SAM-BOMS FORTUNE.C.

16/ENG07/033

PETROLEUM ENGINEERING

PTE 516

1. SUMMARY ON ALL THE HORIZONTAL MULTIPHASE FLOW REGIMES

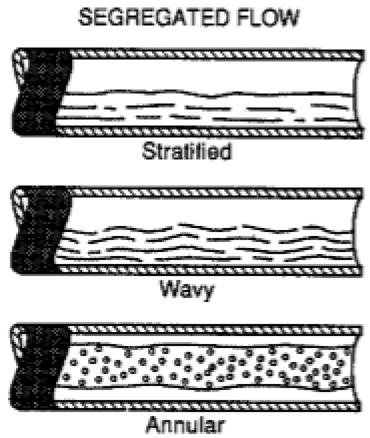
Two-phase flow in horizontal pipes differs markedly from that in vertical pipes; except for the Beggs and Brill correlation (Beggs and Brill 1973), which can be applied for any flow direction, completely different correlations are used for horizontal flow than for vertical flow. Flow regimes in horizontal gas-liquid flow is considered.

FLOW REGIMES

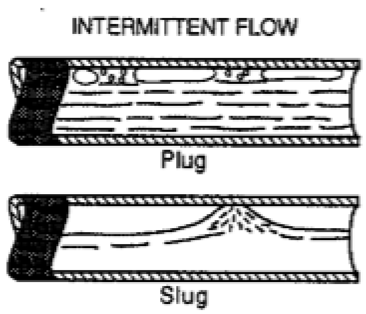
The flow regime does not significantly affect the pressure drop in horizontal flow as it does in vertical flow. This is because there is no potential energy contribution to the pressure drop in horizontal flow.

The commonly described flow regimes in horizontal gas-liquid flow are classified into three types of regimes:

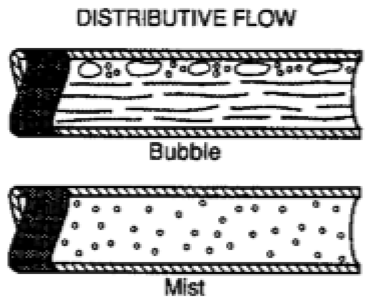
A. SEGREGATED FLOW (the two phases are for the most part separate): It is classified as being stratified smooth, stratified wavy or annular. Stratified smooth flow consists of liquid flowing along the bottom of the pipe and gas flowing along the top of the pipe, with a smooth interface between the phases. This flow regime occurs at relatively low rates of both phases. At higher gas rates, the interface becomes wavy, and stratified wavy flow results.



B. INTERMITTENT FLOW (gas and liquid are alternating): They are slug flow and plug (elongated bubble) flow. Slug flow consists of large liquid slugs alternating with high-velocity bubbles of gas that fill almost the entire pipe. In plug flow, large gas bubbles flow along the top of the pipe, which is otherwise filled with liquid.



C. DISTRIBUTIVE FLOW (one phase is dispersed in the other phase): This flow regime includes bubble, dispersed bubble, mist, and froth flow. The bubble flow regimes differ from the vertical flow in that the gas bubbles in a horizontal flow will be concentrated on the upper side of the pipe. Mist flow occurs at high gas rates and low liquid rates and consists of gas with liquid droplets entrained. Mist flow will often be indistinguishable from annular flow, and many flow regime maps use “annular mist” to denote both of these regimes. Froth flow is used by some authors to describe the mist or annular mist flow regime.



4. SUMMARY ON FLOW THROUGH RESTRICTION ON BOTH SINGLE-PHASE LIQUID FLOW AND SINGLE-PHASE GAS FLOW

The flow rate from almost all flowing wells is controlled with a wellhead choke, a device that places a restriction in the flow line. A variety of factors may make it desirable to restrict the production rate from a flowing well, including the prevention of coning or sand production, satisfying production rate limits set by regulatory authorities, and meeting limitations of rate or pressure imposed by surface equipment.

A. SINGLE-PHASE LIQUID FLOW: The flow through a wellhead choke will rarely consist of single-phase liquid, since the flowing tubing pressure is almost always below the bubble point. However, when this does occur, the flow rate is related to the pressure drop across the choke by

$$q = CA\sqrt{\frac{2g_c\Delta p}{\rho}}$$

Where C = flow coefficient of choke

A = cross-sectional area of choke

The above equation is derived by assuming that the pressure drop through the choke is equal to the kinetic energy pressure drop divided by the square of a drag coefficient. This equation applies for subcritical flow, which will usually be the case for single-phase liquid phase.

B. SINGLE PHASE GAS FLOW: When a compressible fluid passes through a restriction, the expansion of the fluid is an important factor. For isentropic flow of an ideal gas through a choke, the rate is related to the pressure ratio, p_2/p_1

$$q_g = \frac{\pi}{4} D^2{}_{\cdot 2}\, p_1 \frac{T_{sc}}{P_{sc}} \sqrt{\left(\frac{2g_c R}{28.97\gamma_g T_1}\right)\left(\frac{\gamma}{\gamma-1}\right)[(\frac{p_2}{p_1})^{\frac{2}{\gamma}} - (\frac{p_2}{p_1})^{\frac{(\gamma+1)}{\gamma}}]}$$

Which can be expressed in oilfield units as

$$q_g = 3.505 D^2{}_{\cdot 64} (\frac{p_1}{p_{sc}})\alpha \sqrt{(\frac{1}{\gamma_g T_1})(\frac{\gamma}{\gamma-1})[(\frac{p_2}{p_1})^{\frac{2}{\gamma}} - (\frac{p_2}{p_1})^{\frac{(\gamma+1)}{\gamma}}]}$$

Where qg is in MSCF/d, D64 is the choke diameter (bean diameter) in 64ths of inches, T1 is the temperature upstream of the choke in oR, γ is the heat capacity ratio, Cp/Cv, α is the flow coefficient of the choke, γg is the gas gravity, psc is standard pressure, and p_1 and p_2 are the pressure upstream and downstream of the choke, respectively.

The above equations apply when the pressure ratio is equal to or greater than the critical pressure ratio, given by

$$\left(\frac{p_2}{p_1}\right) = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

When the pressure ratio is less than the critical pressure ratio, p_2/p_1 should be set to (p_2/p_1) c and the equation above used, since the flow rate insensitive to the downstream pressure whenever the flow is critical. For air and other diatomic gases, γ is approximately 1.4, and the critical pressure ratio is 0.53; in petroleum engineering operations, it is commonly assumed that flow through a choke is critical whenever the downstream pressure is less than about half of the upstream pressure.

QUESTION 2 & 3

Sam-Boms Fortune. C.
16/ENG07/033
Petroleum Engineering
PTE 516

Assignment
Question 10-4

Parameters: $q_L = 500$ bbl/d

$GOR = 1000$ scf/bbl

$\sigma = 20$ dynes/cm

$T = 120°F = 580°R$

$P = 1000$ psia

$Z = f\left(580/395,\ 1000/667\right) = 0.85$

$\gamma_o = 32°API$

$\gamma_g = 0.71$

$D = 2$ Inches

$\mu_L = 2.0$ cp

$T_{pc} = 395°R$

$P_{pc} = 667$ Psi

$\rho_g = ?$

$\rho_L = ?$

$\mu_g = 0.0131$

$GOR = \dfrac{q_g}{q_L}$

$q_g = GOR \times q_L$

$q_g = 1000 \times 500$

$q_g = 500 \times 10^3\ ft^3/D$

$$GOR = \frac{q_g}{q_L}$$

$$q_g = GOR \times q_L$$

$$q_g = 1000 \times 500$$

$$q_g = 500 \times 10^3 \ ft^3/D$$

Baker's Correlation

$$A = (\pi/4)(2/12)^2$$

$$A = 0.02182 \ ft^2$$

$$\rho_g = \frac{28.97 \gamma_0 P}{ZRT}$$

$$\rho_g = \frac{28.97 \times 0.71 \times 1000}{0.85 \times 10.73 \times 580}$$

$$= 3.89 \ lbm/ft^3$$

$$\gamma_o = \frac{141.5}{32 + 131.5} = 0.865$$

$$\rho_o = 0.865 \times 62.4$$

$$\rho_o = 54 \ lbm/ft^3$$

$$u_{SL} = \frac{q_L}{A} = \frac{500 \times 5.615}{86400 \times 0.02182}$$

$$= 1.4892 \ ft/s$$

$$u_{sg} = \frac{4}{\pi D^2} \times q \times z \times \left(\frac{T}{T_{sc}}\right) \times \left(\frac{P_{sc}}{P}\right)$$

$$u_{sg} = \frac{4}{\pi (2/12)^2} \times \frac{500000}{86400} \times 0.85 \times \frac{580}{520} \times \frac{14.7}{1000}$$

$$u_{sg} = 3.697 \ ft/s$$

$$\lambda = \left[\left(\frac{\rho_g}{0.075}\right)\left(\frac{\rho_L}{62.4}\right)\right]^{1/2}$$

$$\lambda = \left[\left(\frac{3.89}{0.075}\right)\left(\frac{54}{62.4}\right)\right]^{1/2}$$

$$\lambda = 6.6996$$

$$\phi = \frac{73}{\sigma_L}\left[\mu_L\left(\frac{62.4}{\rho_L}\right)^2\right]^{1/3}$$

$$= \frac{73}{20}\left[2\left(\frac{62.4}{54}\right)^2\right]^{1/3}$$

$$\phi = 5.064$$

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$$= \frac{73}{20}\left[2\left(\frac{62.4}{54}\right)^2\right]^{1/3}$$

$$\phi = 5.064$$

$$Q_g = u_{sg} \times \rho_g$$

$$= 3.697 \times 3.89 \times 3600$$

$$= 5.1773 \times 10^4$$

$$Q_L = u_{SL} \times \rho_L$$

$$= 1.4892 \times 54 \times 3600$$

$$= 2.895 \times 10^5$$

$$\frac{Q_g}{\lambda} = \frac{5.1773 \times 10^4}{6.6996}$$

$$= 7.728 \times 10^3$$

$$\frac{Q_L \lambda \phi}{Q_g} = \frac{2.895 \times 10^5 \times 6.6996 \times 5.064}{5.1773 \times 10^4}$$

$$= 189.71$$

Slug flow (i.e flow is a function of G_g/λ, $\frac{Q_L \lambda \phi}{G_g}$ from Baker's map)

Mandhane

Flow = (U_{SL}, U_{sg})

$U_{SL} = 1.4892$ ft/s

$U_{sg} = 3.697$ ft/s

From Mandhane flow map;

Flow regime = Slug flow ie flow regime is slug flow

Bogg's and Brills

Flow = $f(N_{FR}, \lambda_L)$

$$N_{FR} = \frac{U_m^2}{gD}$$

$U_m = U_{sg} + U_{SL}$

$U_m = 1.4892 + 3.697 = 5.1862$ ft/s

$g = 32.17$ ft/sec^2

$D = (2/12)$ ft

Mandhane

Flow = (U_{SL}, U_{sg})

$U_{SL} = 1.4892$ ft/s

$U_{sg} = 3.697$ ft/s

From Mandhane flow map;

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Begg's and Brills

Flow = $f(N_{FR}, \lambda_L)$

$$N_{FR} = \frac{U_m^2}{gD}$$

$U_m = U_{sg} + U_{SL}$

$U_m = 1.4892 + 3.697 = 5.1862$ ft/s

$g = 32.17$ ft/sec^2

$D = (2/12)$ ft

$$N_{FR} = \frac{5.1862^2}{32.17 \times 2/12} = 5.0165$$

$$\lambda_L = \frac{U_{SL}}{U_{SL} + U_{sg}} = \frac{1.4892}{1.4892 + 3.697}$$

$\lambda_L = 0.287$

Flow regime = Intermittent

Question 10-6

Parameters: $q_o = 4000\,bbl/d$ $\qquad \gamma_o = 32°API$

$GOR = 500\,scf/bbl$ $\qquad \gamma_g = 0.71$

$D = 3$ inches $\qquad \mu_L = 2cp$

$\epsilon = 0.001$ $\qquad \mu_g = 0.0131cp$

$T = 150°F = 610°R$ $\qquad T_{pc} = 395°R$

$P = 200\,psia$ $\qquad P_{pc} = 667\,psi$

$\sigma_L = 20\,dynes/cm$

Derived Parameters

$Z = f(610/395,\ 200/667) = 0.97$

$A = (\pi/4)(3/12)^2 = 0.0491\,ft^2$

$$\gamma_o = \frac{141.5}{32 + 131.5} = 0.8654$$

$\rho_o = 0.565 \times 62.4 = 34\,lbm/ft^3$

$$\rho_g = \frac{28.97\,\gamma_g P}{ZRT}$$

$$= \frac{28.97 \times 0.71 \times 200}{0.97 \times 10.73 \times 610}$$

$$= 0.648\,lbm/ft^3$$

$\rho_o = 0.585 \times 62.4 = 37 \text{ lbm/ft}$

$$\rho_g = \frac{28.97\,\gamma_g P}{ZRT}$$

$$= \frac{28.97 \times 0.71 \times 200}{0.97 \times 10.73 \times 610}$$

$$= 0.648 \text{ lbm/ft}^3$$

$q_g = GOR \times q_L$

$q_g = 500 \times 4000 = 2 \times 10^6 \text{ ft}^3/\text{d}$

Beggs and Brill Method

Flow Regime calculation:

$$U_{SL} = \frac{q_L}{A} = \frac{4000 \times 5.615}{86400 \times 0.0491}$$

$$= 5.2944 \text{ ft/s}$$

$$U_{sg} = \frac{4}{\pi D^2} \times q \times Z \times \left(\frac{T}{T_{sc}}\right) \times \left(\frac{P_{sc}}{P}\right)$$

$$= \frac{4}{\pi \left(3/12\right)^2} \times \frac{2 \times 10^6}{86400} \times 0.97 \times \frac{610}{520} \times \frac{14.7}{200}$$

$U_{sg} = 39.4395 \text{ ft/s}$

Question 10-6 cont'd.

$$U_m = U_{sL} + U_{sg}$$
$$= 39.4395 + 5.2944$$
$$= 44.7339$$

$$\lambda = \frac{5.2944}{44.7339}$$
$$= 0.11835$$

$$N_{FR} = \frac{U_m^2}{gD} = \frac{44.7339^2}{32.17 \times 3/12} = 248.818$$

$$L_1 = 316 \times (0.11835)^{0.302} = 165.876$$
$$L_2 = 0.0009252\,(0.11835)^{-2.4684} = 0.1795$$
$$L_3 = 0.1\,(0.11835)^{-1.4516} = 2.2151$$
$$L_4 = 0.5\,(0.11835)^{-5.738} = 104{,}023.273$$

Flow is distributive since $\lambda_L < 0.4$ and $N_{FR} \geq L_1$

Hold-up calculation

Hold-up calculation

$$y_L = y_{L0}\,\psi$$

$$y_L = \frac{a\lambda_L^{\,b}}{N_{Fr}^{\,c}}$$

$$y_{L0} = \frac{1.065 \times (0.11835)^{0.5824}}{248.818^{0.0609}}$$

$$y_{L0} = \frac{0.3073}{1.3993} = 0.21961$$

Note: $\lambda_L = 1 - \lambda_g$

$$\rho_m = \rho_L\lambda_L + \rho_g\lambda_g$$

$$\rho_m = (54 \times 0.11835) + (0.648 \times 0.88165)$$

$$\rho_m = 6.9622\,lbm/ft^3$$

$$\mu_m = \mu_L\lambda_L + \mu_g\lambda_g$$

$$= (2 \times 0.11835) + (0.0131 \times 0.88165)$$

$$= 0.24825$$

$$N_{Rem} = \frac{\rho_m U_m D}{\mu_m} = \frac{6.9622 \times 44.7339 \times 3/12}{6.72 \times 10^{-4} \times 0.24825}$$

$$N_{Rem} = \frac{934.3391}{2.002 \times 10^{-3}}$$

$$N_{Rem} = 466,728.96$$

$$\simeq 4.7 \times 10^{5}$$

$$f_n = 0.006$$

calculating for x, S, f_{tp}

$$x = \frac{\lambda_L}{y_{L0}^2} = \frac{0.11835}{0.21961^2}$$

$$= 2.434$$

$$S = \frac{\ln(x)}{[-0.523 + 3.182 \ln(x) - 0.8725 [\ln(x)]^4 + 0.01853 [\ln(x)^4]]}$$

$$S = \frac{0.89772}{2.8042 - 0.7031 + 0.012}$$

$$S = \frac{0.89772}{0.1131} = 0.4248$$

$$f_{tp} = f_n e^{s}$$

$$f_{tp} = 0.006 \times e^{0.4248}$$

$$f_{tp} = 9.1757 \times 10^{-3}$$

$F_{tp} = f_n e^{s}$

$f_{tp} = 0.006 \times e^{0.4248}$

$f_{tp} = 9.1757 \times 10^{-3}$

$= 0.009176$

Eaton correlation

Calculation of mass flow rate

$\dot{m}_L = q_L \rho_L$

$q_L = 4000 \frac{bbl}{d} \times \frac{5.615 ft^3}{86400 s}$

$q_L = 0.26 ft^3/s$

$\dot{m}_L = 0.26 ft^3/s \times 54 lbm/ft^3$

$= 14.038 lbm/s$

$\dot{m}_g = q_g \rho_g$

$q_g = A \times U_{sg}$
$= 0.0491 \times 39.4395 = 1.936$

$\dot{m}_g = \varepsilon_g \rho_g$
$= 1.936 \times 0.648 = 1.255 \text{ lbm/s}$

$\dot{m}_m = \dot{m}_L + \dot{m}_g = 14.038 + 1.255$
$= 15.293 \text{ lbm/s}$

Gas viscosity (μ_g)

$\mu_g = 0.0131 \times 6.72 \times 10^{-4}$
$= 8.8 \times 10^{-6} \text{ lbm/ft-sec}$

Duckler correlation

$$\frac{dp}{dx} = \left(\frac{dp}{dx}\right)_F + \left(\frac{dp}{dx}\right)_{KE}$$

Frictional pressure drop; $\left(\frac{dp}{dx}\right)_F = \frac{f \rho_K . U_m^2}{2 g_c D}$

$$\rho_K = \frac{\rho_L \lambda_L^2}{y_L} + \frac{\rho_g \lambda_g^2}{y_g}$$

Frictional pressure drop; $\left(\frac{dP}{dx}\right)_F = \frac{f \rho_K u_m^2}{2 g_c D}$

$$\rho_K = \frac{\rho_L \lambda_L^2}{y_L} + \frac{\rho_g \lambda_g^2}{y_g}$$

and $N_{ReK} = \frac{\rho_K u_m D}{\mu_m} = N_{Rem}\left(\frac{\rho_K}{\rho_m}\right)$

Assuming $\lambda_L = y_L$

$\rho_K = \rho_m$

$N_{Rem} = N_{ReK}$

$$\lambda_L = y_L = 0.11835$$

$$\rho_K = \frac{54 \times 0.11835^2}{0.11835} + \frac{0.648 \times 0.88165^2}{0.88165}$$

$$\rho_K = 6.962 \text{ lbm}/ft^3$$

$$N_{ReK} = 4.7 \times 10^5 \left(\frac{6.962}{6.962}\right)$$

$$N_{ReK} = 4.7 \times 10^5$$

$$f_n = 0.0056 + 0.5\,(N_{Rer})^{-0.32}$$
$$= 0.0056 + 0.5\,(4.7 \times 10^5)^{-0.32}$$
$$= 0.013$$

$$\frac{f}{f_n} = 1 - \left[\frac{\ln \lambda_L}{1.281 + 0.478(\ln \lambda_L) + 0.444(\ln \lambda_L)^2 + 0.094(\ln \lambda_L)^3 + 0.00843(\ln \lambda_L)^4}\right]$$

$$\frac{f}{f_n} = 1 - \left[\frac{-2.13411}{1.281 - 1.0201 + 2.0222 - 0.9136 + 0.1749}\right]$$

$$f/f_n = 1 - (-1.3818)$$
$$f/f_n = 2.3818$$
$$f = f_n \times 2.3818$$
$$f = 0.013 \times 2.3818$$
$$f = 0.031$$

$$\left(\frac{dP}{dx}\right)_f = \frac{f \rho_x u_m^2}{2 g_c D}$$
$$= \frac{0.013 \times 6.962 \times 44.7339^2}{2 \times 32.17 \times 0.25}$$
$$= 11.26\ \text{lbf}/\text{ft}^3$$
$$\simeq 0.078\ \text{psi}/\text{ft}$$

calculating f

$$\frac{(0.057)(\dot m_g \dot m_m)^{0.5}}{\mu_g D^{2.25}} = \frac{0.057 \times (1.255 \times 15.293)^{0.5}}{8.8 \times 10^{-6}(3/12)^{2.25}}$$
$$= 0.24971 \qquad = 6.42 \times 10^5$$

calculating f

$$\frac{(0.057)(\dot{m}_g \dot{m}_m)^{0.5}}{\mu_g D^{2.25}} = \frac{0.057 \times (1.255 \times 15.293)^{0.5}}{8.8 \times 10^{-6} (3/12)^{2.25}}$$

$$= \frac{0.24971}{3.8891 \times 10^{-7}} = 6.42 \times 10^{5}$$

From figure 10.6 : $f(\dot{m}_L/\dot{m}_m)^{0.1} = 0.02$

$$f = \frac{0.02}{\left(\frac{14.038}{15.293}\right)^{0.1}} = 0.0202$$

$$\left(\frac{dp}{dx}\right)_F = \frac{f \rho_m U_m^2}{2 g_c D}$$

$$= \frac{0.0202 \times 6.9622 \times 44.7339^2}{2 \times 32.17 \times (3/12)}$$

$= 17.496 \ \text{lbf}/\text{ft}^3$

$= 0.122 \ \text{psi}/\text{ft}$

Frictional pressure gradient calculation

$$\left(\frac{dp}{dz}\right)_f = \frac{2 f_{tp} \rho_m u_m^2}{g_c D}$$

$$\frac{dp}{dz} = \frac{2 \times 0.009176 \times 6.9622 \times 44.7339^2}{32.17 \times 3/12}$$

$$\frac{dp}{dz} = 31.792 \ lbf/ft^3$$

$$\frac{dp}{dz} = 31.792 \frac{lbf}{ft^3} \times \frac{1 ft^2}{144 in^2}$$

$$= 0.221 psi/ft.$$