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Carrying gas handling to excellence

C, b - Mass flow model for gases in high-pressure range

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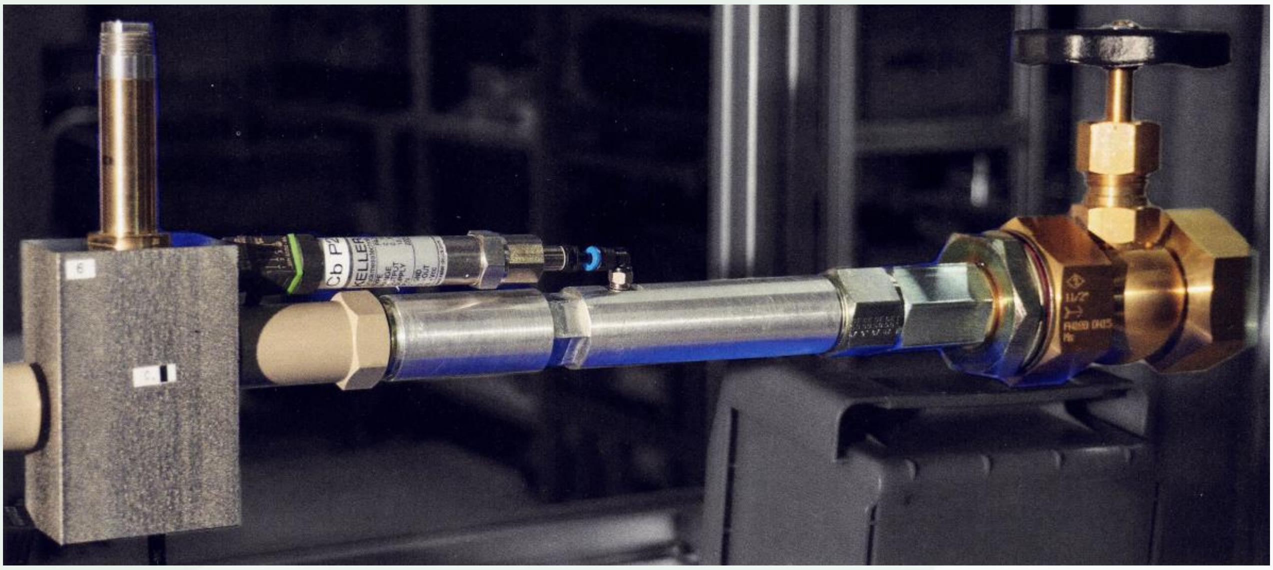

Executive Summary

For many decades now, valves have been designed using the K_V value. This article shows the development path from the K_V value for water and gases to the C, b - model for gases, which is already used with real gas data for high pressure hydrogen applications. Results indicate that the C, b - model is more suitable than the K_V value when it comes to gases, in particular for describing mass flow through a valve with gaseous hydrogen. The C, b values are also beneficial for system simulation and for the design of complete systems, e.g. refueling stations for hydrogen car or buses.

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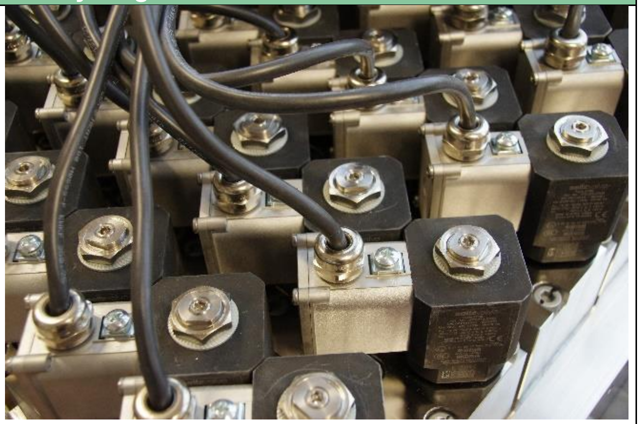
01 Hydrogen Refueling Station (HRS)	02 Section of HyValve Mosaic 1000 bar hydrogen valves DN 6 Matrix 5x8
	

1. History of the K_V value

In 1957, Früh /1/ was the first to introduced to German-speaking experts a flow rate value, the K_V value which is closely based on the US "C_V factor". This was implemented by the Mason-Neilan Regulator Company in 1944 /2/. The flow coefficient C_V describes the number of US gallons[1] per minute of water, at T = 60°F, that flow through a given flow restrictor, at a pressure drop of one PSI[2].

Früh's /1/ proposal to introduce the term C_V value in the German-speaking world most likely caused confusion among experts, as it referred to a "coefficient", which usually has no unit of measurement (the abbreviation "C_V" refers to the first letters of the English words Coefficient and Valve, as Wiedmann /3/ later clarified.

2. The K_V - value for incompressible fluids (liquids)

The K_V value is a specific flow rate at a pressure difference of one bar. With the measured volume flow Q, the static pressure difference of $\Delta p_w = 1\ \mathrm{bar}$, the measured static differential pressure across the valve Δp in bar, the density of the medium ϱ and the density of water ϱ_w at 15 °C, the K_V according to /4/. The K_V - value, valid for turbulent flow, is calculated according to equation (1).

$$K_V = Q \cdot \sqrt{\frac{\Delta p_w}{\Delta p} \cdot \frac{\varrho}{\varrho_w}} \quad in\ [m^3/h] \tag{1}$$

Image 01: scharfsinn86-stock.adobe.com; all other Eugen Seitz AG

[1] 1 US liquid gallon = 3.78541 liter
[2] 1 Pound per square inch (PSI) = 0.0689476 bar

3. The K_V - value for compressible fluids (gases)

Regarding the K_V value for gases, it must be noted that gases are compressible. In addition, since gases cannot exceed the speed of sound, there is a physical limitation to the flow rate in the narrowest cross-section. For this reason, in the narrowest cross-section of gas flow, a distinction is made between a subcritical area (velocity < speed of sound) and a supercritical area (velocity = speed of sound). The parameter b, known as the critical pressure ratio b, is used to characterise this transition. The equations for the K_V value for gases are calculated using the general equation of state for gases, the DIN 1343 /5/ and the general flow equation, see /7/.

$$K_V = \frac{\dot{Q}_N \cdot \sqrt{T_1}}{\sqrt{p_2 \cdot \Delta p}} \cdot \sqrt{\frac{\varrho_N \cdot \Delta p_W \cdot p_N}{\varrho_W \cdot T_N}} \qquad \text{for } b \leq \frac{p_2}{p_1} \leq 1 \quad \text{(subcritical)} \qquad (2)$$

$$K_V = \frac{2 \cdot \dot{Q}_n \sqrt{T_1}}{p_1} \cdot \sqrt{\frac{\varrho_N \cdot \Delta p_W \cdot p_N}{\varrho_W \cdot T_N}} \qquad \text{for } 0 \leq \frac{p_2}{p_1} \leq b \quad \text{(supercritical)} \qquad (3)$$

Equations (2) and (3) are used to specify "ideal" K_V values, as it does not account for the influences of energy dissipation and jet constriction, which are difficult to determine or measure in a practical case /6/. Further restrictions are added by setting the critical pressure ratio to the value $b = 0.5$, which does not correspond to reality in most cases.

The values for the critical pressure ratio in valves can be in the range of $b = 0.2 \ldots 0.7$. Valves with large pressure losses (baffles, etc.) tend to have smaller values, whereas more flow-favourable, diffuser-like geometries have b values > 0.5.

It can be stated that there are significantly more disadvantages when using K_V values for air, as a second parameter is missing and therefore K_V values should not be used when selecting valves for gases. It is recommended to use a model that takes into account the specific characteristics of gas flows.

4. C, b model for compressible fluids (gas)

The mass flow model for air according to ISO 6358, see /7/ Annex C, or /8/ Eq. (E.5) and (E.6), is fully defined with the standard conditions $\varrho_0 = 1{,}185 \frac{kg}{m^3}$ and $T_0 = 293.15\ \mathrm{K}$ and with equations (4) and (5), /9/.

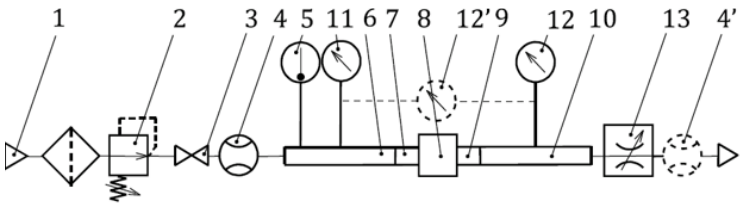
$$\dot{m} = p_1 \cdot C \cdot \varrho_0 \cdot \sqrt{\frac{T_0}{T_1}} \qquad \text{for } 0 \leq \frac{p_2}{p_1} \leq b \qquad \text{supercritical} \qquad (4)$$

$$\dot{m} = p_1 \cdot C \cdot \varrho_0 \cdot \sqrt{\frac{T_0}{T_1}} \sqrt{1 - \left(\frac{\frac{p_2}{p_1} - b}{1 - b}\right)^2} \qquad \text{for } b \leq \frac{p_2}{p_1} \leq 1 \qquad \text{subcritical} \qquad (5)$$

This model contains two parameters: the conductance C in the supercritical flow range and the critical pressure ratio b (see equations 4 and 5). The critical conductance C includes the maximum of the flow function ψ_{max} as well as the cross-sectional area A_2 and the flow-reducing effects (friction, wall friction, flow constriction, constrictions, deflections, velocity losses) (see equations 6, 7 and 8). With the ratio $\sqrt{T_0/T_1}$, the mass flow model was formulated independently of the temperature at which the conductance C was measured. The conductance C, which was determined at a temperature T_1, is therefore related to the temperature T_0 as a reference value to calculate the mass flow at any temperature T_1. Equations (4) and (5) are only valid for an ideal gas. However, these can be extended to real gases with the aid of a simulation.

The following shows the procedure for determining the C, b values for a hydrogen valve using a finite element calculation with ANSYS CFX Version 2022 R2. The simulation is carried out with air analogous to the measurement on a test bench, **Figures 03 - 05.**

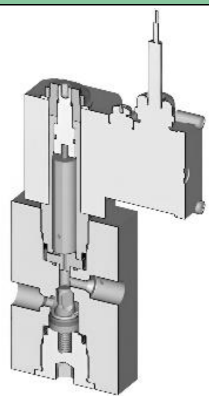
03 Test rig according to ISO 6358-1 /10/ for constant flow rate



4 - Flow sensor
5 - Temperature measuring point
8 - Test specimen (valve)
11 - Pressure measuring point
12 - Pressure measuring point
13 - Throttle valve

04 Measurement setup C, b – test stand with a H_2 valve DN6 – 1000 bar

05 Cross-section of a H_2 valve DN 6 – 1000 bar



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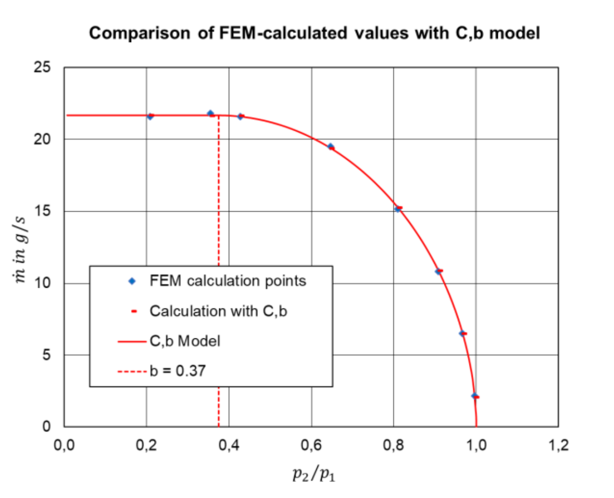
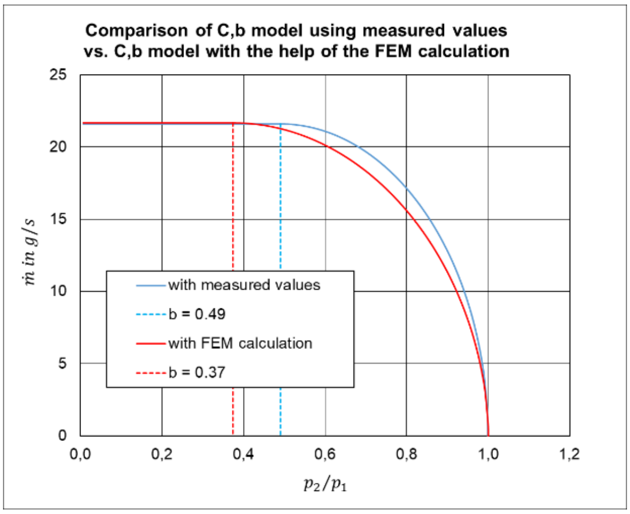
06 Results of the FEM simulation with air as Ideal Gas

C = 2.63E-8 m^4 ·s/kg
b = 0.37



07 Comparison of C, b - model using measured values vs. C, b - model using FEM calculation

C = 2.63E-8 m^4 ·s/kg , b = 0.49 (measured values)
b = 0.37 (FEM calculation)



The inlet pressure is kept constant at a value of $p = 6.96\ \mathrm{bar\ (abs.)}$. Eight results of an FEM calculation are required to determine the parameters C and b, **Table 01.**

Table 01: Calculations of C, b values using the FE analysis with air according to ISO 6358-1 /10/

Inlet [bar]	Outlet [bar]	Test point 11 p_1 [bar]	Test point 12 p_2 [bar]	$\dot{m}$ [g/s]	p_2/p_1 [-]	T_1 [K]	C $[m^4 s/kg]$	C_e $[m^4 s/kg]$	C_e/C [-]
6.96	1.43	6.957	1.45	21.6	0.208	293	2.620E-08		
6.96	2.46	6.951	2.47	21.8	0.355	293	2.646E-08		
6.96	2.96	6.950	2.97	21.6	0.427	293	2.622E-08		
6.96		6.952	4.49	19.5	0.646	293		2.366E-08	0.9001
6.96		6.955	5.63	15.2	0.810	293		1.840E-08	0.6997
6.96		6.958	6.32	10.8	0.908	293		1.314E-08	0.4996
6.96		6.959	6.73	6.5	0.967	293		7.880E-09	0.2997
6.96		6.960	6.93	2.2	0.996	293		2.626E-09	0.0999

Figures 6 and 7 show typical curves for the C,b – model measure experimentally or obtained with the help of FEM simulation. It is apparent that there are only minor differences between the simulation and experimental measurement in terms of the conductance C, and therefore also in terms of mass flow. Which is In line with our expectations. However, there are visible differences for the critical pressure ratio. This can be explained by the critical pressure ratio b in reality being a transitional range. In metrology, measurement uncertainty increases as the pressure drop decreases because the measurement uncertainty increases in pressure and volume flow measurements. Haack /6/ has shown that deviations of up to $\Delta b = \pm 0.1$ can occur when determining the critical pressure ratio b, using metrological tests.

5. Extension of the C, b - model for the high-pressure range

The starting point was the method described in ISO 6358-1 /8/ for determining the parameters C and b. As part of a study by Ramsperger /10/, the C, b - model was successfully used for air and hydrogen in a pressure range up to $p = 300$ bar. The methods were published in /11/ and have since been continuously developed and refined.
Since the first publication of ISO 6358 in 1989 /7/, the measurement and documentation of the characteristic values C and b have been established, according to ISO 6358, in the field of pneumatics applications. A new version of the standard took place in 2013 with ISO 6358-1 /8/ and was extended in 2019 in the ISO 6358-2 /12/, with the "discharge test", which is applied when working with valves of large nominal diameters. In addition, ISO 6358-3 /13/ presents methods that can also be used to measure other resistances in pipelines with the aid of C and b and can be, therefore, used to calculate larger systems.

Equation (6) describes the mass flow in classical notation according to citation /14/. The friction losses due to a flow constriction with a coefficient $\alpha < 1$ and the influence of the velocity with the coefficient $\varphi < 1$, were considered.

$$\dot{m} = \alpha\, \varphi\, A_2\, \psi \sqrt{2\, p_1\, \rho_1} \tag{6}$$

The outflow function ψ in Equation (6) describes the dependence on the pressure ratio in the subcritical range, see Equation (7).

$$\psi = \sqrt{\frac{\kappa}{\kappa-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}}\right]} \tag{7}$$

On the other hand, in the supercritical flow range, the outflow function depends solely on the isentropic exponent κ, i.e. on the thermodynamic properties of the fluid and the pressure ratio. This function is obtained by calculating the maximum of the outflow function from equations (7) and (8), see /11/.

$$\psi_{max} = \sqrt{\frac{\kappa}{\kappa+1}}\left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \tag{8}$$

The critical pressure ratio b is also no longer a constant. This depends on the isentropic exponent, see Equation 9, and Citation /11/.

$$b = \left(\frac{2}{\kappa+1}\right)^{\frac{k}{\kappa-1}} \tag{9}$$

The maximum flow rate must be considered. Here, ψ_{max} as described in Equation (8) must be used instead of ψ featured in Equation (6), Equation (10).

$$\dot{m} = \alpha\,\varphi\,A_2\,\psi_{max}\sqrt{2\,p_1\,\rho_1} \quad (10)$$

We can now convert a mass flow of air into the mass flow of another gas, such as hydrogen. To do so, we use Equation (10) as the theoretical mass flow and calculate it for air and H_2 as a real gas.

$$\dot{m}_L = A \cdot \sqrt{2 \cdot p_1 \cdot \varrho_{1Luft}} \cdot \psi_{max,L} \quad (11)$$

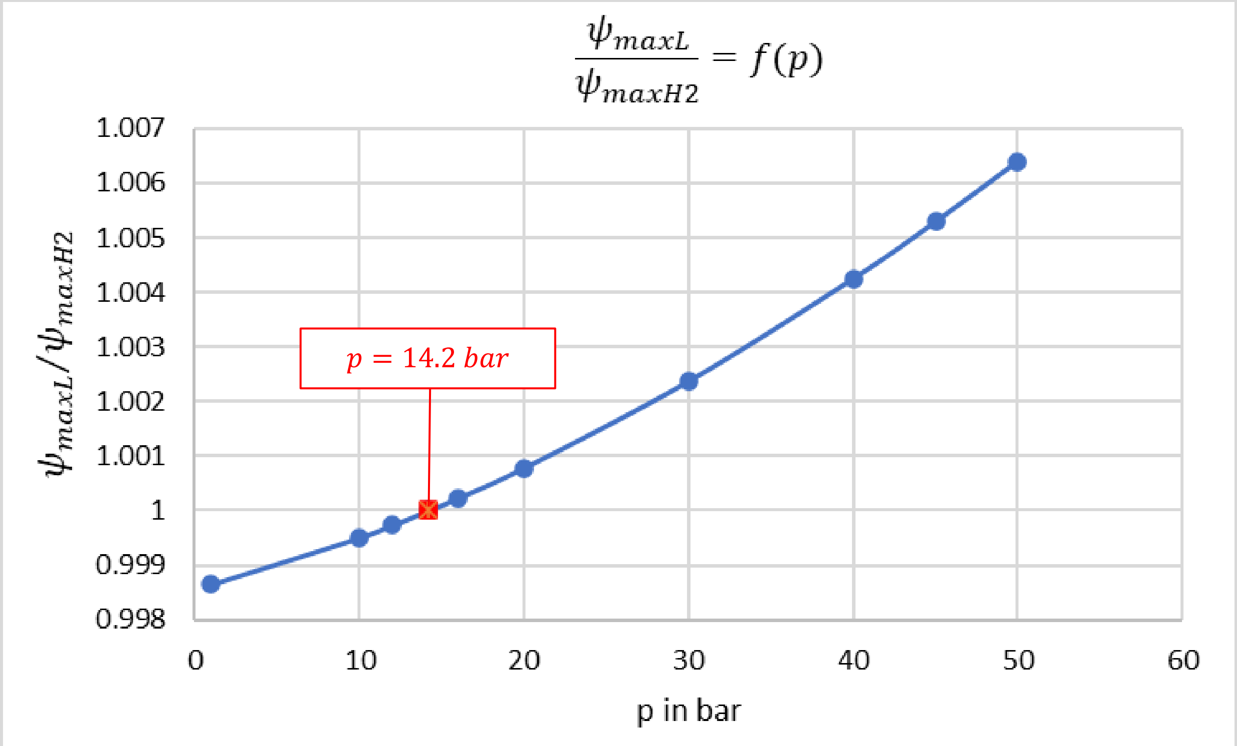
$$\dot{m}_{H2} = A \cdot \sqrt{2 \cdot p_1 \cdot \varrho_{1H2}} \cdot \psi_{max,H2} \quad (12)$$

Now we form the ratio $\dot{m}_L / \dot{m}_{H2}$

$$\frac{\dot{m}_L}{\dot{m}_{H2}} = \frac{\sqrt{\varrho_{1L}}}{\sqrt{\varrho_{1H2}}} \cdot \frac{\psi_{max,L}}{\psi_{max,H2}} \quad (13)$$

A comparison of $\frac{\psi_{max,L}}{\psi_{max,H2}}$ with real gas data leads to the following result: the ration equals 1 at a pressure of $p = 14.2\ bar$, see **Figure 8**.

08 Progression of the ratio of the maximum outflow function of air and hydrogen at $T = 20°C$, /15/



At a pressure of $p_1 = 14.2$ bar, the mass flow $\dot{m}$ and consequently also the conductance C_{H_2} depends solely on the square root ratio of the two densities, see Eq. (14).

$$C_{H_2} = C_L \cdot \sqrt{\frac{\varrho_{1L}}{\varrho_{1H2}}} \qquad \text{for } p_1 = 14.2\ bar \text{ and } T = 20°C \qquad (14)$$

$$\sqrt{\frac{\varrho_{1L}}{\varrho_{1H2}}} = 3.786 \qquad \text{for } p_1 = 1 \text{ bar and } T = 20°C \qquad (15)$$

In Equation (15) the reference density was used at $T_0 = 20°\text{C}$ and $p_0 = 1$ bar for Hydrogen H_2 with $\varrho_{H2} = 0.08266 \frac{kg}{m^3}$ and $\varrho_L = \varrho_0 = 1.185 \frac{kg}{m^3}$ (air at standard conditions, $T_0 = 20°\text{C}$, $p_0 = 1$ bar, 65% relative humidity). For the square root of the densities ratio according to Eq. (14), which is determined at a pressure of $p_1 = 14.2$ bar and a temperature of $T = 20°C$ for dry air and hydrogen H_2, a deviation of 0.76 % from the value in Eq. (15) is obtained. This deviation can be neglected. In the following, the value from Eq. (15) is used. The mass flow rate Air in the supercritical range has an almost linear pressure dependence up to a pressure of $p = 14.2$ bar and can be easily determined.

Example 1

A mass flow of air in the supercritical range at a pressure of $p_1 = 14.2$ bar and a temperature of $T_1 = 20°C$ is given with

$\dot{m}_L = 56.12\ g/s$ mass flow of air

Eq. (4) converted to C gives Eq. (16)

$$C = \frac{\dot{m}}{p_1 \cdot \varrho_0} \sqrt{\frac{T_1}{T_0}} \qquad (16)$$

$$C_L = \frac{56.12\ g/s}{14.2 \cdot 10^5 N/m^2 \cdot 1.185 kg/m^3} = 3.335 \cdot 10^{-8} \frac{m^4 \cdot s}{kg}$$

Using Eq. (15), the following calculation for hydrogen can now be made:

$$C_{H_2} = 3.786 \cdot 3.335 \cdot 10^{-8} \frac{m^4 \cdot s}{kg} = 1.2637 \cdot 10^{-7} \frac{m^4 \cdot s}{kg}$$

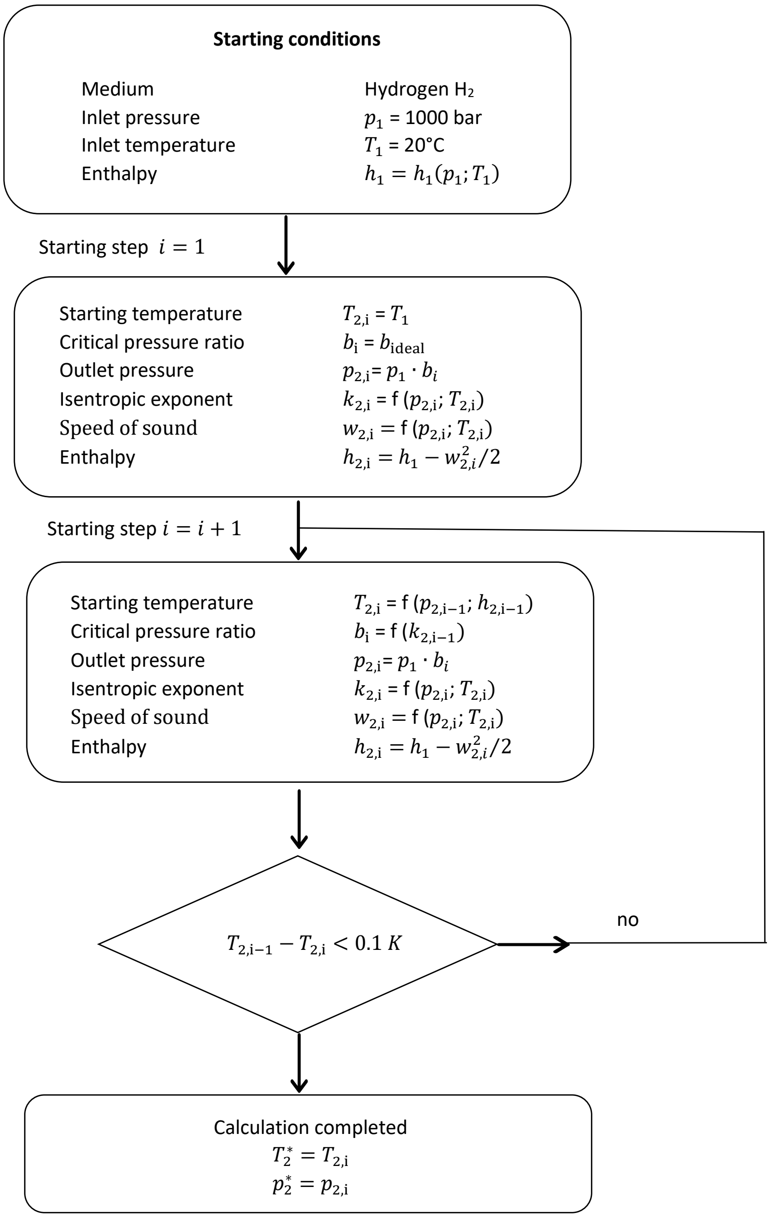
The critical conductance for hydrogen at $p_1 = 14.2$ bar is 3.786 times higher than that for air. The task now is to determine this conductance C for different pressures. To do this, we use the state variables in the narrowest cross-section, i.e. in the state in which the speed of sound is given. These can be determined with an iterative calculation, see flow chart **Figure 09**. Ideal gas was assumed for the starting point, so that there is an isentropic change of state at the beginning, /11/. We use the Kretzschmar /15/ substance database, since when using the database from NIST /17/, the isentropic exponent κ could not be extracted. This value can be calculated for real gases using Eq. (17), see /16/. The frequently used ratio of the specific heat capacities

$k = \frac{c_p}{c_v}$ only applies to ideal gases.

$$k = \frac{w_{schall}^2}{p \cdot v} \tag{17}$$

The goal of the iteration is to determine the actual pressure p_2^* and the actual temperature T_2^* in the narrowest cross-section. Starting with the "ideal" critical pressure ratio, p_2^* which can be calculated iteratively. With the corresponding data of the real gas, a new critical pressure ratio can be calculated for the next iteration step. As a result, this method leads to a lower pressure in the narrowest cross-section. The enthalpy and pressure can be used to determine the temperature of hydrogen as a real gas. With pressure and temperature, the density of hydrogen as a real gas in the narrowest cross-section is also known, see flow diagram for iterative calculation in **Figure 9**.

09 Flow chart for iterative calculation of the state variables in the narrowest cross-section



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The flow simulation has shown that the local speed of sound can also occur after the narrowest cross-section.

The density of hydrogen, in the narrowest cross-section, can now be calculated as a real gas using the substance database and as an ideal gas with the pressure p_2^* and temperature T_2^* using Equation (18), **Table 02**.

$$\varrho_2^* = \frac{p_2^*}{R_{H2} \cdot T_2^*} \qquad \text{Density in the narrowest cross-section – } H_2 \text{ as an ideal gas} \qquad (18)$$

Table 02 State variables of H_2 in the narrowest cross-section			
In the narrowest cross-section	State variables	Density H_2 real gas /15/	Density H_2 ideal gas, Eq. (18)
Pressure p_2^*	$p_2^* = 442.8$ bar	$\varrho_2^* = 34.10\ kg/m^3$	$\varrho_{2ideal}^* = 46.00\ kg/m^3$
Temperature T_2^*	$T_2^* = -39.7°C$		

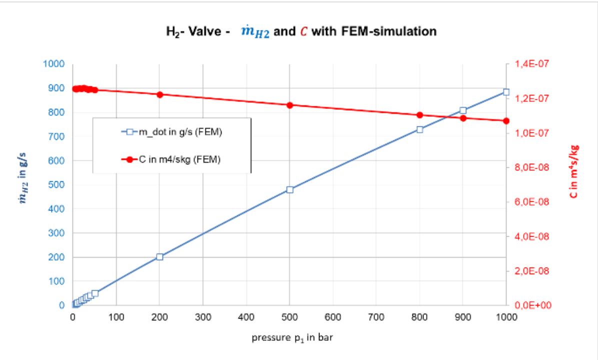
$$C_{H_2}(p = 1000\ bar) = C_{H_2}(p = 14.2\ \text{bar}) \cdot \sqrt{\frac{\varrho_{2real}^*}{\varrho_{2ideal}^*}}$$

Determining the density ratio leads to the following correction:

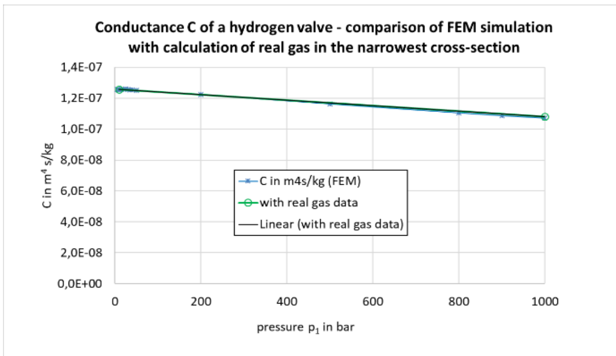
$$\sqrt{\frac{\varrho_{2real}^*}{\varrho_{2ideal}^*}} = 0.86$$

$$C_{H_2}(1000\ bar) = 1.086782 \cdot 10^{-7} \frac{m^4 \cdot s}{kg}$$

10 Conductance C and mass flow – H_2 valve up to 1000 bar, FEM simulation with ANSYS CFX



11 Conductance C – for a H_2- valve as a function of pressure from $p_1 = 1 \ldots 1000$ bar

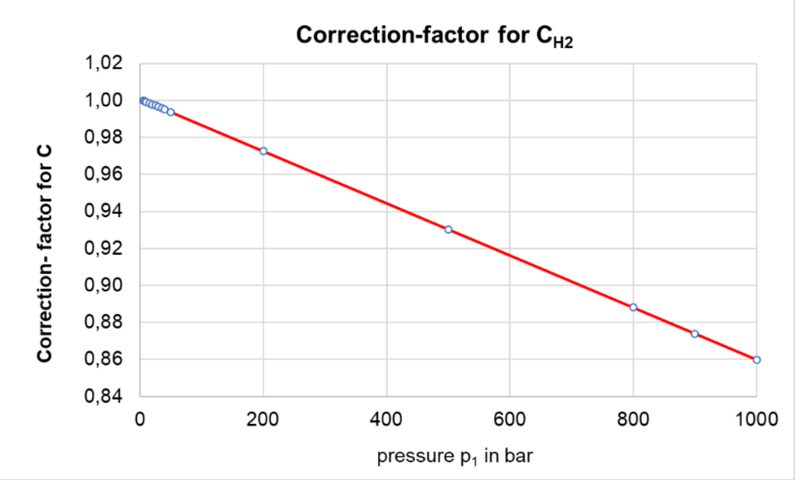


The conductance C_{H2} in the supercritical flow range was determined for a hydrogen valve at various inlet pressures up to a pressure $p_1 = 1000$ bar with the Soave-Redlich-Kwong real gas material law using FEM simulations, **Figures 10 and 11**.

The deviation between simulation and calculation with the square root of the density ratio in the narrowest cross-section is 3.2 % at $p_1 = 1000\,\text{bar}$, **Figure 11**.

As the relationship is almost linear, a correction factor can be used as an approximation, **Figure 12.**

12 Correction-factor for the conductance C_{H2} in the super critical flow range for hydrogen as a function of the inlet pressure p_1



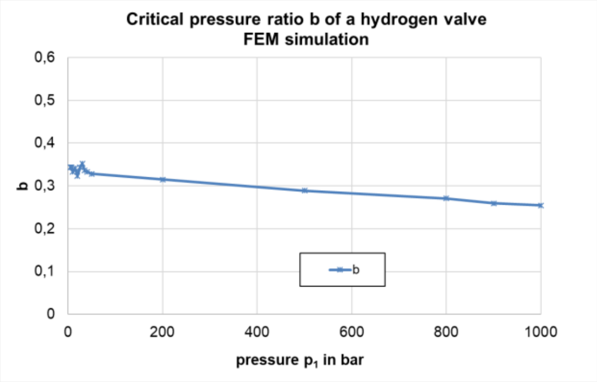
6. The critical pressure ratio in the high-pressure range

The critical pressure ratio was determined experimentally in the low-pressure range, **Figures 6 and 7**. With the help of the real gas data, an approximation can be found for the critical pressure ratio at very high pressure. This can be explained via an example.

The critical pressure ratio b represents the transition from the supercritical flow range to the subcritical range. This parameter of the model includes both the geometric shape of the component and the gas properties. From an experimental perspective, it must be noted that this is a fluid transition and therefore subject to inaccuracy. Deviations in the range of $\Delta b = \pm 0.1$ are possible. However, the influence on the characteristic curve is significantly smaller in contrast to influence of the conductance C. An incorrect conductance C immediately leads to a visible change in the characteristic curve.

At the time of writing, it has not been possible to measure the valve at an inlet pressure of $p_1 = 1000\,\text{bar}$. Hence, we refer to a series of relevant FEM simulations that were carried out at various inlet pressures. Each simulation determined a critical pressure ratio, as shown in **Figure 13**.

13 FEM simulation of an H_2 valve with pressure of $p_1 = 1000\ \text{bar}$



14 Critical pressure ratio b based on the real gas properties of hydrogen

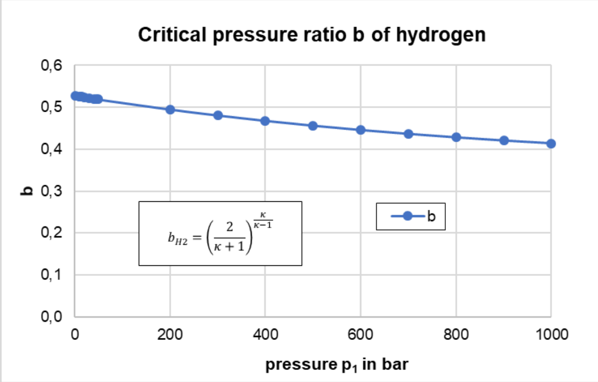


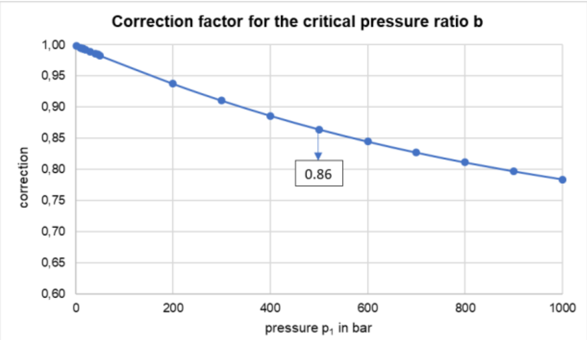
Figure 13 shows a slight scattering of the critical pressure ration for pressure ranging from $p_1 = 0\ \text{bar}$ up to 50 bar. This is due to unstable flow in this pressure range. From $p_1 = 50\ \text{bar}$ to $1000\ \text{bar}$, an almost linear dependency is clearly visible. What could be the explanation for this curve?

To find out, we use the critical pressure curve of the "ideal" b value, which can be determined for hydrogen as a real gas using Equation (9), see **Figure 14**.

A comparison of Figures 13 and 14 shows that the critical pressure ratio for hydrogen, taken as a real gas, without the influence of geometry, Figure 14, has a similar curve to the critical pressure ratio calculated with the aid of FEM, Figure 13. The results of the FEM simulation, Figure 13, are taking into consideration the influence of the geometry of the valve as well as the influence of the real gas. Therefore, an approximation can be made by taking the course of the critical pressure ratio into account with the help of a correction factor, **Figure 15.**

With this correction, the behavior of the real gas is considered depending on the pressure p_1. For a pressure $p_1 = 1000\ \text{bar}$, a maximum deviation of 6.7 % could be determined. This value is acceptable, as a slight shift in the transition between the supercritical and subcritical flow range. This shift has a much smaller effect on the flow characteristics compared to the influence of the critical conductance C. If more precise data are required for C and b in the high-pressure range, iterative determination of the state variables in the narrowest cross-section, **Figure 09**, is recommended.

15 Correction factor for the critical pressure ratio b for H_2 in the pressure range up to 1000 bar



Example 2

$C_L = 5.034 \cdot 10^{-8} \frac{m^4 \cdot s}{kg}$ and $b = 0.294$ for <u>air</u> at $p_1 = 7.5 \text{ bar (abs.)}$ and $T = 20°C$

The question is about the maximum mass flow rate with <u>hydrogen</u> H_2 at $p_1 = 500 \text{ bar}$ and $T_1 = 20°C$.

Equations (15) provides the C_{H2} value for hydrogen at $p = 14.2 \text{ bar}$:

$$C_{H_2} = C_L \cdot 3.786 = 1.906 \cdot 10^{-7} \frac{m^4 \cdot s}{kg}$$

In the next step, the correction for the pressure of $p_1 = 500\ bar$ is determined using the state variables in the narrowest cross-section, Table 03, according to flow diagram from Figure 09.

Table 03 State variables of H_2 in the narrowest cross-section			
In the narrowest cross-section		H_2 real gas	H_2 ideal gas
Pressure p_2^*	$p_2^* = 238.5 \text{ bar}$	$\varrho_2^* = 20.73\ kg/m^3$	$\varrho_{2ideal}^* = 24.39\ kg/m^3$
Temperature T_2^*	$T_2^* = -36.1°C$		

$$\sqrt{\frac{\varrho_{2real}^*}{\varrho_{2ideal}^*}} = 0.92$$

This could also be obtained with the approximation of the correction value of 0.93, taken in **Figure 12**.

$$C_{H_2}(500bar) = C_L \cdot 0.93 = 0.93 \cdot 1.906 \cdot 10^{-7} \cdot 10^{-7} \frac{m^4 \cdot s}{kg}$$

The following approximation can be used for the critical pressure ratio b, **Figure 15**.

$$b = 0.86 \cdot 0.294 = 0.253$$

The supercritical mass flow is calculated according to equation (4) as follows

$$\dot{m}_{H2} = 732.6 \frac{g}{s}$$

where the temperature correction is omitted. For the density we use

$$\varrho_{H2} = 0.08266 \frac{kg}{m^3}.$$

For subcritical flow conditions, the corresponding mass flow is obtained with Eq. (5), depending on the respective pressure ratio p_2/p_1.

7. Comparison of the C, b - model and K_V value

An advantage of the C, b model is that it can reproduce the desired mass flow characteristic of a valve as a function of the pressure ratio over the entire operating range. This understanding of mass flow is particularly important for practical hydrogen applications, such as in the design of Hydrogen Refueling Stations. On the other hand, a K_V value does not offer this advantage. Moreover, this inevitably leads to a volumetric flow, which must then be converted into a mass flow using the density. Calculating mass flow using the K_V value can lead to a deviation of up to 15%, which is a higher deviation than what is obtain with the C, b - model.

8. Summary

This study demonstrated the path from the K_V value to the C, b - model for gases in the high-pressure range. The following table offers a comparison of select advantages and disadvantages of both model approaches.

Table 04 Advantages and Disadvantages of the C, b - model and K_V value

Disadvantage / Advantage	K_V value	C, b - model
Airflow rate	Describes volumetric flow rate	Describes mass flow
Air characteristic curve	Critical pressure ratio, usually assumed to be a constant with b = 0.5, which severely limits validity	Valid for all possible valve designs; b is determined experimentally in the low-pressure range
Transferability of gasses at low pressure	VDI/VDE 2173 /4/ is possible, but overly complicated	Simple to apply
Transferability to high-pressure range	Only selectively possible with equations according to /4/	With real gas data for the entire curve range
Pressure drop across the valve	Not possible according to VDI/VDE 2173 /4/, as characteristic curves are displayed via the ratio of the valve lift	Can be easily determined using the characteristic curve. $\Delta p = p_1(1 - p_2/p_1)$

9. Outlook

Following this study on mass flow of gaseous hydrogen through valves up to a pressure of 1000 bar, the results were determined exclusively using FEM simulations with ANSYS CFX. Further development is expected on this topic in the future. Thus, experimental data in the high-pressure range should complement and complete the results presented here.

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11. Symbol key

A	[m²]	Cross-sectional area
b	[-]	Critical pressure ratio
C	[s·m⁴/kg], [Nl/s·bar]	Conductance in the supercritical range according to ISO 6358
C_e	[s·m⁴/kg], [Nl/s·bar]	Conductance through a component (valve, throttle, etc.)
C_V	[US gallon/minute]	Flow Coefficient C_V (US)
c_p	[kJ/kg·K]	Specific heat capacity at constant pressure
c_v	[kJ/kg·K]	Specific heat capacity at constant volume
h	[kJ/kg]	Specific enthalpy
K_V	[m³/h]	Flow coefficient (K_V value)
k	[-]	Isentropic exponent of the fluid
$\dot{m}$	[kg/s], [kg/h]	Mass flow
p	[Pa], [bar]	Pressure
Δp	[Pa], [bar]	Differential pressure
R	[J/kg·K]	Gas constant
T	[K], [°C]	Temperature
v	[m³/kg]	Specific volume
w	[m/s]	Speed
ψ	[-]	Outflow function
Q	[m³/h]	Volumetric flow rate
ϱ	[kg/m³]	Density
α	[-]	Beam contraction number
β	[-]	Flow coefficient
φ	[-]	Speed characteristic number

12. Indices

0	Standard conditions for air according to ISO 6358: $T_0 = 293.15\text{ K}; p_0 = 1\ bar; \varrho_0 = 1.185\frac{kg}{m^3}; R = 288\frac{J}{kg \cdot K}$; relative humidity 65%
1	Status before the throttling element
2	Status after the throttling element
$abs.$	Absolute (pressure)
$*$	Supercritical flow conditions ($w = w_{Schall}$ and $p_2/p_1 \leq b$)
max	Maximum value
L	German: Luft (Air)
N	Standard condition according to DIN 1343 (p = 760 Torr = 1.01325 bar; T = 273.15 K)
H_2	Gaseous hydrogen (normal hydrogen in the single-phase region)
w	Water
v	Loss (pressure loss)
i	Iteration step
$ideal$	ideal (calculated as ideal gas)
$krit$	German: kritisch (Critical)
$real$	real (calculated as real gas)
$Schall$	German: Schall (Speed of sound)