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METHODOLOGY FOR TESTING FLOW CAPACITY IN SAFETY VALVES OPERATING WITH COMPRESSED AIR AND ATMOSPHERIC BACK PRESSURE

Thiago de Freitas Hülle Sant'Anna
Rogério Ramos
Gabriel da Fontoura Alves
Federal University of Espírito Santo – UFES
Av. Fernando Ferrari, 514, Campos Universitário de Goiabeiras, Vitória ES, CEP 29075-910, Brazil.
thiagofreitash@hotmail.com, ramosrogerio@hotmail.com, gabrielfontoura.nemog@gmail.com

Abstract. *It is presented and evaluated a methodology to define flow capacity of safety valves to relieve compressed air operating at atmospheric back pressure. ASME PTC 25 and ASME UG-131 recommendations are considered as a base lines, in order to validate the methodologies developed. The primary element for flow measurement is an orifice plate, data acquisition and test operations are done through a supervisory control and data acquisition system. First tests are performed on a safety valve calibrated to opening pressure of 6 kgf/cm^2. Readings are analyzed according to the instructions and parameters established in the ASME recommendations. Results and methodologies of the tests are calculated and criticized. All the results obtained fulfill all requirements, except by the oscillation of the mass flow, which shows to be higher than the established limits. Solutions are addressed to surpass such question.*

Keywords: *Safety valve, flow capacity, safety valve performance test.*

1. INTRODUCTION

The use of high pressure processes occurs concomitantly with the evolution of materials and search for more efficient and efficient processes. This subjects the human being to the risk of catastrophic events due to the occurrence of failures in such process technologies. That is the context where act security devices, generally to prevent these events or, at least, to soften them.

Designed to be installed on pressure vessels, safety valves principle is basically based on the compression of a spring exerting a force that obstructs the outlet of a nozzle, connected to the pressure vessel. Upon reaching set point pressure, the static pressure inside the vessel acts on the area of the sealing disc and, if it exceeds the spring force and the weight of the moving components, causes the valve to open and relieve the internal pressure.

Regulation and standardization have become necessary to ensure the performance of safety valves. The subject motivates discussions like design, installation, fabrication and constructive aspects of these safety equipment. The valves mainly have three main operating processes: i) open at set point pressure, ii) discharge all predetermined volume at the permitted overpressure and iii) close at a set pressure range, maintaining the initial seal. Therefore, the main parameters to be tested for valve design are: opening and closing pressure, sealing performance and flow capacity. The first two procedures are usually tested by valve manufacturers. However, the flow capacity is difficult to perform due to the complexity of measurement and the experimental apparatus, since the required fluid volume necessary to reach the pressure set point, is negligible in view of the volume required to correctly test its flow capacity.

There are several studies on safety valves in the literature, but most of the work interests are not associated with flow measurement tests, and can be separated into three major areas:

1 -The components influence, Singh (1982) through mathematical modeling analyzes the effects of different adjusting ring configurations, spring stiffness and trim friction damping, as well as Ortega et al. (2008) which also presents a mathematical model for a control volume inside the nozzle, analyzing the discharge coefficient, the initial spring displacement and the flow-related spring coefficient, but none of these studies present experimental tests.

2 - Phenomena that occur in the valve opening process, such as Hos et al. (2014) comparing a mathematical model with experimental data analyzing instability phenomena such as flutter and chatter, however does not evaluate the methodology for flow measurement that is the main interest for the present work, the great experimental difference is that in the work of Hos et al. (2014) used nitrogen gas that fed the system through a sonic nozzle, thus allowing a constant flow.

3 - Fluid-mechanical valve modeling, such as Scuro et al. (2018) which presents a CFD model analyzing pressure and Mach number at the valve inlet (nozzle), curtain area and outlet, and the normal force on the sealing disc. To compare the flow rate, the ASME I - PG 69 2.3 standard was used, which deals with boilers and consequently steam, unlike what was used in the present work.

The standards that address flow capacity testing for pressure relief devices and guided this work are American Society of Mechanical Engineers Performance Test Code 25 (ASME PTC 25) and ASME Section VIII UG 131 (ASME UG 131). Currently these documents make up the main standard for testing flow capacity for safety and relief devices. These texts do not characterize complete procedures for performing flow tests, they dictate limits and parameters for testing, and procedures for handling data, but do not present a clear methodology to follow, without specifying all test steps. Other standards also cite flow capacity in safety valves, e.g. American Petroleum Institute (API 520) and International Organization for Standardization (ISO 4126-1) but for flow capacity only present mathematical formulations to measure the capacity of a valve to from fluid, set pressure, overpressure and temperature. Therefore two methodologies are proposed and compared in this paper to evaluate a complete methodology for measuring the flow of a safety valve.

2. METHODOLOGY

The standards mentioned above establish technical requirements to define the flow capacity of the safety valves. However, the texts do not provide all the technical details necessary to proceed with a methodology for carrying out flow capacity tests in the form of a step-by-step methodology. Therefore, the purpose of this work is to develop and evaluate two methodologies that conform to ASME PTC 25 and ASME UG 131 standards.

2.1 Experimental apparatus

The facilities that house the structure of the proposed experiment are located at NEMOG/UFES. The test plant is represented by the P&ID diagram of Figure 1.

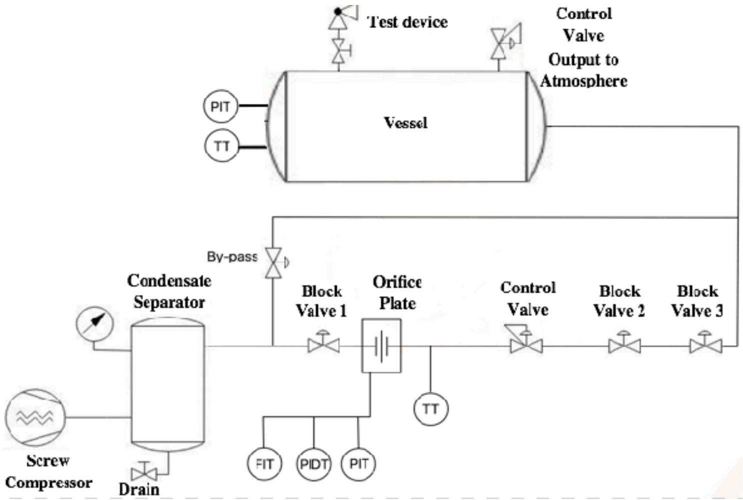

Figure 1. Test line P&ID diagram (Prepared by the author)

The plant is powered by a screw type compressor, model ASD 40 from KAESER manufacturer 30kW of power, working pressure from 5,3 to 8,6bar (± 0,3bar) and flow rate of 2,247Nm^3/h, equipped with an air dryer. Block valves feature only the open/closed configuration. Test methodology is performed by actuating the control valve, pneumatically driven. Flow measurement is monitored by an orifice plate (D = 0,0501m; d = 0,2501m; β = 0,4993; ΔPmax= 6350mmH20). All meters (pressure, temperature and pressure variation) are set at a distance specified in the standard and are certified and calibrated. A LabView supervisory system is specially designed for this application. Data acquisition is performed at a rate of 200ms.

To proceed comparison of proposed methodologies, it is used a safety valve VS-140N (Fluid Controls do Brasil), with set pressure of 6gkf/cm^2, process connection ϕ1/4 ". The valve is basically made of brass, equipped with spring made of carbon steel. The specimen used is calibrated for pressure opening by the manufacturer's own laboratory, see Figure 4.

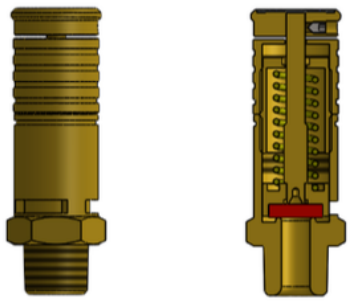

Figure 2 - Safety valve VS-140N (Fluid Controls do Brasil).

2.2 Test development and methodologies

Two distinct methodologies are compared, as shown in Table 1.

In methodology I the compressor is kept at same vessel internal pressure. In methodology II is generated higher pressure in compressor and separator of condensate, than in pressure vessel, similar to a long process. Both methodologies are applied to the same valve (6kgf / cm^2) and the valve is kept open is kept during the interval of 200s (3,33min), pressure varying within the maximum and minimum limits adopted by the standard (as defined by ASME UG 131 (c) (1)).

Table 1: Description of methodologies I and II steps.

Methodology I	Methodology II
Step I.1. A compressor range is selected at 90% of the opening pressure (as defined by ASME PTC 25/4-4.4 (a)) and watch for the pressure to stabilize	**Step II.1.** Idem step I.1
Step I.2. Increase the compressor pressure by 0.1 bar (as defined by ASME PTC 25/4-4.4 (a)**)** and watch for pressure stabilization, observe if the valve has opened, otherwise keep increasing the pressure until it opens	**Step II.2.** Close the vessel valves
Step I.3. Have an eye on valve closing with the compressor in the valve opening configuration, otherwise reduce the pressure often by 0,1 bar (as defined by ASME PTC 25/4-4.4 (b) and ASME UG 131 (c) (1)**)**	**Step II.3.** Increase to 8,6bar (maximum) compressor pressure
	Step II.4. Open the valves, but the control valve with small openings
	Step II.5. Idem step I.3

2.3 Feedback Control System

In defining the best methodology for flow measurement in safety valves, a feedback control system for the pressure was designed to reach the steady state more accurately and quickly. For this test a valve with larger inlet diameter was used, but set pressure of 3kgf/cm^2. The valve was the VS-1200 from the Fluid Controls do Brasil company with 3/4" inlet diameter. The specimen used was calibrated for pressure opening by the manufacturer's own laboratory, see Figure 3.

Figure 3 - Safety valve VS-1200 (Fluid Controls do Brasil).

In order to evaluate the valve performance, a certain condition for the plant must be met. This condition involves a steady pressure on the Vessel. The best the pressure stability is, the better the results are. However, once there is leakage on the Vessel due to the safety valve action, pressure tends to decay. To avoid this effect the control valve opening must be set to a higher value. By doing so, pressure on the vessel tends to increase. Also, the compressor dynamic has a high influence on the pressure, i.e., when it turns on, pressure increases; when it turns off, pressure decreases. The overall effect of all these natural conditions of the plant results on a noticeably complex system to be controlled by a human being and maintain high accuracy at the same time. This kind of problem is very common in industry.

To overcome these difficulties, a simple Feedback Control System was designed. In these types of system, a controller is always trying to track a reference input signal by means of an actuator even with the presence of disturbance, so that the desirable output can be achieved. On this study, the reference input signal is the desired pressure on the vessel, the actuator is the control valve and the process variable is the pressure on the vessel. A representation of the structure is shown in Figure 4.

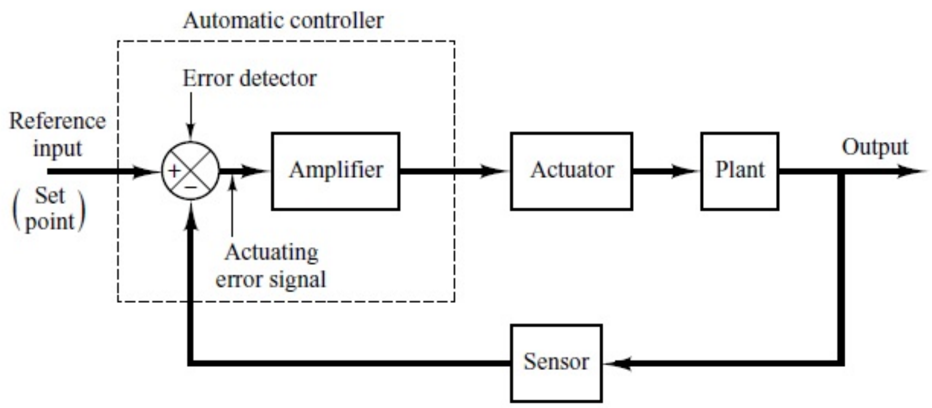

Figure 4. Representation of a Feedback Control System Architecture.
(Fonte: Modern control Engineering, 5th Edition, Katsuhiko Ogata.)

3. RESULTS AND DISCUSSION

In Methodology I the tests are performed with the control valve fully open. The tank pressure is controlled by the compressor pressure switch, operating in 0,3 bar cycles. The tank and compressor are at the same pressure. The figure below (Figure 5) shows the pressure and flow behavior for methodology I.

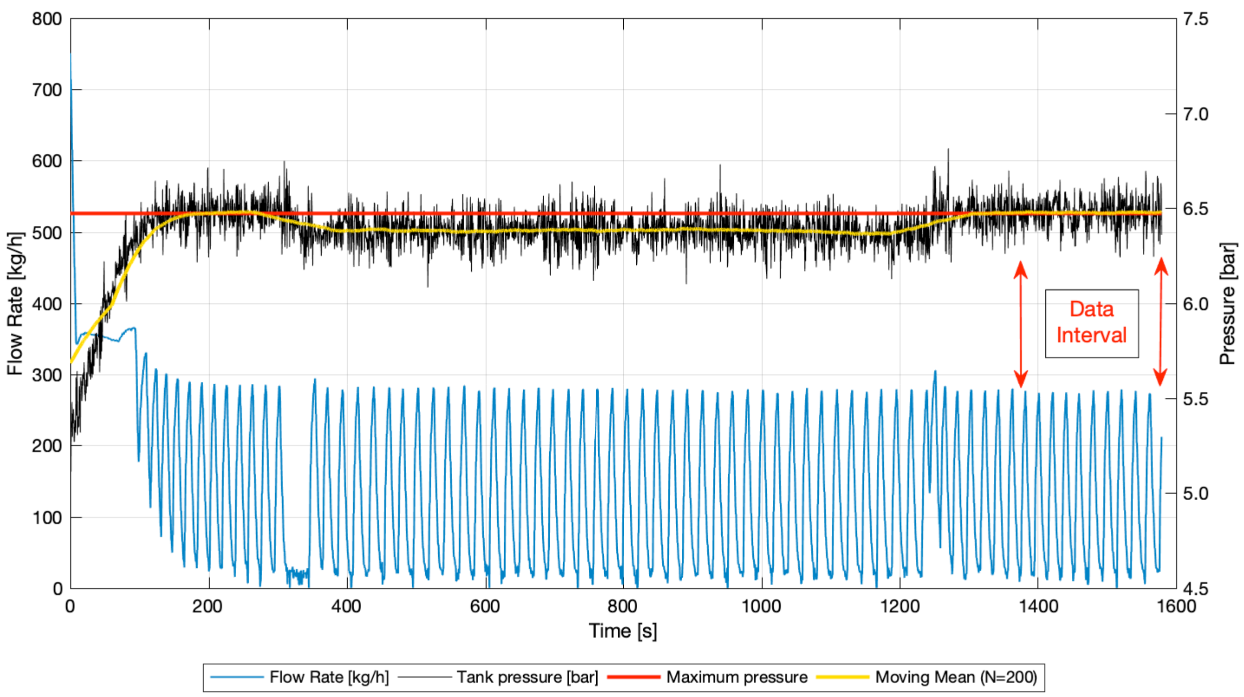

Figure 5. Methodology I - Flow Rate [kg/s] and Reservoir Pressure [bar].

As defined in ASME UG 131 (c) (1), the minimum pressure must be 3 psi or 20 kPa greater than the set pressure (6kgf/cm^2 = 5,88 bar soon the minimum will be 6,08bar) and the maximum 10% or 3 psi = 20 kPa, whichever is greater, above set pressure, as for this valve 10% of the set pressure is greater than 3psi so the maximum pressure will be 6,6kgf/cm^2 = 6,47bar. As the interest of the study is to measure the maximum flow of the safety valve, it stabilized at the maximum pressure. For a better visualization of the mean pressure variation a moving mean was placed.

The data interval went from 1380s to 1580s, because that is where a steady state of pressure is present, so the flow rate that enters the tank is the same as that which flows out of the valve. Data of average temperature, vessel pressure and flow measurement are given in Table 2.

Table 2. Data of average for methodology I.

	Methodology I						
	Mean	Std Deviation	% Mean	Max	% ↑ Mean	Min	% ↓ Mean
Pressure [bar]	6,48	0,08	1,22%	6,70	3,38%	6,24	3,63%
Temperatura [°C]	27,26	0,18	0,66%	27,78	1,90%	26,86	1,47%
Flow Rate [kg/h]	125,23	90,69	72,42%	278,44	122,34%	0,00	100,00%

It is possible to observe a great variability in the flow caused by the compressor cycles, since the flow goes from zero to twice the average. Variations in pressure and temperature are negligible compared to the flow rate.

For Methodology II (Table 3 and Figure 6), a manual control of the control valve was performed so that the tank pressure reaches the pressure limit required by the standard and reached steady state with the compressor at maximum pressure (8.6 bar). The data interval was from 1682s to 1882s, in this range the control valve was 65% closed.

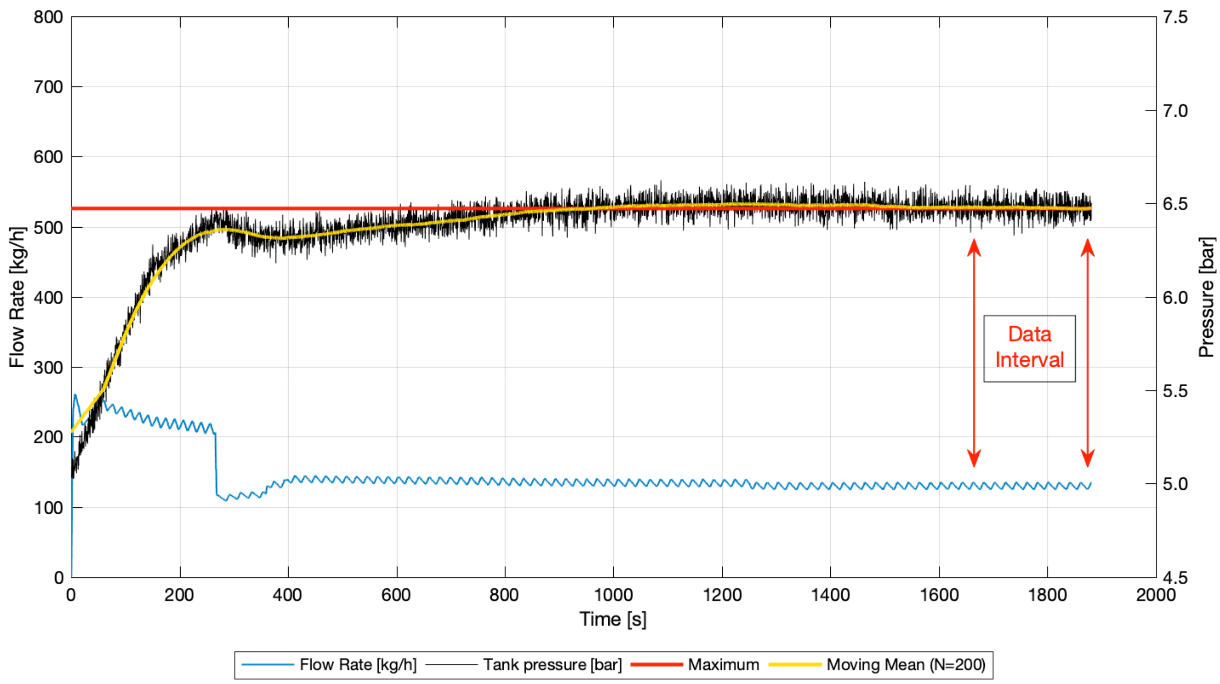

Figure 6. Methodology II - Flow Rate [kg/s] and Reservoir Pressure [bar].

Data of average temperature, vessel pressure and flow measurement are given in Table 3.

Table 3. Data of average for methodology II.

	Methodology II						
	Mean	Std Deviation	% Mean	Max	% ↑ Mean	Min	% ↓ Mean
Pressure [bar]	6,48	0,05	0,78%	6,60	1,87%	6,33	2,30%
Temperatura [°C]	27,96	0,21	0,77%	28,57	2,24%	27,45	1,85%
Flow Rate [kg/h]	129,70	3,14	2,42%	135,30	4,47%	124,49	4,15%

The average flow measured in methodology II is only 3,57% higher than methodology I but the standard deviation presents a considerable difference. While for methodology II the standard deviation of flow represents 2,42% of the average, for methodology I represents 72,42%. Corroborating this observation, the peak-to-peak distance of methodology II is 8,33% of the average, in contrast to methodology I, which is 222,34% of the average.

It is also noted a smaller variation in the tank pressure for methodology II than for methodology I, since the temperatures presented irrelevant variations.

For the tests with and without the feedback control system, methodology II was used, as it presented less variability in the data. Remember that the valve used for these tests is different from the one used in the tests already presented, as shown in figures 2 and 3.

Pressure and flow behavior for the case with manual control is shown in Figure 7.

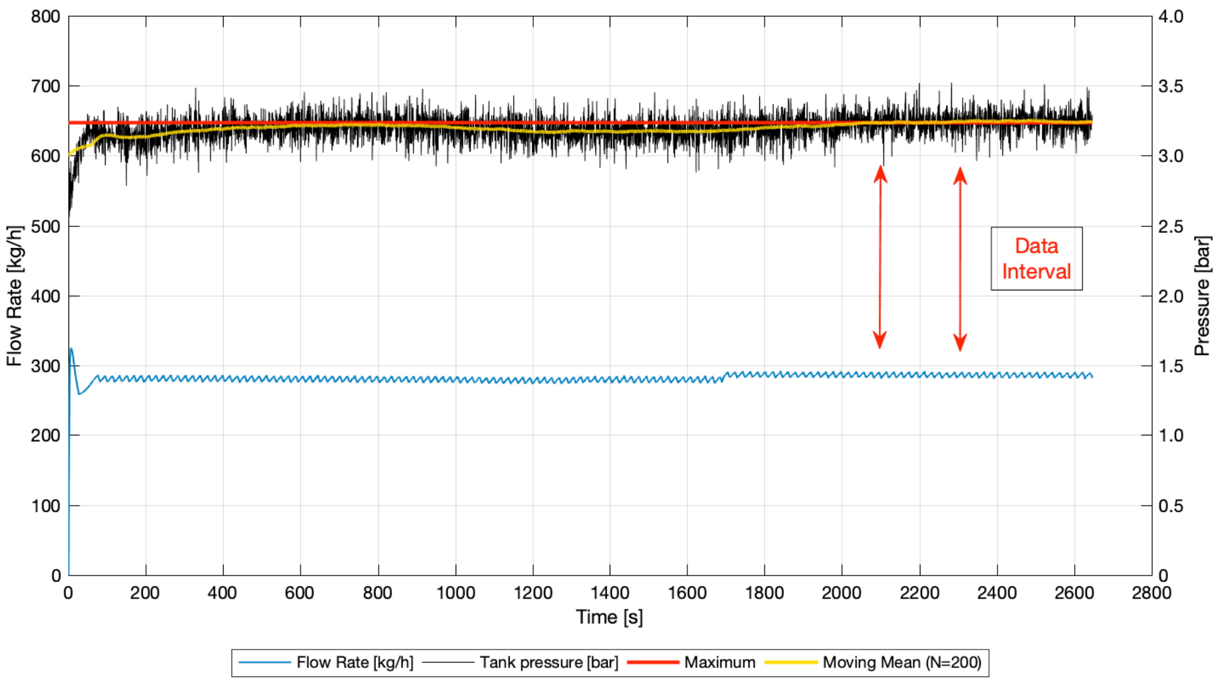

Figure 7. Methodology II with manual control - Flow Rate [kg/s] and Reservoir Pressure [bar].

Average temperature, vessel pressure, and flow measurement data in the interval 2100s to 2300s are given in Table 4.

Table 4. Data of average for methodology II with manual control.

	Methodology II - Manual Control						
	Mean	Std Deviation	% Mean	Max	% ↑ Mean	Min	% ↓ Mean
Pressure [bar]	3,24	0,08	2,46%	3,52	8,77%	2,93	9,66%
Temperatura [°C]	25,91	0,20	0,76%	26,60	2,67%	25,42	1,89%
Flow Rate [kg/h]	286,02	2,83	0,99%	291,83	2,03%	280,37	1,97%

Using the feedback control system, the steady state of pressure and the data interval are obtained faster, as shown in figure 8.

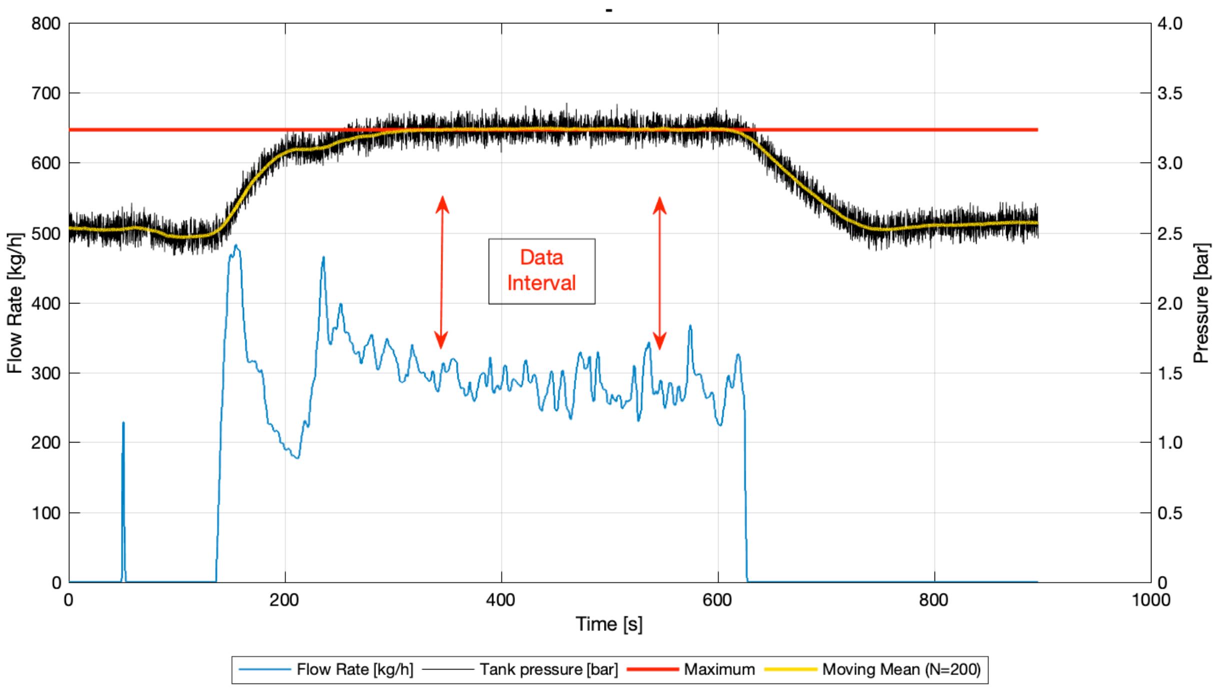

Figure 8. Methodology II with control feedback control system - Flow Rate [kg/s] and Reservoir Pressure [bar].

Average temperature, vessel pressure, and flow measurement data in the interval 340s to 540s are given in Table 5.

Table 5. Data of average for methodology II with control feedback control system

	Methodology II - Control Mesh						
	Mean	Std Deviation	% Mean	Max	% ↑ Mean	Min	% ↓ Mean
Pressure [bar]	3,24	0,06	1,89%	3,43	5,81%	3,07	5,17%
Temperatura [°C]	22,02	0,34	1,53%	23,06	3,99%	20,89	4,37%
Flow Rate [kg/h]	284,12	24,17	8,51%	343,72	20,84%	229,89	18,96%

The average flow in both cases are very close, being that of the manual control test 0,67% higher than the feedback control system test, however the first case presented a smaller variation, with standard deviation of approximately 1% of the compared to 8,5% of the second case. In contrast, the pressure with the feedback control system was more stable, thus ensuring a better steady state pressure.

Another point to note is the duration of the test, in the first case it took 2100s to obtain the steady state of pressure, in the second only 340s, or 83,81% less.

4. CONCLUSION

It can be concluded that the two methodologies, I and II, presented similar average flows, 3,57% of difference, but the second presented a much smaller variability with standard deviation of 2,42% in relation to the average, whereas the methodology I 72.42%. This variation is due to the fact that in methodology I the compressor and the tank are at the same pressure, which causes the tank to be subjected to the cycle of the compressor that turns on and off more often, and the measurement presents greater oscillation. In methodology II, however, with the compressor at a higher pressure, the region upstream of the control valve acts as a capacitance making the cycles smaller and affecting the flow measurement less.

Therefore, the best methodology for measuring the flow capacity of safety valves is the methodology that has a compression system at a higher pressure, with a control to obtain the pressure required by the safety valve and to measure the flow. To control the pressure in the tank to remain steady at 10% above the set pressure was used in two ways, one with manual process control, i.e. an operator indicated the valve opening to obtain the correct pressure and constant, in the other form a feedback control system has been developed to automatically control this valve, where the operator would only indicate the pressure set point.

The tests for both types of process control indicated practically the same average flow, with a difference of 0,67%. The largest difference for the cases was in the variation of flow, for manual control the flow showed a standard deviation of approximately 1% in relation to the mean and the feedback control system 8,5%, such variation is negligible when compared to methodology I. As expected, the control loop presented a smaller variation in pressure than the manual control, thus obtaining a better steady state.

An important point to note is that the minor variation for the manual process is due to the fact that the operator knows the process very well, and has undergone several unsuccessful tests to achieve this result. Linked to this is the time difference for the test, being 83,31% smaller for the feedback control system.

Therefore, it can be concluded that the methodology II and the feedback control system obtain the most efficiently and correctly the flow of a safety valve following the standards.

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