Gas Flow at Very High Pressure and Speeds

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Abstract: This article was created on the basis of long-term practical experience with the flow of compressed gases in pipelines and fittings. In areas of low pressures, up to about 0.4 MPa, the physical phenomena regarding the outflow of gas from pressure systems are relatively consistent with theoretical calculations. The higher the pressure in the pressure reservoir system (most often a container or a bundle of pressure cylinders), the greater the difference between the theoretical calculation and the actual behavior of the discharged gas. The data for this article are based on the calculation of the flow of compressed natural gas during uncontrolled discharge from a pressure container with a volume of 2 500 m3 and a pressure of 30 MPa.

Keywords: Container; compressed gas; cylinder; pressure; flow.

1.Introduction

In the case of uncontrolled outflow of gas from pressure systems at high pressures, the critical outflow rate is first reached immediately, as long as the pressure in the mouth of the system drops below the critical limit. Subsequently, all relevant parameters begin to change over time, the flow rate, pressure and volume flow decrease. At the same time, the temperature, density, kinematic viscosity and pressure losses in the valves also change. The whole task is extremely non-stationary. During individual iterations of theoretical calculations (compared to practical experiments), it was found that both the outflow and velocity coefficients must be regression-based backwards at gas outflows at such high pressures, and that they have an inverse functional course before changing speed and pressure [1, 2].

2. Gas discharge at high speeds

When gas flows at high velocities, a change in density with pressure must be considered. This is because each gas has its critical limitations, given the configuration of the elementary particles in its molecule. The mass flow of the gas is then converted to a volume flow [1, 2].

$$Q_\mathrm{M} = S.w.\rho \quad \left(kg{\cdot}s^{-1} \right) \tag{1}$$

Where: Q_M is mass flow (kg·s⁻¹), S - the outflow area through which the medium passes (m²), w - flow rate (m·s⁻¹), ρ - density (kg·m⁻³).

Now we convert the mass flow into a volume flow (Qv) by dividing the density (ρ):

$$Q_\mathrm{V} = \frac{Q_\mathrm{M}}{\rho} \quad \left(m^3{\cdot}s^{-1} \right) \tag{2}$$

The critical speed we then determine from the relationship:

$$w = \sqrt{\frac{2.k}{k-1}.r.T\left[1-\left(\frac{p_{kr}}{p} \right)^{\frac{k-1}{k}} \right]} \quad \left(m{\cdot}s^{-1} \right) \tag{3}$$

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Where: k is adiabatic coefficient (1), r - specific gas constant (J·kg^{-1}·K^{-1}), T - gas thermodynamic temperature (K), p - pressure (Pa), p_{kr} - critical pressure (Pa).

The critical pressure is calculated using the relation:

$$p_{kr} = p \cdot \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \quad (Pa) \tag{4}$$

And critical density like:

$$\rho_{kr} = \rho_1 \cdot \left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \quad (kg \cdot m^{-3}) \tag{5}$$

The following values are based on the previous relations [1, 2] for the system examined above:

The critical pressure: 15,85 MPa

The critical density: 132,07 kg·m^{-3}

The above computational methodology was taken from the literature [1, 2].

3. Flow changes at high speeds

Based on these critical values, it was possible to analytically calculate the change in flow rate over time and predict the decrease in pressure, change in density and other dependent variables. The change in volume with temperature is also included in the calculation [3].

3.1 Experimental verification

To support the following calculations, an experiment was performed to discharge a bundle of cylinders into space. Compressed nitrogen was used as the experimental technical gas, the compressibility factor of which is 0.95 close to natural gas [6]. Before the actual experimental measurement, about 30 MPa was read on the main pressure gauge of the whole system (see the left pressure gauge in Fig. 1). At the beginning of the discharge, the critical pressure at the outlet of approx. 15 MPa would be read, which gives a critical velocity of approx. 400 m.s^{-1} at the decisive cross-section of the outlet pipe (in the first seconds after opening).

During the subsequent verification of the calculation, the change of the Speed coefficient (SC) and the Discharge coefficient (DC), depending on the flow rate, was regression-calculated so that the total gas outflow time corresponded to the actual values.

The following table (1) shows the results of the calculations.
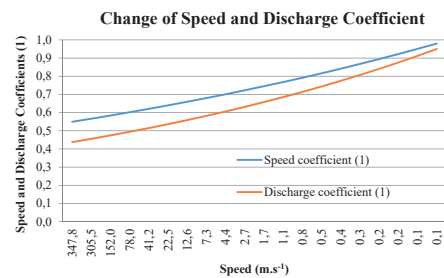

Figure 1: Pressure gauge at the outlet.

Figure 2: Change of Speed and Discharge Coefficient.

Table 1: Analytical calculation of flow change over time

Time (min)	Pressure (Pa)	Density (kg.m^{-3})	Speed (m.s^{-1})	Volume flow (m^3.s^{-1})
0	30 000 000	132,07	347,85	1020,95
5	21 600 000	132,07	305,53	934,11
10	15 472 629	99,71	152,00	365,48
15	11 488 103	75,28	77,96	147,42
20	8 625 468	56,84	41,22	61,30
25	6 499 510	42,91	22,47	26,28
30	4 903 543	32,40	12,63	11,61
35	3 701 100	24,46	7,31	5,29
40	2 793 988	18,47	4,37	2,49
45	2 109 345	13,94	2,69	1,20
50	1 592 514	10,53	1,71	0,60
55	1 202 333	7,95	1,12	0,31
60	907 755	6,00	0,75	0,16
65	685 352	4,53	0,52	0,09
70	517 440	3,42	0,38	0,05
75	390 666	2,58	0,28	0,03
80	294 953	1,95	0,21	0,02
85	222 689	1,47	0,17	0,01
90	168 130	1,11	0,13	0,01

It is clear from the process of changing the volume flow that after only five minutes almost 40 % of the gas flows out and after ten minutes about 75 % of the volume of the entire container escapes.

The above analytical calculations are based on an experiment for a specific type of pressure container, taking into account the above-mentioned boundary conditions. With any change in pressure and outlet dimensions, the coefficient values will be

different [4].

The graph in Figure 3 shows the pressure drop over time with the gradual uncontrolled discharge of gas from the entire system. The pressure drop was calculated by regressing from the critical pressure value from the moment of discharge to atmospheric pressure [5].
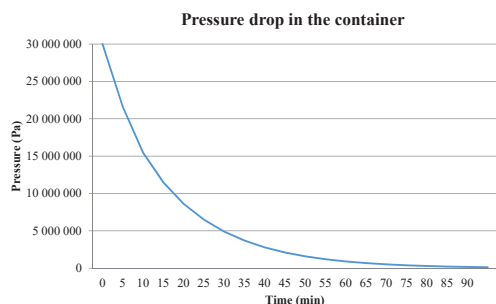
Pressure drop in the container

Figure 3: Graph of pressure drop.

The following graph in Figure 4 shows the plot of the decrease in speed over time with the gradual discharge of gas from the entire system.
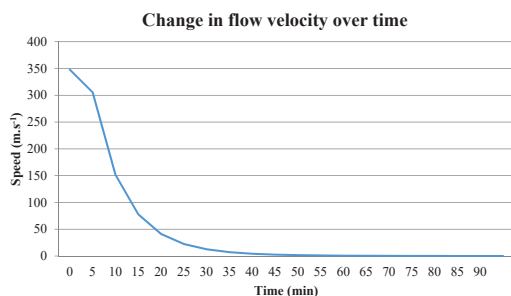
Change in flow velocity over time

Figure 4: Speed drop graph.
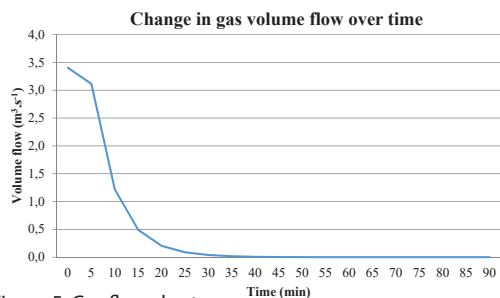
Change in gas volume flow over time

Figure 5: Gas flow chart.

3.2 Gas flow in time

Theoretical flow characteristics of the gas volume flow (as in all previous calculations) are reduced in technical practice by empirical coefficients. In the graph of Figure 2, these coefficients were related to the flow rate, which best corresponds to technical practice, and were used to recalculate the volume flow.

The graph in Figure 5 shows the decrease in volume flow over time with the gradual uncontrolled discharge of gas from the entire pressure system.

4. Conclusion

In conclusion, it must be stated that for each specific case, it is necessary to perform an experiment that specifies the change in the velocity and flow coefficients with respect to the diameter and shape of the outlet. Based on previous calculations, further experiments will be performed under different conditions.

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