Flow Calculations for the V-Cone® and Wafer-Cone® Flowmeters

Basic flow equation:

English Units:

$$Q_{acfs} = \frac{\pi}{4}\sqrt{\frac{2g_c}{\rho}}\frac{D_{ft}^{\,2}\beta^2}{\sqrt{1-\beta^4}}\sqrt{\Delta P_{psf}} \times C_f \times Y$$ Volume flowrate

$$Q_{\frac{lb}{s}} = \frac{\pi}{4}\sqrt{2g_c \times \rho}\frac{D_{ft}^{\,2}\beta^2}{\sqrt{1-\beta^4}}\sqrt{\Delta P_{psf}} \times C_f \times Y$$ Mass flowrate

$$D_{ft} = \frac{D_{in}}{12} \qquad \Delta P_{psf} = \Delta P_{wc} \times 5.197$$

$$Q_{acfm} = Q_{acfs} \times 60 \qquad Q_{acfh} = Q_{acfs} \times 3600$$

$$Q_{gpm} = Q_{acfm} \times 7.4805 \qquad Q_{gph} = Q_{acfh} \times 7.4805$$

Metric Units:

$$Q_{\frac{m^3}{s}} = \frac{\pi}{4}\sqrt{\frac{2}{\rho^*}}\frac{D_m^{*\,2}\beta^2}{\sqrt{1-\beta^4}}\sqrt{\Delta P_{Pa}^*} \times C_f \times Y$$ Volume flowrate

$$Q_{\frac{kg}{s}} = \frac{\pi}{4}\sqrt{2\rho^*}\frac{D_m^{*\,2}\beta^2}{\sqrt{1-\beta^4}}\sqrt{\Delta P_{Pa}^*} \times C_f \times Y$$ Mass flowrate

$$D_m^* = \frac{D_{mm}^*}{1000} \qquad \Delta P_{Pa}^* = \Delta P_{mbar}^* \times 100$$

$$Q_{\frac{m^3}{min}} = Q_{\frac{m^3}{s}} \times 60 \qquad Q_{\frac{m^3}{h}} = Q_{\frac{m^3}{s}} \times 3600$$

$$Q_{\frac{L}{min}} = \frac{Q_{\frac{m^3}{min}}}{1000} \qquad Q_{\frac{L}{h}} = \frac{Q_{\frac{m^3}{h}}}{1000}$$

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Gas Expansion Factor

Precision tube V-Cone and Insertion Top-plate V-Cone Flowmeters (Rev. May 2001)

The equation for gas expansion for compressible fluid flow:

NOTE: Y=1 for noncompressible fluids (e.g. water, oil etc.).

$$Y = 1 - (0.649 + 0.696\beta^4)\frac{\Delta P}{k \cdot P}$$

Note that ΔP and P can be in any units as long as they are the same.

Wafer-Cone Flowmeters (Rev. Oct 2001)

The equation for gas expansion for compressible fluid flow:

NOTE: Y=1 for non-compressible fluids (e.g. water, oil etc.).

$$Y = 1 - (0.755 + 6.787\beta^8)\frac{\Delta P}{k \cdot P}$$

The equation to convert from actual to standard / normal volume units:

NOTE: This conversion is only used in compressible fluids.

English Units:

$$Q_{scfs} = Q_{acfs}\left(\frac{P_L}{P_b} \times \frac{T_b}{T} \times \frac{Z_b}{Z}\right)$$

Metric Units:

$$Q_{\frac{Nm^3}{s}} = Q_{\frac{m^3}{s}}\left(\frac{P_L^*}{P_b^*} \times \frac{T_b^*}{T^*} \times \frac{Z_b}{Z}\right)$$

The basic equation in terms of C:

NOTE: C is used to simplify the flow equation by combining the constant and geometric variables.

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English Units:

$$Q_{acfs} = C \times \sqrt{\frac{\Delta P_{psf}}{\rho}} \times Y \qquad C = 6.3002 \frac{D_{ft}^{2} \beta^{2}}{\sqrt{1-\beta^{4}}} C_{d}$$

Metric Units:

$$Q_{\frac{m^3}{s}} = C^* \times \sqrt{\frac{\Delta P^*_{Pa}}{\rho^*}} \times Y \qquad C^* = 1.1107 \frac{D^{*}_{m}{}^{2} \beta^{2}}{\sqrt{1-\beta^{4}}} C_{d}$$

Note that calibrated meters have C_d expressed as a function of Reynolds Number. Therefore for the case of calibrated meters C or C^* will be expressed as functions of Reynolds Number.

Linear velocity equations:

English Units:

$$v = \frac{4Q_{acfs}}{\pi D_{ft}^{2}} \qquad v_{throat} = \frac{4Q_{acfs}}{\pi \beta^{2} D_{ft}^{2}}$$

Metric Units:

$$v^* = \frac{4Q_{\frac{m^3}{s}}}{\pi D^{*\,2}_{m}} \qquad v^*_{throat} = \frac{4Q_{\frac{m^3}{s}}}{\pi \beta^{2} D^{*\,2}_{m}}$$

Beta ratio and cone diameter equations:

English Units:

$$\beta = \sqrt{1 - \frac{d_{in}^{2}}{D_{in}^{2}}} \qquad d_{in} = D_{in}\sqrt{1-\beta^{2}}$$

Metric Units:

$$\beta = \sqrt{1 - \frac{d^{*\,2}_{mm}}{D^{*\,2}_{mm}}} \qquad d^*_{mm} = D^*_{mm}\sqrt{1-\beta^{2}}$$

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Beta Ratios:

The standard beta ratios for V-Cone flowmeters are: 0.45, 0.55, 0.65, 0.75, and 0.8. Alternative beta ratios can be used if required. Note that differential pressure and/or gas expansion factor may limit the availability of even standard beta ratios. In a liquid application, beta ratios should not be used that cause static line pressure minus the differential pressure to be less than the fluid's vapor pressure. In vapor or gas applications, beta ratios should not be used that generate a gas expansion factor less than 0.84.

Reynolds number equation:

English Units:

$$\mathrm{Re} = 123.9\frac{\mathrm{v} \times \mathrm{D_{in}} \times \rho}{\mu}$$

Metric Units:

$$\mathrm{Re} = \frac{\mathrm{D^{*}_{mm}} \times \mathrm{v^{*}} \times \rho^{*}}{\mu}$$

The V-Cone meters discharge coefficient is related to the flows Reynolds number. It is advised that the V-Cone meter be calibrated across the range of Reynolds numbers for which it is to be used. That is a plot of discharge coefficient to the Reynolds number should be produced and a line fit relating discharge coefficient to the Reynolds number should then be made.

Flowing density equations:

Liquids: $\rho = \mathrm{Gr_f} \times \rho_{\mathrm{water}}$

Steam: $\rho = \dfrac{1}{\mathrm{Sp.Vol.}}$

Gas: $\rho = 2.6988\dfrac{\mathrm{S_g} \times \mathrm{P_L}}{\mathrm{Z} \times \mathrm{T}}$

Metric units: $\rho^{*} = \rho \times 16.0184$

Thermal expansion equation:

When meters are subjected to substantially different temperatures than those at which they were calibrated, there can be an effect on meter performance due to the expansion of the cone and meter tube materials. Use this equation if the thermal expansion coefficients for the pipe and cone are equal:

$$\mathrm{F_a} = 1 + 2\alpha(\mathrm{T} - 528)$$

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Use this set of equation if the coefficients are different:

$$Fa = \frac{D_{in}{}^2 - d_{in}{}^2}{((1-\alpha_{pipe}\cdot(T-528))\cdot D_{in})^2 - ((1-\alpha_{cone}\cdot(T-528))\cdot d_{in})^2}$$

To calculate the thermal expansion factor at operating temperature based on beta ratio:

Calculate pipe diameter at operating temperature: $D'_{in} = D_{in} + \left(D_{in}\cdot\alpha_{pipe}\cdot\left(T' - T_c\right)\right)$

Calculate cone diameter at operating temperature: $d'_{in} = d_{in} + \left(d_{in}\cdot\alpha_{cone}\cdot\left(T' - T_c\right)\right)$

Calculate beta ratio at operating temperature: $\beta' = \sqrt{1 - \frac{d'_{in}{}^2}{D'_{in}{}^2}}$

Calculate thermal expansion factor at operating temperature: $F_a = \dfrac{\dfrac{D'_{in}{}^2\cdot\beta'^2}{\sqrt{1-\beta'^4}}}{\dfrac{D_{in}{}^2\cdot\beta^2}{\sqrt{1-\beta^4}}}$

The example below demonstrates the use of this term:

$$Q_{acfs(at\_new\_temp)} = Q_{acfs}\times F_a$$

Permanent pressure loss equation:

Permanent pressure (or "total head") loss in differential pressure meters is typically described as a percentage of the differential pressure created at a particular flowrate. An approximate V-Cone Meter permanent pressure loss can be found by applying the following equation:

$$\%P_{loss} = (1.3 - 1.25\beta)\times 100$$

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Nomenclature

C	meter constant
C^*	metric meter constant
C_d	discharge coefficient of the meter
D_{ft}	meter inside diameter in feet
D_{in}	meter inside diameter in inches
D'_{in}	pipe diameter at operating temperature in inches
D^*_m	meter inside diameter in meters
D^*_{mm}	meter inside diameter in millimeters
d_{in}	cone diameter in inches
d'_{in}	cone diameter at operating temperature in inches
d^*_{mm}	cone diameter in millimeters
F_a	meter thermal expansion factor
g_c	dimensional conversion constant, $32.174\ lb_m ft / lb_f\ sec^2$
k	fluid isentropic exponent at flowing conditions
P	absolute pressure in same units as ΔP
P_b	base absolute pressure in psi *(typically 14.696 psia)*
P^*_b	base absolute pressure in bars *(typically 1.013 bara)*
P_L	absolute static line pressure in psi at the meter
P^*_L	absolute static line pressure in bars or psi at the meter
Q_{acfs}	volume flow rate in actual cubic feet per second
Q_{acfm}	volume flow rate in cubic feet per minute
Q_{acfh}	volume flow rate in cubic feet per hour
Q_{gpm}	volume flow rate in gallons per minute
Q_{gph}	volume flow rate in gallons per hour
$Q_{kg/s}$	mass flow rate in kilograms per second
$Q_{L/min}$	volume flow rate in liters per minute
$Q_{L/h}$	volume flow rate in liters per hour
$Q_{lb/s}$	mass flow rate in pounds mass per second
$Q_{m3/min}$	volume flow rate in cubic meters per minute
$Q_{m3/h}$	volume flow rate in cubic meters per hour
$Q_{m^3/s}$	volume flow rate in actual cubic meters per second
$Q_{Nm^3/h}$	volume flow rate in normal cubic meters per hour
Q_{scfh}	volume flow rate in standard cubic feet per hour
Q_{scfm}	volume flow rate in standard cubic feet per min
R	simplification term used in Y factor
Re	Reynolds number
S_g	specific gravity of the gas
$Sp.Vol.$	specific volume of the vapor

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T	flowing temperature in degrees Rankine
T^*	flowing temperature in degrees Kelvin
T_b	base temperature in degrees Rankine *(typically 520 R)*
T^*_b	base temperature in degrees Kelvin *(typically 288.15 K)*
T_c	calibration temperature
T'	operating temperature
v	fluid velocity through the pipe, in feet per second
v^*	fluid velocity through the pipe, in meters per second
v_{throat}	fluid velocity at the throat, in feet per second
v^*_{throat}	fluid velocity at the throat, in meters per second
Y	adiabatic expansion factor for contoured elements note: $Y = 1$ for liquid flow applications
Z	flowing gas compressibility factor
Z_b	base gas compressibility factor
$\%P_{loss}$	permanent pressure loss across the meter as a percentage of differential pressure

Greek symbols:

α_{PE}	pipe and cone material coefficient of thermal expansion
α_{cone}	thermal expansion coefficient of cone material
α_{pipe}	thermal expansion coefficient of pipe material
β	meter beta ratio
β'	beta ratio at operating temperature
ΔP	differential pressure in same units as P
ΔP^*_{Pa}	differential pressure in Pascals
ΔP^*_{mbar}	differential pressure in millibars
ΔP_{wc}	differential pressure in inches of water column
μ	operating fluid viscosity, in centipoise
π	*3.14159*
ρ	flowing fluid density in pounds mass per cubic foot
ρ^*	flowing fluid density in kilograms per cubic meter

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Electronic Instrumentation for Remote Display and Control

U.S. Patents 4638672, 4812049, 5363699, 4944190 and 5,814,738; Canadian Patent 1325113; European Patent 0277121; Japan patent 1,858,116
Wafer-Cone: Hong Kong Patents HK1027622 & HK1066054; Other U.S. and Foreign patents pending

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