Tishk International University
Engineering Faculty
Petroleum and Mining Department

Petroleum Production Engineering II

Lecture 2: Choke Performance

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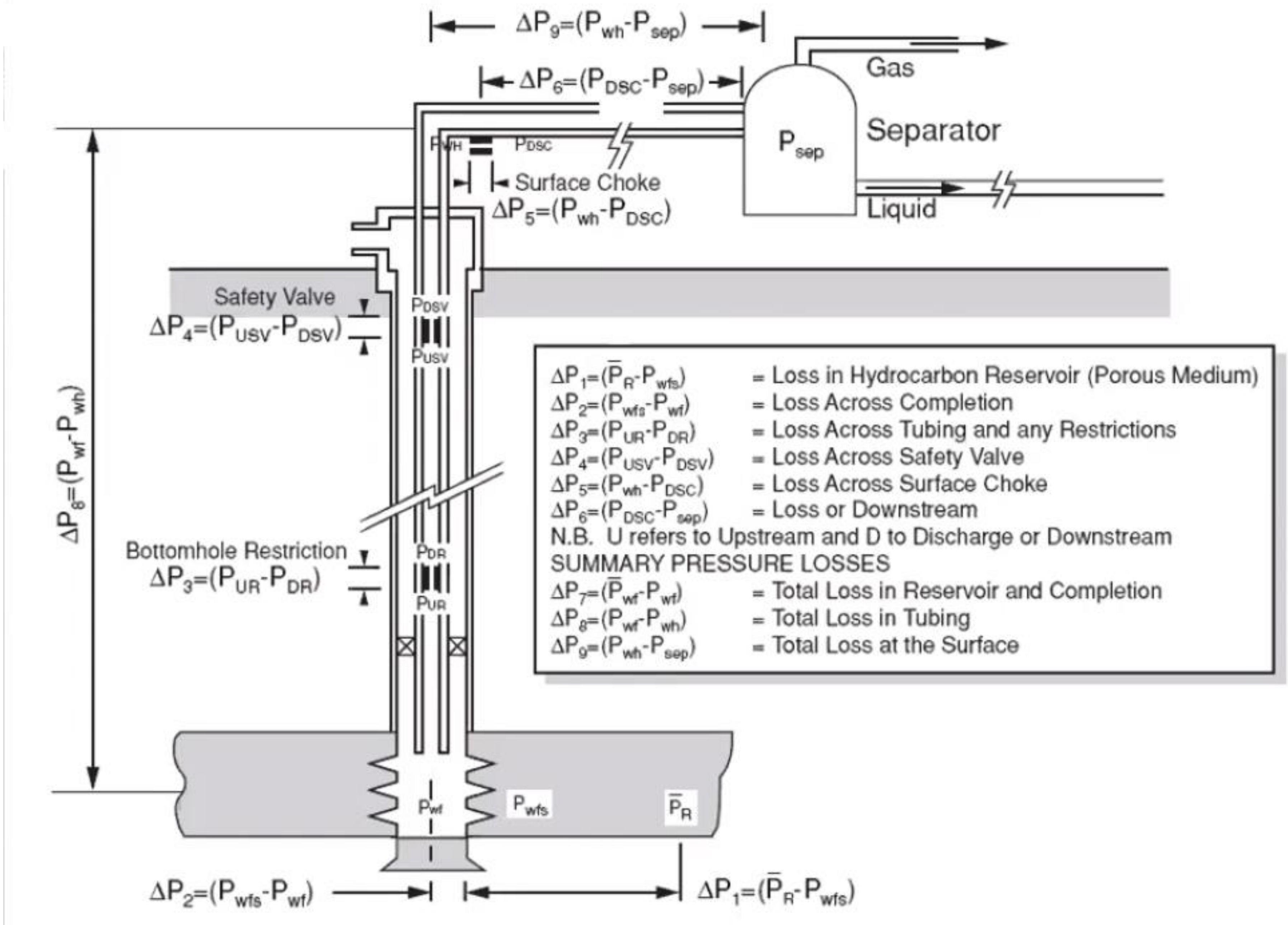
Various Pressure Losses in The Production System



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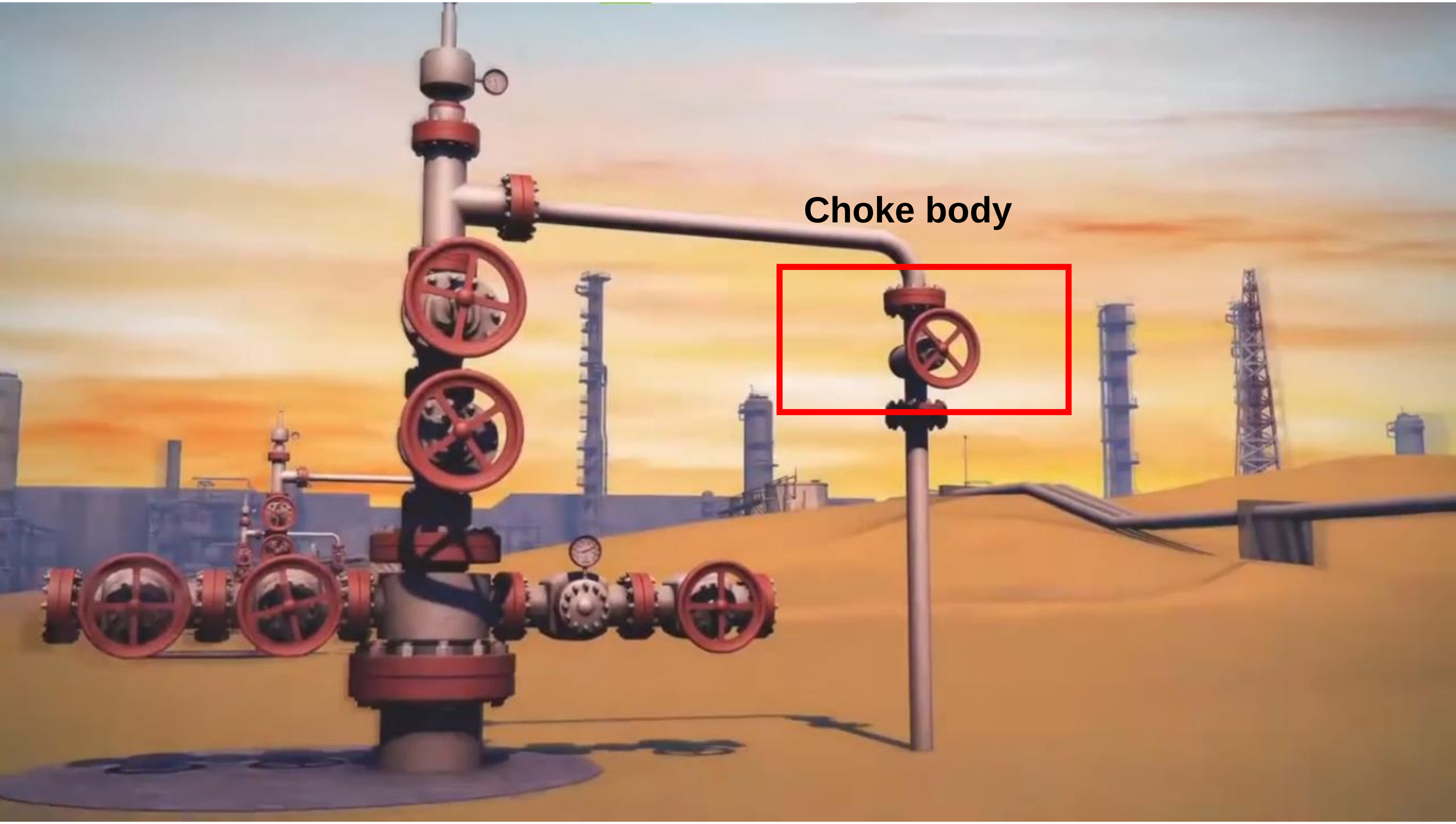
1.1 Introduction

- Wellhead chokes are used to **limit production rates for regulations**, **protect surface equipment from slugging**, **avoid sand problems due to high drawdown**, and **control flow rate to avoid water or gas coning**.

- Two types of wellhead chokes are used.

1. **Positive (fixed) chokes**
2. **Adjustable chokes**

- Placing a choke at the wellhead means **fixing the wellhead pressure** and, thus, the **flowing bottom-hole pressure and production rate**. For a given wellhead pressure, by calculating pressure loss in the tubing the flowing bottomhole pressure can be determined. If the reservoir pressure and productivity index is known, the flow rate can then be determined on the basis of inflow performance relationship (IPR).


Choke body

1.2 Sonic and Subsonic Flow

- Both sound wave and pressure wave are **mechanical waves**. When the fluid flow velocity in a choke **reaches the traveling velocity of sound** in the fluid under the in situ condition, the flow is called **"sonic flow."**
- Under sonic flow conditions, the pressure wave downstream of the choke cannot go upstream through the choke because the medium (fluid) is traveling in the opposite direction at the same velocity.
- Therefore, a pressure discontinuity exists at the choke, that is, the downstream pressure does not affect the upstream pressure. Because of the pressure discontinuity at the choke, any change in the downstream pressure cannot be detected from the upstream pressure gauge. Of course, any change in the upstream pressure cannot be detected from the downstream pressure gauge either.
- This sonic flow provides a unique choke feature that stabilizes well production rate and separation operation conditions.

1.2 Sonic and Subsonic Flow

- Whether a sonic flow exists at a choke depends on a downstream to-upstream pressure ratio. If this pressure ratio is less than a critical pressure ratio, sonic (critical) flow exists. If this pressure ratio is greater than or equal to the critical pressure ratio, subsonic (subcritical) flow exists.
- The critical pressure ratio through chokes is expressed as:

$$\left(\frac{p_{outlet}}{p_{up}}\right)_c = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \quad \text{..............(1.1)}$$

where *Poutlet* is the pressure at choke outlet, *Pup* is the upstream pressure, and k = Cp/Cv is the specific heat ratio.

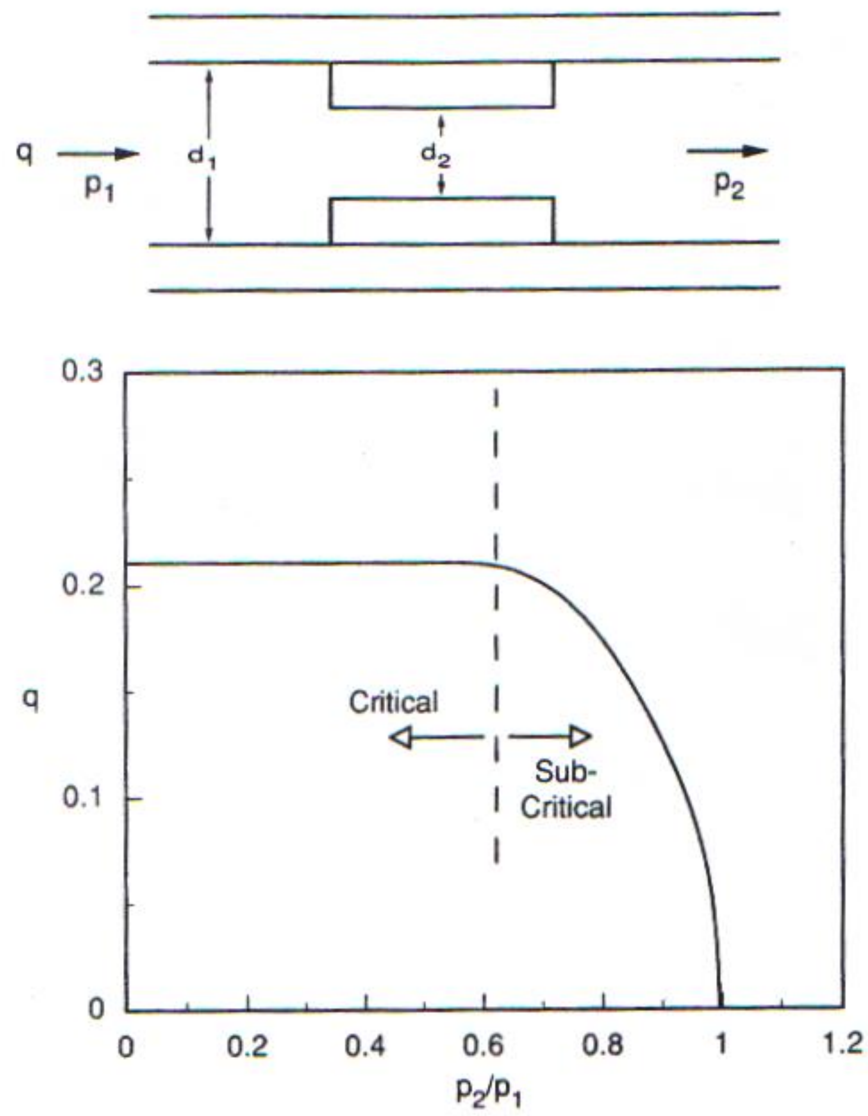


Figure 1-1: A typical choke performance curve

1.3 Single-Phase Liquid Flow

$$\Delta P = P_1 - P_2 = \frac{g}{g_c}\rho\Delta z + \frac{\rho}{2g_c}\Delta u^2 + \frac{2f_F\rho u^2 L}{g_c D}$$

$$q = C_D A\sqrt{\frac{2g_c\Delta P}{\rho}} \qquad \ldots\ldots\ldots\ldots\ldots\ (1.2)$$

where

q = flow rate, ft^3/s
C_D = choke discharge coefficient
A = choke are, ft^2
g_c = unit conversion factor, 32.17 $lb_m\text{-}ft/lb_f\text{-}s^2$
ΔP = pressure drop, lb_f/ft^2
ρ = fluid density, lb_m/ft^3

If U.S. field units are used, Eq (1.2) is expressed as

$$q = 8{,}074 C_D d_2^2 \sqrt{\frac{\Delta p}{\rho}} \qquad \text{..............(1.3)}$$

where

q = flow rate, bbl/d
d_2 = choke diameter, in.
Δp = pressure drop, psi

- The following correlation has been found to give reasonable accuracy for Reynolds numbers between 10^4 and 10^6 for nozzle-type chokes (Guo and Ghalambor, 2005):

$$C_D = \frac{d_2}{d_1} + \frac{0.3167}{\left(\frac{d_2}{d_1}\right)^{0.6}} + 0.025[\log(N_{\text{Re}}) - 4] \quad \text{............(1.4)}$$

where

d_1 = upstream pipe diameter, inch
d_2 = choke diameter, inch
N_{Re}= Reynolds number based on d_2.

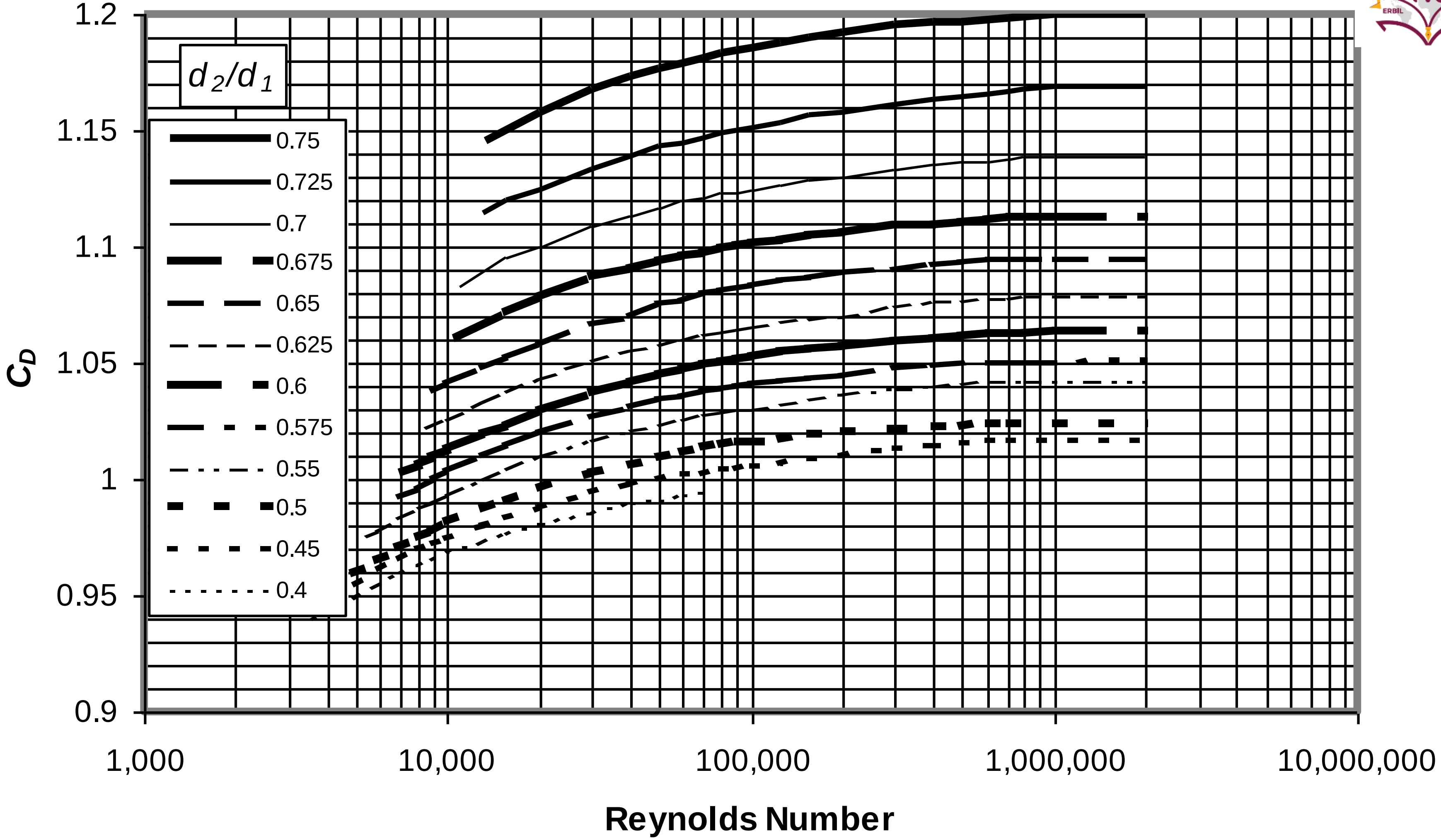


Figure 1.2: Choke flow coefficient for nozzle-type chokes (Data source: Crane, 1957)

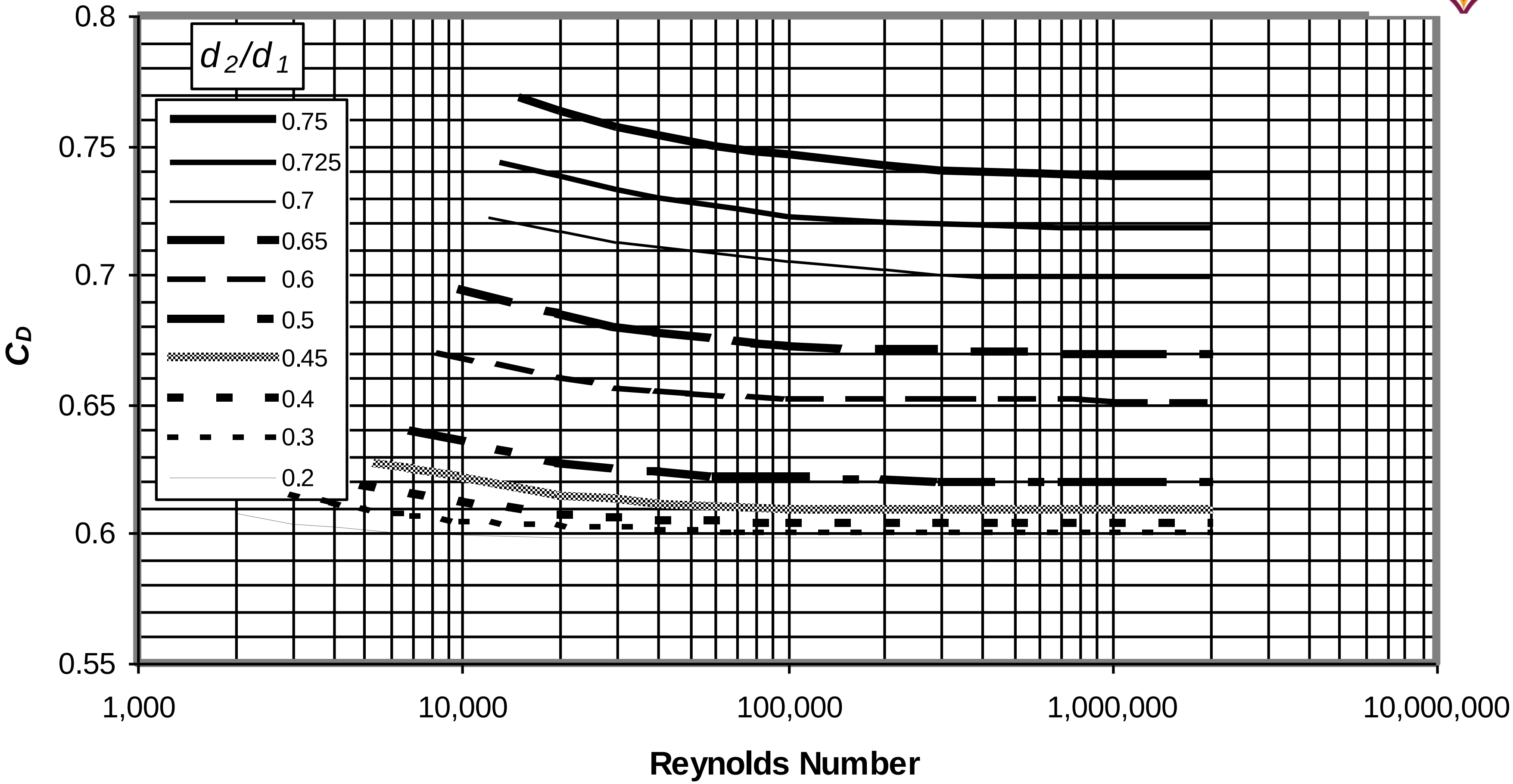


Figure 1.3: Choke flow coefficient for orifice-type chokes (Data source: Crane, 1957)

1.4 Single-phase Gas Flow

1.4.1 Subsonic Flow

Under subsonic flow conditions, gas passage through a choke can be expressed as:

$$q_{sc} = 1{,}248 C_D A_2 p_{up} \sqrt{\frac{k}{(k-1)\gamma_g T_{up}} \left[\left(\frac{p_{dn}}{p_{up}} \right)^{\frac{2}{k}} - \left(\frac{p_{dn}}{p_{up}} \right)^{\frac{k+1}{k}} \right]} \quad \text{.....(1.5)}$$

where

q_{sc} = gas flow rate, Mscf/d
p_{up} = upstream pressure at choke, psia
A_2 = cross-sectional area of choke, in.^{2}
T_{up} = upstream temperature, °R
g = acceleration of gravity, 32.2 ft/s^2
γ_g = gas-specific gravity related to air

The Reynolds number for determining C_D is expressed as:

$$N_{\mathrm{Re}} = \frac{20 q_{sc} \gamma_g}{\mu d_2} \qquad \text{.............(1.6)}$$

where μ is gas viscosity in cp.

Gas velocity under subsonic flow conditions is less than the sound velocity in the gas at the in-situ conditions:

$$v = \sqrt{v_{up}^{2} + 2g_c C_p T_{up}\left[1 - \frac{z_{up}}{z_{dn}}\left(\frac{p_{down}}{p_{up}}\right)^{\frac{k-1}{k}}\right]} \quad ....(1.7)$$

where *Cp* = specific heat of gas at constant pressure (187.7 lbf-ft/lbm-R for air).

1.4.2 Sonic Flow

- Under sonic flow conditions the gas passage rate reaches its maximum value. Gas passage rate is expressed in the following equation for ideal gases:

$$Q_{sc} = 879 C_D A p_{up} \sqrt{\left(\frac{k}{\gamma_g T_{up}}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \quad \text{.......(1.8)}$$

- Gas velocity under sonic flow conditions is equal to sound velocity in the gas under the in-situ conditions:

- The choke flow coefficient C_D is not sensitive to the Reynolds number for Reynolds number values greater than 10^6. Thus, the C_D value at the Reynolds number of 10^6 can be assumed for C_D values at higher Reynolds numbers.

$$v = \sqrt{v_{up}^{2} + 2 g_c C_p T_{up} \left[1 - \frac{z_{up}}{z_{outlet}} \left(\frac{2}{k+1} \right) \right]} \quad \text{..........(1.9)}$$

or

$$v \approx 44.76 \sqrt{T_{up}} \quad \text{...........(1.10)}$$

1.4.3 Temperature at Choke

- Depending on the upstream-to-downstream pressure ratio, the temperature at choke can be much lower than expected. This low temperature is due to the Joule–Thomson cooling effect, that is, a sudden gas expansion below the nozzle causes a significant temperature drop. The temperature can easily drop to below ice point, resulting in ice-plugging if water exists. Even though the temperature still can be above ice point, hydrates can form and cause plugging problems.

- Assuming an isentropic process for an ideal gas flowing through chokes, the temperature at the choke downstream can be predicted using the following equation:

$$T_{dn} = T_{up} \frac{z_{up}}{z_{outlet}} \left(\frac{p_{outlet}}{p_{up}} \right)^{\frac{k-1}{k}} \qquad \text{..........(1.11)}$$

The outlet pressure is equal to the downstream pressure in subsonic flow conditions.

1.4.4 Applications

Equations (1.5) through (1.11) can be used for estimating:

- Downstream temperature;
- Gas passage rate at given upstream and downstream pressures;
- Upstream pressure at given downstream pressure and gas passage; and
- Downstream pressure at given upstream pressure and gas passage.

To estimate gas passage rate at given upstream and downstream pressures, the following procedure can be taken:

__Step 1:__ Calculate the critical pressure ratio with equation (1.1).

__Step 2:__ Calculate the downstream to upstream pressure ratio.

__Step 3:__ If the downstream to upstream pressure ratio is greater than the critical pressure ratio, use equation (1.5) to calculate gas passage. Otherwise, use equation (1.8) to calculate gas passage.

Example Problem 1.1:

A 0.6 specific gravity gas flows from a 2-in pipe through a 1-in orifice-type choke. The upstream pressure and temperature are 800 psia and 75 ^{o}F, respectively. The down stream pressure is 200 psia (measured 2 ft from the orifice). The gas-specific heat ratio is 1.3.

(a) What is the expected daily flow rate?
(b) Does heating need to be applied to assure that the frost does not clog the orifice?
(c) What is the expected pressure at the orifice outlet?

***Solution:* (a)**

$$\left(\frac{P_{outlet}}{P_{up}}\right)_c = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3-1}} = 0.5459$$

$$\frac{P_{dn}}{P_{up}} = \frac{200}{800} = 0.25 \quad < 0.5459$$

Sonic flow exists.

$$\frac{d_2}{d_1} = \frac{1''}{2''} = 0.5$$

Assuming $N_{Re} > 10^6$, Figure 1.2 gives $C_D = 0.62$

$$q_{sc} = 879 C_D A P_{up} \sqrt{\left(\frac{k}{\gamma_g T_{up}}\right)\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$$

$$q_{sc} = (879)(0.62)[\pi(1)^2/4](800)\sqrt{\left(\frac{1.3}{(0.6)(75+460)}\right)\left(\frac{2}{1.3+1}\right)^{\frac{1.3+1}{1.3-1}}}$$

$$q_{sc} = 12{,}743$$ Mscf/d

Check *NRe*:

$$\mu = 0.01245$$

cp by the Carr-Kobayashi-Burrows correlation.

$$N_{\mathrm{Re}} = \frac{20 q_{sc} \gamma_g}{\mu d_2} = \frac{(20)(12{,}743)(0.6)}{(0.01245)(1)} = 1.23 \times 10^7 \quad > 10^6$$

(b)

$$T_{dn} = T_{up} \frac{z_{up}}{z_{outlet}} \left(\frac{P_{outlet}}{P_{up}} \right)^{\frac{k-1}{k}} = (75 + 460)(1)\left(0.5459\right)^{\frac{1.3-1}{1.3}} = 465$$

^oR = 5 ^oF < 32 ^oF

Therefore, heating is needed to prevent icing.

(c)

$$P_{outlet} = P_{up} \left(\frac{P_{outlet}}{P_{up}} \right) = (800)\left(0.5459\right) = 437 \text{ psia}$$

Example Problem 1.2:

A 0.65 specific gravity natural gas flows from a 2-in pipe through a 1.1-in nozzle-type choke. The upstream pressure and temperature are 100 psia and 70 oF, respectively. The down stream pressure is 80 psia (measured 2 ft from the nozzle). The gas specific heat ratio is 1.25.

(a) What is the expected daily flow rate?

(b) Is icing a potential problem?

(c) What is the expected pressure at the nozzle outlet?

Solution: (a)

$$\left(\frac{P_{outlet}}{P_{up}}\right)_c = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{1.25+1}\right)^{\frac{1.25}{1.25-1}} = 0.5549$$

$$\frac{P_{dn}}{P_{up}} = \frac{80}{100} = 0.8 \qquad > 0.5549$$

Subsonic flow exists.

$$\frac{d_2}{d_1} = \frac{1.5''}{2''} = 0.75$$

Assuming $N_{Re} > 10^6$, Figure 1.1 gives $C_D = 1.2$

.

$$q_{sc} = 1{,}248 C_D A P_{up} \sqrt{\frac{k}{(k-1)\gamma_g T_{up}} \left[\left(\frac{P_{dn}}{P_{up}} \right)^{\frac{2}{k}} - \left(\frac{P_{dn}}{P_{up}} \right)^{\frac{k+1}{k}} \right]}$$

$$q_{sc} = (1{,}248)(1.2)[\pi(1.5)^2/4](100) \sqrt{\frac{1.25}{(1.25-1)(0.65)(530)} \left[\left(\frac{80}{100} \right)^{\frac{2}{1.25}} - \left(\frac{80}{100} \right)^{\frac{1.25+1}{1.25}} \right]}$$

$q_{sc} = 5{,}572$ Mscf/d

Check N_{Re}:

$\mu = 0.0108$ cp by the Carr-Kobayashi-Burrows correlation.

$$N_{\mathrm{Re}} = \frac{20 q_{sc} \gamma_g}{\mu d} = \frac{(20)(5{,}572)(0.65)}{(0.0108)(1.5)} = 4.5 \times 10^6 \quad > 10^6$$

(b)

$$T_{dn} = T_{up} \frac{z_{up}}{z_{outlet}} \left(\frac{P_{dn}}{P_{up}} \right)^{\frac{k-1}{k}} = (70 + 460)(1)(0.8)^{\frac{1.25-1}{1.25}} = 507$$

^oR = 47 ^oF > 32 ^oF

Heating may not be needed.

But hydrate curve may need to be checked.

(c)

$$P_{outlet} = P_{dn} = 80$$ psia for subcritical flow.

1.5 Multiphase Flow

- When the produced oil reaches the wellhead choke, the wellhead pressure is usually below the bubble-point pressure of the oil. This means that free gas exists in the fluid stream flowing through choke. Choke behaves differently depending on gas content and flow regime (sonic or subsonic flow).
- Tangren et al. (1949) performed the first investigation on gas-liquid two-phase flowthrough restrictions. They presented an analysis of the behavior of an expanding gas liquid system. They showed that when gas bubbles are added to an incompressible fluid, above a critical flow velocity, the medium becomes incapable of transmitting pressure change upstream against the flow

1.5.1 Critical (Sonic) Flow

- Several empirical choke flow models have been developed in the past half-century. They generally take the following form for sonic flow:

$$p_{wh} = \frac{CR^m q}{S^n} \quad ,,,,,,,(1.12)$$

Pwh = upstream (wellhead) pressure, psia
q = gross liquid rate, bbl/day
R = producing gas-liquid ratio, Scf/bbl
S = choke size, 1⁄64 in.

Correlation	C	m	n
Gilbert	10	0.546	1.89
Ros	17.4	0.5	2
Baxendell	9.56	0.546	1.93
Achong	3.82	0.65	1.88
Pilehvari	46.67	0.313	2.11

A summary of *C, m* and *n* values given by different researchers

1.5.2 Subcritical (Subsonic) Flow

- Sachdeva's multiphase choke flow mode is representative of most of these works and has been coded in some commercial network modeling software. This model uses the following equation to calculate the critical–subcritical boundary:

- This model uses the following equation to calculate critical-subcritical boundary:

$$y_c = \left\{ \frac{\frac{k}{k-1} + \frac{(1-x_1)V_L(1-y_c)}{x_1 V_{G1}}}{\frac{k}{k-1} + \frac{n}{2} + \frac{n(1-x_1)V_L}{x_1 V_{G2}} + \frac{n}{2}\left[\frac{(1-x_1)V_L}{x_1 V_{G2}}\right]^2} \right\}^{\frac{k}{k-1}} \quad (1.13)$$

y_c = critical pressure ratio
$k = C_p/C_v$, specific heat ratio
n = polytropic exponent for gas
x_1 = free gas quality at upstream, mass fraction
V_L = liquid specific volume at upstream, ft^3/lbm
V_{G1} = gas specific volume at upstream, ft^3/lbm
V_{G2} = gas specific volume at downstream, ft^3/lbm.

$$n = 1 + \frac{x_1(C_p - C_v)}{x_1 C_v + (1 - x_1)C_L}. \quad (1.14)$$

1.5.2 Subcritical (Subsonic) Flow

- The gas-specific volume at upstream (VG1) can be determined using the gas law based on upstream pressure and temperature. The gas-specific volume at downstream (VG2) is expressed as

$$V_{G2} = V_{G1} y_c^{-\frac{1}{k}}. \quad ....(1.15)$$

The critical pressure ratio Yc can be solved from Eq. (1.13) numerically.

The actual pressure ratio can be calculated by

$$y_a = \frac{p_2}{p_1} \quad ,,,,,,(1.16)$$

y_a = actual pressure ratio
p_1 = upstream pressure, psia
p_2 = downstream pressure, psia.

1.5.2 Subcritical (Subsonic) Flow

If $y_a < y_c$, critical flow exists, and the y_c should be used ($y = y_c$). Otherwise, subcritical flow exists, and y_a should be used ($y = y_a$).

The total mass flux can be calculated using the following equation:

$$G_2 = C_D\left\{2g_c * 144\, p_1 \rho_{m2}{}^2 \left[\frac{(1-x_1)(1-y)}{\rho_L} + \frac{x_1 k}{k-1}(V_{G1} - yV_{G2})\right]\right\}^{0.5} \quad \textbf{(1.17)}$$

G_2 = mass flux at downstream, $lbm/ft^2/s$
C_D = discharge coefficient, 0.62–0.90
ρ_{m2} = mixture density at downstream, lbm/ft^3
ρ_L = liquid density, lbm/ft^3

1.5.2 Subcritical (Subsonic) Flow

The mixture density at downstream (ƥm2) can be calculated using the following equation:

$$\frac{1}{\rho_{m2}} = x_1 V_{G1} y^{-\frac{1}{k}} + (1 - x_1) V_L \qquad \textbf{(1.18)}$$

- Once the mass flux is determined from Eq. **(1.17)** , mass flow rate can be calculated using the following equation:

$$M_2 = G_2 A_2 \qquad \textbf{(1.19)}$$

A_2 = choke cross-sectional area, ft^2

M_2 = mass flow rate at down stream, lbm/sec.

Liquid mass flow rate is determined by

$$M_{L2} = (1 - x_2) M_2 \qquad \text{,,,,,,,,}\textbf{(1.20)}$$

1.5.2 Subcritical (Subsonic) Flow

At typical velocities of mixtures of 50–150 ft/s flowing through chokes, there is virtually no time for mass transfer between phases at the throat. Thus, x2 ¼ x1 can be assumed. Liquid volumetric flow rate can then be determined based on liquid density.

- Gas mass flow rate is determined by

$$M_{G2} = x_2 M_2 \qquad \textbf{(1.21)}$$

Gas volumetric flow rate at choke downstream can then be determined using gas law based on downstream pressure and temperature.

1.5.2 Subcritical (Subsonic) Flow

Based on the cases studied, Guo *et al.* (2002) drawn the following conclusions:

1) The accuracy of Sachdeva's choke model can be improved by using different discharge coefficients for different fluid types and well types.

2) For predicting liquid rates of oil wells and gas rates of gas condensate wells, a discharge coefficient of CD =1.08 should be used.

3) A discharge coefficient CD =0.78 should be used for predicting gas rates of oil wells.

4) A discharge coefficient CD =1.53 should be used for predicting liquid rates of gas condensate wells.

An Example Calculation with Sachdeva's Choke Model

Input Data:

Choke Diameter (d_2):	24	1/64th in.
Discharge Coefficient (C_D):	0.75	
Downstream Pressure (P_2):	50	psia
Upstream Pressure (P_1):	80	psia
Upstream Temperature (T_1):	100	^oF
Downstream Temperature (T_2):	20	^oF
Free Gas Quality (x_1):	0.001	mass fraction
Liquid Specific Gravity:	0.9	water=1
Gas Specific Gravity:	0.7	air=1
Specific Heat of Gas at Constant Pressure (C_p):	0.24	
Specific Heat of Gas at Constant Volume (C_v):	0.171429	
Specific Heat of Liquid (C_L):	0.8	

Pre-Calculations:

Gas Specific Heat ratio ($k=C_p/C_v$):	1.4	
Liquid Specific Volume (V_L):	0.017806	ft^3/lbm
Liquid Density (r_L):	56.16	lb/ft^3
Upstream Gas Density (ρ_{G1}):	0.27	lb/ft^3
Downstream Gas Density (ρ_{G2}):	0.01	lb/ft^4
Upstream Gas Specific Volume (V_{G1}):	3.70	ft^3/lbm
Polytropic Exponent of Gas (n):	1.000086	

Critical Pressure Ratio Computation:

$k/(k-1)$ =	3.5	
$(1-x_1)/x_1$ =	999	
$n/2$ =	0.500043	
V_L/V_{G1} =	0.004811	
Critical Pressure Ratio (y_c):	0.353134	
V_{G2} =	7.785109	ft^3/lbm
V_L/V_{G2} =	0.002287	
Equation Residue (Goal Seek 0 by changing y_c):	0.000263	

Flow Rate Calculations:

Pressure Ratio (y_{actual}):	0.625	
Critical Flow Index:	-1	
Subcritical Flow Index:	1	
Pressure Ratio to Use (y):	0.625	
Downstream Mixture Density (ρ_{m2}):	43.54	lb/ft^3
Downstream Gas Specific Volume (V_{G2}):	5.178032	
Choke Area (A_2)=	0.000767	ft^2
Mass Flux (G_2) =	1432.362	$lbm/ft^2/s$
Mass Flow Rate (M) =	1.098051	lbm/s
Liquid Mass Flow Rate (M_L) =	1.096953	lbm/s
Liquid Flow Rate =	**300.5557**	bbl/d
Gas Mass Flow Rate (M_G) =	0.001098	lbm/s
Gas Flow Rate =	**0.001772**	MMscfd

Homework

1.1 A well is producing 40^o API oil at 200 stb/d and no gas. If the beam size is 1", estimate pressure drop across the choke.

1.2 A well is producing at 200 stb/d of liquid along with a 900 scf/stb of gas. If the beam size is 1/2", assuming sonic flow, calculate the flowing wellhead pressure using Gilbert's formula.

1.3 A 0.65 specific gravity gas flows from a 2-in pipe through a 1-in orifice-type choke. The upstream pressure and temperature are 850 psia and 85 oF, respectively. The down stream pressure is 210 psia (measured 2 ft from the orifice). The gas-specific heat ratio is 1.3. (a) What is the expected daily flow rate? (b) Does heating need to be applied to assure that the frost does not clog the orifice? (c) What is the expected pressure at the orifice outlet?

1.4 A 0.70 specific gravity natural gas flows from a 2-in pipe through a 1.5-in nozzle-type choke. The upstream pressure and temperature are 120 psia and 75 oF, respectively. The down stream pressure is 90 psia (measured 2 ft from the nozzle). The gas specific heat ratio is 1.25.

(a) What is the expected daily flow rate?
(b) Is icing a potential problem?
(c) What is the expected pressure at the nozzle outlet?

1.5 For the following given data, estimate upstream gas pressure at choke:

Downstream pressure:	350	psia
Choke size:	32	1/64 in
Flowline ID:	2	in
Gas production rate:	4,000	Mscf/d
Gas-specific gravity:	0.70	1 for air
Gas-specific heat ratio:	1.25	
Upstream temperature:	100	^{o}F
Choke discharge coefficient:	0.95	

1.6 For the following given data, estimate downstream gas pressure at choke:

Upstream pressure:	620	psia
Choke size:	32	1/64 in
Flowline ID:	2	in
Gas production rate:	2,200	Mscf/d
Gas-specific gravity:	0.65	1 for air
Gas-specific heat ratio:	1.3	
Upstream temperature:	120	^oF
Choke discharge coefficient:	0.96	

1.7 For the following given data, assuming subsonic flow, estimate liquid and gas production rate:

Choke Diameter:	32	1/64th in.
Discharge Coefficient:	0.85	
Downstream Pressure:	60	psia
Upstream Pressure:	90	psia
Upstream Temperature:	120	^oF
Downstream Temperature:	30	^oF
Free Gas Quality:	0.001	mass fraction
Liquid Specific Gravity:	0.85	water=1
Gas Specific Gravity:	0.75	air=1
Specific Heat of Gas at Constant Pressure:	0.24	
Specific Heat of Gas at Constant Volume:	0.171429	
Specific Heat of Liquid:	0.8	