x_i = L_0 x_0 + G_{i+1} y_{i+1} \quad \text{eq 1.}$$

objective: x_i y_i for each tray

clear y_{i+1} from equation (1)

$$y_{i+1} = \frac{-L_0 x_0 + L_i x_i}{G_{i+1}} + \frac{G_1 y_1}{G_{i+1}}$$

y_{i+1} → molar fraction of water leaving the tray (liquid)

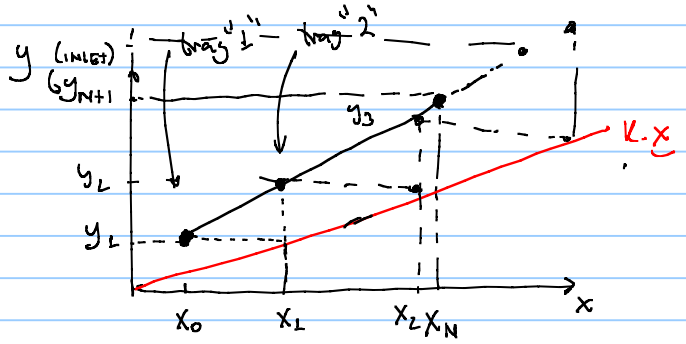
$\frac{-L_0 x_0 + L_i x_i}{G_{i+1}}$ → operational equation of column

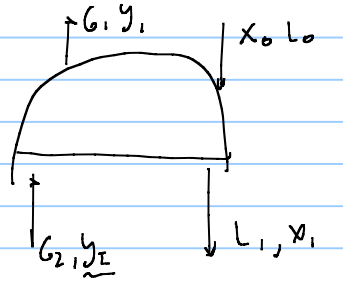
$\frac{G_1 y_1}{G_{i+1}}$ → molar fraction of water entering the tray (gas)

assumption 1) $G_{i+1} \simeq G_1 \simeq G$ ☺

assumption 2) $L_i \simeq L_0 \simeq L$ not so good assumption ☹

operational line of column $\quad y_{i+1} = \frac{L}{G}(x_0 - x_i) + y_1$





$$y_{i+1} = \frac{L}{G}(x_0 - x_i) + y_1$$

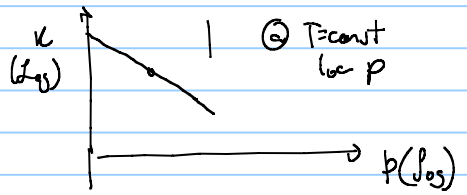
for tray 2

$$y_2 = \frac{L}{G}(x_0 - x_1) + y_1$$

we also know column is at constant p, T

$$K_i = \frac{y_i}{x_i} \qquad K_{H_2O} = \frac{y_{H_2O}}{x_{H_2O}}$$

↑ component "i"

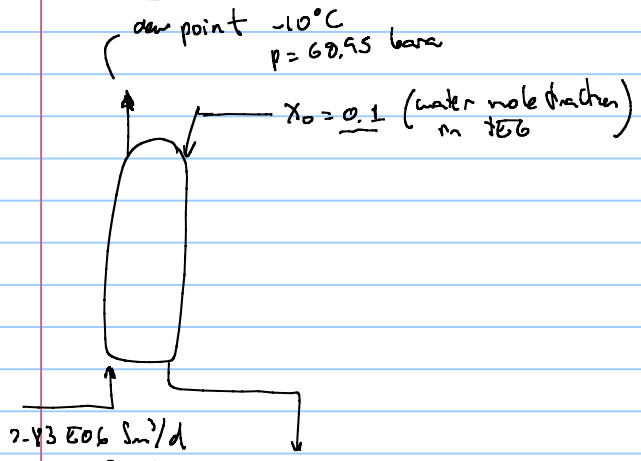


K_{H_2O} in the tower is constant

$$y_{H_2O} = K_{H_2O}\, x_{H_2O}$$

equilibrium line

Class exercise:



① determine water content in inlet gas stream

r_{sw} @ 68.95 bar, 38°C = 1005 $\frac{kg}{1E06\ Sm^3}$

② determine desired water content in outlet gas stream

r_{sw} @ 68.95 bara, -10 °C

$r_{sw} = 61.8 \frac{kg}{(1E06\ Sm^3)}$

③ water to be removed

$$\dot{m}_w = \left(r_{sw}\Big|_{\substack{68.95 \\ 38}} - r_{sw}\Big|_{\substack{68.95 \\ -10}} \right) q_g$$

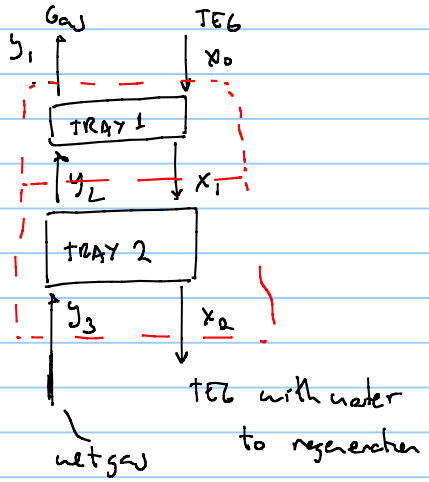
$\dot{m}_w = 2670$ kg/d

④ Equilibrium line $y_{i+1} = \frac{L}{G}(x_0 - x_i) + y_1$

? ? I have

Cont. Class exercise in excel ~> Gas dehydration with TEG
TEG regeneration

class exercise in Hysys ~> TEG column.

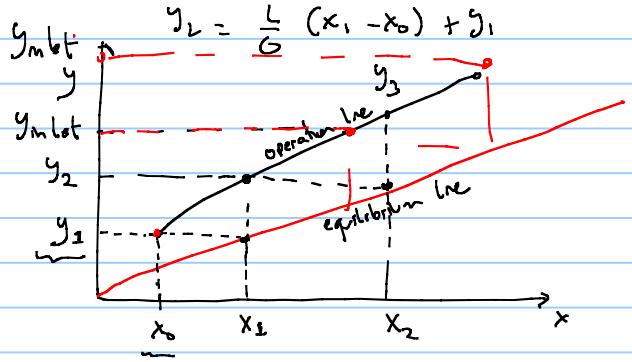


↳ i can measure y_{inlet}

operation line equation

$$y_{i+1} = \frac{L}{G}(x_i - x_0) + y_1$$

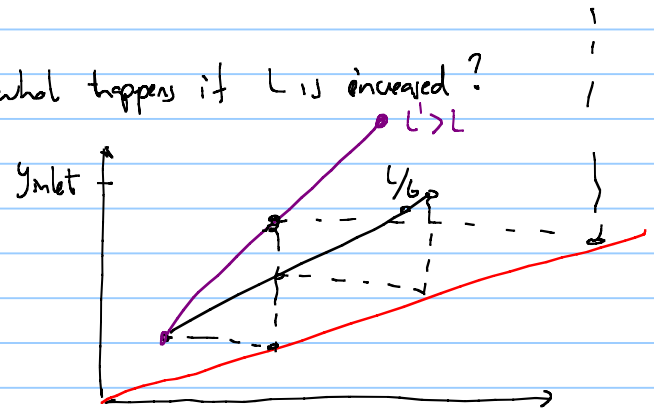
$$y_L = \frac{L}{G}(x_1 - x_0) + y_1$$



if $y_{inlet} > y_3$ ~> NOT enough stages ! increase stages

if $y_{inlet} < y_3$ ~> more than enough

what happens if L is increased ?



$$y_{i+1} = \frac{L}{G}(x_i - x_0) + y_1$$

(desired molar fraction of H_2O in gas)

↳ molar flow rate of gas

(4.a) calculate G

$q_g = 2.83\,E03$ $[Sm^3/d]$

↳ to $[Kmol/d]$

EOS $pV = znRT$

for standard conditions

$p_{sc} = 1.01325$ bara

$T_{sc} = 15.56$ °C

$z = 1$

molar density $\frac{n}{V} = \bar{\rho} = \left[\frac{Kmol}{Sm^3}\right]$

$$\frac{n}{V} = \frac{p_{sc}}{z_{sc} R T_{sc}}$$

Gas dehydration exercise, TPG4135, Prof. Milan Stanko						
gas rate	2.83E+00	1E06 Sm3/d				
Gas γg	0.65					
p	68.95	bara				
T	37.8	C				
xo	0.1	[-]				
gas sc molar density	0.042	[Kmol/Sm3]				
MW water	18	kg/Kmol				
TEG concentration	33	l/kg H2O				
TEG density @ 25 C	1130	kg/m3				
TEG MW	150					
Desired dewpoint						
T	-10	C				
p	68.95	bara				
rsw_inlet	1005	[kg/1e06 Sm3]				
rsw_outlet	61.8	[kg/1e06 Sm3]				
m_water_to_remove	2.67E+03	[kg/d]				
y1		[-]				
yN+1		[-]				
G		[kmol/d]				
L		[kmol/d]				
xN		[-]				
					k	0.00062
	Operation line				Equilibrium	
	x	y		x	y	

$$\bar{\rho} = 0.042 \left[\frac{kmol}{Sm^3}\right]$$

$$\dot{n}_g = q_{\bar{g}} \cdot \bar{\rho}_{sc} = 2.83\,E06\ Sm^3/d \cdot 0.042\ \frac{kmol}{Sm^3}$$

$$\dot{n} = 120000\ kmol/d$$

(4.6) $$y_1 = \frac{\dot{n}_{H_2O@out1}}{\dot{n}_{H_2O@out} + \dot{n}_{gas\,out}}$$

$$\rho_{sc@outlet} = 61.8 \left[\frac{kg}{1E06\ Sm^3}\right]$$

$$\dot{m}_{\bar{w}@outlet} = \rho_{sc@outlet} \cdot q_{\bar{g}}$$

$$= 2.83 \cdot 61.8 = 174.89\ kg/d$$

$$\dot{n}_{H_2O@outlet} = \frac{\dot{m}_{\bar{w}@outlet}}{MW_{H_2O}} = \frac{174.89\ kg/d}{18\ kg/kmol}$$

$$\dot{n}_{H_2O@outlet} = 9.78\ kmol/d$$

$$y_1 = \frac{\dot{n}_{H_2O\,outlet}}{\dot{n}_{H_2O\,outlet} + \dot{n}_{gas\,outlet}}$$

$$y_1 = 8.11\,E05\ [-]$$

(4.c) calculate L rule of thumb $_{TEG}$
need 12 - 40 l/kg water

we will use 33 L TEG/kg water

$$\dot{m}_{H_2O\text{-}to\text{-}remove} = 2670\ kg/d$$

$$q_{TEG} = 2670\ kg/d \cdot 33\ L/kg = 88110\ l/d$$

$$\dot{m}_{TEG} = q_{TEG} \cdot \rho_{TEG} = \frac{88110\ \cancel{l}}{1000\ \cancel{l}/\cancel{m^3}\ d} \cdot 1130\ \frac{kg}{\cancel{m^3}}$$

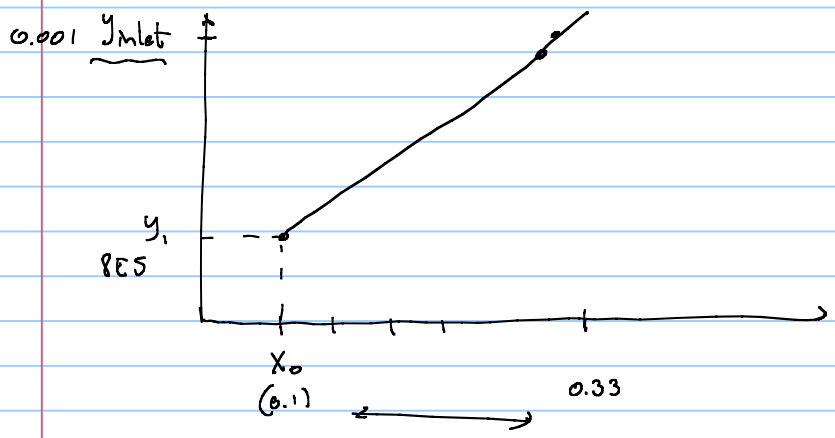
$$\dot{m}_{TEG} = 99564\ kg/d$$

$$\dot{n}_{TEG} = L = \frac{\dot{m}_{TEG}}{MW} = \frac{99564}{150} = 664\ kmol/d$$

Assumption L is constant in the colum

$$\dot{m}_{H_2O\,remove} = 2670\ kg/d$$

$$\dot{n}_{H_2O\,remove} = 148\ kmol/d$$



(4.d) Calculate $y_{inlet} = y_{N+1}$

$\rho_{sw@inlet} = 1005 \text{ kg/m}^3$

$\dot{m}_{H_2O@inlet} = 1005 \cdot 2.83 =$

$\dot{n}_{H_2O@inlet} = \frac{\dot{m}_{H_2O\,inlet}}{MW_{H_2O}}$

$y_{inlet} = \frac{\dot{n}_{H_2O@inlet}}{\dot{n}_{H_2O@inlet} + \dot{n}_{gas\ inlet}} = 0.00132$

y_{inlet}	$\longrightarrow$	y_1 (y_{outlet})
0.00132		0.0000811

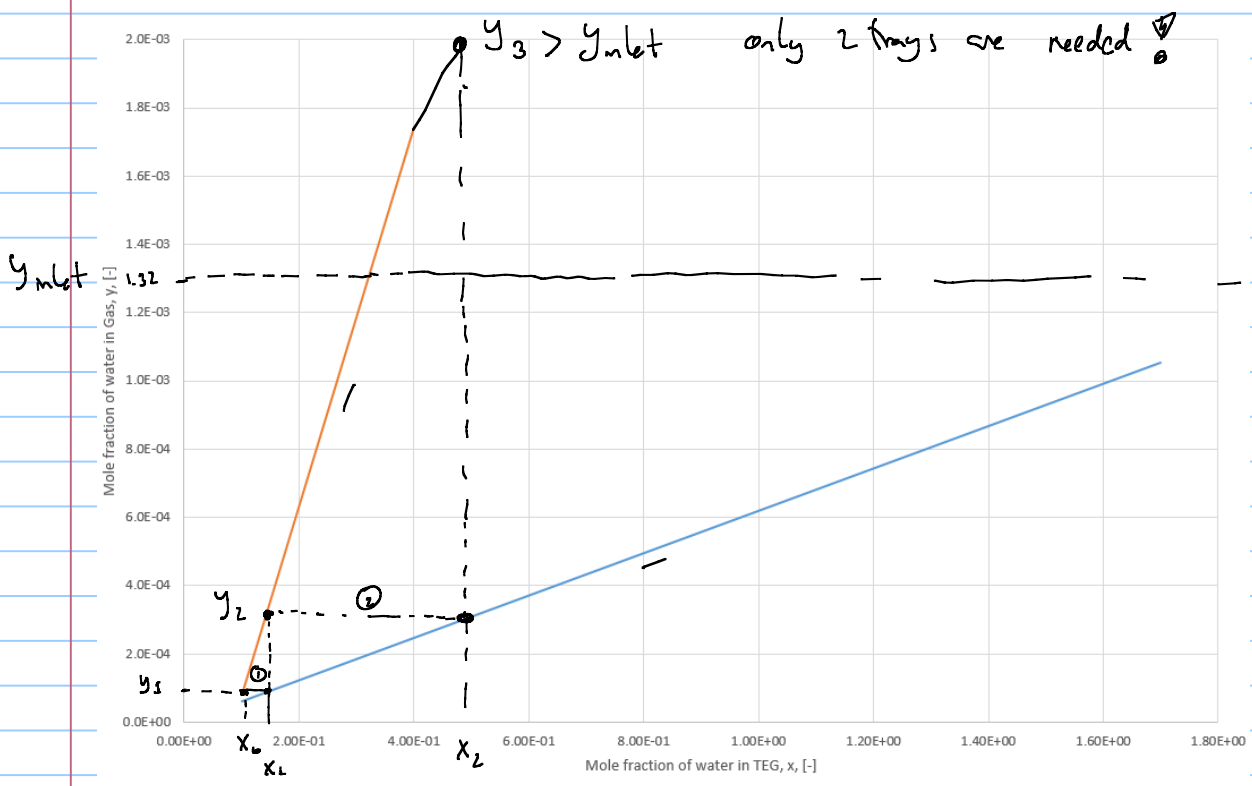
(4.e) what is X_N (molar fraction of water in the TEG exiting the column)

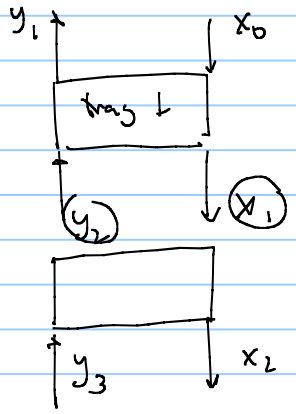
$$G \cdot y_1 + L X_N = y_{N+1} \cdot G + L X_0$$

clearing X_N

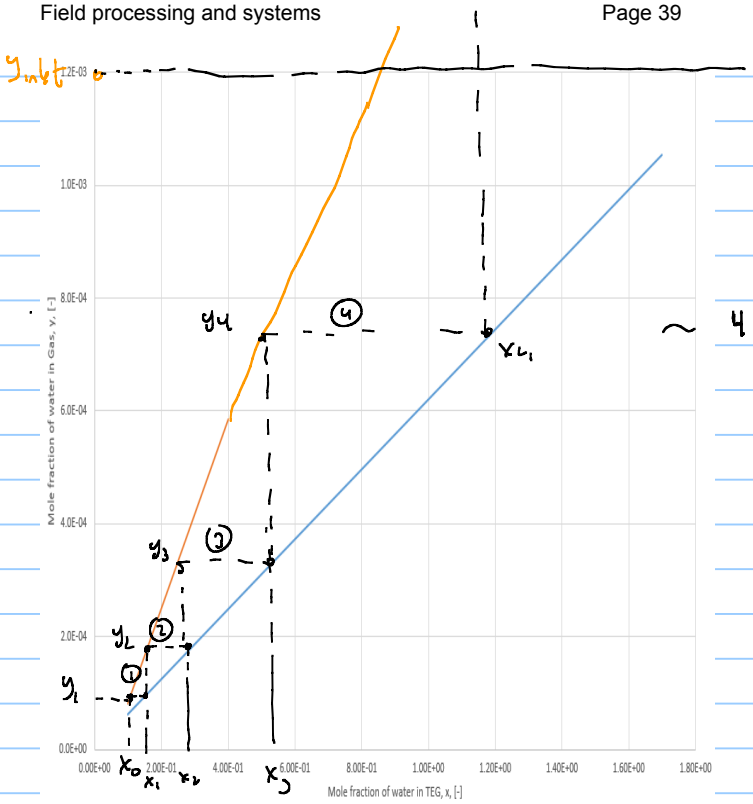
$$X_N = \frac{(y_{N+1} \cdot G + L X_0 - G \cdot y_1)}{L}$$

$X_N = 0.323$



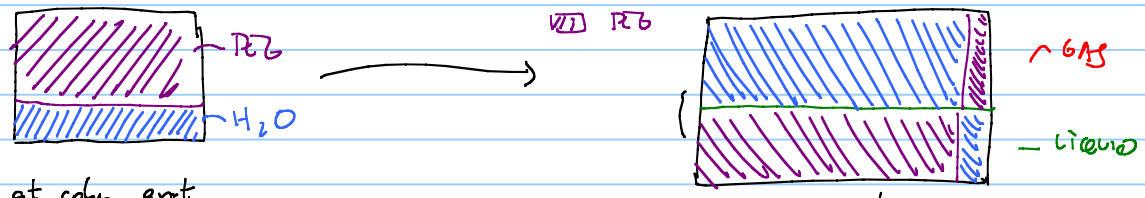


what happens if L is reduced (10 L TEG/kg H_2O)



~ 4 trays are needed

TEG regeneration (removing water from TEG leaving the TEG column)



at colum exit
69 bara
39 °C

at regenerator
9.01325 bara
T = 200 °C

mechanically separate liquid from gas
- vapour mostly water vapour
- liquid mostly TEG

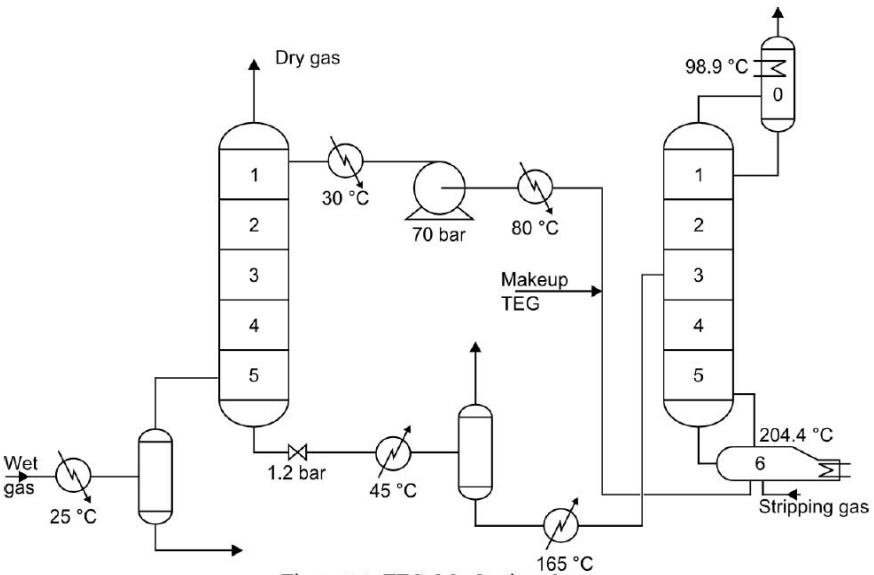


Figure 7-1: TEG dehydration plant.

to calculate the spliting @ T = 200 C, p = 1.01325 bara — calculate y_{H2O}, x_{H2O}, y_{TEG}, x_{TEG}

Use Rachford Rice

T	472.15	K									
p	101.325	Kpa									
Only TEG and Water											
Fv											
					pv	Z	K	RR_term	xi	yi	MW	Mass fraction
	A	B	C		[Kpa]	[-]	[-]		[-]	[-]		
H20	3.55959	643.748	-198.043			0.56						
TEG	6.7568	3715.222	-1.299			0.44						
				sum=		1	SUM=					

composition of liquid stream leaving column x_N

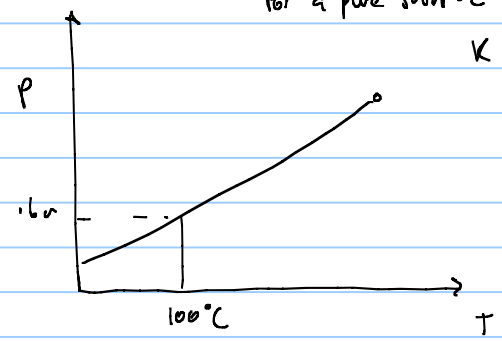
$K = f(p, T)$

Raoult's law

$p_v x_i = P \cdot y_i$ (partial pressure)

for a pure substance

$K = \frac{(p_v)}{P} = \frac{y_i}{x_i}$



Antoine $P_v = f(T)$

```
Function pvap_antoine(T, A, B, C)
'T in K
'p in Kpa
pvap_antoine = (10 ^ (A - (B / (T + C)))) * 100
End Function
```

A, B, C are constant for each pure substance

T	472.15	K									
p	101.325	Kpa									
Only TEG and Water											
Fv	0.303										
					pv	Z	K	RR_term	xi	yi	MW	Mass fraction
	A	B	C		[Kpa]	[-]	[-]		[-]	[-]		
H20	3.55959	643.748	-198.043		1625.78	0.323	16.045	0.874	0.0581	0.9317		
TEG	6.7568	3715.222	-1.299		7.35	0.677	0.073	-0.874	0.9419	0.0683		
				sum=		1	SUM=	0.000				

liquid — water vapour (back to atmosphere)

$\dot{n} \rightarrow \dot{n}_v$, $\dot{n}_L$ — how much TEG am I losing to atmosphere?

$\dot{n}_v = \dot{n} \cdot F_v$ $\quad \dot{n}_{v\_TEG} = \dot{n} \cdot F_v \cdot y_{TEG}$

$\dot{n} = L + W = 664 \frac{kmol}{d} + 148 \frac{kmol}{d} = 812 \frac{kmol}{d}$ $\quad \dot{n}_v = 812 \cdot 0.303 = 246 \frac{kmol}{d}$

make-up TEG $\dot{n}_{v_{TEG}} = 246 \cdot 0.0581 = 14 \text{ kmol/d}$

$\dot{m}_{v_{TEG}} = 14 \text{ kmol/d} \cdot 150 \frac{\text{kg}}{\text{kmol}}$

$= 2141 \text{ kg/d}$

Hysys example