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DYNAMIC BEHAVIOR OF SPRING-LOADED PRESSURE RELIEF VALVE: NUMERICAL AND EXPERIMENTAL ANALYSIS

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ABSTRACT
The majority of oil and refined-product pipelines in Brazil have their protection system designs based on spring-type pressure relief valves. Thus, the proper design and operation of these valves is essential to ensure the safety of transport pipelines and loading/unloading terminals during any abnormal operation conditions that generate a surge pressure. In simple terms, these valves have a disk which is pressed by a spring against the inlet nozzle of the valve. When the pressure rises, the force generated on the surface of the disc increases and, depending on the pressure relief valve set point, the force due to pressure overcomes the force exerted by the spring, causing the disk to rise and discharge the fluid through the outlet nozzle to the relief line, reducing the pressure level within the pipeline. Despite its importance, most commercial applications do not present a specific model to simulate the transient behavior of pressure relief valves. This paper presents an experimental study aimed at determining the dynamic behavior of a commercial spring-type relief valve. The valve was installed in a pipe loop instrumented with pressure and flow transducers. The transient motion of the valve disc was measured with a fast-response displacement transducer. The transient in the flow loop was generated by the controlled closing of a block valve positioned downstream of the relief valve. The recorded transient data for disc position, upstream and downstream pressures, and discharge flow rates were used to compute the discharge coefficient as a function of opening fraction and the opening fraction as a function of time. Simulation models based on a spring-mass damped system were developed and implemented in a PID-actuator-control valve system. The systems were implemented in a commercial pipeline simulation program modeling the experimental loop employed in the tests. The numerical and experimental data of the block valve closure transient were compared displaying good agreement. Simulations results employing a generic relief valve model frequently used in simulations were also obtained revealing problems associated with this approach.

INTRODUCTION
Pressure relief valves (PRV) are of fundamental importance in ensuring the safe operation of liquid pipelines and loading/unloading terminals. The proper design and operation of this equipment protects life, property and the environment. They are designed to act as the last line of defense in overpressure protection.

The majority of Brazilian oil pipelines and loading/unloading terminals employ PRVs of the spring-loaded type. These are purely mechanical devices which are activated when the internal pressure in the pipeline rises above a pre-determined set point and forces a spring-loaded disc to displace, allowing fluid to flow through the relief line, thereby decreasing the pressure level in the pipeline.

Figure 1 presents an illustration of the expected pressure behavior at a specific position in a large liquid pipeline after the sudden blockage of the flow caused by the fast closing of a block valve. Following the blockage, the pressure, initialy at steady state level, P_{st}, rises sharply up to the surge pressure value, P_{surge}. After that, the pressure keeps rising but at a lower rate, depending on the pump characteristics and the initial fluid flow. If a PRV is used to protect such a pipeline, its dynamic characteristics should be compatible with the surge behavior. If the PRV's set point is located between the steady state and the surge pressure value, the response time of the PRV must be very fast, since the rate of pressure increase is high in this region. For set points above the surge pressure, the pressure rate increase is not so fast, and PRVs with slower response times can be employed.

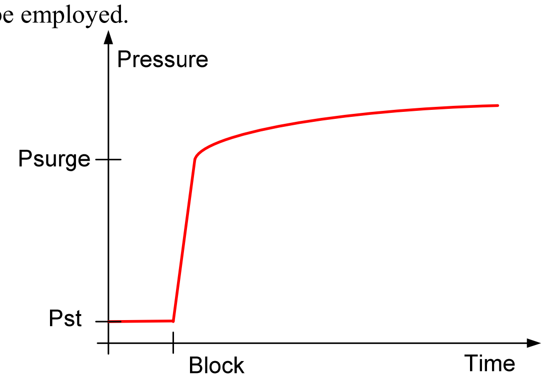

Figure 1 – Typical pressure rise caused by a fast closing of a pipeline block valve

As seen by the above exercise, a good understanding of the dynamic behavior of Pressure Relief Valves is of fundamental importance for the proper choice and operation of these devices. The equation that defines the dimensions of relief valves is specified in the standards ASME section VIII and API 520 [1], and relates the valve geometric characteristics, fluid properties and the square root of the differential pressure, as indicated in eq(1). Thus,

$$A = \frac{11{,}78\,Q}{K_d\,K_w\,K_c\,K_v}\sqrt{\frac{G_l}{P_1 - P_2}} \qquad (1)$$

Where,

- A is the required effective discharge area, (mm^2);
- Q is the flow rate, (liters/min);
- K_d is the coefficient of discharge that should be obtained from the valve manufacturer. For preliminary sizing, an effective discharge coefficient can be used as follows: 0,65 when a PRV is installed with or without a rupture disk in combination, 0,62 when a PRV is not installed and sizing is for a rupture disk.
- K_w is the correction factor due to backpressure. If the backpressure is atmospheric, a value of K_w equal to 1 should be used.
- K_c is the combination correction factor for installations with a rupture disk upstream of the PRV. It should be equal to 1, when a rupture disk is not installed, and equal to 0,9, when a rupture disk is installed in combination with a PRV and the combination does not have a certified value.
- K_v is the correction factor due to viscosity given by $K_v = \left(0{,}9935 + \frac{2{,}878}{Re^{0,5}} + \frac{342{,}75}{Re^{1,5}}\right)^{-1,0}$, *Re* is the Reynolds number.
- G_l is the specific gravity of the liquid at the flowing temperature referred to water at standard conditions
- P_1 is the upstream relieving pressure, (kPag). This is the set pressure plus allowable overpressure
- P_2 is the backpressure, (kPag).

It should be mentioned that equation (1) is valid for steady state conditions and there is no standard available to guide the specification of relief valves for transient operation conditions. As will be demonstrated in the present work, the knowledge of the discharge coefficient during the opening of the valve is a key piece of information to allow for the proper prediction of the valve behavior and its impact on the transient pressure in the pipeline. The relationship between the discharge coefficient and the valve opening fraction is dependent on the particular valve design, and it is information not readily available from valve manufacturers.

The API 520 standard [1] classifies the pressure relief valves in three different categories, according to its activation method: spring type, pilot operated and others. Figure 2 presents schematic views of spring-type pressure relief valves, the focus of the present work. Spring-type PRVs are available with or without a bellow. One of the purposes of the bellow is eliminate the effect of the backpressure on the disc and on the pressure set point.

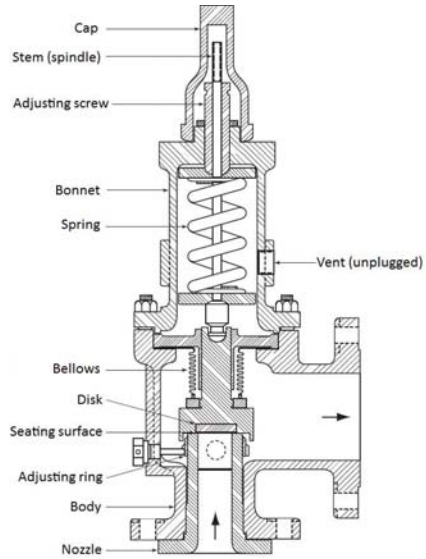

Figure 2 – Pressure relief valve with bellows (API 520 [1])

Although the dynamic behavior of a PRV is strongly influenced by its geometric configuration and dimensions, a simplified geometry, as shown in Figure 3, was considered for the development of a mathematical model [2]. The simplified system is composed of a spring, a cap or disc and an input flow pipe (valve wall)

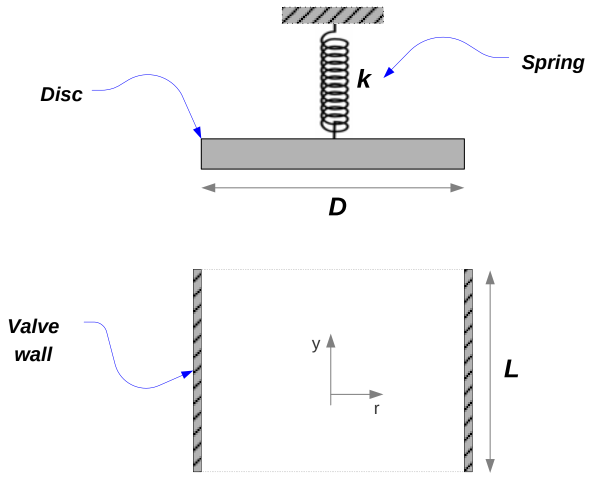

Figure 3 – PRV simplified geometry

TRANSIENT FLOW SIMULATION

The dynamic behavior of a Pressure Relief Valve depends not only on the characteristics of the valve itself, but on its interaction with the transient flow in the pipeline system. In the present work, the dynamic behavior of the PRV was modeled in conjunction with the transient flow in the test. The commercial software Stoner Pipeline Simulator (SPS) developed by GL Noble Denton, was utilized to model the PRV and the flow loop. As other transient pipeline flow simulators, SPS solves the one-dimensional formulation of the conservation laws (mass conservation, linear momentum and energy) using a finite-difference technique. The SPS software has a built in PRV model, but the software documentation shows [3] it works in a very simplistic way. In order to improve the models available, this paper has developed three different models of a spring type PRV to work coupled to the SPS [4]. These models are based on the adaptation of a PID-actuator-control valve system present in the SPS, to represent a spring-mass-damped system with the characteristics of the valve in question.

From Figure 3, the simplest mathematical model that can represent the PRV is a mass-spring-damped system, mathematically described by Eq. (2):

$$m\ddot{y} + c\dot{y} + k(y + y_0) = f(t) \tag{2}$$

Where

m	mass of the moving parts, disc + shaft (kg);
c	system damping coefficient (kg/s);
k	elastic spring constant (N/m);
$f(t)$	external force (N);
y_o	initial disc displacement (m);
y	disc displacement (m).

The actuator model in the SPS is represented by the differential equation:

$$A_3\ddot{y} + A_2\dot{y} + A_1\big(y - X(V)\big) = 0 \tag{3}$$

Where y is the real position and X(V) is the position where the actuator should be, based on the output signal (V) from the PID controller. The proposed model is based on the similarity between equations (2) and (3).

The PID output signal voltage, V(t), is calculated by:

$$\mathrm{V(t)} = \mathrm{K_c}\left[E(t) + T_D E'(t) + \left(\frac{1}{T_I}\right)\int_o^t E(t)dt\right] + V_s \tag{4}$$

where K_c is the controller gain, T_I is the reset time, T_D is the derivative time, V_s is the bias, and E(t) is the error, calculated by:

$$\mathrm{E(t)} = \frac{\mathrm{C(t) - S(t)}}{\mathrm{NC}} \tag{5}$$

where C(t) is the pipeline pressure, S(t) is the pressure set point and NC is a normalization constant. If the following set of values were used: $T_I = 0$, $T_D = \infty$, $V_s = 0$, the output signal will be proportional to the pipeline pressure.

The SPS software solves the actuator second order differential equations at each time step, having as input data A_1 the elastic spring constant (k), A_2 the system damping coefficient (c) and A_3 the mass of the moving parts (m). The valve discharge-coefficient versus opening-fraction curve is entered as the control valve data and is obtained experimentally [5].

- **Model 1**

This model is based on the equation that governs the behavior of the displacement of a spring-mass-damped system, considering the difference between the internal pressure of the pipeline and the set point pressure of the PRV as the only terms acting for the displacement of the moving parts. Thus,

$$m\ddot{y} + c\dot{y} + ky = A(P_a - P_{SP}) \tag{6}$$

where,

A	Valve inlet area, (m^2);
P_a	valve inlet pressure (Pa);
P_{SP}	valve set point pressure (Pa);

- **Model 2**

This model is based on the API 520 standard [1] determinations where it is stated that, for a certified valve, relief flow must be achieved without surpassing the upstream pressure by 10% of the set point pressure. So, this model considers that the valve would be completely open for an upstream pressure of $1.1P_{SP}$.

- **Model 3**

This model is based on the resulting equation for force acting on the PRV disk combined with the application of the principle of conservation of linear momentum in the control volume inside the PRV [2]. The resulting equation was simplified to enable it to be implemented in the SPS software. Thus,

$$m\ddot{y} + c\dot{y} + ky = \left(2{C_D}^2 A(P_a - P_{BK}) + (P_a - P_{SP})A\right) \quad (7)$$

where,

C_D	Discharge coefficient (Pa);
P_{BK}	valve backpressure (Pa).

All three formulations of the PID-actuator-control valve system, adapted to work as a PRV, were modeled in the software through the use of the available resources in SPS. The devices described in the "Experiments section" with all its characteristics were also modeled in SPS, in order to represent the real situation, in which the data used in the comparisons were obtained.

EXPERIMENTS

Figure 4 presents a schematic view of the test section designed and constructed to conduct the experiments to determine the dynamic behavior of a commercial pressure relief valve [6]. The flow loop was fabricated from 2-inch galvanized steel pipe with a total length of 8 meters. A centrifugal pump was used to circulate water through the loop from an elevated, 150-liters tank. A globe valve was used to control the flow rate in the loop. The spring-loaded pressure relief valve to be studied was installed at a T junction located five meters downstream from the pump. A 2-inch ball valve was installed just downstream of the T junction to block the flow and produce the pressure transient necessary to activate the relief valve. This block valve was motorized to allow for its closing time to be consistently controlled. After passing through the block valve the flow returned through the main line directly to the tank. An electromagnetic meter was installed in the return line to measure the steady state flow rate. When the flow was blocked and the PRV was activated, the flow was diverted through the PRV to a relief line of the same diameter as the main line. A turbine flow meter positioned in the relief line was used to measure the transient relief flow rate.

Two fast-response pressure transducers were installed upstream and downstream of the PRV to monitor the transient pressure difference across the valve. A displacement transducer of the LVDT type was connected to the shaft of the valve that, in turn, was connected to the valve disc. This transducer furnished the transient position of the disc during the action of the valve. A high data acquisition rate system was employed to register the pressure, position, and flow rate data.

The PRV tested was dimensioned using the API 520 standard [1] for a flow rate of 3.7 m^3/h at a set point pressure of 2.0 kgf/cm^2 and a back pressure of 0.2 kgf/cm^2. The area of the orifice was equal to 70.97 mm² or 0.110 in², and the connecting flange was 1-in in diameter.

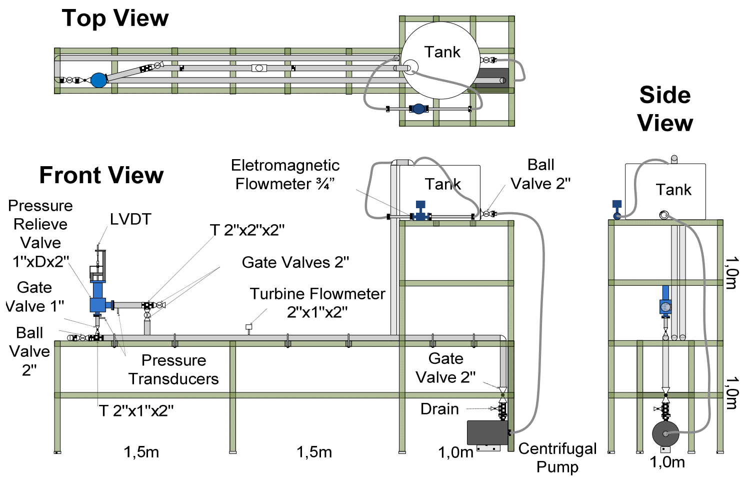

Figure 4 – Schematic view of the experimental test section

RESULTS

The results obtained in the present study will be presented in this section. The presentation starts with a description of the procedure developed to obtain the flow characteristics of the pressure relief valve, represented by the steady state and transient discharge coefficients. Following that, a comparison between the experimental data and the numerical predictions obtained for the three valve models developed is presented.

Steady State Discharge Coefficient

The discharge coefficient, C_d, for the pressure relief valve during steady flow was determined for different flow rates and valve openings. For this purpose, the shaft connected to the valve disc was fixed at different positions, ranging from fully open to 10% open. For each position, five values of the steady sate flow rates were tested, namely, 2, 2.5, 3, 3.5 and 4 m^3/h. The upstream and downstream pressure values were registered and the discharge coefficient was calculated by using equation (8). In this equation the area, A, was taken as 70.97mm², and the water density, ρ, as 998 kg/m^3. In the equation, Q_s is the volumetric flow rate through the valve and, P_a and P_o are, respectively, the upstream and downstream pressures measured by the transducers.

$$Q_s = C_d A \sqrt{2\frac{(P_a - P_o)}{\rho}} \quad (8)$$

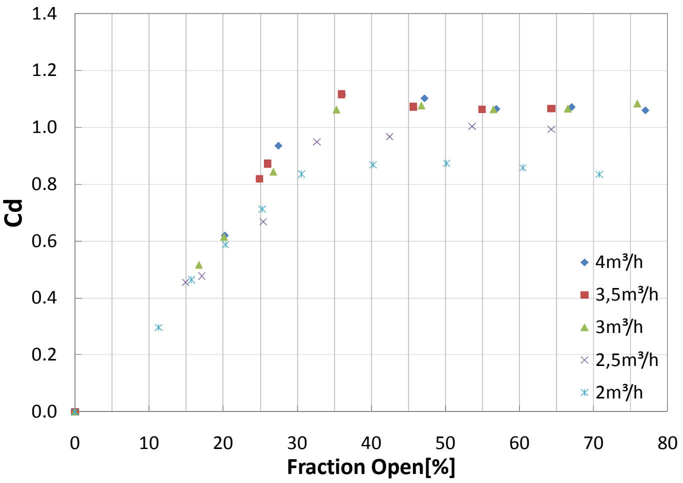

Figure 5 – PRV discharge coefficient versus opening fraction at steady state condition

Figure 5 presents the experimental results obtained for the PRV's discharge coefficient as a function of valve opening fraction, for the different flow rates indicated in the figure. The tests were conducted for the steady state regime, as already mentioned. The results presented indicate that a linear dependence between the discharge coefficient and valve opening exists for opening fractions up to 35%. Further, it is seen that in this region of the curve there is practically no dependence on the flow rate. Beyond the 35% opening fraction, the discharge coefficient is seen to level off and an influence of the flow rate can be observed, especially for the lowest value of the flow rate tested. A possible explanation for this dependence of the flow rate comes from the fact that the flow over sharp-edged bodies, such as the valve disk, tends to present drag coefficients that are practically insensitive to higher flow rates (or to Reynolds number) since the flow separation points are normally fixed at the location of the body's sharp edge. The separation points, however, can move along the disc for lower flow rates (or lower values of the Reynolds number) changing the drag offered by the disc that, in turn, determines the discharge coefficient.

Transient Discharge Coefficient

The instantaneous data measured for the upstream and downstream pressures, relief flow rates and valve opening fractions allows the determination of the transient valve discharge coefficient. The comparison of the transient and steady state discharge coefficients constitutes valuable information for the dynamic simulation of PRVs.

Although the response time of the pressure and displacement transducers employed was considered adequate for the experiments conducted, the turbine flow meter employed for measuring the relief flow rate displayed a time-response slower than what was considered necessary to resolve the initial stages of the transient flow rate measurements. It was verified that the turbine flow data indicated a zero reading when the displacement transducer was indicating that the valve was open and the pressure transducers, at the same instant of time, indicated a differential pressure variation across the valve. This finding was an indication that the inertia of the turbine meter did not allow it to respond to the initial stages of the transient flow. The observation of the displacement and pressure data indicated that this time delay of the turbine meter was of the order of 40 ms.

Figure 6 presents the results obtained for the transient discharge coefficients associated with the PRV tested. The figure presents the value of the coefficient as a function of the opening fraction for a flow rate of 3.7 m^3/h. The transient was generating by closing the block valve in 1.5 s. The steady state discharge coefficient is plotted in the figure for comparison purposes. Two transient discharge coefficients are plotted in the figure. The curve to the right refers to the actual data measured in the experiments. The curve to the left was determined by correcting the flow data by the 40 ms time delay mentioned above.

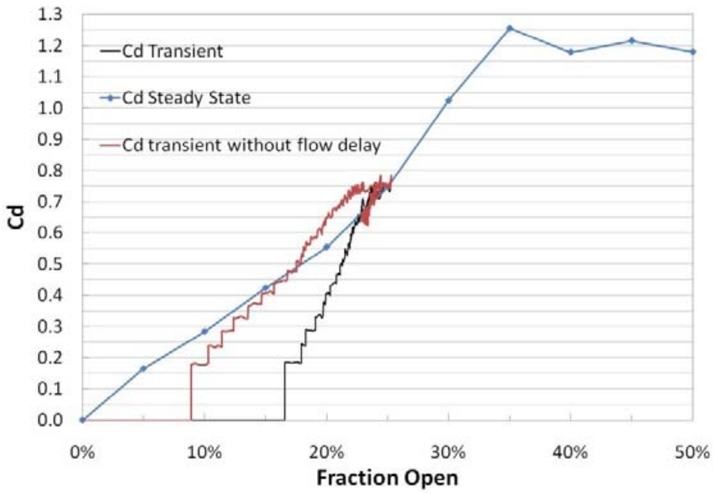

Figure 6 – PRV discharge coefficient for steady state and transient flow conditions

An analysis of the data presented in Figure 6 leads to useful information. A remarkable agreement can be observed between the transient and steady state values of the discharge coefficient, after the time delay correction is applied. This is an indication that the steady state discharge coefficient can be used to model the dynamic behavior of pressure relief valves. Experiments for the determination of steady state values of discharge coefficients are much easier to conduct and require less expensive equipment. This finding needs to be supported by additional experimental data for other flow rate values and for others transients levels generated by closing of the block valve with different times. These experiments are presently being conducted in our laboratory.

Comparison of Experimental and Numerical Simulation Results

This section presents the main results of this study, namely, the comparisons of the dynamic behavior of the tested PRV, obtained from the experiments and the numerical simulations.

To obtain the following results, the numerical models had as input data, the characteristic parameters of the relief valve and peripheral devices. This information was collected from the data sheets provided by each of the equipments' manufacturers. The combination of this set of parameters, associated with the control loop adjusted to work as a spring-loaded relief valve, define the dynamic behavior and, consequently, the opening time of the PRV.

The comparisons are presented in Figures 6 to 14, respectively for upstream pressure, relief flow rate, and valve opening fraction, for each model developed, as shown in the "transient flow simulation" section. These data were obtained from a closing operation of a block valve positioned in the pipeline downstream of the PRV, closing in of 0.2 s, at an initial flow rate of 5.9 m³/h. In each figure, two curves are presented. One of them represents the experimental data obtained from the tests conducted, while the other is the numerical prediction obtained by employing the SPS software using the different simulation models for the PRV dynamics. These models employ an experimentally determined curve for the discharge coefficient as a function of valve opening, such as that presented in Figure 5. It's worth mentioning that tests were conducting without employing this curve presenting, however, a much lower level of agreement with the experiments.

Figures 7, 8 and 9 show the comparison between the data for the dynamic behavior of the PRV obtained experimentally and by simulations using Model 1. At steady state, the upstream pressure is constant up to the time when the block valve starts to close. The pressure is seen to increase sharply up to 3.5 kgf/cm^2 when the PRV starts opening, and then the pressures levels off at about 2.75 kgf/cm^2. The upstream pressure level after stabilization is higher than the initial value due to the fact that, after the blockage, all the flow passes through the PRV, which presents a higher pressure drop to the flow.

An observation of the results shown in Figure 7, indicates that the formulation of Model 1 shows good agreement with experimental data, predicting satisfactorily the peak pressure value, the decay rates of pressure upstream of the relief valve and the steady state pressure relief value. The formulation also provides good agreement with the oscillatory behavior of the flow, as well as its value at steady state, as seen in Figure 8. The lag in the position of the peak flow between experiments and model can be credited to the inertia of the flow meter turbine used to measure flow through the valve relief [6]. Figure 8 shows that the behavior of the opening fraction was also in good agreement with experiments.

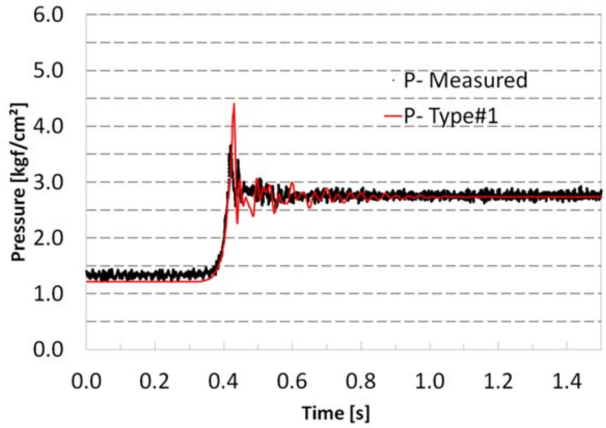

Figure 7 – Measured and Model 1 predicted upstream pressure values

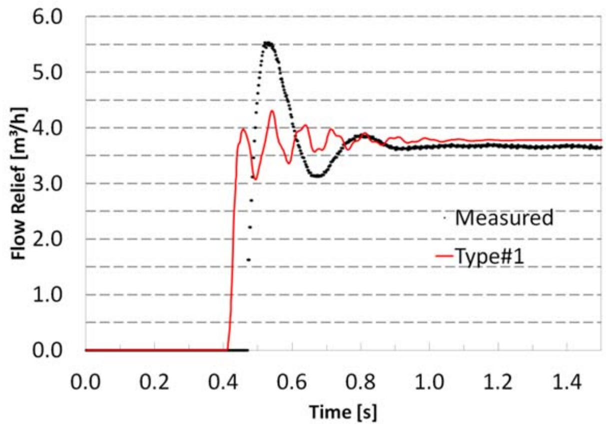

Figure 8 – Measured and Model 1 predicted relief flow rates

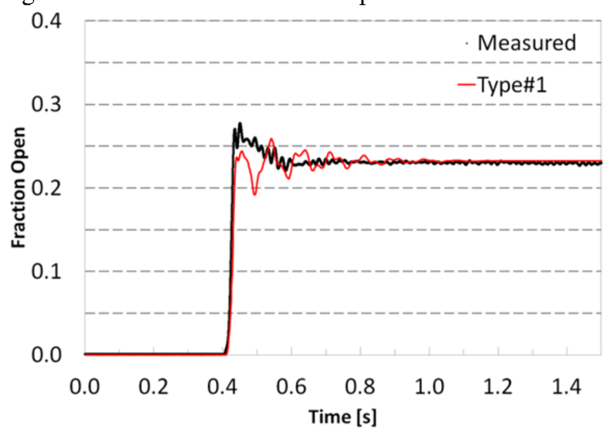

Figure 9 – Measured and Model 1 predicted valve opening fractions

Figures 10, 11 and 12 show the comparison between the dynamic behavior of the PRV obtained experimentally with that predicted by simulations using Model 2.

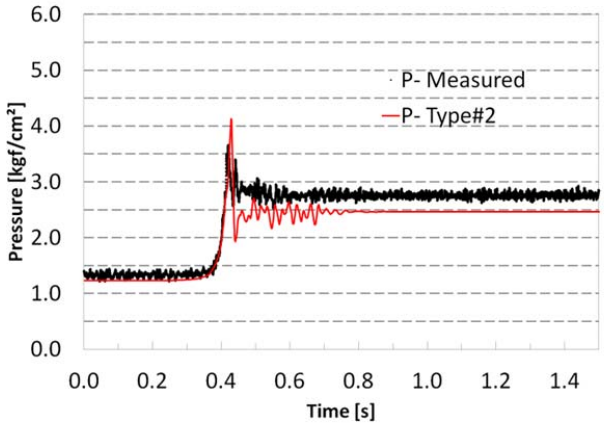

Figure 10 – Measured and Model 2 predicted upstream pressure values

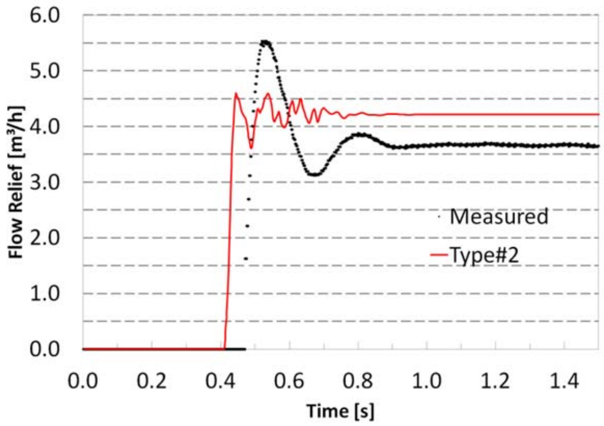

Figure 11 – Measured and Model 2 predicted relief flow rates

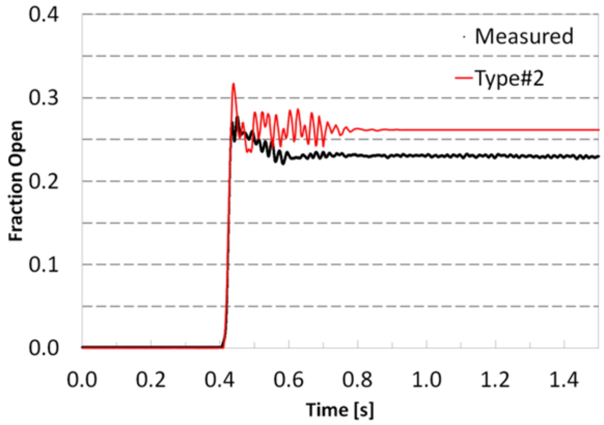

Figure 12 – Measured and Model 2 predicted valve opening fractions

The results of Figure 10 show that simulation using Model 2 provide reasonable agreement with the experimental data, predicting satisfactorily the value of the peak pressure and the decay rates of the pressure upstream of the relief valve. However, steady state values of pressure relief levels are under predicted with respect to the experiments. This is probably due to the overestimation of the forces acting to open the valve. as seen in Figure 12. As a consequence, steady state relief flow values appear at a level above that obtained from the experiments.

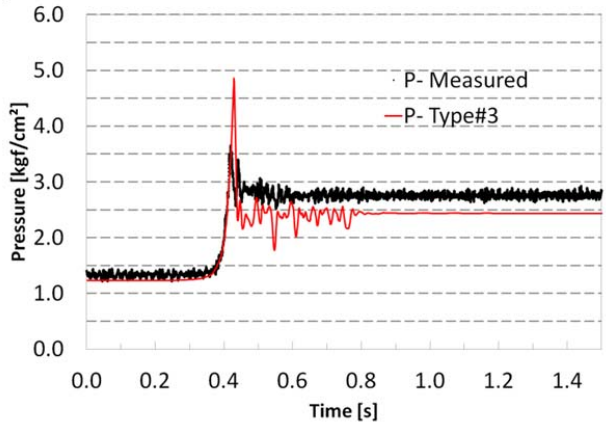

Figure 13 – Measured and Model 3 predicted upstream pressure values

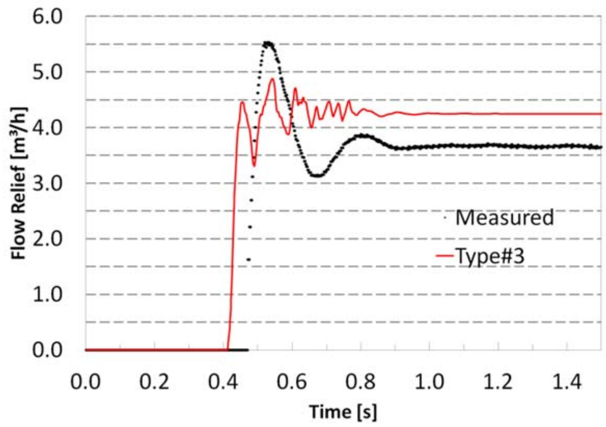

Figure 14 – Measured and Model 3 predicted relief flow rates

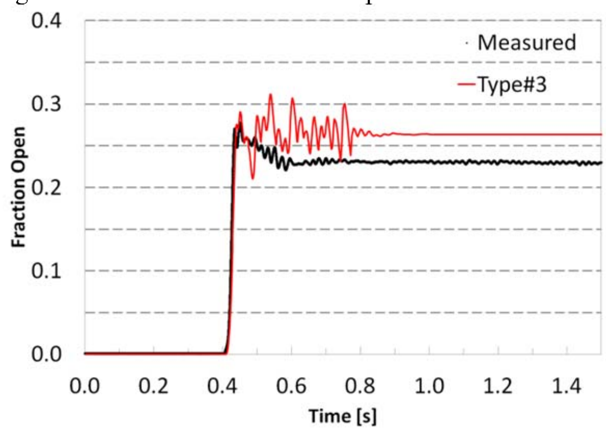

Figure 15 – Measured andModel 3 predicted valve opening fractions

Figures 13, 14 and 15 show the comparison between the data of dynamic behavior of the PRV obtained experimentally and by simulations using Model 3.

The results displayed in Figure 13, indicate that simulations using Model 3 present a reasonable agreement with the experimental data, predicting satisfactorily the decay rates of the upstream pressure relief valve. However, the amplitude of the peak pressure was overestimated. The steady state pressure relief value is predicted to be at a lower level than the measurements while the steady state relief flow values are over predicted. This is due to overestimation of the forces acting to open the valve, as seen in Figure 15.

As mentioned in the “transient flow simulation” section, SPS has among its available features, a generic pressure relief valve model. Due to its wide use in industry, comparisons were made between PRV’s behavior data obtained from the model proposed by the SPS simulator, and Model 1 developed in the present work, since this model presented the best agreement with experiments. Figures 16, 17 and 18 show this comparison.

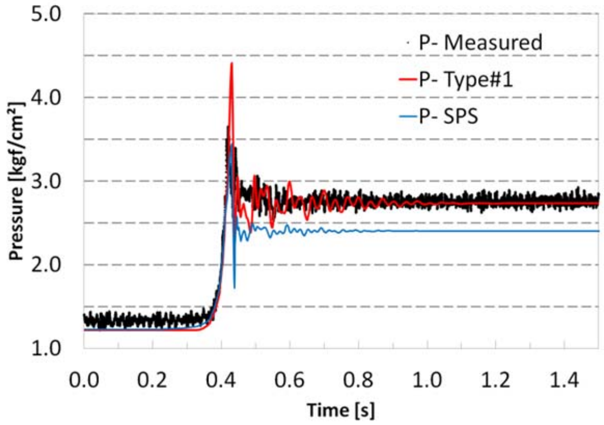

Figure 16 – Measured, Model 1 predicted and sps predicted upstream pressure values

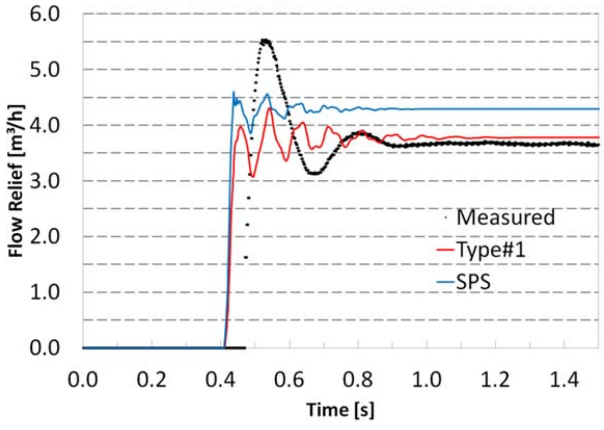

Figure 17 – Measured and Model 1 predicted relief flow rates

The results of Figure 16 indicate that the model proposed by SPS shows reasonable agreement with the experimental data, predicting satisfactorily the value of the peak pressure and the decay rates of the upstream pressure relief valve. However, the steady state pressure relief values are under predicted with respect to the experimental values. The SPS model captures the oscillatory behavior of relief flow, however, the steady state value is predicted to be at a higher level, as seen in Figure 17.

In Figure 18 one can note that the amplitude of the valve opening fraction was strongly overestimated, stabilizing close, but, above the experimentally determined values.

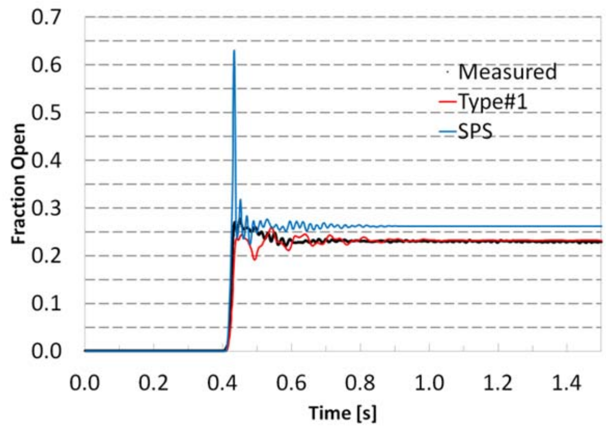

Figure 18 – Measured and Model 1 predicted valve opening fractions

The results presented indicate that a better prediction of the real dynamic behavior of the PRV was obtained using the developed Model 1. A positive characteristic of this model is the use, as input parameters, of the physical properties and the hydraulic characteristics of the real valve being modeled.

CONCLUSIONS

The present paper has analyzed the dynamic behavior of a spring-type pressure relief valve. In the experimental part of the work a commercial valve was mounted in a flow loop where transient flows of different intensities could be imposed by controlling the closing time of a block valve positioned downstream of the pressure relief valve tested. The valve and the flow loop were instrumented so as to allow the measurement of relevant transient quantities, namely, pressure difference across the valve, relief flow rate and valve opening fraction. A commercially available software was employed for simulating the transient pipeline flow in the test loop, including the pressure relief valve dynamics. The software offers users a generic PRV model to simulate the valve behavior, where a control strategy is used to sense the transient pressure level in the pipeline, compare it with the user input valve pressure set point and activate the valve opening and control its dynamic behavior. The generic valve model available utilizes a linear relationship between valve discharge coefficient and valve opening fraction. Alternatively, the software allows for the input of an experimentally determined relationship between valve opening and discharge coefficient.

Experimental results were obtained for the valve discharge coefficient as a function of the valve opening fraction for steady state and transient flow conditions. A comparison of these two discharge coefficients displayed a remarkably good agreement. This is an important finding that allows the utilization of discharge coefficients measured at steady state conditions, for transient applications. Steady state measurements of discharge coefficients are easier and cheaper to perform.

In order to represent the dynamic behavior of a spring type PRV, three different models were developed to work using the resources of the SPS. These models were implemented by the adjustment of a PID-actuator-control valve system to represent a PRV, based on physical principles, especially the classic formulation of a mass-spring-damped system. All the proposed models received the characteristics information of the relief valve in question as input parameters. In order to validate the proposed models, comparison of the experimental result and the numerical prediction for upstream pressure, relief flow rate and valve opening fraction as a function of time were performed. The comparisons indicated that models incorporating characteristics information of the relief valve in question have satisfactory performance, being able to predict the transient behavior of variables such as the relief flow, the valve opening fraction and the pressure in the line. Among the models studied, stands out the formulation of Model 1, for the accuracy in predicting the real behavior of the relief valve and showing better results than other models, including the one proposed by the commercial software.

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