RESTRICTION ORIFICE PLATE (GAS) SIZING CALCULATOR

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Introduction

This document describes the basis and operation of the Blackmonk Engineering Restriction Orifice Plate (Gas) Sizing Calculator.

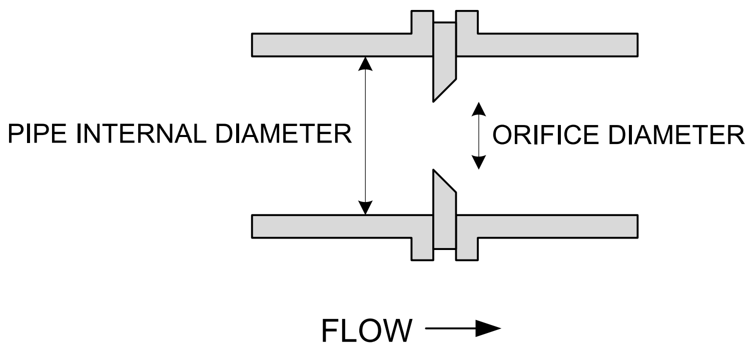
The calculation methodology is based on that described in Crane Technical Paper 410M “The Flow of Fluids Through Valves, Fittings and Pipes”.

The calculator determines the orifice size required to limit the flow of a gas or vapour to a specified flow rate given the upstream pressure, the permanent pressure loss across the orifice and the pipe diameter in which the restriction orifice plate is to be installed.

The calculator determines the orifice flow coefficient, the fluid net expansion factor, the orifice velocity head loss coefficient and the pressure difference across the orifice between 1 pipe diameter upstream and 0.5 pipe diameters downstream of the orifice plate.

The calculator is applicable to the flow of incompressible fluids through square and sharp-edged orifices.

System Diagram



Calculation Inputs

The following parameters are user specified inputs to the calculation:

Input	Description	Units
Upstream pressure	Mandatory user specified pressure upstream of the orifice plate	bara
Pressure difference across orifice	Mandatory user specified pressure difference across the orifice plate	bar

Fluid density	Mandatory user specified fluid density	kg/m^3
Fluid viscosity	Mandatory user specified fluid viscosity	cP
Ratio of specific heats	Mandatory user specified fluid ratio of specific heat capacities	N/A
Flow rate	Mandatory user specified flow rate	m^3/hr
Pipe internal diameter	Mandatory user specified pipe internal diameter	mm

Calculation Outputs

The following parameters are calculated by the software and displayed to the user:

Output	Description	Units
Orifice velocity head loss coefficient	Permanent pressure loss across orifice expressed in terms of velocity head loss	N/A
Beta ratio	Ratio of the calculated orifice diameter to the pipe internal diameter	N/A
Reynolds number	Fluid Reynolds number based on the pipe internal diameter	N/A
Flow coefficient	Orifice flow coefficient	N/A
Pressure difference across orifice	Unrecovered pressure loss across orifice equivalent to the pressure difference between 1 pipe diameter upstream and 0.5 pipe diameters downstream of the orifice plate	bar
Orifice flow area	Cross sectional area of the orifice	m^2
Pressure ratio	Ratio of downstream to upstream pressures	N/A
Net expansion factor	Net expansion factor for compressible flow of gas or vapour through an orifice	N/A
Calculated orifice diameter	Calculated orifice diameter	mm

Flow of Gases and Vapours Through an Orifice

The flow of a compressible fluid through an orifice is determined from the following equation:

$$Q = YCA\sqrt{\frac{2\Delta P_{orifice}}{\rho}} \quad \textbf{Equation 1}$$

Where $\Delta P_{orifice}$ is the pressure difference across the orifice between 1 pipe diameter upstream and 0.5 pipe diameters downstream of the orifice. This downstream location approximates to the position of the vena contracta of the flowing fluid where the fluid pressure is at a minimum.

Permanent Pressure Loss Across Orifice

Some pressure is recovered downstream of the vena contracta as the fluid velocity reduces as the fluid returns to flowing in the full cross-section of the pipe. The fully recovered downstream pressure, typically 4 to 8 pipe diameters downstream of the orifice, is therefore higher than the pressure 0.5 pipe diameter downstream of the orifice.

The permanent pressure loss across the orifice can be approximated by (Ref: Perry's Chemical Engineering Handbook 7th Ed, Page 10-16):

$$\Delta P_{permanent} = \Delta P_{orifice}\left(1 - \mathrm{B}^2\right) \quad \textbf{Equation 2}$$

In designing a restriction orifice plate, it is the permanent pressure loss that is specified. The pressure difference across the orifice must then be estimated using by rearranging the above equation:

$$\Delta P_{orifice} = \frac{\Delta P_{permanent}}{\left(1 - \mathrm{B}^2\right)} \quad \textbf{Equation 3}$$

Alternatively, the permanent pressure loss across the orifice can be expressed as a velocity head loss coefficient (Ref: Crane Technical Paper 410M "Flow of Fluids Through Valves, Fittings and Pipes" Page A-20):

$$K_{permanent} = \frac{\left(1 - \mathrm{B}^2\right)}{C^2 \mathrm{B}^4} \quad \textbf{Equation 4}$$

Net Expansion Factor

The net expansion factor, Y, is a correction factor applied to the basic orifice equation to compensate for the changes in fluid properties due to expansion of the fluid. It is a function of:

- Ratio of specific heat capacities of the fluid
- Beta ratio (orifice diameter : pipe internal diameter)
- Pressure ratio (downstream pressure : upstream pressure)

Net expansion factors are determined experimentally.

For pressure ratios greater or equal to 0.63, the calculator utilises the following correlation to determine the net expansion factor (Ref: Perry's Chemical Engineering Handbook 7th Ed, Page 10-16):

$$Y = 1 - \left[\frac{\left(1 - \frac{P_2}{P_1}\right)}{k}\right]\left(0.41 + 0.35\mathrm{B}^4\right) \quad \textbf{Equation 5}$$

For pressure ratios less than 0.63, the calculator uses the following correlation developed by D. Kirk-Burnnand (Ref: http://www.cheresources.com/high_dp_orifice_flow.shtml) which is based on the above correlation for higher pressure ratios:

$$Y = 1 - \frac{0.4604}{k} - \frac{0.413}{k}\mathrm{B}^4 + \left(0.49 + 0.45\mathrm{B}^4\right)\left(\frac{P_2}{P_1}\frac{1}{k}\right)$$ **Equation 6**

This correlation accounts for the fact that volumetric flow rate of a compressible fluid continues to increase through a square or sharp-edged orifice even as the downstream pressure is reduced below the corresponding critical pressure ratio (Ref: Perry's Chemical Engineering Handbook 7th Ed, Page 10-16).

Flow Coefficient

The flow coefficient accounts for the reduction in effective flow area through the vena contracta as a fluid flows through an orifice and frictional effects. The flow coefficient is a function of:

- Reynolds number
- Beta ratio (orifice diameter : pipe internal diameter)

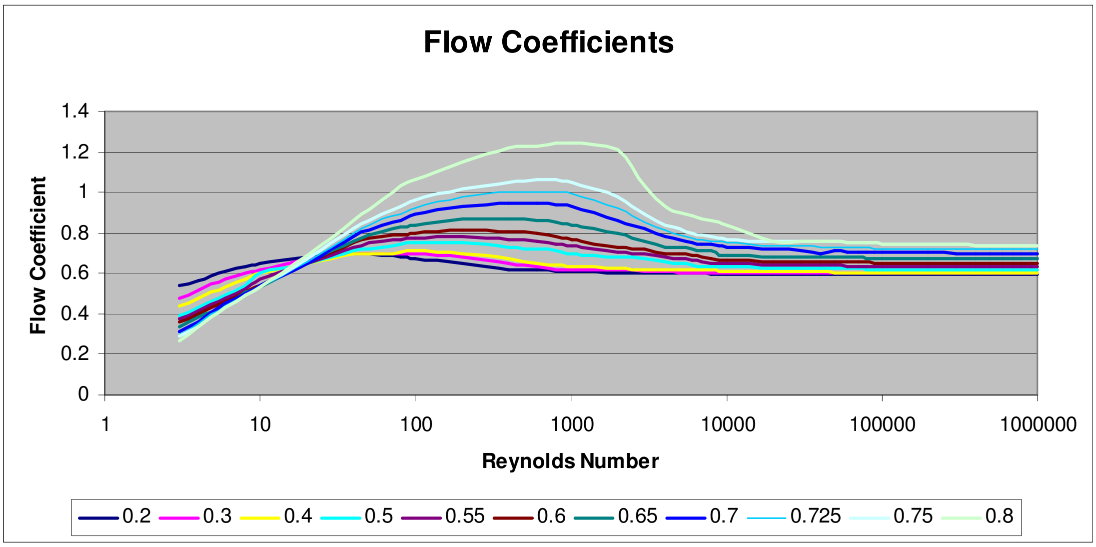
Flow coefficients are determined experimentally.

Various numerical correlations have been developed for determining the flow coefficient through orifices but each correlation is only accurate for a specific range of Reynolds number and Beta ratios.

This calculator uses a database of flow coefficients derived from the curves presented in Crane Technical Paper 410M representing all Reynolds numbers greater than 3 and Beta ratios from 0 to 0.8.

Note: Reynolds number used in this calculation is the pipe Reynolds number based on the pipe internal diameter and fluid velocity in the pipe.

Chart 1: Flow Coefficients for Orifices



Beta Ratio

The Beta ratio is defined as the ratio of the orifice diameter to the pipe internal diameter:

$$B = \frac{d_{orifice}}{d_{pipe}}$$ **Equation 7**

Reynolds Number

Reynolds number is determined using the relationship:

$$Re = \frac{4Q\rho}{\pi\mu d_{pipe}}$$ **Equation 8**

Pressure Ratio

The pressure ratio is the ratio of the pressure downstream of the orifice to the pressure upstream of the orifice:

$$r = \frac{P_2}{P_1}$$ **Equation 9**

Orifice Flow Area

The orifice flow area is given by:

$$A_{orifice} = \frac{\pi d_{orifice}^{\ 2}}{4}$$ **Equation 10**

Calculation of Orifice Diameter

The required orifice diameter is determined from the specified permanent pressure loss across the orifice, the fluid density, fluid viscosity, fluid ratio of specific heat capacities, the specified flow rate and the internal diameter of the pipe in which the orifice plate is to be located.

First, the calculator determines the Reynolds number using Equation 6 and the pressure ratio using Equation 9. Then the calculator makes an initial estimate of the beta ratio. The calculator then estimates the flow coefficient based on the Reynolds number and beta ratio and estimates the net expansion factor using Equations 5 & 6. Next, the calculator estimates the pressure difference across the orifice using Equation 3.

The orifice diameter is then estimated using the beta ratio directly according to Equation 8 below:

$$d_{orifice} = \mathrm{B} d_{pipe}$$ **Equation 11**

The orifice diameter is also estimated using the rearranged orifice equation:

$$d_{orifice} = \left[\frac{4Q}{\pi Y C} \sqrt{\frac{\rho}{2\Delta P_{orifice}}} \right]^{0.5}$$ **Equation 12**

The 2 estimates of the orifice diameter generated by Equation 8 and Equation 9 are then compared. If the 2 values are equivalent within the tolerance of 0.01 mm, the orifice diameter is defined and the calculation routine is complete. If the 2 values are not within the specified tolerance, the beta ratio is re-estimated and the calculation steps are reiterated until the 2 estimates of the orifice diameter are within tolerance.

The orifice velocity head loss coefficient and orifice flow area are calculated for information during each iteration.

The calculation routine is described in the following steps:

1. Calculate Reynolds number
2. Calculate pressure ratio
3. Estimate Beta ratio
4. Estimate net expansion factor
5. Estimate flow coefficient using Beta ratio estimate
6. Estimate orifice velocity head loss coefficient

7. Estimate orifice diameter using Beta ratio estimate directly
8. Estimate pressure difference across orifice
9. Estimate orifice diameter using the estimated flow coefficient in the orifice equation
10. Compare calculated orifice diameters from Step 7 and Step 9
11. If the 2 calculated orifice diameters are equal, the orifice diameter is defined and the calculation has been solved.
12. Re-estimate Beta ratio
13. Re-iterate calculation procedure from Step 3 to Step 11 until orifice diameter is defined

To solve the calculation accurately, the beta ratio must be ≤ 0.8. The calculator generates a warning if the beta ratio is out of this range.

Nomenclature

$\rho =$ Density of fluid (kg.m^{-3})

$\mu =$ Viscosity of fluid (Pa.s)

$k =$ Ratio of specific heat capacities (dimensionless)

$d_{pipe} =$ Pipe internal diameter (m)

$d_{orifice} =$ Orifice diameter (m)

$\mathrm{Re} =$ Reynolds number (dimensionless)

$C =$ Flow coefficient (dimensionless)

$A_{orifice} =$ Orifice flow area (m^2)

$Q =$ Flow rate through orifice (m^3.s^{-1})

$Y =$ Net expansion factor (dimensionless)

$\Delta P_{orifice} =$ Pressure difference across orifice (Pa) $= P_1 - P_2$

$\Delta P_{permanent} =$ Permanent pressure loss across orifice (Pa) $= P_1 - P_3$

$P_1 =$ Upstream pressure [1 pipe diameter upstream of orifice] (Pa)

$P_2 =$ Downstream pressure [0.5 pipe diameter downstream of orifice] (Pa)

$P_3 =$ Fully recovered downstream pressure [4 to 8 pipe diameters downstream of orifice] (Pa)

$r =$ Pressure ratio (dimensionless)

$\mathrm{K}_{permanent} =$ Orifice velocity head loss coefficient (dimensionless)

$\mathrm{B} =$ Orifice diameter : Pipe internal diameter (dimensionless)

Example

The following example was taken from Crane Technical Paper 410M “Flow of Fluids Through Valves, Fittings and Pipes” Example 2 page 3-26.

Description:

A differential pressure of 0.2 bar is measured across taps located 1 diameter upstream and 0.5 diameters downstream from the inlet face of an 18 mm inside diameter square edged orifice assembled in a 25.7 mm inside diameter steel pipe in which dry ammonia gas is flowing at 2.75 barg and 10C.

Fluid density = 2.76 kg/m^3
Fluid viscosity = 0.010 cP
Fluid ratio of specific heats = 1.32

Requirement:

Find the flow rate in kilograms per second of ammonia through the orifice.

Solution:

The calculator determines the orifice diameter for a specified flow rate of gas or vapour. For the purpose of this example, the flow rate determined in the Crane example was input into the calculator and the orifice diameter calculated.

Flow rate = 205 kg/hr = 74.28 m^3/hr

Pressure difference across orifice = 0.193 bar (cf Crane published value of 0.20 bar)

Calculated orifice diameter = 18 mm

Restriction Orifice Plate (Gas) Calculator Screenshot:

INPUTS

Upstream pressure	P_1	3.763	bara
Permanent pressure loss across orifice	$\Delta P_{permanent}$	0.10	bar
Fluid density	ρ	2.76	kg/m3
Fluid viscosity	μ	0.01	cP
Ratio of specific heats	k	1.32	
Flow rate	Q	74.3	m3/hr
Pipe internal diameter	d_{pipe}	25.7	mm

OUTPUTS

Orifice velocity head loss coefficient	$K_{permanent}$	4.331	
Beta ratio	B	0.700	
Reynolds number	Re	282210	
Flow coefficient	C	0.700	
Pressure difference across orifice	$\Delta P_{orifice}$	0.193	bar
Orifice flow area	$A_{orifice}$	0.00025	m2
Pressure ratio	r	0.95	
Net expansion factor	Y	0.98	
Estimated orifice diameter		18.0	mm
Calculated orifice diameter	$\mathbf{d_{orifice}}$	18.0	mm