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K_v-value and Head Loss Factor in Control Valves

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Summary

Cryogenic valves are usually characterised through design coefficients, indicated as K_v in DIN/IEC534. In this note we show how to use the K_v coefficient to compute the head loss factor for valves to be used in models of the type inplemented in `flower`.

1. Introduction

Cryogenic control valves are often specified using a valve sixing factor, K_v that has been detailed in the norm DIN/IEC534. The physical meaning of K_v is the numerical value in m^3/h of water at 5 to 40 °C flowing through the valve under a pressure drop of 1 bar. This value has an analog in the US in the coefficient c_v, defined as the numerical value in US gal/min of water at 5 to 40 °C flowing through the valve under a pressure drop of 1 psi. The conversion between the two factors is thus straightforward:

$$K_v = 0.86\, c_v.$$

Both coefficients are widely used as design parameters for valves, and they can be found in the catalogs of valves manufacturers. In this note we show how these coefficients can be used directly in a simple model of the flow through the valve, as the one implemented in the hydraulic network solver `flower` [1].

2. K_v-value in accordance with DIN/IEC534

The valve sizing factor K_v is often quoted in the characteristics of a flow regulation cryogenic valve, and is in fact the main design parameter for the selection of a specific valve type. According to DIN/IEC534 the sizing factor K_v for turbulent compressible flow can be computed as:

$$K_v = \frac{W}{31.6\, F_p\, Y \sqrt{X\, p_1\, \rho_1}} \tag{1}$$

where W is the mass-flow in [Kg/h]. The two quantities p_1 and ρ_1 are respectively inlet pressure in [bar] and density in [Kg/m^3]. The parameter X is the non-dimensional pressure drop ratio defined as:

$$X = \frac{p_1 - p_2}{p_1} \tag{2}$$

where p_2 is the outlet pressure. The parameter Y is a non-dimensional expansion factor between 0.667 and 1 defined as:

$$Y = 1 - \frac{X}{3\, F_k\, X_T} \tag{3}.$$

Above F_k is a specific heat ratio factor given by:

$$F_k = \frac{\kappa}{1.4} \tag{4}$$

where κ is the ratio of specific heat under constant pressure and constant density conditions, C_p and C_v:

$$\kappa = \frac{C_p}{C_v} \tag{5}.$$

The factor X_T in Eq. (3) is typically in the range of 0.65 (for flow closing the valve) to 0.75 (for flow opening the valve). Finally F_p is a non-dimensional piping geometry factor defined as:

$$F_p = \frac{1}{\sqrt{1 + \frac{\sum \zeta}{0.0016}\left(\frac{K_v}{d^2}\right)^2}} \tag{6}$$

where d is the valve diameter in [mm] and the sum is defined as:

$$\sum \zeta = \zeta_1 + \zeta_2 + \zeta B_1 - \zeta B_2 \tag{7}.$$

The four non-dimensional terms in Eq. (7) are the upstream resistance coefficient with inlet reducer ζ_1:

$$\zeta_1 = \frac{1}{2}\left[1 - \left(\frac{d}{D_{reducer}}\right)^2\right]^2 \quad (8)$$

where $D_{reducer}$ is the reducer diameter, the downstream resistance coefficient ζ_2:

$$\zeta_2 = \left[1 - \left(\frac{d}{D_{reducer}}\right)^2\right]^2 \quad (9),$$

the valve inlet Bernoulli coefficient ζB_1:

$$\zeta B_1 = 1 - \left(\frac{d_{inlet}}{D_{inlet}}\right)^4 \quad (10),$$

where d_{inlet} is the inlet diameter and D_{inlet} is the valve inlet diameter (both in [mm], and finally the valve outlet Bernoulli coefficient ζB_2:

$$\zeta B_1 = 1 - \left(\frac{d_{outlet}}{D_{outlet}}\right)^4 \quad (11)$$

where d_{outlet} is the outlet diameter and D_{outlet} is the valve outlet diameter (bpth in [mm]). In the case that inlet and outlet valve diameter are the same, the two coefficients ζB_1 and ζB_2 cancel out from the sum in Eq. (7).

3. Simplified flow model for the valve

In spite of the apparent complexity of the equations necessary to determine the flow in the valve, it can be shown that Eq. (1) can be easily converted into the following form:

$$p_1 - p_2 = \frac{2\xi}{A^2}\frac{\dot{m}^2}{\rho} \quad (12)$$

that is identical to the one used in the hydraulic network solver `flower`[1] and where $\dot{m}$ is the mass-flow in [Kg/s], ρ is an average density that we can take for simplicity identical to the inlet density, A is the cross section of the valve in [m^2]

and ξ is a non-dimensional head loss factor. The factor 10^{-5} in front of the r.h.s. of Eq. (12) is used to convert the pressure drop from [Pa] to [bar].

To show that Eq. (12) is identical to Eq. (1), we can write explicitly the definition of the head loss factor using the factors defined in the previous section. We start writing the relation between mass-flow in [Kg/h] and [Kg/s]:

$$W = 3600\ \dot{m} \tag{13}$$

We can now use Eq. (13) in Eq. (1) and group terms conveniently to obtain:

$$\sqrt{X\ p_1} = \frac{3600\ \dot{m}}{31.6\ K_v\ F_p\ Y\sqrt{\rho_1}} \qquad (14).$$

If we now use the definition Eq. (2) to substitute in Eq. (14) and take the square of the result we obtain:

$$p_1 - p_2 = \left(\frac{3600}{31.6}\right)^2 \left(\frac{1}{K_v\ F_p\ Y}\right)^2 \frac{\dot{m}^2}{\rho_1} \qquad (15).$$

We now compare Eqs. (12) and (15), and we see immediately that the head loss factor is related to the valve design parameters by:

$$\xi = \frac{10^5}{2}\left(\frac{3600}{31.6}\right)^2 \left(\frac{A}{K_v\ F_p\ Y}\right)^2 \tag{16}$$

and eliminating the numerical factor we obtain the desired result:

$$\boxed{\xi = 6.48\ 10^8 \left(\frac{A}{K_v\ F_p\ Y}\right)^2} \qquad (17).$$

Note that most of the coefficients appearing in Eq. (17) are known (the valve cross section A, the valve sizing factor K_v as well as the valve piping factor F_p). The expansion factor Y depends on the pressure drop ratio, and therefore should be recomputed during the flow calculation. However its range of variation is small (0.667 to 1) and therefore an approximate value can be determined that satisfies well the whole range of expected pressure drop across the valve. In fact we can approximate Eq. (17) if we assume a large diffuser diameter before and after the valve, compared to the valve diameter, and a small pressure drop ratio, resulting in $F_p \approx 1$ and $Y \approx 1$, so that we have:

$$\xi \approx 6.48\ 10^8 \left(\frac{A}{K_v} \right)^2 \tag{18}$$

that is generally a good approximation of the more complex Eq. (17).

4. Examples of calculation

We take as an example two very different valves of the manufacturer WEKA AG (CH). The first valve, type DN2, is a small size control valve for which we select a K_v of 0.004 (type 2/10-0.1). The valve has a diameter d of 2 [mm] and a cross section A of 3.14 10^{-6} [m^2]. We assume for simplicity that the walve has the same inlet and outlet diameter so that the Bernoulli terms ζB_1 and ζB_2 cancel out. We take a reducer diameter $D_{reducer}$ of 5 [mm] before and after the valve. In this case we have that:

$\zeta_1 = 0.353$ $\qquad \zeta_2 = 0.706$

so that the valve piping factor is:

$F_p = 0.9997$

very close to 1. If we further assume that the pressure drop is small with respect to the absolute pressure itself, we can safely take:

$Y = 1$.

Using Eq. (17) we obtain finally a head loss factor of:

$\xi \approx 400$.

If we use now Eq. (12) to compute the flow of water at 25 °C (ρ = 1000 [Kg/m^3]) under a pressure drop ($p_1 - p_2$) of 1 [bar] we obtain a value of:

$\dot{m}$ = 1.11 10^{-3} [Kg/s]

that corresponds to a volume flow of approximately 0.004 [m^3/h] as expected (the same value as the K_v).

As a second example we take a large valve of type DN50, with a K_v of 66. The valve has in this case a diameter d of 50 [mm] and a cross section A of 19.6 10^{-4} [m^2]. We take again the same inlet and outlet diameter so that the Bernoulli terms cancel out, and a reducer diameter $D_{reducer}$ of 60 [mm] before and after the valve. In this case we have that:

ζ_1 = 0.047 ζ_2 =0.093

and the valve piping factor is:

F_p = 0.971.

Also in this case we assume that:

Y = 1.

and we compute from Eq. (17):

$\xi \approx 0.61$.

Using Eq. (12) we can estimate that a relatively large massflow $\dot{m}$ of 1 [Kg/s] of helium at 4.5 [K] and 10 [bar] (density ρ = 147 [Kg/m^3]) would cause a pressure drop (p_1 - p_2) of 0.021 [bar]. The large valve offers little resistance as expected.

As a final remark, we note that the values computed here are for valves completely opened. Control valve generally have the capability to vary the valve sizing coefficient K_v following pre-defined waveforms (e.g. linearly, constant percentage, and others) from the fully opened value, computed here, to zero for a valve completely closed. The calculation of the head loss factor ξ can be performed in accordance inserting the K_v variation in Eqs. (17) or (18).

5. References

[1] L. Bottura, C. Rosso, *Hydraulic Netowrk Simulator Model*, CryoSoft Internal Note, CRYO/97/004, December 1997, revised February 1999.