5.4.4. Influence of vaporization (choked flow)

At a flow through a throttling area the velocity of the liquid is always increased with a simultaneous lowering of the static pressure. Thus the static pressure falls often below the vapor pressure line, schematically represented in Figure 5.4.4.-1.

Depending on the vapor pressure of the liquid, different effects occur:

- Cavitation (vapor pressure line 2) and
- Evaporation or flashing (vapor pressure line 3).

In both cases a liquid/vapor mixture occurs at the narrowest point of the throttling area under the defined prerequisites whose mean density differs from the real density of the liquid. The inevitable consequence is a deviation of the mass flow rate from the theoretical. The vapor pressure of the liquid is in the first case very low (p_{v1}), i.e. it lies below the lowest pressure inside the control valve. Neither cavitation nor evaporation exists here. A flow correction isn't required.

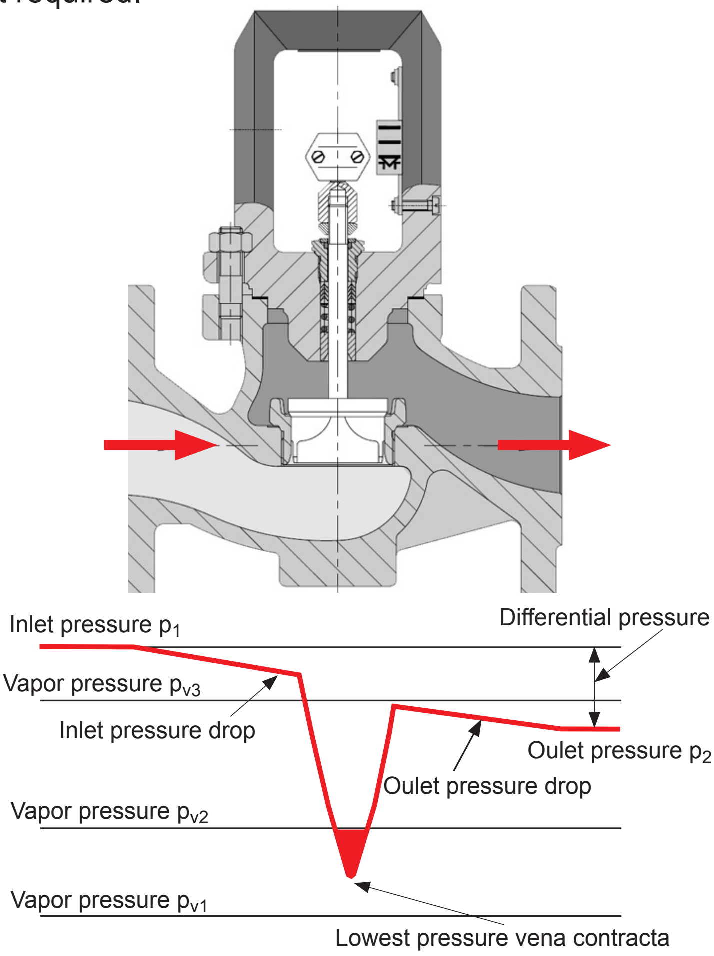

Figure 5.4.4.-1: Pressure profile in a control valve at different vapor pressures p_v

In the second case the vapor pressure of the liquid is increased, (e.g. by heating) to a value of p_{v2}. The area of the lowest pressure (shadowed area) lies now, below the vapor pressure line. This causes temporary evaporation of the fluid with following liquefaction of the vapor bubbles, because the pressure rises steeply again behind the throttling area. This condition is described as cavitation. Caused by a partial evaporation of the liquid, the mean density decreases slightly. This effect is taken into account by the correction factor, F_y.

The vapor pressure is, in the third case, so high that it is only a little below the inlet pressure p_1, but above the outlet pressure p_2. Under these circumstances complete evaporation of the liquid occurs in the throttling area and partial evaporation behind the valve. The degree of evaporation behind the control valve depends on the new heat balance between outlet temperature and vapor pressure, since heat losses of the liquid appear due to the vaporizing process. An exact estimate of the degree of vaporizing is difficult but is possible by including the parameters for calculating the new heat balance.

Following on from Figure 5.4.4.-2, the flow increases in the beginning proportional with the root of the differential pressure. From a definite point (Δp_c) on, it differs progressively from the ideal line to a final value. The cause is evaporation of the liquid in the valve when the pressure at the vena contracta falls below the vapor pressure as previously explained before.

To take this effect into consideration, at high pressure differentials is a further correction factor (F_y) required. A first measurable deviation from the ideal flow occurs at the critical differential pressure Δp_c. Since this differential pressure is difficult to determine, one uses simply the intersection point (Δp_m) of the two tangents as the characteristic value.

In Anglo-American literature, this point (K_m) is often incorrectly described as „cavitation index“ or „onset of cavitation“. In reality cavitation appears indeed at considerably lower differential pressures as will be explained later on.

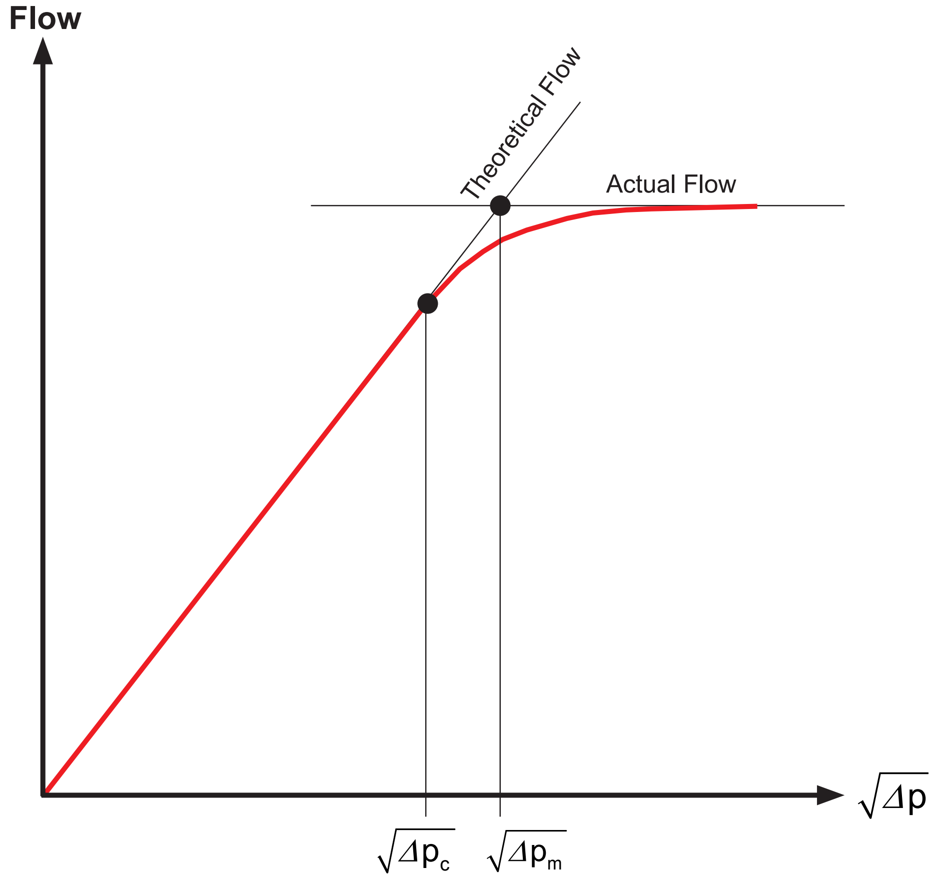

Figure 5.4.4.-2: Liquid flow as a function of the differential pressure

Another valve coefficient which plays an important role in the calculation of the flow or flow coefficient is the F_L-value. This is the liquid pressure recovery factor of a control valve without attached fittings. It accounts for the influence of the internal valve geometry on the valve capacity at choked flow. F_L is defined as the ratio of the actual maximum flow rate under choked flow conditions to a theoretical, non-choked flow rate, which would be calculated if the pressure differential used was the difference between valve inlet pressure and the apparent **vena contracta** pressure at choked flow conditions. In other words, F_L defines the pressure recovery in a control valve and can be determined by measurements only. When the internal pressures of a control valve are known, the F_L value can be calculated - referring to Figure 5.4.4.-1 - as follows:

$$\boxed{F_L = \sqrt{\frac{p_1 - p_2}{p_1 - p_{vc}}}} \qquad (5\text{-}5)$$

The pressure p_{vc} is the lowest pressure in the **vena contracta**, i. e. the negative pressure peak in Figure 5.4.4.-1. When no pressure recovery occurs in the control valve, the F_L value becomes 1.0. Another method of roughly determining F_L is by flow measurement (intersection point of the tangents). With the help of the characteristics (**Δp_m**) and (**K_m**) the F_L value can be calculated.

$$\boxed{K_m = \frac{\Delta p_m}{p_1 - p_v}} \qquad (5\text{-}6)$$

When K_m and the vapor pressure p_v of the liquid is known, the factor F_L becomes:

$$\boxed{F_L \approx \sqrt{K_m}} \text{ or replacing } K_m \text{ directly with the value } F_L^2 \qquad (5\text{-}6)$$

The correction factor F_y can finally be determined by means of the auxiliary variable F_F as follows:

$$\boxed{F_F = 0.96 - 0.28 \cdot \sqrt{\frac{p_v}{p_c}}} \qquad (5\text{-}8)$$

$$\boxed{F_y = F_L \cdot \sqrt{\frac{p_1 - F_F \cdot p_v}{p_1 - p_2}} < 1.0} \qquad (5\text{-}9)$$

If the calculation gives values of $F_y > 1.0$ then there is no limitation of flow due to cavitation or flashing. In such a case F_y must be set to a value of 1.0.

Another possibility to be considered when seeking an accurate calculation of the flow coefficient, taking incipient evaporation into account, is the inclusion of the „maximum allowable differential pressure“ in the working equation.

$$\boxed{\Delta p_{max} = \Delta p_c = F_L^2 \cdot (p_1 - F_F \cdot p_v)} \qquad (5\text{-}10)$$

This method, which is also proposed by the valid IEC standard is, however, troublesome.

In this case the user must firstly identify whether the actual differential pressure is smaller or greater than the „maximum allowable differential pressure". The value of the actual differential pressure to be inserted in equation (5-10) must be, in the latter case, limited to the „maximum allowable differential pressure" ($\Delta p_{max} = \Delta p_{pc}$). This measure becomes with the introduction of the auxiliary variable F_y superfluous, since the complete equation for the calculation of the flow or the flow coefficient is corrected by the factor F_y automatically. This is particularly advantageous when using computers and corresponding software.

As mentioned before, control valves are often equipped with attached fittings, i.e. reducers. Therefore the pressure recovery factor F_L and the pipe geometry factor F_p are often combined into the factor F_{LP}. This is obtained by measurements in the same way as F_L. When estimated values are permissible, a reasonable accuracy can be obtained by use of the following equation:

$$\boxed{F_{LP} = \frac{F_L}{\sqrt{1 + \frac{F_L^{\,2}}{0.00214} \cdot \left(\Sigma\varsigma_1\right) \cdot \left(\frac{C_v}{d^2}\right)^2}}} \tag{5-11}$$

Here the term $\Sigma\varsigma_1$ is the velocity head loss coefficient ($\varsigma_1 + \varsigma_{B1}$) of the fitting attached upstream of the valve as measured between the upstream pressure tap and the control valve body inlet. The effect of a diffuser fitting in front of a control valve may produce sizing errors greater than 5%.

Summary

How to understand the message "choked flow" if Δp operation is $> \Delta p_c$?

Replacing Δp operation with Δp_c result in the flow equation to a smaller flow or in the C_v equation to a larger C_v-value. On one hand **"choked flow"** occurs only in case of flow calculations with the unchanged C_v-value but at the other hand in case of C_v calculation the larger C_v value avoid any choked flow – the full flow can pass the valve. This avoid misunderstanding because the majority of calculations are C_v calculations with the computer message "choked flow" which should be understood as "choked flow is prevented".

What is the major difference operating a valve, if

a) Δp operation is $< \Delta p_c$ or

b) Δp operation is $> \Delta p_c$? (choked flow condition)

In case a) the valve is able to reduce Δp operation completely (converting into heat). The downstream pipe is handling p_2 only.

In case b) the valve can convert only Δp_c (converting into heat) and the downstream pipe must handle the residual pressure differential $\Delta p_{residual} = \Delta p$ operation - Δp_c.

If $\Delta p_{residual}$ becomes a larger part of Δp operation a long term reliability aspect must be handled with care. If rotary valves operate under choked flow conditions the downstream pipe take over an uncontrolled throttling and non wanted effects like severe pipe vibration, increased non predictable sound and damage of valve parts and downstream pipe sections are possible. In case of globe valves this effect is much smaller but if the negative impact is not negligible a proper sized downstream baffle system – multi-hole orifice plates single or several – can control $\Delta p_{residual}$ to avoid all troubles.