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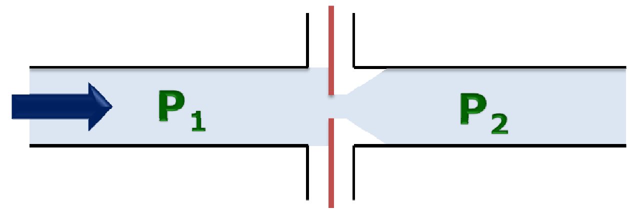
Control of Flow Rates at Startup

Either by nature, or by training, engineers are conservative. That is generally a good thing, but we sometimes go too far. For example, chokes and control valves are often oversized even for normal operation, and are sometimes far too large to provide adequate control of low flow rates at initial startup.

Startup planning should include an assessment of the operability of chokes and control valves.



Five different conditions exist for flow through restrictions:

1) Liquid flow
2) Non-critical gas flow
3) Critical gas flow
4) Non-critical two-phase flow
5) Critical two-phase flow

Vapor Phase Critical Flow

For a gas stream, critical flow occurs when the velocity through the orifice reaches sonic velocity. For pressure drop calculations, the important feature of critical flow is that decreasing downstream pressure no longer impacts the flow rate. Critical flow in a vapor occurs when the downstream pressure is about half of the upstream pressure, see Figure 1, (pressure ratio Y = 0.5), or more precisely as determined via equation 3.

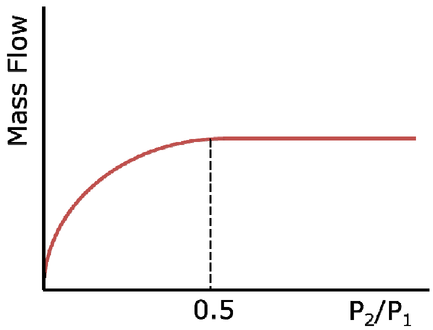


Figure 1: Pressure Ratio Y = 0.5

It is a common misconception that, in critical flow, changing the pressure or the pressure drop doesn't change the flow rate. Changing the upstream pressure always changes the flow rate as illustrated in Figure 2.

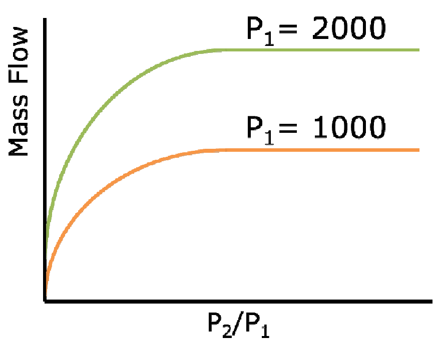


Figure 2: Changing the Upstream Pressure

Why Does Critical Flow Occur

Critical flow occurs because pressure waves in a fluid travel at a finite speed (speed of sound in the fluid). At critical flow, the velocity of the fluid equals the speed of the pressure wave; hence, downstream pressure information cannot be communicated upstream through the orifice and the feedback loop is broken.

Two-Phase Critical Flow

Critical flow occurs in two-phase streams (vapor/liquid) as well. The calculations are more complex as shown below, but the phenomena is analogous to vapor critical flow.

Calculation Methods

With five possible flow conditions we need five calculation methods. We can collapse this into three methods by substituting the effective P_2 for the downstream pressure in critical flow conditions. This results in three calculations methods:

1) Liquid flow
2) Gas Flow
3) Two-phase flow

$$q = .525\ C_d d^2 \sqrt{\frac{\Delta P}{\rho_l}} \qquad \text{(Equation 1)}$$

$$M = .525\ Y\ d^2 \sqrt{\Delta P\ \rho_g} \qquad \text{(Equation 2)}$$

$$y_c = \left(\frac{2}{k+1}\right)^{k/(k-1)} \qquad \text{(Equation 3)}$$

$$y_c = \left[\frac{a + \dfrac{b\ V_l(1-y_c)}{V_{g1}}}{a + \dfrac{n}{2} + bn\dfrac{V_l}{V_{g2}} + \dfrac{n}{2}\left(b\dfrac{V_l}{V_{g2}}\right)^2}\right]^a \qquad \text{(Equation 5)}$$

Where: $a = \frac{k}{k-1}$ $\qquad b = \frac{1-x_1}{x_1}$

Variables List

A	area, ft^2
C_d	orifice coefficient
C_v	valve coefficient, gal/min-psi $^{0.5}$
c_p	gas heat capacity – constant P, btu/lb-°F
c_v	gas heat capacity – constant volume, btu/lb-°F
d	diameter, inches
FWHP	Flowing Wellhead Pressure, psig
g_c	gravity force factor, 32.2 ft-lbm/lbf-sec ^{2}
k	$c_p/\ c_v$
M	mass flow rate, lb/sec
n	polytropic exponent for gas
ΔP	pressure drop, psi
P	pressure, psia
P_1	pressure upstream of choke, psia
P_2	pressure at choke throat, psia
q	flow rate, gal/min
ρ	density, lb/ft^3
ρ_l	liquid density, lb/ft^3
ρ_{g1}	gas density upstream of choke, lb/ft^3
ρ_{g2}	gas density at choke throat, lb/ft^3
ρ_{m1}	mixture density upstream of choke, lb/ft^3
ρ_{m2}	mixture density at choke throat, lb/ft^3
V_{g1}	gas specific volume gas upstream of choke, ft^3/lb
V_{g2}	gas specific volume gas at choke throat, ft^3/lb
V_l	liquid specific volume, ft^3/lb
x_1	gas mass fraction
Y	gas expansion coefficient
y	pressure ratio, P_2/P_1
y_c	critical pressure ratio, P_2/P_1

Given three equations, we then need to worry about discontinuities between the calculations methods at the transition points. We use the Sachdeva (1986, SPE 15657-MS) correlation for two-phase calculations. Though not currently state-of-the-art, Sachdeva is accurate enough for most purposes. And it has the very useful feature of being accurate in all flow regimes (liquid, two-phase non-critical, two-phase critical, gas and gas critical) with no discontinuities at either regime or critical flow boundaries.

Liquid flow through Chokes

Liquid flow through chokes is described effectively via equation 1 from Crane (1988).

Non-Critical Vapor Flow through Chokes

Non-critical vapor flow is described by equation 2, also from Crane (1988).

Vapor Phase Critical Flow

For critical flow use equation 2, but substitute the critical pressure drop for ΔP. Critical flow in a vapor occurs when the downstream pressure is about half of the upstream pressure (pressure ratio $y_c = 0.5$), or more precisely as determined via equation 3.

Two-phase Flow through Chokes

Sachdeva solved the mass, momentum and energy balance equations assuming no-slip flow and no mass transfer between phases at the orifice to develop this equation for two-phase flow through a choke:

$$M = A\ C_d \left\{\left(2\, g_c\ 144\, P_1\ \rho_{m2}^2\right)\left[\frac{(1-x_1)(1-y)}{\rho_l} + x_1\left(\frac{k}{k-1}\right)\left(V_{g1} - yV_{g2}\right)\right]\right\}^{0.5} \qquad \text{(Equation 4)}$$

Where: $V_{g2} = V_{g1}\ y^{(-1/k)}$ $\qquad \frac{1}{\rho_{m2}} = x_1\ V_{g1} y^{(-1/k)} + (1-x_1)V_l$

Note that the equations for V_{g2} and ρ_{m2} follow from the assumption of no-slip flow and no mass transfer between phases at the orifice. Further note that V_{g2} must be calculated exactly as shown above, though the astute reader may detect an apparent error.

Two-phase Critical Flow

The Sachdeva correlation above applies to non-critical flow. Sachdeva provides equation 5 for determining the critical flow boundary.

Critical flow exists when $y > y_c$. When critical flow exists, y_c is used in equation 3 rather than y.

Correlation of C_V to d

Information on chokes is usually given in the form of C_V tables or C_V plots. The Sachdeva correlation uses orifice area. A method of converting C_V to d or A is required.

C_V is defined by the equation:	For water at standard conditions:	Comparing this to the Crane equation for liquid flow:
$q = C_V\sqrt{\frac{\Delta P}{SG}}$	$q = C_V\sqrt{\frac{\Delta P}{\rho_l/62.4}}$ $\qquad q = 7.9\ C_V\sqrt{\frac{\Delta P}{\rho_l}}$	$q = 0.525\ C_d d^2\sqrt{\frac{\Delta P}{\rho_l}}$ Yielding: $0.525\ C_d d^2 = 7.9\ C_V$
Using a C_d of 0.85 as suggested by Sachdeva for two-phase flow:		$\mathbf{d^2 = 0.04\ C_V}$