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PRESSURE DROP ANALYSIS IN SOLENOID-TYPE VALVES: DISCREPANCIES BETWEEN EXPERIMENTAL RESULTS AND MANUFACTURER DATA

Emanuel Alexander MORENO ALDANA[1], Maurício NOGUEIRA FROTA[1,*]

[1]Postgraduate Metrology Programme, Metrology for Quality and Innovation
Pontifical Catholic University of Rio de Janeiro/Brazil
*Corresponding author: mfrota@puc-rio.br

Abstract: *This paper investigates the actual performance of a solenoid valve in comparison to the technical specifications provided by the manufacturer. If the manufacturer's data is found to be unreliable, it may result in significant miscalculations in the specifications for other critical components used in industrial equipment design, such as hydraulic pumps and specialized built-in control instrumentation. Experimental results measuring pressure drops across the valve at various flow rates revealed a substantial discrepancy—over 100%—compared to the manufacturer's information. After repeating and validating the experimental data, the unusual behaviour of the valve was attributed to undesirable deformation of the polymer diaphragm. These findings emphasize the limitations and design flaws that could negatively impact the valve's performance in its intended industrial applications.*

Keywords: *Solenoid valve; Control valve flow coefficient; Metrology; Pressure drop; Technical specifications verification.*

1. INTRODUCTION

A literature survey [1], [2], [3], [4], has confirmed that while studies evaluate the technical specifications of valves and identified a recent update to an international standard guiding appropriate tests [5], [6], only a limited number of studies focus on the reliability of the technical requirements provided by manufacturers.

Recently, Zhong Li et al. [7] proposed an alternative methodology for calculating the flow coefficient, ensuring that the maximum error does not exceed 10 % according to industrial standards. Cheng et al. [8] investigated the factors affecting the discharge coefficient of natural gas control ball valves, emphasizing the importance of determining the actual value of this coefficient for optimization and intelligent control processes. Additionally, Xun Sun et al. [9] conducted a numerical study on the impact of friction on the flow coefficient of a triple eccentric butterfly valve at various opening degrees, revealing discrepancies of up to 17 % between the flow coefficients obtained from their numerical simulations.

Unlike the information provided by manufacturers (https access in 2025), which lacks experimental support, this study aimed to investigate a 2-inch diameter, normally closed (NC), servo-piloted solenoid control valve featuring a polymer diaphragm with a K_v = 48 m³/h flow coefficient. This valve underwent rigorous and systematic experimental evaluation while keeping the manufacturer's confidentiality. Mainly, it aims to improve the understanding of effective alternatives for reducing pressure losses in control valves while seeking to protect users and designers of industrial equipment from the often-unreliable technical information that is frequently advertised.

2. VALVE FLOW COEFFICIENT DERIVED FROM THE BERNOULLI EQUATION

The existing theory for calculating the K_v flow coefficient of control valves is based on the Bernoulli equation, grounded in the principle of conservation of pressure (P_1/γ), kinetic ($v_2^2/2g$) and potential energy (z). This principle is evaluated at two points along a particular streamline and governed by a modified version of the Bernoulli Equation, given in Equation (1):

$$\left(\frac{P_1}{\gamma} + z_1 + \frac{v_1^2}{2g}\right) - \left(\frac{P_2}{\gamma} + z_2 + \frac{v_2^2}{2g}\right) = h_L \quad (1)$$

However, when examining the flow of water through a horizontally positioned solenoid valve installed between two segments of a tube with a constant diameter, as illustrated in Figure 1, one must correct the Bernoulli equation to account for the localized pressure loss term h_L. This inclusion updates for the deviations from ideal flow conditions yielded by the presence of the valve, which unsettles the flow being studied, as given in Equation (2):

$$\frac{P_1}{\gamma} - \frac{P_2}{\gamma} = h_L \quad (2)$$

By invoking the Darcy-Weisbach Equation to relate the pressure loss h_L to the square of the fluid velocity and to a dimensionless resistance coefficient K_L, Equation (3) can be rewritten as:

$$\frac{\Delta P}{\rho} = K_L \frac{V^2}{2} \quad (3)$$

where $\Delta P = (P_2 - P_1)$; ρ, the specific mass of the fluid; g, the acceleration due to gravity, and $\gamma = \rho g$, the specific weight of the fluid flowing through the valve. This equation can be once again be rewritten in terms of the volumetric flow rate ($Q = v.A$), where A is the cross-sectional area of the flow upstream and downstream of the valve, yielding:

$$\Delta P = \rho\, K_L \frac{Q^2}{2A^2} \quad (4)$$

Finally, by expressing the relative density of the fluid $SG = \rho/\rho_o$ in terms of the specific mass of the fluid (ρ_o stated at a reference temperature), the volumetric flow rate can be expressed as a function of the pressure drop ΔP and of the coefficient K_L, or, alternately, in terms of the valve flow coefficient K_v:

$$Q = \sqrt{\frac{2A^2}{\rho_0\, K_L}} \sqrt{\frac{\Delta P}{SG}} = K_v \sqrt{\frac{\Delta P}{SG}} \quad (5)$$

Rewriting Equation (5), we can thus recover the definition of the valve flow coefficient K_v in industry terms; i.e., the valve flow coefficient K_v can be expressed by the volumetric flow rate (Q, in m^3/h) that induces a pressure loss of ΔP = 1 bar, given by Equation (6):

$$K_v = Q(\frac{m^3}{h}) \sqrt{\frac{SG(=1)}{\Delta P(=1\ bar)}} \quad (6)$$

This equation helps understand why the valve flow coefficient, K_v, is defined in industry terms as the volumetric flow rate, Q (in m^3/h), resulting in a pressure loss of ΔP = 1 bar. While this definition has its limitations, it remains practical. Notably, when considering the density of water (with a specific gravity of 1.0 at a reference temperature of 25 °C), the general equation for K_v can be simplified. In other words, for a particular flow rate that produces a pressure loss of 1 bar, the value of K_v numerically matches the volumetric flow rate, Q (in m^3/h), through the valve.

Although industry professionals commonly report the valve flow coefficient K_v in terms of volumetric flow rate (m^3/h), it is essential to notice that its proper SI unit is (m^3·h^{-1}·bar$^{-0.5}$).

3. EXPERIMENTAL SETUP AND PROCEDURES

Figure 1 depicts the experimental setup used to evaluate the flow coefficient of the 2-inch diameter solenoid valve assessed during laboratory testing installed between two segments of an internal smooth tube of the same diameter. The setup included two independent pressure measurement systems to determine the pressure drop (ΔP) caused by the valve during the flow.

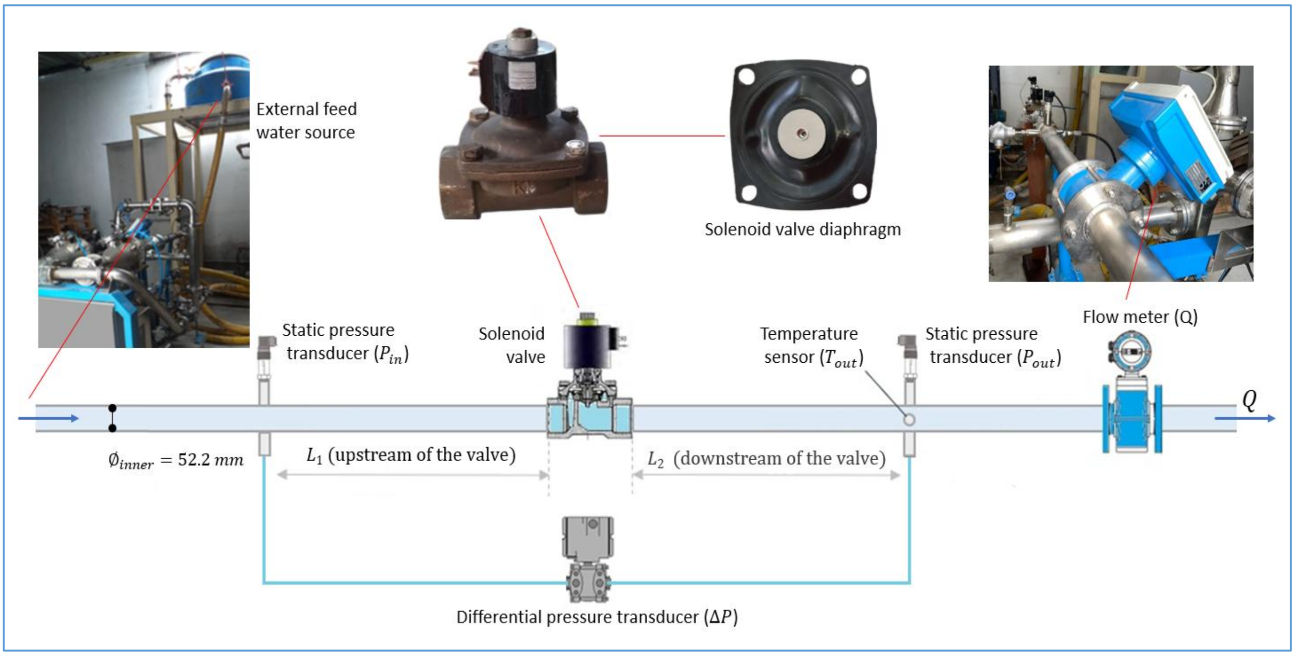

Figure 1. Experimental setup used to test the solenoid valve

These systems comprised two static pressure transmitters (Wika, Model S-11, Resolution 0.01 bar), positioned at L_1 (upstream) and L_2 (downstream) of the valve, as well as an independent differential pressure gauge (Novus, Model NP860-HRT-8, Resolution 0.01 bar) for direct measurement of the pressure drop. Although both pressure-drop measuring systems yielded results that agreed within 0.5 %, the measurements from the differential pressure gauge were preferred because they had a lower uncertainty budget of ±0.1 bar.

As shown above, a hydraulic pump (KSB, Model 065-040-200, 20 CV), which draws water from a 1000-liter reservoir positioned two meters above the pump's entrance, was coupled with a frequency inverter (Mitsubishi, Model FR-D720-15K) to experimentally evaluate a normally closed type (NC) solenoid valve's flow coefficient at variable flow rates, measured by a magnetic type flow meter (Endress Hauser; Model Promag D 400 2", Resolution: 0.001 m^3/h).

The water temperature was monitored through a Pt-100 type temperature sensor installed at the valve outlet (Salvi Casagrande, Model TR315, Resolution: 0.1 °C). In this preliminary setup, the water circulated in a closed circuit between the valve and the reservoir, leading to a temperature variation that ranged from 22 °C to 37 °C as the test progressed. This undesirable temperature effect will be briefly discussed below.

The measuring instruments used were duly calibrated based on the t-student statistical distribution corresponding to the value k = 2.0 (infinite degrees of freedom) for a confidence level of 95 %, whose procedures are discussed in Moreno-Aldana [10].

The calculated expanded uncertainties are reported in Table 1, in compliance with the international consensus calibration procedure ISO-GUM [11].

In compliance with the applicable international standards (IEC 60534 part 2-3:2015 [5] and 2-1:2015) [6], several key factors were considered during the experimental setup, some of which are highlighted below:

- the correct placement of upstream and downstream pressure taps;
- ensuring that the inside diameter (ID) of the pipes at both the inlet and outlet of the tested valve is within ±2 % of the actual diameter;
- the use of new smooth-type PVC tubes to guarantee frictionless flow condition at the short-connected tubes; and

- freshwater as the working fluid, ensuring it is free from significant amounts of suspended solids and dissolved salts.

Table 1. Expanded uncertainties associated with the used measuring instruments

Instrument	Physical Quantity	Expanded uncertainty [U]
Static pressure [Wika, Model S-11]	P_{in} (bar)	$U(P_{in}) = 0.015\ bar$
Static pressure [Wika, Model S-11]	P_{out} (bar)	$U(P_{out}) = 0.015\ bar$
Differential pressure gauge [Novus, Model NP860-HRT-8]	ΔP(bar)	$U(\Delta P) = 0.012\ bar$
Magnetic type flow meter [Endress Hauser; Model Promag D 400 2"]	Q (m³/h)	$U(Q) = 0.063\ m^3/h$
Pt-100 Thermoresistances, Temperature Sensor (100 mm rod) [Salvi Casagrande, Serie TR315]	T_{out} (°C)	$U(T_{out}) = 0.2\ °C$

In contrast to a more fundamental approach discussed later in this paper, which is based on the modified Bernoulli equation (the energy equation along a flow streamline), it is essential to consider the practical significance of the valve flow coefficient, K_v, as it is defined in industrial terms. In industry, K_v is defined as the volumetric flow rate, Q (measured in m³/h), that results in a pressure loss of ΔP = 1 bar. While this definition has its limitations, it remains practical. In other words, for a given flow rate that produces a pressure loss of 1 bar, the value of K_v numerically matches the volumetric flow rate, Q (in m³/h), through the solenoid valve.

3.1. FIRST ROUND OF EXPERIMENTS

Figure 2 summarizes the results from the first round of experiments, where pressure-drop measurement systems (consisting of two static transducers and one differential transducer) were positioned upstream of the valve, at L_1 = 53 mm (1 $\emptyset_{inner}$), and downstream of it, at L_2 = 250 mm (4 $\emptyset_{inner}$). This positioning was in accordance with the recommendations of the international standard IEC 60534-2-3:2015 to ensure proper flow conditioning, which is also referenced in the ASME Performance Test Code PTC 19.5-2004, "Flow Measurement" [12].

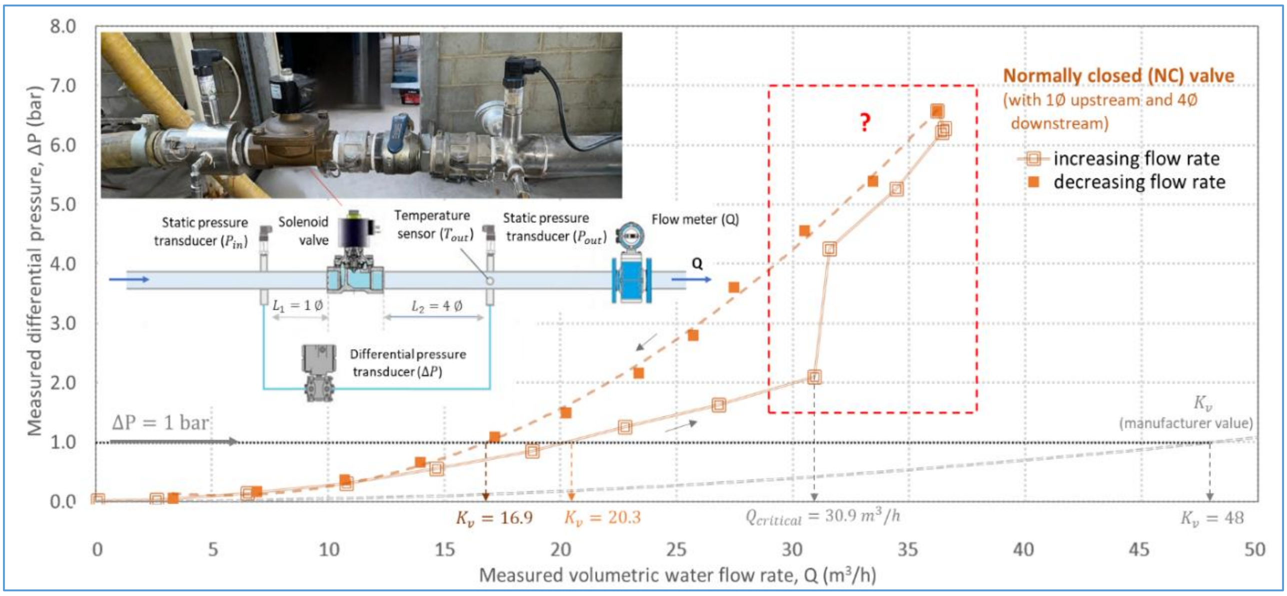

Figure 2. Pressure-drop measurements for increasing and decreasing volumetric flow regimes

The valve tested exhibited a flow coefficient value over 100 % lower than the manufacturer's stated value of K_v = 48 m^3/h. This is significantly different from the experimental value obtained. The experiment results demonstrate that the solenoid valve shows a flow coefficient value of 20.3 m^3/h, for increasing flow rates, achieved through the action of the frequency inverter connected to the hydraulic pump. Unexpectedly, when the differential pressure (ΔP) measured during the increasing flow rate regime reached a critical value $Q_{critical}$ = 30.9 m^3/h —referred to as critical volumetric flow rate by the authors— the ΔP (bar) versus Q (m^3/h) graph displayed a sharp increase. This jump to significantly higher ΔP values occurred as the experiment reached the maximum flow rate due to the limitations of the pump's power (KSB Pump, 20 HP).

3.2. SECOND ROUND OF EXPERIMENTS

Following this experimental test, the experiments were repeated for a decreasing flow regime, starting at approximately 40 m^3/h and continuing until reaching zero flow rate as the hydraulic pump was de-energized, whose results are shown in Figure 3. However, this decreasing flow regime revealed a different flow coefficient value of 20.3 m^3/h.

In summary, the flow coefficient value declared by the manufacturer (K_v = 48 m^3/h) was not only found to be overestimated, which can mislead designers whenever sizing critical components in their projects but also exhibited two distinct values when associated with tests of pressure drop for increasing and decreasing volumetric flow rates.

The above Figure 3 summarizes the results of the repeated tests conducted under the new conditions established. The unusual behaviour was confirmed, with slight differences in the K_v values for both flow regimes. Specifically, both K_v values —associated with the ascending and descending regimes— increased by about 4 %, while the $Q_{critical}$ value increased by 9 %. These changes can be attributed to the temperature variation of the working fluid used in the valve tests (in this case, water), which likely affects the performance of the solenoid valve diaphragm.

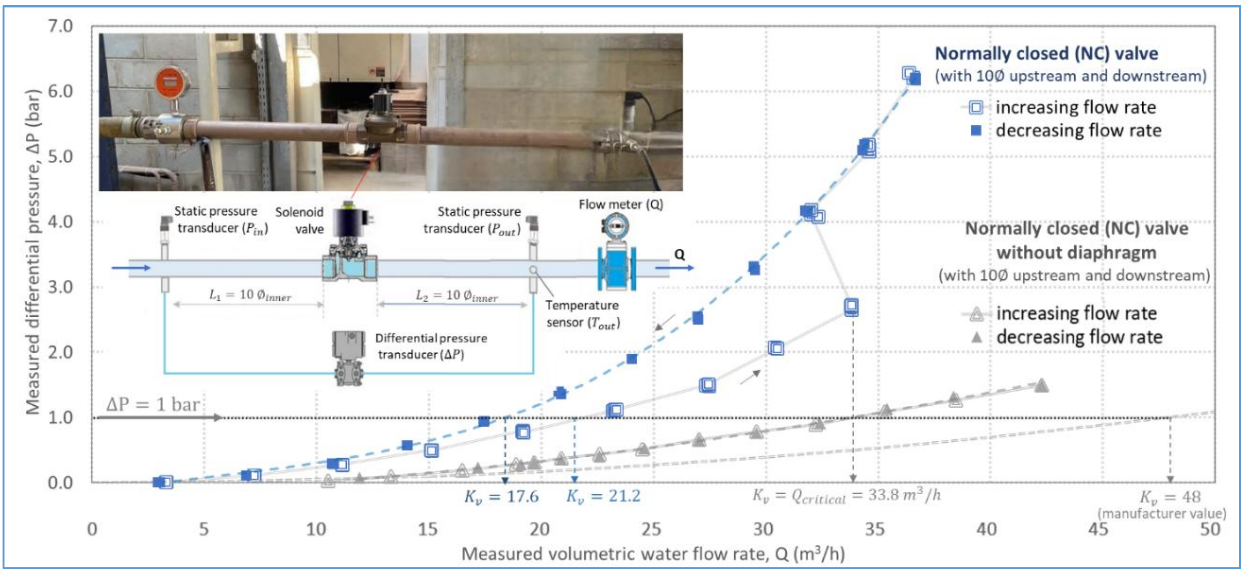

Figure 3. Replication of the pressure-drop experiments for increasing and decreasing flow regimes

4. EXPERIMENTAL RESULTS: DISCUSSION

While the unexpected experimental findings were consistent, it was necessary to identify the source of the strange behaviour revealed by the experimental data. A final, conclusive test was performed to eliminate doubt about the "culprit" in this scenario: the valve's elastomer diaphragm, known for its sensitivity to deformation. This test involved using the same valve specimen but removing the diaphragm, whose function interrupts the flow when the valve's solenoid is activated. The results from this last experimental test, which showed a collapse of the increasing and decreasing flow curves reflecting the valve's performance after the diaphragm was removed, are represented with new symbols in grey triangles in Figure 3. This final test confirms that the deformable valve elastomer diaphragm is the root cause of the unusual behaviours revealed by the experimental study of the solenoid valve flow coefficient.

Additionally, the new round of experiments confirmed two interesting aspects: (i) the K_v value declared by the manufacturers —without any reference to experimental data— is 42 % greater than the experimental value of the valve hypothetically operating without the diaphragm, and (ii) the latter reproduces with fidelity the $Q_{critical}$ value, flow parameter that triggers the discontinuity in the ΔP (bar) versus Q (m^3/h) graph faithfully.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The valve flow coefficient (K_v) is a crucial parameter for every control valve, as it indicates the valve's flow capacity under specific operating conditions. This study emphasizes the importance of the flow coefficient in assessing the valve's performance based on experimental data.

The experimental evaluation challenged the information published by manufacturers of industrial control valves. While manufacturers strive to provide relevant technical specifications, they often discard supporting evidence from experimental studies. Designers and users relying on manufacturers' specifications for industrial equipment and automated valves should recognize that unreliable information can significantly compromise the technical requirements of other components in the engineering project, potentially leading to severe economic consequences.

The study revealed inconsistencies in manufacturers' specifications for flow control valves. The declared flow coefficient values, which lack reference to experimental data, can contain errors exceeding 100 %.

Laboratory experiments uncovered two key findings: (i) the value reported by manufacturers —without any supporting experimental research— was 42 % higher than the actual experimental value of the valve, even when assuming it operates without the diaphragm; and (ii) a flow parameter was identified as a practical criterion for determining a critical value that indicates a discontinuity in the relationship between differential pressure (ΔP) and volumetric flow rate (Q) data used to experimentally evaluate the valve's flow coefficient.

5.2. Recommendations

Additional developments to further advance this study include conducting new tests using different specimens and types of flow control valves operated by various diaphragms. With the easy access to and power of computational tools available today, it is recommended to perform simulations using finite element analysis (FEA) to assess the diaphragm's deformation. Additionally, the pressure drop across the valve should be simulated using experimental data to establish boundary conditions. This approach will enable the simulation of the flow coefficient for automated flow control valves.

Another key aspect for future work is assessing the uncertainty associated with the flow coefficient (K_v) founded on experimental tests. This evaluation will quantify the reliability of the obtained values and provide more accurate information for the design and selection of flow control valves in industrial applications. This approach will contribute to improving engineering decision-making, minimizing errors in the specification of critical components.

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DECLARATION OF COMPETING INTEREST

The authors declare no known competing financial interests or personal connections that could influence the work discussed in this article.

ORCID iDs

Emanuel Alexander MORENO ALDANA
0009-0003-7463-222X
Maurício NOGUEIRA FROTA
0000-0002-5285-5727

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