Day 5:

- Class exercise. Calculate u_g vs TVD for the example we made yesterday
  ↳ gas velocity

TVD [m]	T [K]	p [bara]	z [-]	B_g	q_g at p, T	u_g
0	360	40	zfacStanding	–		
⋮	⋮	⋮		–		
				–		
				–		
				–		
2834	380	85 bara		–		

$$\overset{@\,s.c}{q_g} \cdot B_g(p,T) = q_g$$

↳ volume rate at local conditions

velocity of gas

$$u_g = \frac{q_g}{A} = \frac{q_g}{\pi \phi^2} \cdot 4$$

z

$$\frac{m}{d} \quad \frac{s d}{24 \cdot 3600\, s} =$$

Tubing MD [m]	2837					
Tubing TVD [m]	2837					
Tubing ID [m]	0.157					
Tubing Cross section A [m^2]	0.019					
Wellhead pressure [bara]	40					
Gas gravity	0.55					
Twf [K]	378	104.85				
Twh [K]	360	86.85				
qg [Sm^3/d]	2.85E+06					
liquid density [kg/m^3]	8.97E+02					
TVD	T	p	Z	Bg	qg_local	V_local
[m]	[K]	[bara]	[-]	[m^3/Sm^3]	[m^3/d]	[m/s]
0	360.0	40.0	0.9678	0.031	8.71E+04	52.1
284	361.8	46.0	0.9644	0.027	7.58E+04	45.3
567	363.6	51.5	0.9616	0.024	6.79E+04	40.6
851	365.4	56.5	0.9595	0.022	6.21E+04	37.1
1135	367.2	61.1	0.9577	0.020	5.75E+04	34.4
1418	369.0	65.6	0.9563	0.019	5.38E+04	32.2
1702	370.8	69.8	0.9552	0.018	5.08E+04	30.4
1986	372.6	73.8	0.9544	0.017	4.82E+04	28.8
2269	374.4	77.7	0.9537	0.016	4.60E+04	27.5
2553	376.2	81.4	0.9533	0.015	4.40E+04	26.3
2837	378.0	85.1	0.9531	0.015	4.23E+04	25.3

VBA funct "zfactStanding"

VBA func "Bg"

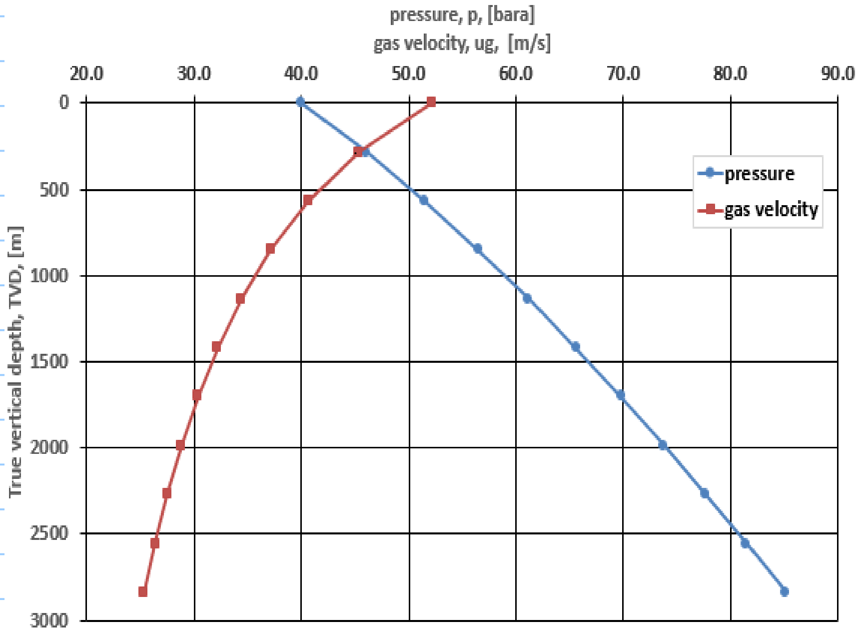
$q_{\bar{g}} \cdot B_g$

$$\frac{q_g}{A\,(24 \cdot 3600)}$$

checking if there is erosion in the tubing:

$$u_g \le V_{erosional} = \frac{100}{\sqrt{\rho_g}}$$

API

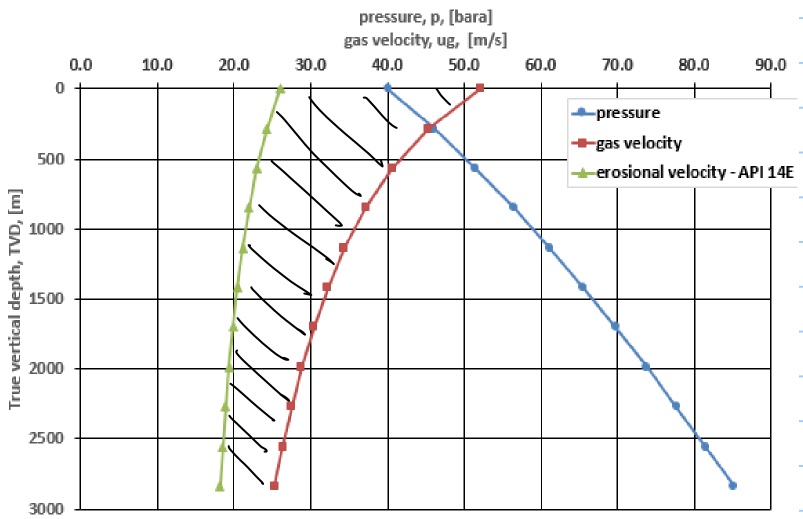


TVD	T	p	Z	Bg	qg_local	V_local	deng	Verosional
Tubing MD [m]	2837							
Tubing TVD [m]	2837							
Tubing ID [m]	0.157							
Tubing Cross section A [m^2]	0.019							
Wellhead pressure [bara]	40							
Gas gravity	0.55							
Twf [K]	378	104.85						
Twh [K]	360	86.85						
qg [Sm^3/d]	2.85E+06							
liquid density [kg/m^3]	8.97E+02							
[m]	[K]	[bara]	[-]	[m^3/Sm^3]	[m^3/d]	[m/s]	[kg/m^3]	[m/s]
0	360.0	40.0	0.9678	0.031	8.71E+04	52.1	22.0	26.01
284	361.8	46.0	0.9644	0.027	7.58E+04	45.3	25.3	24.26
567	363.6	51.5	0.9616	0.024	6.79E+04	40.6	28.2	22.97
851	365.4	56.5	0.9595	0.022	6.21E+04	37.1	30.9	21.96
1135	367.2	61.1	0.9577	0.020	5.75E+04	34.4	33.3	21.13
1418	369.0	65.6	0.9563	0.019	5.38E+04	32.2	35.6	20.45
1702	370.8	69.8	0.9552	0.018	5.08E+04	30.4	37.7	19.86
1986	372.6	73.8	0.9544	0.017	4.82E+04	28.8	39.8	19.35
2269	374.4	77.7	0.9537	0.016	4.60E+04	27.5	41.7	18.89
2553	376.2	81.4	0.9533	0.015	4.40E+04	26.3	43.5	18.49
2837	378.0	85.1	0.9531	0.015	4.23E+04	25.3	45.3	18.13

deng(p, T-273.15, Z, ρ_g)

VBA funct

VBA function "Verosional (ρ_g)"



Checking Turner criteria. Minimum gas velocity required to lift liquid droplet.

≈ constant

$$V = 5.46 \left[\frac{\sigma^{0.25} \left(\rho_L - \rho_g\right)^{0.25}}{\rho_g^{0.5}} \right]$$

if $V_g \geq V_{turner}$

from correlation

```
'   Oil-Gas interfacial tension in N/m
Function STog(DenO, deng)
'Density of the oil,kg/m^3
'Density of the gas,kg/m^3

    STog = (567 * (DenO - deng) * 0.001 / 213) ^ 4
    STog = 0.001 * STog
End Function
```

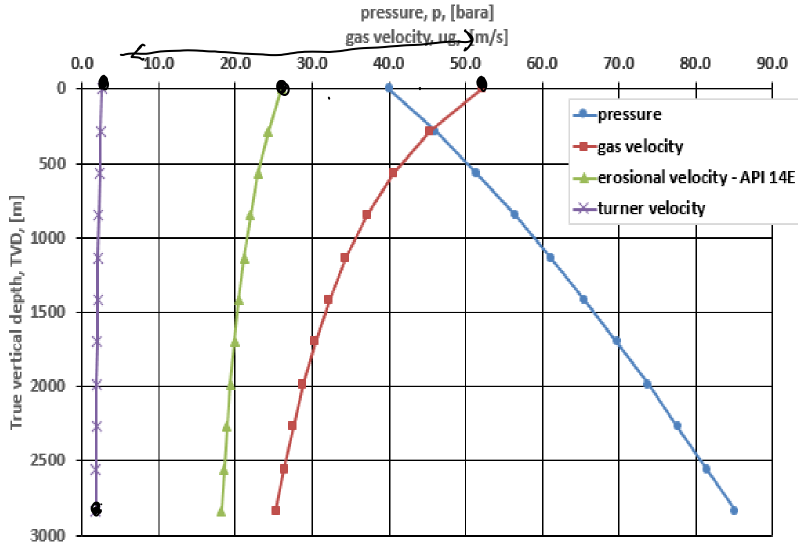
6"

VBA function STog(denl, deng)

VBA function v_turner(ρL, ρg, σg)

Tubing MD [m]	2837	
Tubing TVD [m]	2837	
Tubing ID [m]	0.157	
Tubing Cross section A [m^2]	0.019	
Wellhead pressure [bara]	40	
Gas gravity	0.55	
Twf [K]	378	104.85
Twh [K]	360	86.85
qg [Sm^3/d]	2.85E+06	
liquid density [kg/m^3]	8.97E+02	

TVD	T	p	Z	Bg	qg_local	V_local	deng	Verosional	int_ten_o_g	Vturner
[m]	[K]	[bara]	[-]	[m^3/Sm^3]	[m^3/d]	[m/s]	[kg/m^3]	[m/s]	[N/m]	[m/s]
0	360.0	40.0	0.9678	0.031	8.71E+04	52.1	22.0	26.01	0.029	2.6
284	361.8	46.0	0.9644	0.027	7.58E+04	45.3	25.3	24.26	0.029	2.4
567	363.6	51.5	0.9616	0.024	6.79E+04	40.6	28.2	22.97	0.029	2.3
851	365.4	56.5	0.9595	0.022	6.21E+04	37.1	30.9	21.96	0.028	2.2
1135	367.2	61.1	0.9577	0.020	5.75E+04	34.4	33.3	21.13	0.028	2.1
1418	369.0	65.6	0.9563	0.019	5.38E+04	32.2	35.6	20.45	0.028	2.0
1702	370.8	69.8	0.9552	0.018	5.08E+04	30.4	37.7	19.86	0.027	2.0
1986	372.6	73.8	0.9544	0.017	4.82E+04	28.8	39.8	19.35	0.027	1.9
2269	374.4	77.7	0.9537	0.016	4.60E+04	27.5	41.7	18.89	0.027	1.9
2553	376.2	81.4	0.9533	0.015	4.40E+04	26.3	43.5	18.49	0.027	1.8
2837	378.0	85.1	0.9531	0.015	4.23E+04	25.3	45.3	18.13	0.026	1.8



offshore gas well

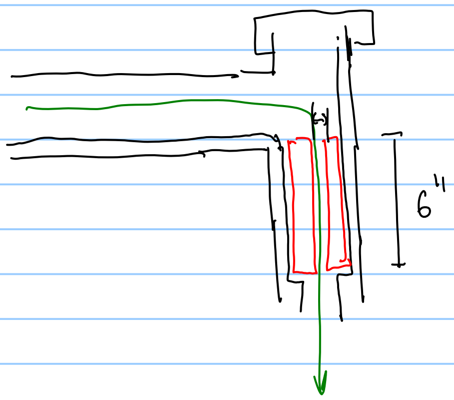
typical production

3 E6 Sm^3/d

30 mmscf/d

Production choke — types:
- Positive / bean choke
- Adjustable

Bean

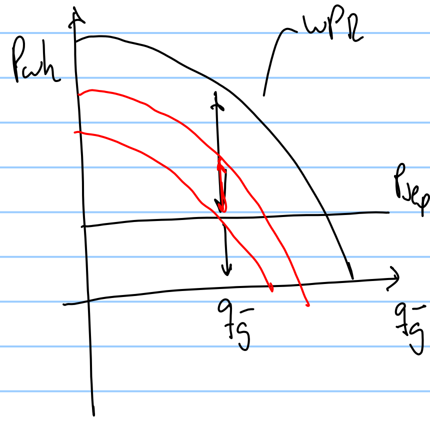


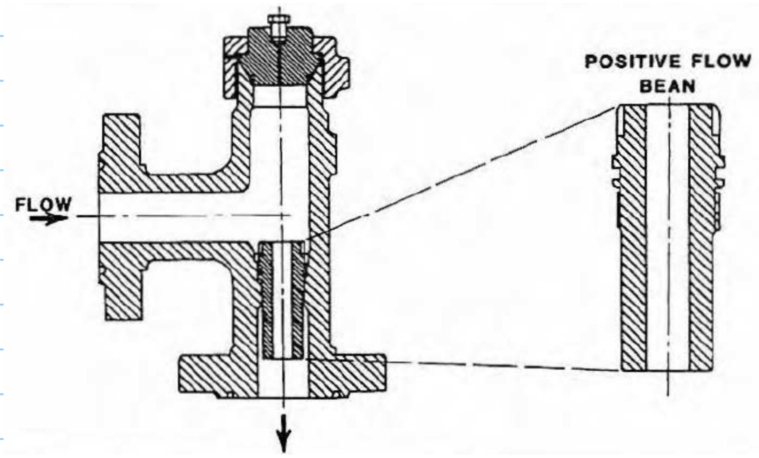
orifice size

1/8'' → 2''

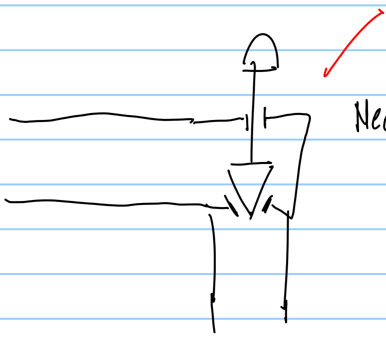
Steps 1/64''

$\frac{8}{64}'' \longrightarrow \frac{256}{64}''$

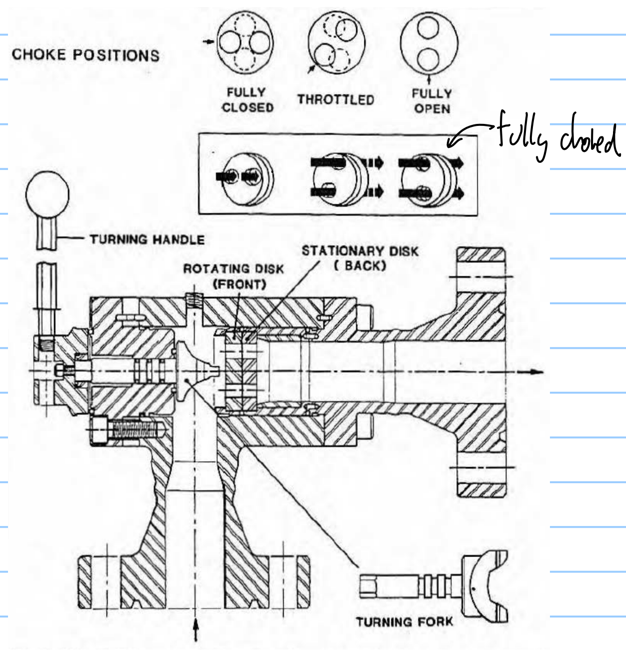




Adjustable



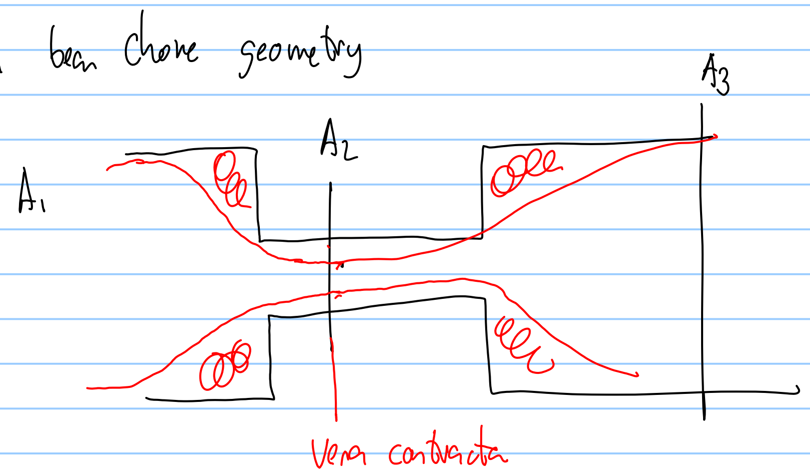
Needle choke, Rotary disk

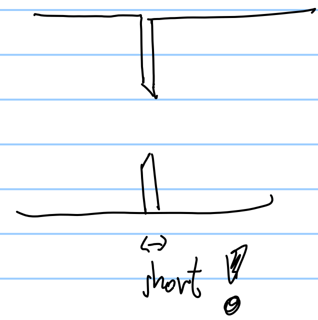


Cage choke

! Different than orifice for metering

focusing on bean choke geometry



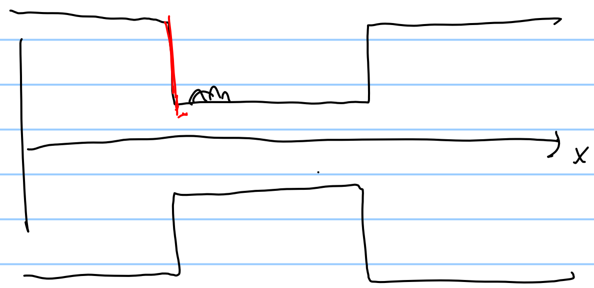


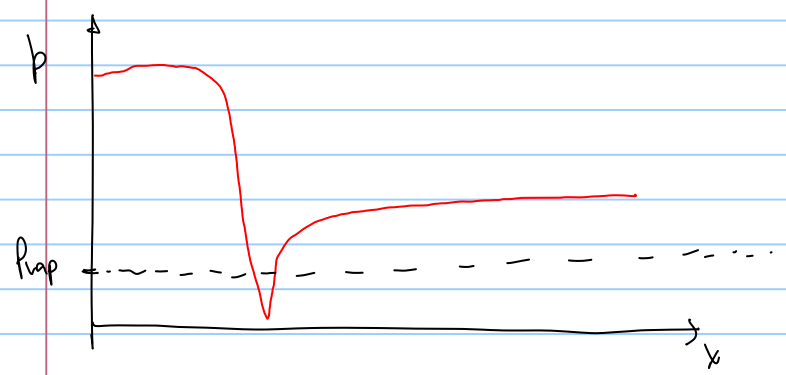
main function of choke: dissipate a lot of energy in a concentrated place ↓p

→ control production!

undesired consequences

- p drops ~> in oil you get gas vaporization
  - → if gas you get liquid condensation
- erosion ~> due to high velocities in chokes
  - sand - worsens the problem.
- cooling ~> for gas Joule-Thomson effect
  - → more liquid condensation
  - → free water + low T ~> ice block!
- cavitation.

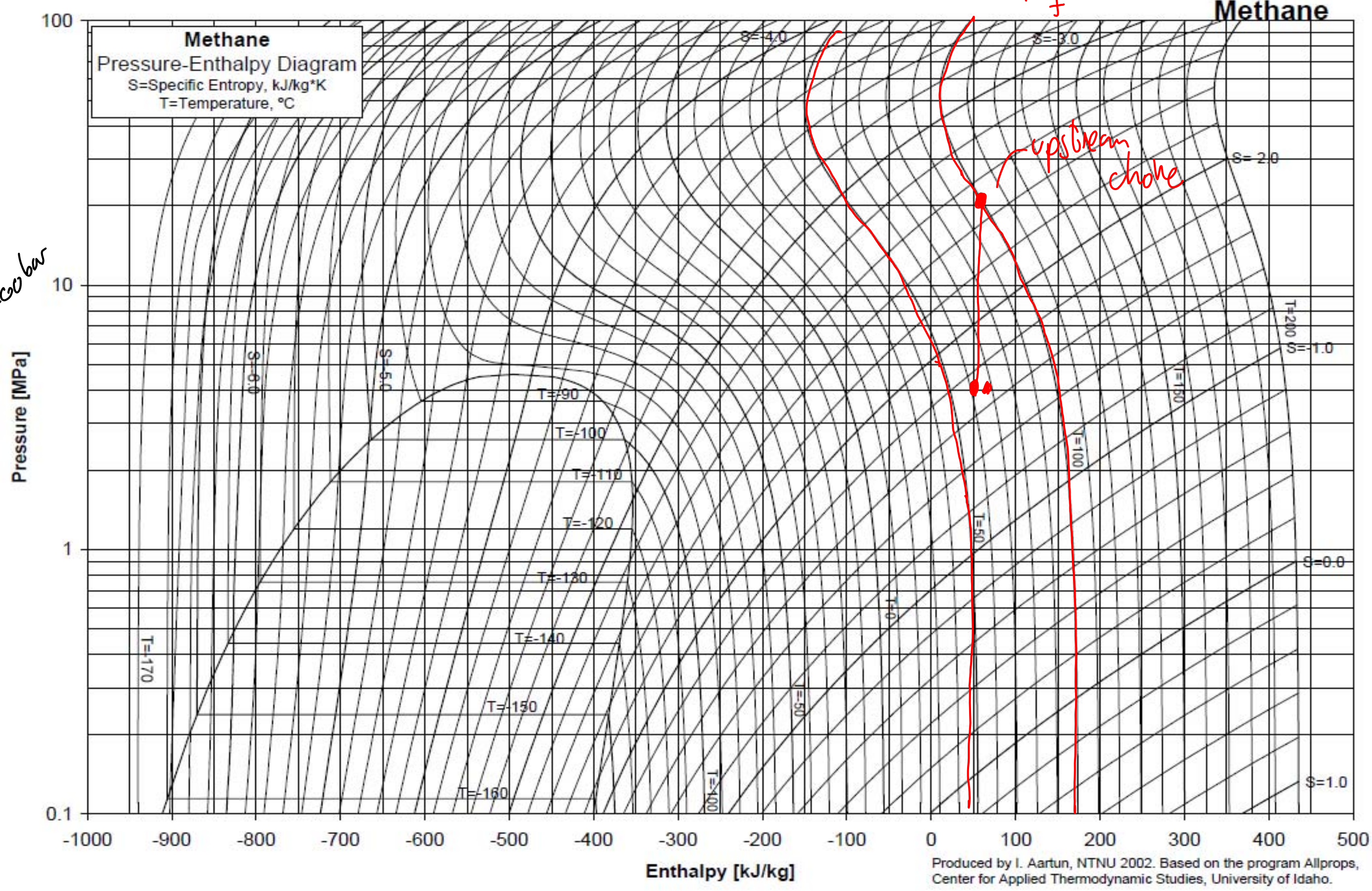




p vs. h diagram

Pwh avail = 205 bara T=100°C

Pwh Req = 40 bara



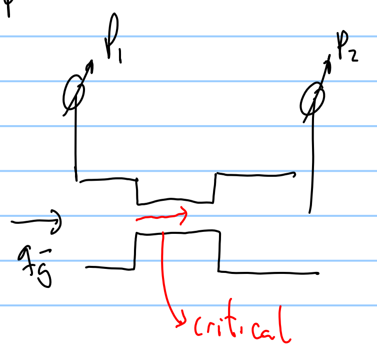
the process in the choke is isenthalpic ! (no $\dot{q}$ or $\dot{w}$ transferred out of the control volume)

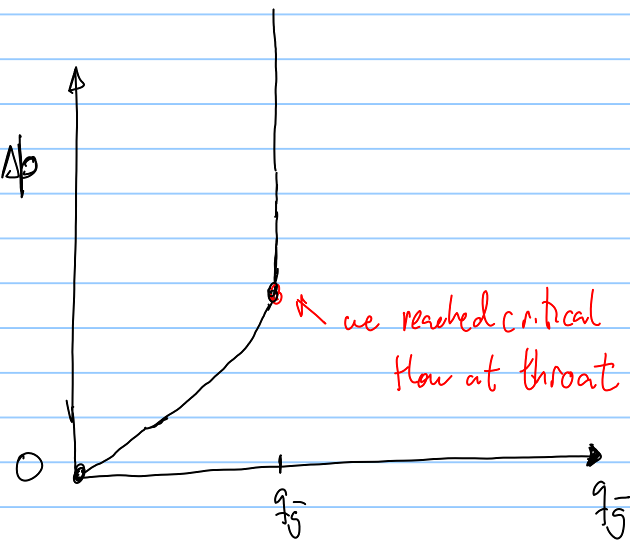
1st law of thermodynamics for open systems $\dot{m}(h_2 - h_1) = \dot{q} - \dot{w}$, with $\dot{q} = 0$ and $\dot{w} = 0$

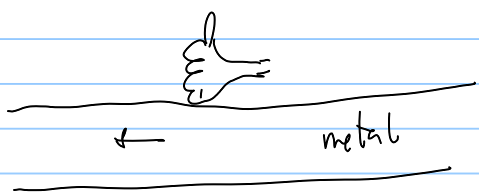
$\boxed{h_2 = h_1}$!

Experiment

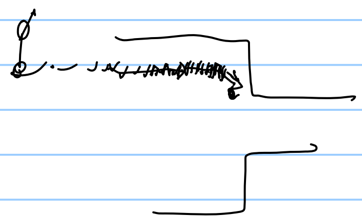
p_1 is fixed







velocity of sound in a real gas $a = \sqrt{\frac{k Z R T}{M_w}}$



$$\widetilde{k = \frac{C_p}{C_v}}$$

a $k=1.6$

$R = 8314.3$

$T = 80+273.15$

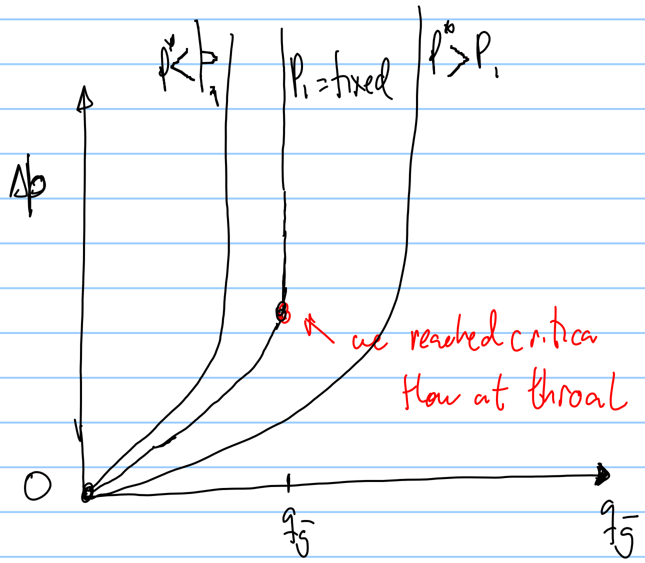
$M = 16$

as a rule of thump critical pressure ratio is

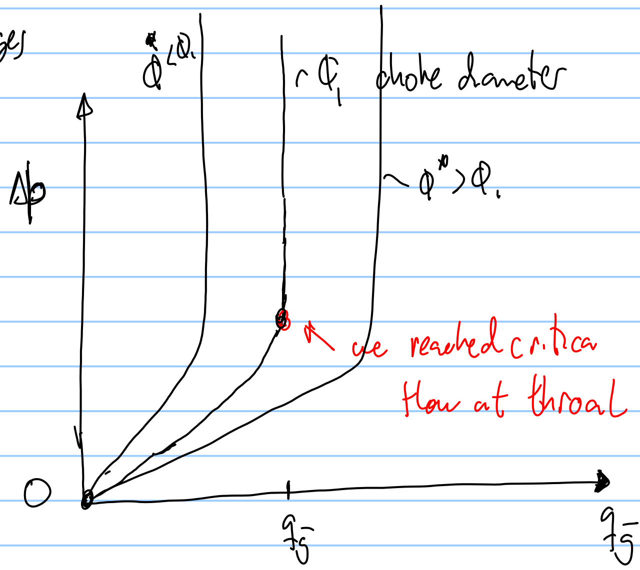
$a \approx 542$ m/s

$$\frac{P_2}{P_1} \approx 0.5 \checkmark$$

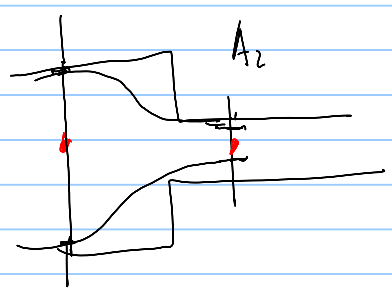
in gas $\left(\frac{P_2}{P_1}\right)_c = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$



if the orifice changes



Choke equation for Liquid:



$$dp + \frac{\rho}{2} 2u\,du + \rho g \cancel{dz} = 0$$

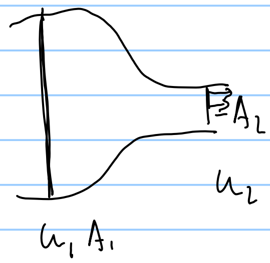
distance short no frictional losses

$$\int_1^2 \frac{dp}{\rho} + \int_1^2 u\, du = 0$$

$$p_2 - p_1 = \rho_L \cdot 0.5 \cdot (u_1^2 - u_2^2)$$

$\underbrace{q_{sc} \text{ vs } \Delta p}$

mass balance



$$u_2 \cdot A_2 = u_1 A_1$$

$$(u_1)^2 = \left(\frac{d_2^2}{d_1^2}\right)^2 (u_2)^2$$

$$\beta = \frac{d_2}{d_1}$$

$$A_1 = \frac{\pi \cdot d_1^2}{4}$$

$$A_2 = \frac{\pi\, d_2^2}{4}$$

$$u_1^2 = \beta^4 u_2^2$$

$$p_2 - p_1 = \rho_L\, 0.5 \left(\beta^4 u_2 - u_2^2\right)$$

$$\frac{\Delta p\, 2}{\rho_L (1-\beta^4)} = u_2^2$$

$$u_2 = \sqrt{\frac{\Delta p\, 2}{\rho_L (1-\beta^4)}}$$

$$q_{sc} = \underbrace{u_2 \cdot A_2}\, C_d$$

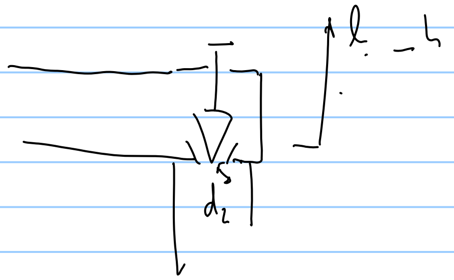
flow coefficient

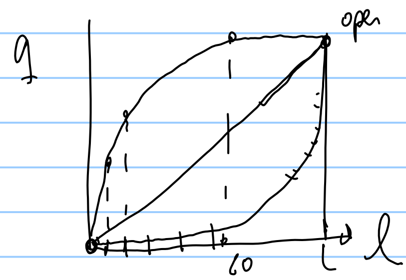
to account for vena contraction

$$\boxed{q = A_2\, C_d \sqrt{\frac{\Delta p\, 2}{\rho_L (1-\beta^4)}}}$$

in adjustable chokes d_2 is changing

$$q = f(l) \cdot C_d \sqrt{\frac{\Delta p \cdot 2}{\rho}}$$





if Δp is fixed

Derivation of choke equation for gas $\rightsquigarrow$ orifice

$$\int_1^2 \frac{dp}{\rho} + \int_1^2 u\,du \qquad , \quad \int_1^2 \frac{dp}{\rho} = 0.5\left(u_1^2 - u_2^2\right)$$

$u_2 \gg u_1 \quad u_2^2 \gg u_1^2$

$u_2^2 - u_1^2 \approx u_2^2$

$$\rho = \frac{p\, M_w}{z R T}$$

$p v^n = \text{constant}$

$n = k$

adiabatic: $\quad p \dfrac{1}{\rho^k} = \text{constant} = C \qquad \rho = \dfrac{p^{1/k}}{\underset{\sim}{C^{1/k}}}$

$$C^{1/k} \int_1^2 \frac{dp}{p^{1/k}} = C^{1/k} \left(\frac{k}{k-1}\right)\left(p_2^{\frac{k-1}{k}} - p_1^{\frac{k-1}{k}}\right)$$

$$C^{1/k} \frac{k}{k-1} p_1^{\frac{k-1}{k}} \left(\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right) \qquad y = \frac{p_2}{p_1}$$

$$C^{1/k} = \frac{p_1^{1/k}}{\rho_1}$$

$$-u_2^2 = 2\frac{p_1}{\rho_1} \frac{k}{k-1}\left(y^{\frac{k-1}{k}} - 1\right) \qquad \rho_1 = \frac{p_1 M_w}{R z_1 T_1}$$

$$u_2 = \sqrt{2 \frac{\cancel{p_1} R z_1 T_1}{\cancel{p_1} M_w} \left(\frac{k}{k-1}\right)\left(y^{\frac{k-1}{k}} - 1\right)}$$

$$\rho_1 = \frac{p_1 M_w}{R z_1 T_1}$$

$$u_2 = \frac{\dot m}{\underset{\sim}{\rho_2} \cdot \underline{C_d} A_2} \qquad p \rho^k = \text{Constant}$$

$$p_1 \rho_1^k = p_2 \rho_2^k \qquad \rho_2 = \left(\frac{p_1}{p_2}\right)^{1/k} \rho_1$$

$$\dot{m} = q_{sc} \cdot \rho_{sc} \qquad \rho_{sc} = \frac{p_{sc} M}{T_{sc} \cancel{Z} R}$$

$$q_{sc} = c_d A_2 p_1 \left(\frac{T_{sc}}{p_{sc}}\right) \sqrt{2 \frac{R}{M_g Z_1 T_1}} \sqrt{\left(\frac{k}{k-1}\right)\left[(y)^{\frac{2}{k}} - (y)^{\frac{k+1}{k}}\right]}$$

$$A_2 = \frac{\pi d_2^2}{4}$$

if $y \geq y_c$ (≈ 0.5)

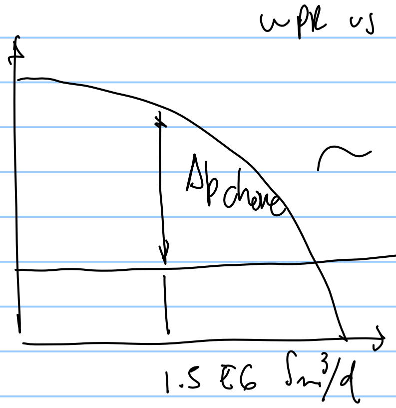
then use this equation

if $y \leq y_c$

then use this equation with

$y = y_c$

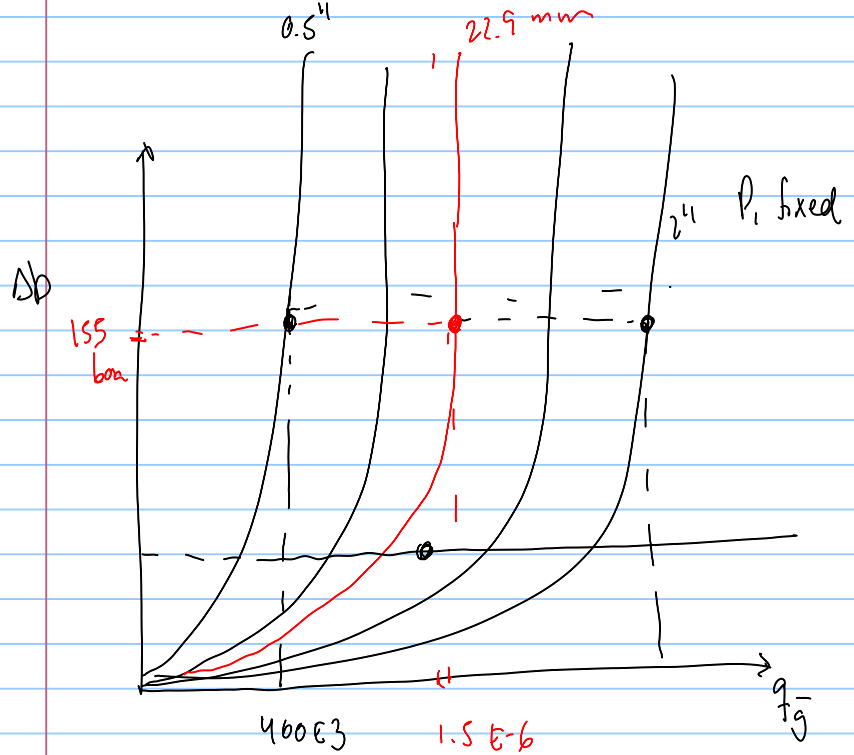
Exercise I performed

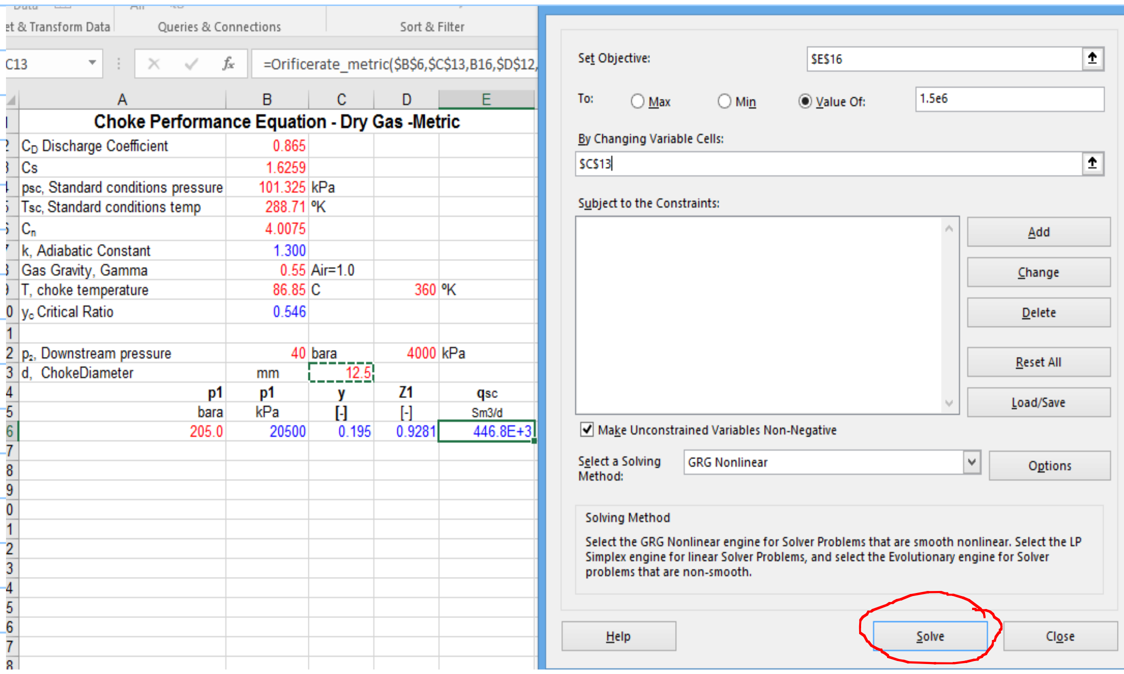


$P_{wh\,avail} = 205$ bara

$P_{wh\,req} = 40$ bara

$\Delta p = 155$ bara





Choke Performance Equation - Dry Gas -Metric				
C_D Discharge Coefficient	0.865			
Cs	1.6259			
psc, Standard conditions pressure	101.325	kPa		
Tsc, Standard conditions temp	288.71	ºK		
C_n	4.0075			
k, Adiabatic Constant	1.300			
Gas Gravity, Gamma	0.55	Air=1.0		
T, choke temperature	86.85	C	360	ºK
y_c Critical Ratio	0.546			
p_2, Downstream pressure	40	bara	4000	kPa
d, ChokeDiameter	mm	22.90383		
p1	p1	y	Z1	qsc
bara	kPa	[-]	[-]	Sm3/d
205.0	20500	0.195	0.9281	1.5E+6

Home exercise

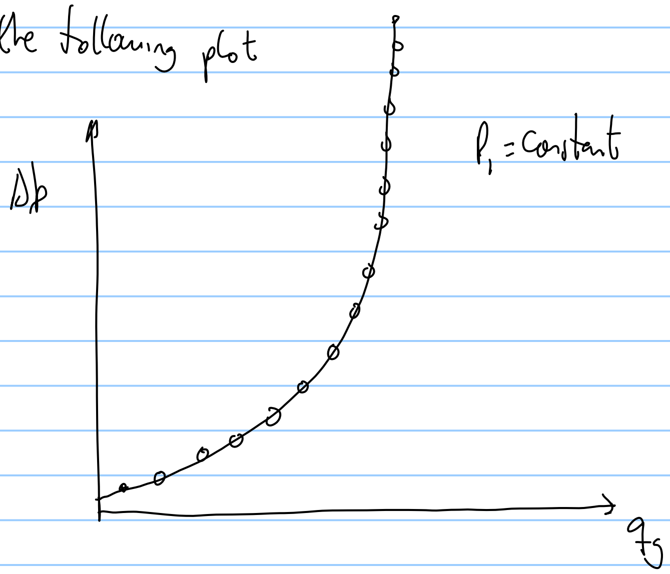
Using the same data shown before

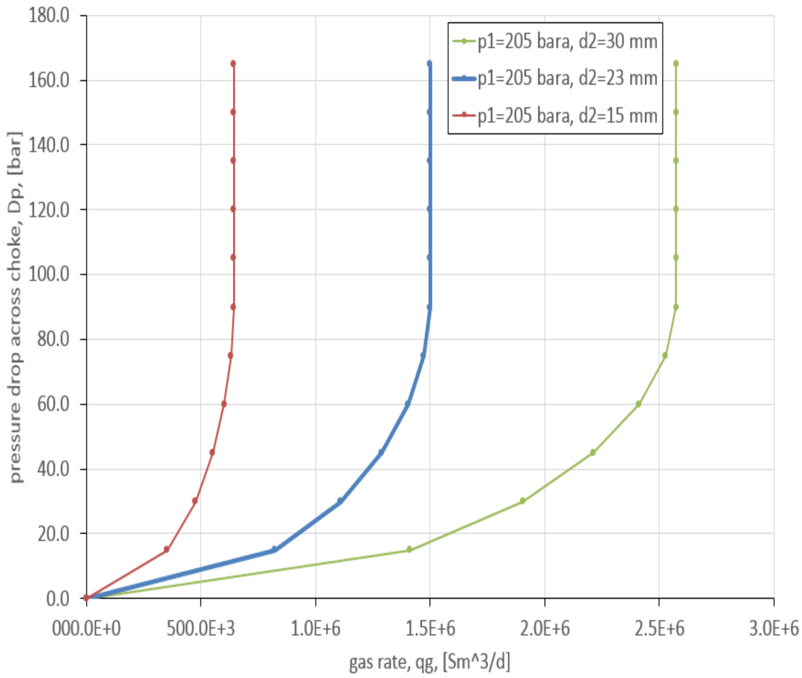
$p_1 = 205$ bara

$p_2 = 40$ bara

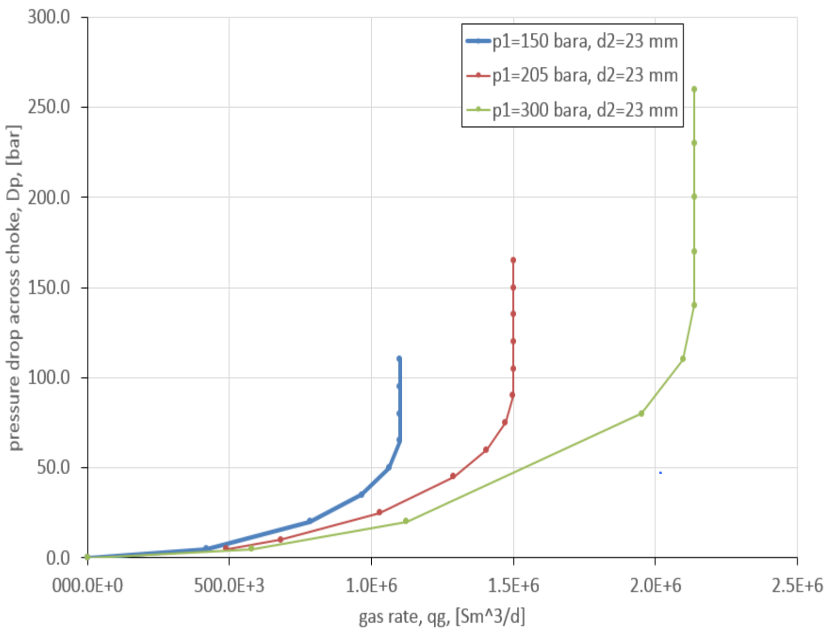
$d_2 = 22.9$ mm

make the following plot





180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
pressure drop across choke, Dp, [bar]
000.0E+0
500.0E+3
1.0E+6
1.5E+6
2.0E+6
2.5E+6
3.0E+6
gas rate, qg, [Sm^3/d]
p1=205 bara, d2=30 mm
p1=205 bara, d2=23 mm
p1=205 bara, d2=15 mm



300.0
250.0
200.0
150.0
100.0
50.0
0.0
pressure drop across choke, Dp, [bar]
000.0E+0
500.0E+3
1.0E+6
1.5E+6
2.0E+6
2.5E+6
gas rate, qg, [Sm^3/d]
p1=150 bara, d2=23 mm
p1=205 bara, d2=23 mm
p1=300 bara, d2=23 mm