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EXPERIMENTAL STUDY OF THE RESPONSE OF A PRESSURE RELIEF VALVE FOR SLOW AND FAST BLOCKAGE EVENTS

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Abstract. *Pressure relief valves (PRVs) are extremely important devices used to ensure operational safety in pipeline systems and their integrity in the case of a sudden blockage event. Depending on the nature and duration of the blockage event, on valve design and on the length of the duct, the dynamic behavior of the valve, i.e., its response time and discharge coefficient as a function of lift fraction can vary considerably. This kind of detailed information about the transient is not specified in norms and is rarely made available, not even by the manufacturer. In any case, a complete dynamic characterization of the PRV can be crucial for the optimization of a given system. Due to the importance of those valves, several research works focusing on their behavior can be found in the literature; however, most of them present simplified models, considering steady flow regime for different fixed lift positions, which may not be a good approximation, especially for very fast transient events. The work presented here comprises the first stage of an experimental investigation of the behavior of a small-scale plexiglass spring-type PRV model. The goal is to perform a series of measurements based on both steady and transient approaches. Lift displacement, pressure, velocity field and discharge flow rate measurements can be acquired in this test section, with the final goal of comparing the coefficient of discharge versus lift displacement behavior observed from the steady state and transient measurements. In the initial stage described in this article, displacement and pressure data are presented for the transient approach, considering both a slow and a very fast blocking event in the piping system. The experimental setup consists of a closed water circuit, with a progressive cavity pump generating the main flow and a coaxial valve placed downstream of the PRV model, to cause the sudden blockage when energized. In order to investigate the changes in behavior between slow and fast blockage events, the coaxial valve is mounted with a solenoid pilot valve that allows control of its closing duration, ranging from 4 ms to 3.5 s. Synchronization and data acquisition systems were developed, allowing a detailed and precise analysis of a series of realizations of the event.*

Keywords: *Pressure relief valve, Particle Image Velocimetry (PIV), transient discharge flow.*

1. INTRODUCTION

Proper operation of fluid transport systems, especially in the oil and gas industry, require reliable safety and control equipment and procedures. Brazil, for example, has a total of approximately 15.000 km of operating pipelines (Transpetro, 2015). The working pressure along those ducts may be quite high, highlighting the importance of operational security measures. Experimental, numerical, and theoretical investigations of these systems thus become more and more crucial.

The correct dimensioning of pressure relief valves (PRV's) is fundamental to ensure safety in the case of unexpected abnormal operational conditions that generate further pressure growth in the duct. These valves work by relieving the internal pressure of the duct in case it grows over a pre-defined value calibrated for the valve (the set pressure, P_{set}). Since the pressure growth rate is usually large, the valve must present a fast response in order to ensure system safety.

Spring-loaded pressure relief valves are the most commonly used in industrial installations to keep ducts and pressure vessels safe. They are passive safety devices, i.e., with no need of an external energy source, being based on the action of the spring force (plus a counterpressure or *back pressure*,P_{back}, from the relief side) against the force exerted by the flow pressure in the duct actuating on the valve's interior surface. A simplified model corresponding to the current experiment is presented in Figure 1. As the force due to the fluid pressure at the inlet bore overcomes the spring force, the valve starts to allow the liquid to escape. A further increase in the system pressure lifts the valve disc further from its seat, and the flow rate increases. Hence, the flow is from the pressurized system axially upwards through the bore, then radially below the disc, when the fluid is then deflected back downwards by the skirt (valve has a “cup” shape), reversing its direction. This creates reaction forces that lift the disc further. The valve discharges to P_2 (equal to P_{back}), commonly the atmospheric pressure, which is the case in our experiment. The unbalance of forces in the opposite sense produces closing of the valve after re-establishment of normal pressure conditions in the system, avoiding further relief of fluid.

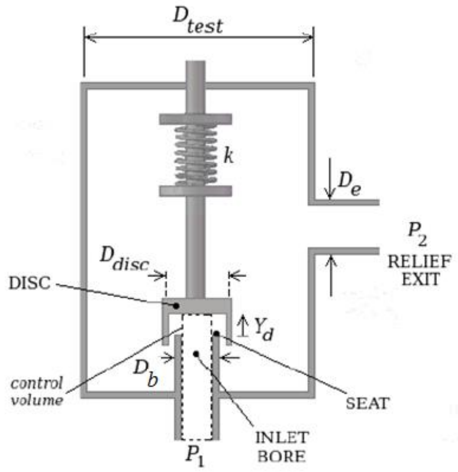


Figure 1. Simple model of the spring-loaded pressure relief valve.

Some of the important user-defined parameters needed for appropriately selecting a valve are the minimum required capacity (usually the expected main flow rate in the duct, Q), the desired set pressure P_{set} , the allowable overpressure P_{over}, and the expected back pressure P_2. Based on those inputs and on the rated coefficient of discharge K_d, the user can estimate the minimum required discharge area A and choose model and geometry of the valve, as defined in the API norm (API 520 standards, 2000):

$$A = \frac{Q}{38 K_d K_w K_v} \sqrt{\frac{G}{P_1 - P_2}}, \qquad (1)$$

where $P_1 = P_{set} + P_{over}$ is the pressure at the inlet bore (upstream of the valve), K_w is the correction factor due to back pressure, K_v is the viscosity correction factor, an G the specific gravity of the liquid at the flowing temperature referred to water at standard conditions.

This equation is employed for initial sizing estimation of the valve for a given application, but there is no way to know if the actual discharge coefficient during valve operation, C_d, is well represented by the value of the rated coefficient K_d. Furthermore, there is usually no information from the manufacturer on how C_d or the actual relief flow rate Q_e through the valve’s discharge behave during the transient lift. In other words, the discharge coefficient versus lift (or open fraction) curve (C_d versus Y_D), which would be a result of each manufacturer’s characteristics and extremely useful for the design of fluid systems incorporating relief valves, is usually not available, and when available, is based on a steady-state analysis for each open fraction.

In the design of complex fluid transport systems, it is crucial to use softwares for controlling and predicting different situations. These softwares should include appropriate models for each specific equipment comprising the system. Models for PRVs are often based on a steady-state valve performance, but hydraulic transients in these valves can have effects worth accounting for. Depending on the response time of the valve, system dynamics can be significantly influenced by its location and characteristics. Furthermore, if the frequency of the inlet pressure variations matches the natural frequency of the valve ($\omega_0 = \sqrt{k/m_D}$), it may oscillate and chatter excessively, which could also affect the system as a whole.

Following an analysis of Newton’s law along with conservation of mass and momentum in the control volume located in the interior of the inlet duct and valve, as depicted in figure 1 (for details refer to Carneiro, 2011), the equation for a simplified mathematical model governing the dynamic behavior of the valve can be obtained, in which all the relevant parameters can be identified:

$$0 = m_D \frac{d^2 Y_D}{dt^2} + \left(C - 2 C_d A_i \sqrt{2\rho (P_1 - P_2)}\right) \frac{dY_D}{dt} + (k + \rho g A_i) Y_D - (P_1 - P_{set}) A_i - \left(\frac{dY_D}{dt}\right)^2 \rho A_i - 2 {C_d}^2 A_i (P_1 - P_2), \qquad (2)$$

where m_D is the mass of the ensemble (valve + rod), Y_D is the valve (disc) displacement (*lift*), C is the damping coefficient of the valve system, A_i the cross-section area of the inlet bore, ρ is the fluid density, k the spring constant, and g the gravitational acceleration.

All of these parameters, or most of them, can be measured experimentally (Carneiro, 2011), and can be very useful to test numerical models or analyze valve dynamics. The actual discharge coefficient C_d is given by

$$C_d = \frac{Q_e}{A\sqrt{\frac{2(P_1 - P_2)}{\rho}}}, \quad (3)$$

and is probably the most relevant practical parameter for the user. In order to predict the behavior of the pressure in the duct during the transient, it is very important to model the valve's dynamics correctly, using its response time and the discharge coefficient curve. Available commercial models for numerical simulation usually do not present satisfactory performance (Carneiro, 2011).

Attempts to understand details of the dynamic behavior of PRVs have been made with both experimental and theoretical approaches for a long time. In 1978, Ray developed a non-linear dynamic model of a spring-loaded valve, based on the fundamental principles of rigid body motion and fluid dynamics. The author concluded that the inertia of the fluid flow in the orifice produces a damping effect on the valve motion resulting in an initial delay, and that the valve opening time is approximately proportional to the ratio between length and radius of the orifice. Also pointed out is the fact that the mass-spring combination can generate oscillations and chattering, which is characterized by violent oscillations of the disc, resulting from high pressure variations in the entrance of the valve and is, in fact, observed in practice.

Sallet *et al* (1981) performed experimental measurements aimed at better understanding the flow characteristics at the interior of the valve in different flow regimes. The authors analyzed the flow and pressure distributions in the internal part of a typical PRV, studying parameters such as valve geometry, open fractions, among others, which affect performance and relief capacity. Analysis of the dynamical stability of a relief valve and the study of the effects of its components in stability was presented by Catalani in 1984. According to the author, the factors affecting the valve's performance are ring adjustment, upstream flow conditions, and upstream duct length. A computational model was developed to investigate the influence of pneumatic and electromagnetic components in the stability of the valve. The conclusion was that the use of such devices improves performance, enabling better control of opening and closing pressures.

MacLeod (1985) explained that, by characterizing the behavior of differential equations in certain regions of critical points, the necessary conditions to avoid chattering can be determined. The author investigated the stability of the valve by using the Routh-Hurwitz criterion. He suggested that the dynamic stability in a relief valve depends on the duct system pressure and on the real characteristics of the valve, and that it is necessary to have a set of concise differential equations for the whole system when one intends to perform a detailed stability analysis.

Francis and Betts (1997) presented an analysis of the incompressible flow inside a relief valve. Using finite elements, the authors simulated the flow in a two-dimensional, axisymmetric model of a real valve. Five lifts were studied, in a steady-state manner. Comparisons were made with experimental results obtained using oil film technique. Simulation results allowed visualization of flow regimes inside the valve, with identification of separation and reattachment regions, which in turn could be related to the changing shape of the C_d versus lift curve. According to the authors, this kind of knowledge can have important implications for effective design.

The same authors published another work (Francis and Betts, 2000) proposing a zonal model to express the thrust on the disc of a high-lift relief valve through a number of key geometric and dynamic parameters. They emphasize that the thrust on the disc of a high-lift relief valve depends on the hydrodynamics of flow through the valve, and consider the compressibility effects on the flow description. Among the geometric parameters identified are the square of the ratio of disc diameter and lift to a nominal valve diameter. Another parameter was the length of the skirt (for a cup-shaped valve) in relation to the nominal diameter, which will significantly influence the overall change in momentum of the flow, and hence the mean pressures experienced at the disc surface. The importance of a detailed characterization is stressed, and represented mainly through curves of discharge coefficient versus lift and thrust versus lift.

More recently, numerical simulations have been performed to further study the dynamic characteristics of relief valves. In the work of Ortega *et al* from 2008, a two-dimensional model is presented for analysis of the flux through a simplified spring-loaded relief valve, with the goal of determining the discharge coefficient C_d with a more rigorous methodology, considering details of the flow. Results were compared with a one-dimensional model and, although different disc equilibrium positions and flow rates were obtained with each method, both models predicted the same behavior for the discharge coefficient as a function of the open fraction of the valve. Song *et al* investigated, in 2010, the turbulent flow of water through the valve using a two-dimensional numerical model with mesh deformation due to the fluid-solid interaction, with different pressure inlet conditions. The authors obtained velocity and pressure distributions through the valve at each time step, concluding that unsteady interaction between the flowing fluid and compressed spring created unsteady loads which make the valve disc oscillate.

In 2011, Carneiro contributed by building an experiment to study the dynamic behavior of a commercial PRV in different operational conditions. Results generated curves of upstream and downstream pressure, flow rate, and open fraction versus time during the transient lift. The author then plotted C_d versus open fraction curves for both steady state (acquiring data for fixed open fractions) and transient regimes, and concluded that steady state data fits well with transient data and provides a good representation, at least for the blockage durations studied, which characterized the transient process as a slow one. According to the literature, a simple and straightforward criterion can be used for characterizing the transient (or the blockage event) as fast or slow. This criterion is based on the relation between the time T needed for the change in fluid velocity – which corresponds to the duration of the blockage event in the test circuit – and the period of the duct, $2L/c$, which represents the time of propagation of a pressure wave back and forth in the main flow duct (c is the velocity of a propagating pressure wave in the fluid). The event can be classified as fast, slow or very slow according to the following expressions, respectively:

$$T \leq 2L/c,$$
$$2L/c \leq T \leq 500\ 2L/c,$$
$$T \geq 500\ 2L/c. \quad (4)$$

The present work aims at further investigating the dynamic behavior of a pressure relief valve, making use of a completely synchronized measurement system to simultaneously measure lift displacement, pressure, and flow velocity field during the transient lift. Based on these results and on the steady-state results to be obtained in the next stage of the project (not presented here), it will be possible to tackle the issue of whether it is reasonable or not to characterize the valve's behavior through a series of steady state valve positions and assume it is a good prediction for the actual transient behavior. The level of accuracy of this kind of assumption can differ depending on blockage duration and nature of the transient.

2. EXPERIMENTAL SETUP

The experimental facility is set up for performing both disc lift displacement (*open fraction*), pressure, and phase-averaged *PIV* measurements in a reduced plexiglass model of a pressure relief valve shaped like an inverse cup. Figure 2(A) shows a general view of the setup. The flow loop was mounted with 32 mm PVC piping, with a total length of 7 meters. In the closed water circuit, a progressive cavity pump generates the main flow. Filtered water from an inlet tank is pumped and circulates through the pipe system. In normal operating conditions, water flows through a horizontal passage drilled in the plexiglass test section, which is depicted in more detail in Figure 2(B). Downstream of the test section, there is a pilot-operated coaxial (pilot valve is a solenoid) valve which can be triggered from the computer to close and cause sudden blockage – and consequently a sharp pressure increase – in the circuit. A LabView program is used to trigger this valve either in a single realization (i.e., closing, waiting a proper amount of time, and then re-opening it), or in a sequence of 250 event realizations, with enough time between them to allow the flow to re-establish its initial conditions. Thus, for every case (see Table 1) studied, a data ensemble of 250 instantaneous realizations was acquired.

Once the coaxial valve is triggered to close (either slowly – 3.5 s – or very fast – 4 ms), the rising pressure will cause the plexiglass PRV inside the test section to open and the water to go through the inlet bore, being relieved to a discharge exit, as depicted in Figure 2(B). Water is discharged to an exit tank and returns to the inlet tank. In this setup the back pressure (pressure downstream of the PRV) is approximately atmospheric ($P_{back} = P_{atm}$) because the discharge tank is left open during measurements for level control. A frequency inverter is installed in the circuit to regulate the desired flow rate Q of the main system.

The internal part of the test section, which is filled with water, is cylindrical with internal diameter D_{test} = 50 mm. The diameter of the horizontal main flow passage is 25 mm and the inlet plexiglass bore diameter is D_b = 9 mm. The spring is positioned in the upper half of the test section, between small disks for adjustable compression. The valve axis rod goes up outside the section, and this will be shown later to be important for displacement (LVDT) measurements.

As previously mentioned, in order to compare dynamic behavior in the cases of slow and fast transients, a pilot-operated coaxial valve (Namur) was used. The solenoid pilot valve has an inlet for compressed air and a couple of restrictors whose screws aperture regulate air outlet, and consequently control opening or closing time of the main coaxial valve (see Figure 3).

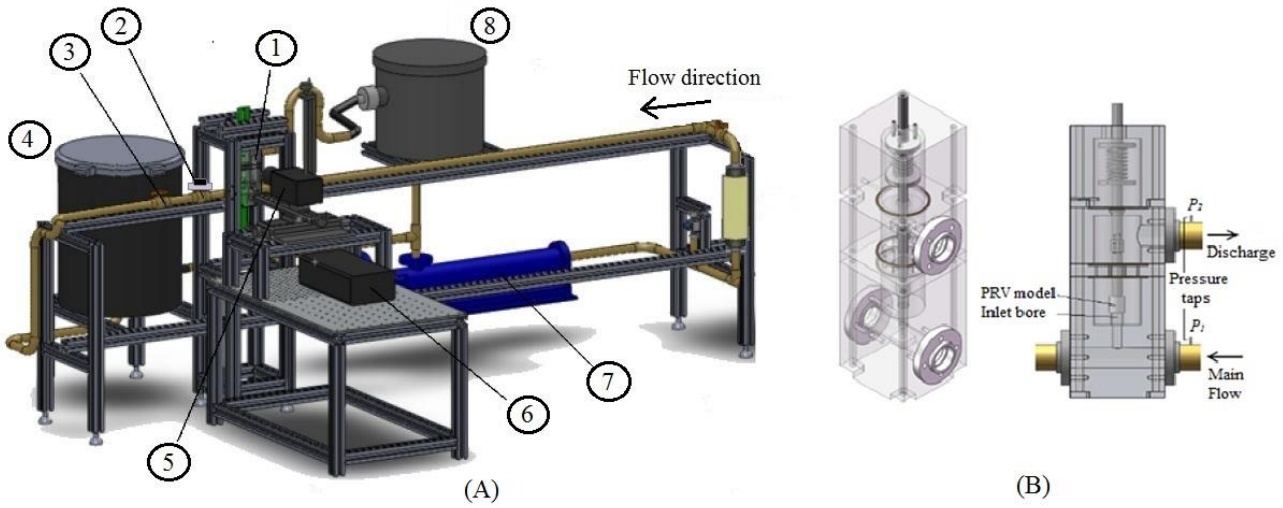


Figure 2. (A) General view of the setup. 1: plexiglass test section; 2: pilot-operated coaxial blockage valve; 3: manually controlled valve (left open); 4: inlet reservoir tank; 5: camera; 6: laser system; 7: progressive cavity pump; 8: discharge tank (exit flow from the PRV). (B) Detail of the plexiglass test section containing the PRV model. Left: Isometric view depicting test section assembly, which is divided in three blocks held together; right: front view with indication of main flow duct, inlet bore, discharge exit and taps for pressure differential ($\boldsymbol{P_1 - P_2}$) measurements.

3. METHODOLOGY

With the goal of characterizing the relief valve and its dynamics when submitted to both fast and slow hydraulic transients, different types of measurements were performed. Initially, attention was focused in the characterization of the blockage event, then on simultaneous pressure and lift displacement measurements for the PRV when submitted to circuit blockage. Each of these steps is explained next.

3.1 Characterization of the blockage event (closing time of coaxial valve)

As an initial step, the nature of the blockage events was analyzed by means of a separate procedure. The coaxial blockage valve with adjustable closing time was removed from the circuit and positioned in an optical table initially open. A LED light source was positioned in one side of the valve, and in the other side a high frame rate camera (Photron FASTCAM SA3) was fixed, aligned with the valve axis. This setup can be observed in Figure 3 (left).

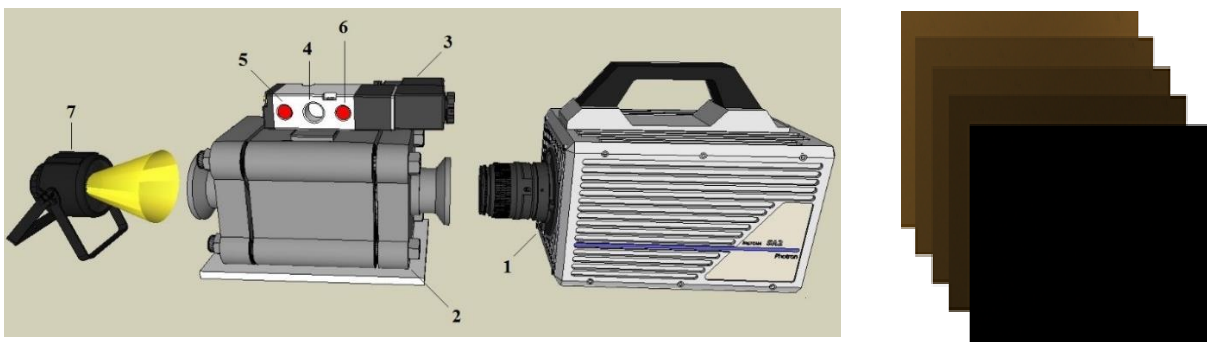
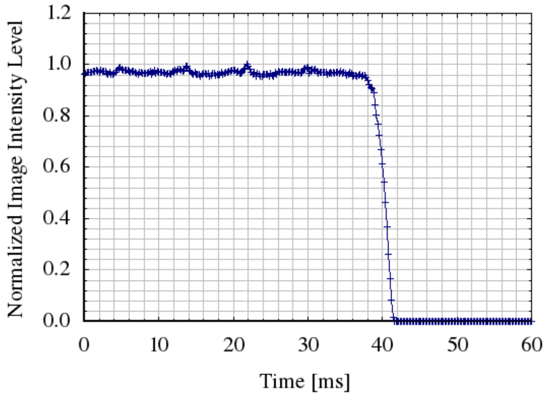
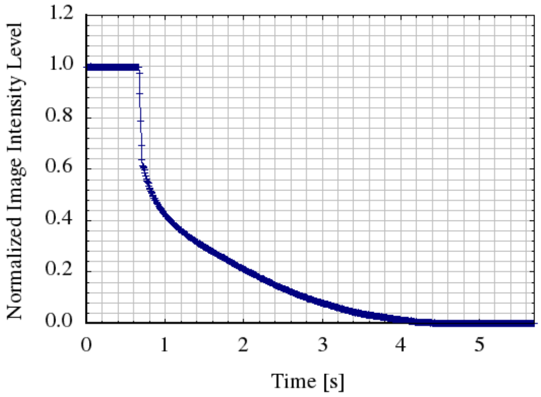


Figure 3. Separate arrangement for estimation of closing times of the blockage valve. Left: 1) high-speed camera; 2) coaxial valve; 3) solenoid pilot valve; 4) compressed air inlet (80 psi); 5) restrictor that regulates closing time; 6) restrictor that regulates opening time (left in the same position for all the main measurements); 7) LED panel. Right: Series of (only a few selected) images taken from valve completely opened towards complete closing.

Valve's air outlet restrictor was then set to provide the shortest closing time and a high-resolution series of temporal images was acquired (see right-hand side of Figure 3, which illustrates the evolution from illuminated images corresponding to the valve completely opened towards complete blockage of the light). Of course, only a few images are used here, but a total of 500 images were acquired. Then, the average grey-level pixel intensity was calculated for each of these images, generating the plot presented in Figure 4(A), in which the full-light and zero-light plateaus can be observed, and from which the closing time can be estimated as 4 *ms* (number of camera frames per second was known, obviously). The same procedure was employed with the restrictor set to a slow closure, generating the plot presented in Figure 4(B), with closing time estimated as 3.5 *s*.



(A)



(B)

Figure 4. Characterization of closing times for the two test cases of interest: fast (A) and slow (B) blockage events.

After these tests, the coaxial valve was mounted back in the circuit, 70 cm downstream of the plexiglass PRV test section in order to initiate the main measurements concerning PRV dynamic behavior. Table 1 lists the test cases for the experimental procedures. The PRV configuration (mass m_D, spring constant k = 1018 *N/m*) was fixed, and three main flow rates were investigated.

Table 1. Matrix of experimental test cases

Number of realizations for each case	**Blockage duration *T* [ms]**	**Classification**	**Main flow rate *Q* [L/min]**	**Test Case**
250	4	$T \leq 2L/c$ (fast transient)	10 17 26	**A** **B** **C**
	3500	$2L/c \leq T \leq 500\ 2L/c$ (slow transient)	10 17 26	**D** **E** **F**

3.2 Set pressure (P_{set}) Estimation

The pressure level upstream of the PRV (where P_1 is measured – see Figure 2(B)) at which the PRV starts to open, that is, the set pressure P_{set}, is an important parameter. For example, the overpressure P_{over} (i.e., the further increase in pressure during lift) and other parameters are defined in relation to the set pressure (API 520 standards, 2000). Once the valve spring was selected and set to a given aperture that allowed proper discharge to be achieved for the main flow rates Q, an initial "static" test was conducted for evaluation of P_{set}. The circuit from Figure 2(A) was blocked at both ends by manual valves. Additional pressure was imposed in a tap downstream of the PRV location with a syringe filled with water. A calibrated mercury manometer was used to measure the imposed additional pressure, and through the data acquisition software displaying LVDT measurements, it was possible to determine the amount of imposed pressure at the moment the PRV reached an open fraction of around 0.5% ($Y_D/D_b \times 100$). From this procedure the set pressure was estimated to be $P_{set} = 1.3$ bar.

3.3 PRV Displacement and Pressure Measurements

The PRV was instrumented with an LVDT sensor (model MHR500, Measurement Specialties, ±12,5mm range) to measure the displacement of its rod (and consequently of the valve's cup – see Figure 5) and with pressure taps (see Figure 2(B)) to measure P_1 and P_2 with a differential pressure transducer (Unik 5000 model, GE, 0 to 5 bar range). A data acquisition system (HBM, QUANTUMX series, MX-840 model) with high acquisition rate (up to 2.4 kHz) was used and controlled by CatmanAP software, also used to visualize data in real time. Calibration procedures were carefully performed for both sensors before beginning of the final tests.

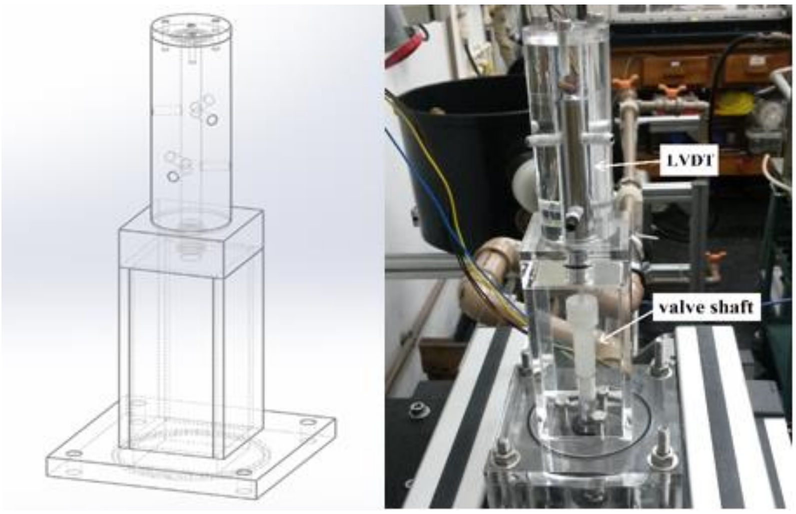


Figure 5. Detail of the dome mounted (completely sealed to prevent air or water leakage that could affect pressure conditions inside the chamber) at the top of the test section to hold the LVDT sensor. An adapter was manufactured to connect the upper part of the PRV shaft to the inner metal shaft of the sensor.

4. RESULTS

Some pressure and displacement data versus time during lift are shown below for the six test cases. Each figure corresponds to a typical instantaneous (single realization) event. Ensemble average curves based on the 250 different realizations are also depicted in the plots. In the top of the figures are the pressure difference curves (instantaneous, red; ensemble average, brown), and in the bottom, lift displacement data (instantaneous, blue; ensemble average, green). In the left column, plots are presented in a time scale such that the overall behavior can be observed, that is, from instant $t = 0$ when the blockage is triggered, up until moments after the blockage valve has been re-opened, the main flow re-established, and the valve has gone back to its seat position. In the right column, time scale has been changed in order to provide for a more detailed visualization of the initial pressure increase and lift. In all cases, it can be observed that when the set pressure is reached, valve rapidly starts to open.

4.1 Fast Blockage Event

For the very fast blockage (figures 6 to 8), the first displacement peak is always a very strong one, which is not true for the cases shown in the following section for the slow events. Because of that and also the fact that each instantaneous realization is slightly different than the others, the ensemble average curves are not quite representative of the valve's typical behavior, and this is by itself a reminder of the importance of analyzing the dynamics from a transient perspective, as opposed to steady state or average perspectives seen in the literature. However, a question is raised about whether this first narrow, strong displacement peak is even noticed by the flow inside the chamber. This can be answered in the near future, once phase-averaged and high-frequency PIV measurements are available.

With increasing flow rate Q, it can be seen that peak pressure values do not change much, while peak displacements increase considerably. As mentioned above, further explanation of these observed dynamic characteristics will be provided in the near future, when PIV flow field results are processed and a detailed analysis of flow structures and evaluation of transient discharge flow rates are performed.

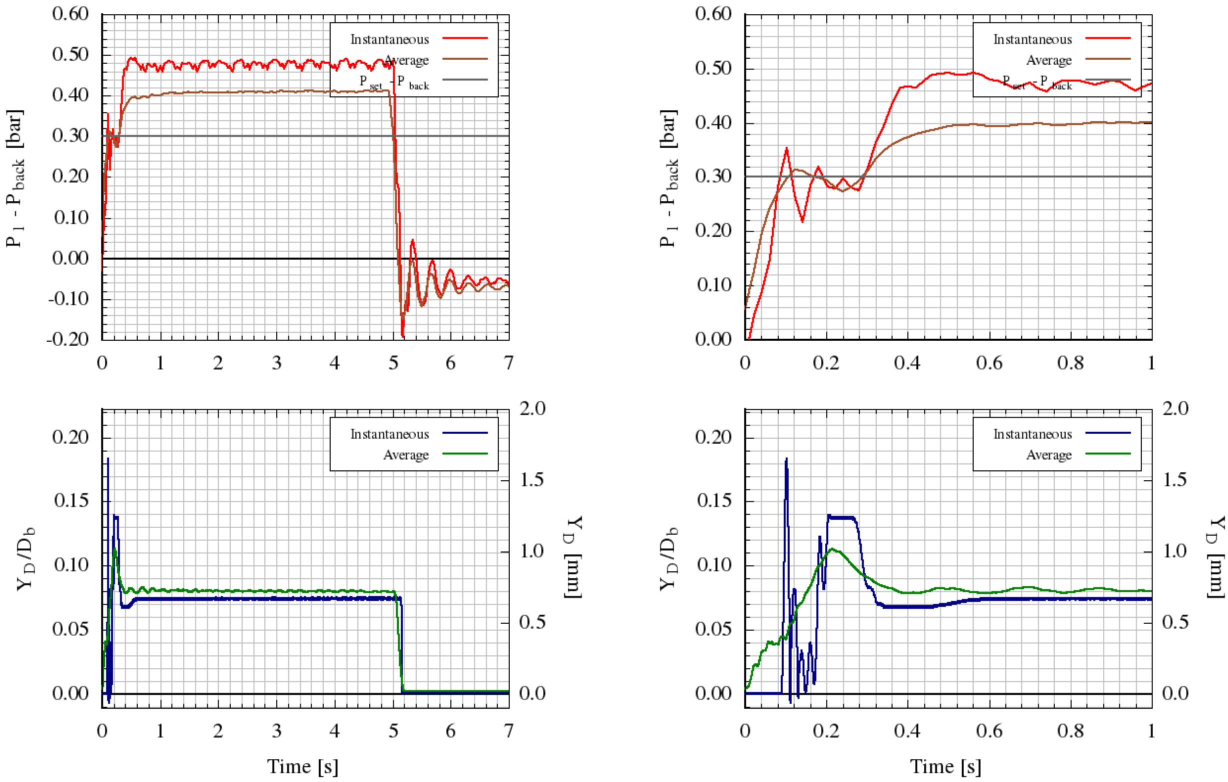


Figure 6. Example of instantaneous (single realization) pressure differential ($P_1 - P_{back} = P_1 - P_2$) and open fraction (Y_D) data. Test case A, Q = 10 L/min, T = 4 ms.

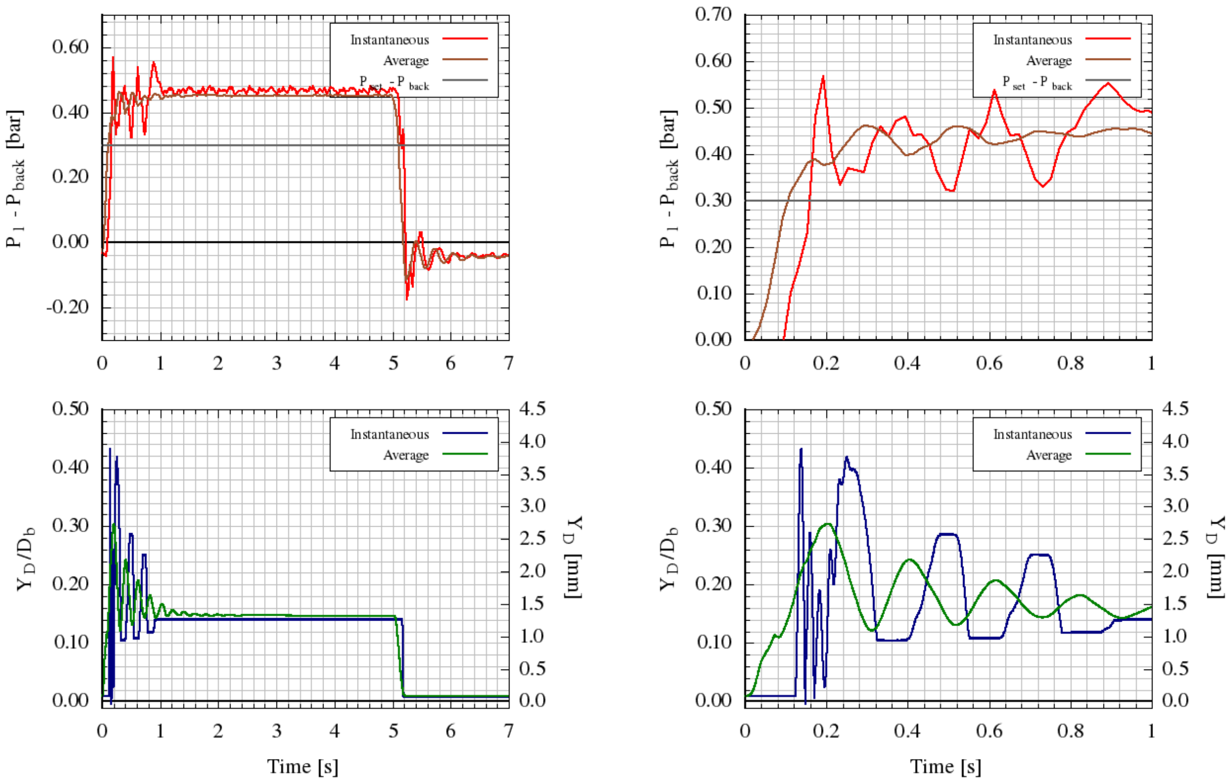


Figure 7. Example of instantaneous (single realization) pressure differential ($P_1 - P_{back} = P_1 - P_2$) and open fraction (Y_D) data. Test case B, Q = 17 L/min, T = 4 ms.

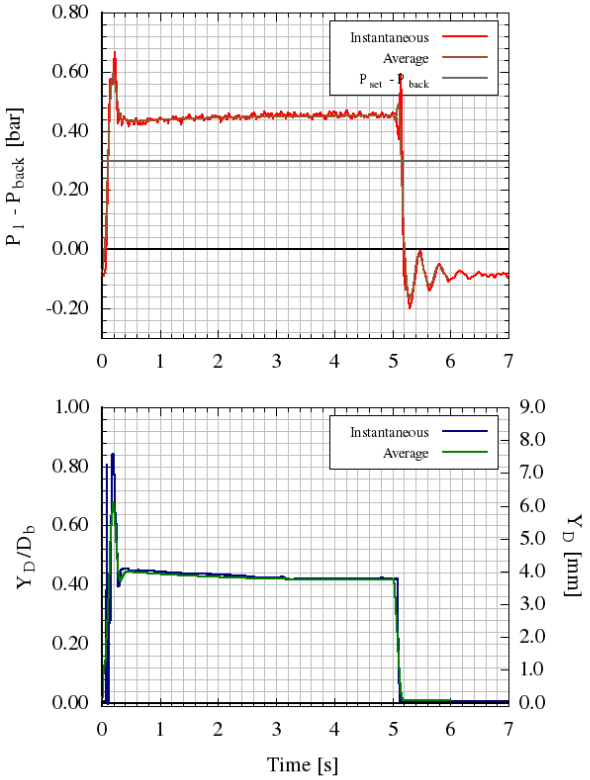


Figure 8. Example of instantaneous (single realization) pressure differential ($P_1 - P_{back} = P_1 - P_2$) and open fraction (Y_D) data. Test case C, Q = 26 L/min, T = 4 ms.

4.2 Slow Blockage Event

For the slow blockage cases (figures 9 to 11), it can be noticed, for all values of Q, that when set pressure is reached, valve goes up slightly, and it is only when hydrodynamic forces cause the pressure to increase further that a sharp displacement peak can be observed. Pressure values at the inlet reach significant values, higher than those for the same flow rate values in the fast blockage event. Indeed, very sharp displacement peaks also occur in the case of slow blockage events. Again, instantaneous flow field data should be crucial to further investigate the reason behind these observations. Another interesting observation is that for Q = 17 L/min, the valve tends to chatter in both cases (fast and slow), which may be due to some flow structure with frequency close to the natural frequency of the valve, $\sqrt{k/m_D}$.

Due to the presence of sharp peaks whose "location" in the time scale varies slightly from one realization to the next, as in the fast blockage cases, the ensemble average curves – especially for the displacement – are not representative of the typical instantaneous behavior.

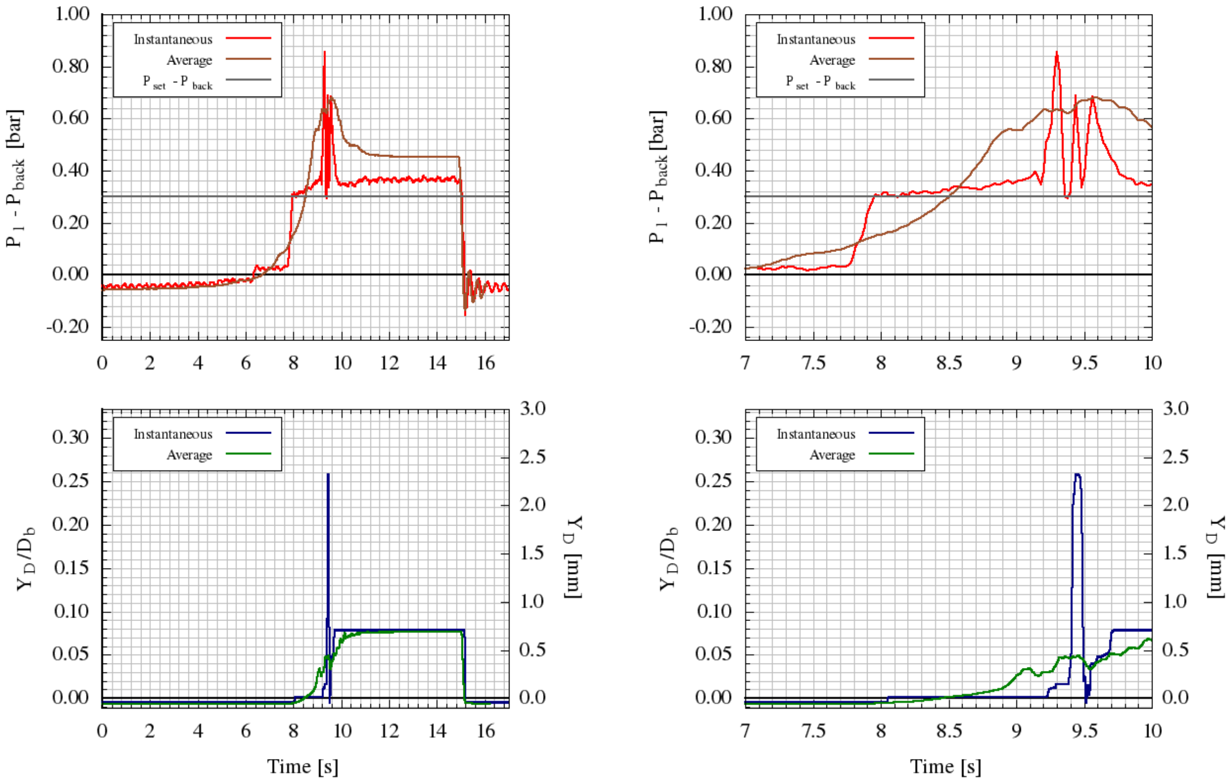


Figure 9. Example of instantaneous (single realization) pressure differential ($P_1 - P_{back} = P_1 - P_2$) and open fraction (Y_D) data. Test case D, Q = 10 L/min, T = 3.5 s.

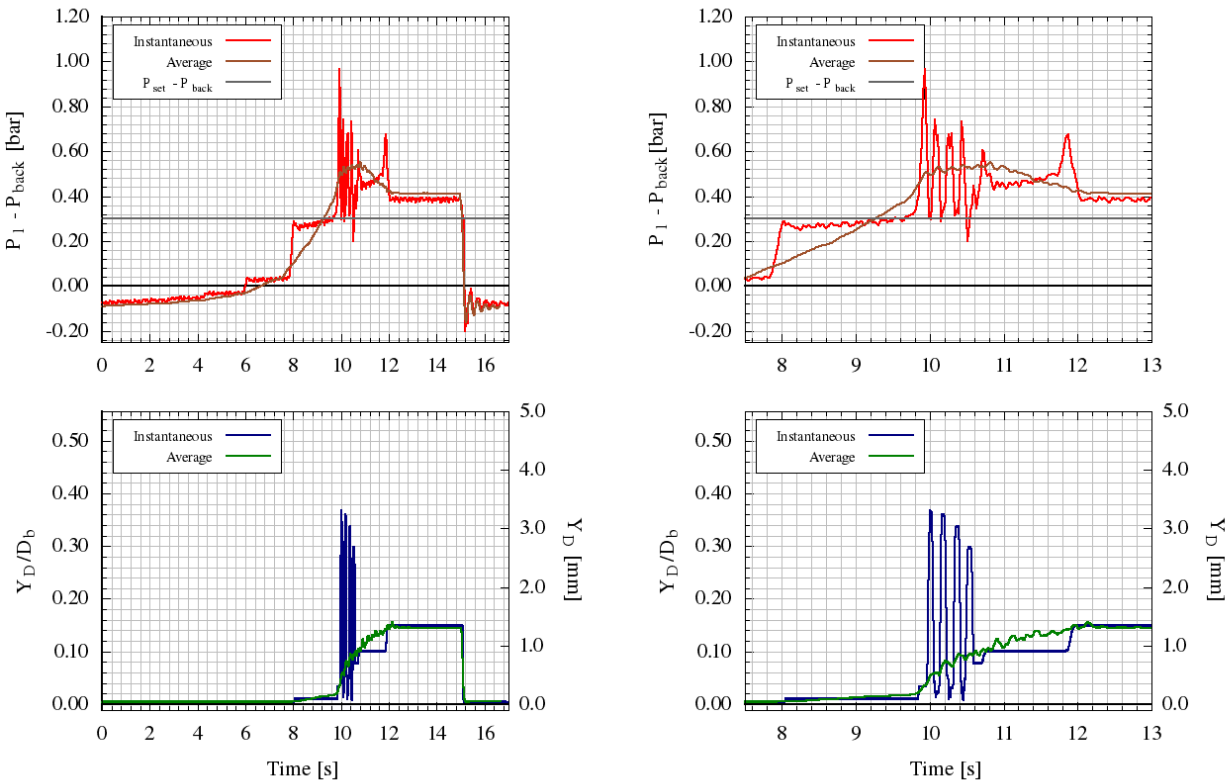


Figure 10. Example of instantaneous (single realization) pressure differential ($P_1 - P_{back} = P_1 - P_2$) and open fraction (Y_D) data. Test case E, Q = 17 L/min, T = 3.5 s.

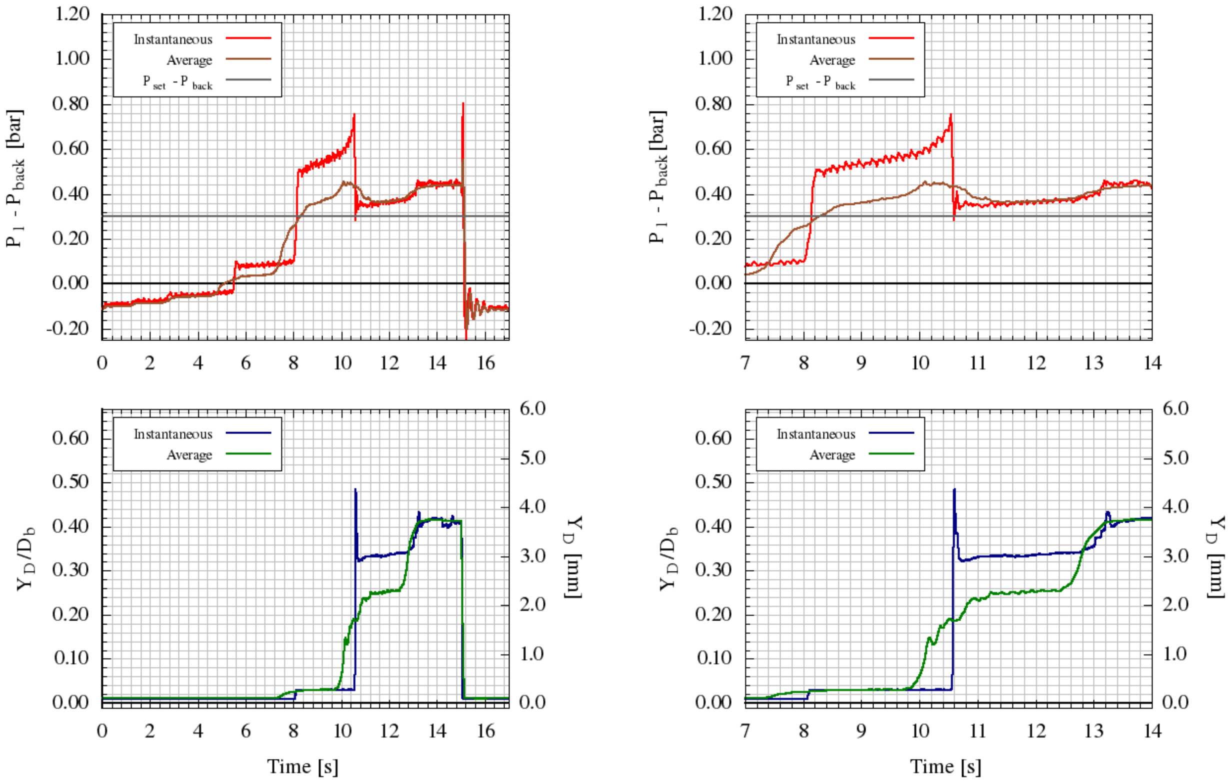


Figure 11. Example of instantaneous (single realization) pressure differential ($P_1 - P_{back} = P_1 - P_2$) and open fraction (Y_D) data. Test case F, Q = 26 L/min, T = 3.5 s.

This paper presented preliminary results from a project aimed at investigating in detail the dynamic behavior of pressure relief valves. These results include, for now, instantaneous pressure and displacement measurements. Following the measurements presented here, phase-averaged and high-frequency PIV measurements will also be processed from this truly transient standpoint (as opposed to a steady-state analysis for each lift position), enabling more interesting discussions of the observed phenomena. PIV results will also allow the calculation (through numerical integration of the velocity profiles) of discharge flow rate, Q_e, with time during lift, and consequently the plot of "truly transient" C_d versus open fraction curves. C_d will be evaluated through Eq.(3). Equation (2) can also be better analyzed in light of the complete data, comprising flow field data as well.

Finally, the steady-state measurements (as most in literature) will be acquired (pressure, LVDT, and PIV) as well, in order to compare results (particularly of the C_d versus open fraction curves) from the two perspectives, and probably contradict other research works that state that this steady-state analysis is a good approximation. In order to study the steady state approximation, a setup is already constructed that can precisely hold the valve still at different pre-selected open fractions.

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