Overfilling Protection for Weak Tanks

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Prepared for Presentation at
American Institute of Chemical Engineers
2015 Spring Meeting
11th Global Congress on Process Relief
Austin, Texas
April 27-29, 2015

UNPUBLISHED

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Keywords: overfilling protection**,** pressure vacuum relief valves, atmospheric tanks, weak tanks

Abstract

In this paper the use of pressure relief valves for protection against overfilling is discussed. Two practical approaches are herein discussed and their strengths are pin-pointed. The validation against measurements with two PROTEGO® relief valves has been successful for both methods. Nevertheless, further research should be done on this topic.

1. Introduction

The protection of near atmospheric or low pressure non-refrigerated aboveground tanks with a design pressure of 15 psig (1.034 bar-g) or below from overpressure due to overfilling by using low pressure relief valves is discussed in this paper. Low pressure relief valves are normally sized for gas flows according to API 2000 [1] and are generally installed at the top of the non-refrigerated tanks. Indeed, API 2000 suggests other solutions for liquid overfilling, like the installation of two repairable level sensing instruments and an independent actuator to close the filling valves and it refers to API RP 2350 [2] for full details.

However, electrical transducers and actuators must be maintained accurate by regular calibration and inspection as specified in API RP 2350, which may be a burden especially for remote tanks, where relief valves are usually already installed. In this context it may be conceivable to use the low pressure relief valve to discharge the liquid overfilling so that acceptable accumulation can be built up in the tank. This solution can be considered as an independent additional measure of protection for the case that the filling sensors are not recently calibrated or the electricity supply to them is interrupted. Indeed, one of the main hindrances in the application of low pressure relief valves for the prevention of liquid overfilling is the paucity of available data to estimate even roughly if an available valve would suffice to prevent overfilling.

In this paper the authors offer two simple and immediate approaches to estimate the liquid capacity of low pressure relief valves. The accuracy of the predictions is compared against measurements performed with two PROTEGO® valves at an independent testing partner. One approach is applicable when little information is available about the pressure relief valve and general literature data must be used, while the second approach may be useful when the air capacity of a selected valve is available.

2. Experimental background

PROTEGO® has several years of experience and a large database of dedicated water capacity measurements through flame arresters and low pressure relief valves.

In accordance with PROTEGO® policy the liquid flow capacity of low pressure relief valves is tested at the facility of an independent partner, Dr.-Ing. T. Bäumer GmbH. Additionally, the flow coefficient K_v is calculated from the measured capacity at each opening pressure in agreement with IEC 60534-2-3 [3] for non-choked turbulent flows using the formula in Eq. 1.

$$K_v = N_{water} \cdot Q \cdot \sqrt{\frac{\rho_1/\rho_0}{\Delta p}} \quad \text{with} \quad N_{water} = 1 bar^{-0.5} \quad \text{[Eq. 1]}$$

In Eq. 1 Q is the volumetric flow rate measured at a certain difference between opening and back pressure, Δp, for a medium of density $\rho_{1,}$ and ρ_0 is the density of water at 15°C (60°F). The constant N is adopted for dimensional correctness and is numerically equal to one for pressure drops given in bar. The opening pressures and the flow coefficients of end-of-line PROTEGO® valves VD/SV DN50 (2 in.) and DN80 (3 in.) at a set pressure of 20 mbar (8 in. WC) gauge and atmospheric discharge are reported in Table 1 for increased water flow capacity. From that table it can be seen that the flow coefficient K_v always reaches an asymptote.

Table 1. Measured opening pressures and calculated flow coefficients of PROTEGO® valves VD/SV DN50 and DN80 at several water capacities at a set pressure of 20 mbar-g.

	VD/SV DN50		VD/SV DN80	
Water capacity [m³/h]	Opening pressure [mbar]	Kv [m³/h]	Opening pressure [mbar]	Kv [m³/h]
10	24	64.5	25	63.2
20	38	102.6	26	124.0
30	77	108.1	29	176.2
40	135	108.9	32	223.6
50	241	101.9	38	256.5
60	298	109.9	48	273.9
70	405	110.0	64	276.7
80	539	109.0	83	277.7
90	657	111.0	105	277.7
100	812	111.0	129	278.4

The test apparatus is schematically described below.

2.1 Description of the test rig

The test facility for the flow capacity measurement of low pressure relief valves is reproduced in Fig. 1a. Water is pumped out from a 1 m^3 (35.3 ft^3) collection tank to the test valve from where it either flows back to the tank or is discharged in the sewers. The distances of the pressure sensors from the valve are in agreement with IEC 60534-2-3 [3]. A temperature sensor is located upstream from the valve to calculate the medium density ρ_1. The volumetric flow capacity is measured with a magnetic inductive mass flow meter in position FIR II.

The accuracy of instrumentation meets the requirements of IEC 60534-2-3, namely for the thermometers ± 1°C (± 1.8°F) and for the flow meter within 2 % of the measured value.

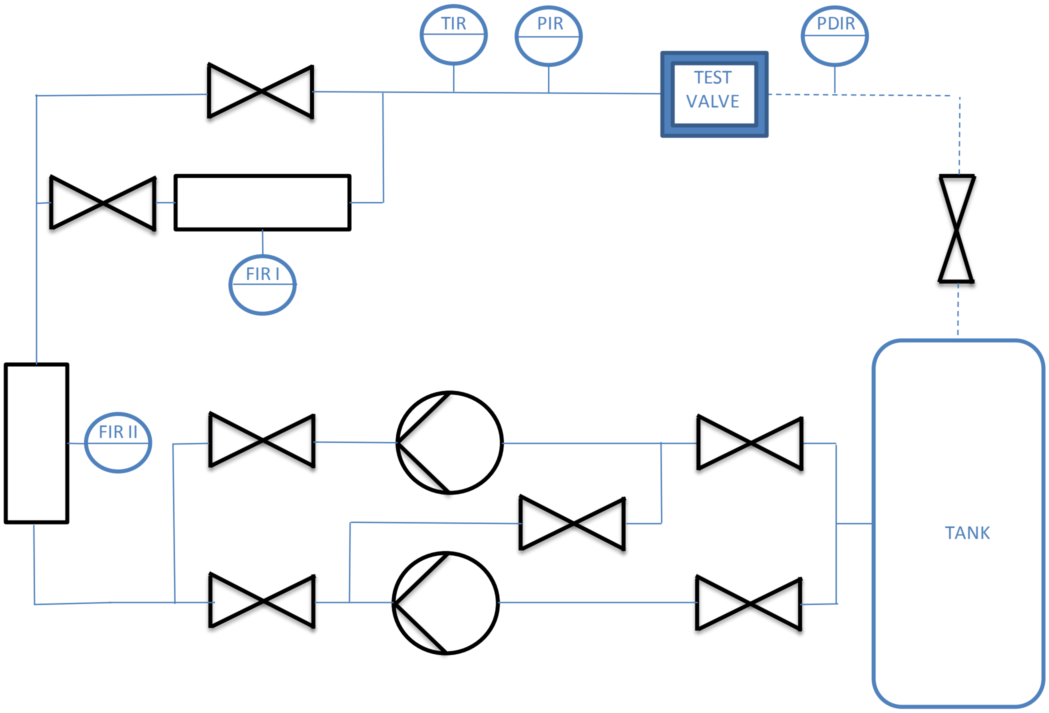

Fig. 1a. Test rig for measurement of relief valves water capacity.

Fig. 1b VD/SV tested with water

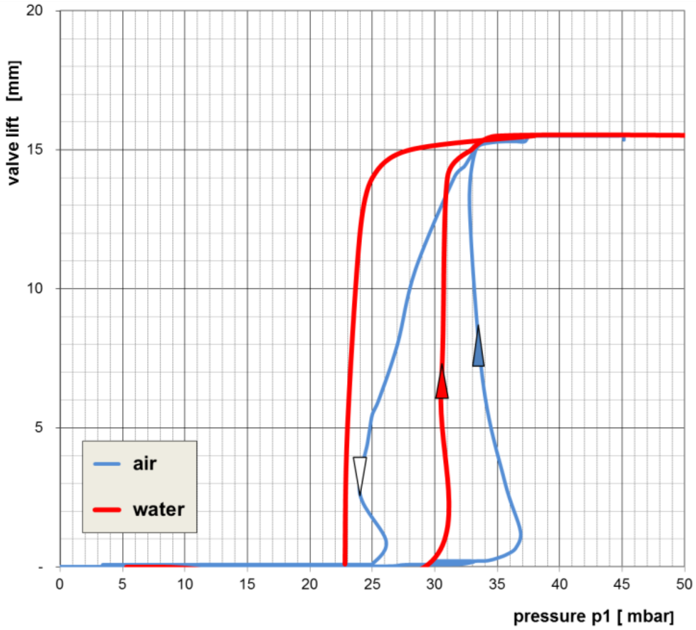

Fig. 1c. Example of Valve function test

2.2 *Valve function*

PROTEGO® relief valves start to open at the set pressure and require 10 % overpressure to achieve full lift. The full lift type technology allows the valve to be set just 10% below the maximum allowable pressure in the tank or equipment.

The opening characteristic is well defined for gas and vapors. But, does the relief valve, like the one in Fig. 1b, show the same characteristic for liquid flows? For any capacity estimation or calculation the valve characteristic curve should be known. To verify the valve characteristic curve the same test apparatus as given in Fig. 1a was used. The valve pallet was equipped with a distance sensor as a lift meter, which was used to indicate the position of the valve pallet, so that the sensor reads zero, when the valve is closed.

Figure 1c shows the lift as a function of tank pressure for air and water. The full lift type valve with a set pressure of 30 mbar-g (12 in. WC-g) shows a hysteresis, with different curves for the opening (pallet moving upwards) and closing (pallet moving downwards) of the valve. The valve opens with an overpressure of 10% for both air and water. For Newtonian liquids with a viscosity close to water, the opening characteristic of full lift relief valves is similar to that of gaseous fluids.

3. Approach using literature data

There are currently limited methods for sizing low pressure relief valves for liquid flow. The method in this section is a quick calculation to estimate the liquid flow through low pressure relief valves based on conventional techniques readily available for engineers at their disposal. A step-by-step approach is suggested and the reader is cautioned to follow all local and federal regulations, and internal company guidelines. Standard formulae are available for performing hydraulic analysis and engineers use a variety of tools at their disposal.

This method is based on first estimating the ideal flow capacity of a relief valve using available methods. The ideal flow capacity is then compared with experimental test data to correlate the calculation and test results. A correction factor is proposed as a function of the percentage overpressure and multiplied by the ideal flow capacity to obtain the corrected flow rate values. The correction factor is generated for both United States Customary System (USCS) and metric units. This is an extension of a previous work already presented at the DIERS User Group Spring 2014 Meeting [9].

3.1 Calculating flow coefficient

Relief system designers often use flow curves or software provided by vendors to size low pressure relief valves for weak tanks. PROTEGO® sizing program offers flow curves for valves in the product catalog [4]. It is suggested to use standard control valve sizing equations to back calculate C_v, the flow coefficient of the valve [3], or control valve manufacturer’s method. Eq. 2 calculates the flow coefficient for a given pressure drop, upstream pressure P_{1a}, W flow rate of the pressure relief valve, and thermo-physical properties of the gas.

$$C_v = \frac{W}{39.612\sqrt{F_\gamma P_{1a}\rho_1}} \text{ [Eq. 2]}$$

The absolute upstream pressure, P_{1a}, should be evaluated 100% overpressure, i.e. at least two times the set pressure. At lower pressures the effect of the weighted pallets are more pronounced and the coefficients therefore need to be calculated at higher overpressures. Essentially at higher overpressure, the resistance of the weights becomes negligible and the valve can be treated as a pipefitting. However, the low pressure vents are typically used for low pressure tanks that have design pressure less than 15 psig.

In addition to the above constraints, the design pressure of the tank is defined at the tangent line and a relief system designer must consider the effects of static head especially for liquid flow through the relief valve. The resulting relief pressure is a combination of the static pressure at which sizing is done, the static head from tangent line to the seat of the atmospheric vent or top face of outlet flange on a pipe away model, and the velocity head to accelerate the fluid from tank nozzle to vent entrance. The relief pressure must not exceed the maximum allowable accumulation pressure of the tank. The capacity calculated using this method should exceed or equal the required capacity of the overpressure scenario.

The set pressure of such devices is typically well below the design pressure of the tank. Typical overpressures that are allowed for such valves range from 10% to roughly 200% of set pressure; see the paper of Moncalvo et al. on the effect of overpressure on valve performance [5].

3.2 Sizing Calculations

Hydraulic analysis of a piping system is a common practice and a day-to-day activity for engineers. CRANE Technical paper no. 410, published in both USCS and Metric units is a useful resource for engineers [6]. A basic review of the required methodology is highlighted here and is not all-inclusive. The pressure drop through valves, fittings, and pipe is calculated using,

$$\Delta P = 1.801 * 10^{-5} * \frac{K * \rho * Q^2}{d^4} \text{ USCS Units [Eq. 3]}$$

$$\Delta P = 225.2 \frac{K * \rho * Q^2}{d^4} \text{ Metric Units [Eq. 4]}$$

The total resistance to flow in the system is defined as a unit-less resistance coefficient, K. This is the sum of the valves, fittings, and pipes. For the purpose of this method, Eq. 4 is considered to be the ideal flow through the system and is next compared with experimental values to obtain a correction factor multiplier to estimate the corrected flow. The flow coefficient calculated using Eq. 1 can be converted to resistance coefficient using the following equations,

$$K_v = 0.865 * C_v \text{ [Eq. 5]}$$

$$K = 890.3 * \frac{d^4}{C_v^2} \text{ USCS Units [Eq. 6]}$$

$$K = 0.0016 * \frac{d^4}{K_v^2} \text{ Metric Units [Eq. 7]}$$

The diameter for the above equations can equal the throat diameter of the relief valve. Typically this can be considered equal to the inlet nominal pipe size of a low pressure relief valve.

3.2.1 Estimation of overpressure correction factor

The flow through the relief valve is affected by the weights of the pallet. At lower pressures the flow is lower than calculated ideal flow through a short piece of pipe. The flow coefficient is added as a resistance coefficient to find the actual resistance caused by the valve without additional resistance created by the weights. In addition to the above, a sharp edged conservative entrance plus the length from the vessel nozzle to the throat of the vent should be considered. In the example calculations shown below, the characteristic nozzle length of 12 inches was considered. The relieving fluid was water and its properties at standard conditions were incorporated for the calculations. The example calculations are shown for a DN80 (3-inch) VD/SV PROTEGO® relief valve in USCS units and the same approach was repeated in Metric units. Eq. 8 calculates K_p, the overpressure correction parameter. See Table. 2 for value of K_p for the given data obtained from flow test. Q_{est} for Table. 2 are calculated using Eq. 3 and Eq. 4 using an iterative calculation.

$$K_p = \frac{Q_{est}}{Q_{data}} \text{ [Eq. 8]}$$

Table 2. Estimated flow rate from Eq. 3 & Eq. 4 for a DN80 (3 inch) VD/DV relief valve

ΔP	% OP	Qest	Qdata	Kp	Qest	Qdata	Kp
[psi]	0%	[gpm]	[gpm]	[--]	[m^3 / hr]	[m^3 / hr]	[--]
0.363	25%	129	44	0.343	10	28.98	0.345
0.377	30%	131	88	0.672	20	29.58	0.676
0.421	45%	138	132	0.954	30	31.32	0.959
0.464	60%	145	176	1.211	40	32.88	1.216
0.551	90%	159	220	1.389	50	35.88	1.395
0.696	140%	178	264	1.482	60	40.32	1.489
0.928	220%	206	308	1.497	70	46.56	1.504
1.204	315%	234	352	1.502	80	53.04	1.509
1.523	425%	264	396	1.502	90	59.64	1.509
1.871	545%	292	440	1.506	100	66.12	1.513

Overpressure correction factor, K_p as a function of percent overpressure is shown in Figure 2 for both valves. A sum of least square method with a third order polynomial was regressed with a maximum constraint of 1.3 for the correction factor. This maximum constraint of 1.3 is chosen in order to obtain conservative flow rates, i.e. lower flow rates and is the lower bound. For higher overpressures the factor does not exceed 1.3 and is considered to be a conservative estimate. Figure 2 shows the Eq. 9 obtained by a sum of least squares method.

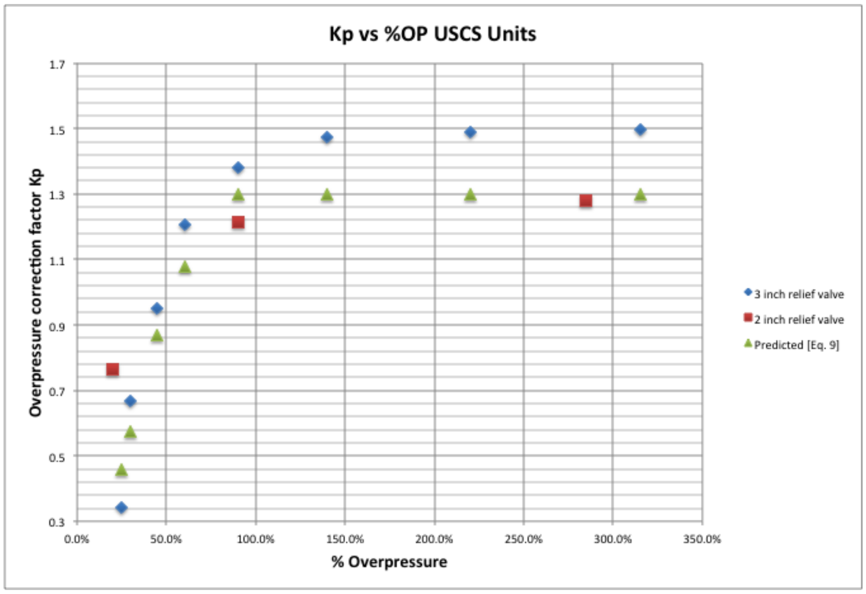

Figure 2. Overpressure Correction Factor Vs % Overpressure USCS Units

$$K_P = 0.577 * \%OP^3 - 2.595 * \%OP^2 + 3.645 * \%OP - 0.299 \text{ USCS Units [Eq. 9]}$$

$$K_P = 0.559 * \%OP^3 - 2.517 * \%OP^2 + 3.535 * \%OP - 0.25 \text{ Metric Units [Eq. 10]}$$

3.2.3 Equations for sizing low pressure relief valves

The correction factors are multiplied to Eq.3 and Eq. 4 to obtain the following equations that can calculate the flow through the relief valve as a function of pressure drop across the valve, throat diameter of the valve, density of fluid, and resistance coefficient.

$$Q = \sqrt{\frac{\Delta P * d^4}{1.801 * 10^{-5} * K * \rho}} * K_p \text{USCS Units [Eq. 11]}$$

$$Q = \sqrt{\frac{\Delta P * d^4}{225.2 * K * \rho}} * K_p \text{ Metric Units [Eq. 12]}$$

The flow capacities of the valves are calculated and compared with test data. Table 3 shows the values for both DN50 (2") and DN80 (3") valves along with error percentages. The Kp curve is modeled using a constraint of 1.3 to ensure that we do not over predict the capacity of the valve. The error percentages can be within a ± 7.5 % error if an unconstrained sum of least square method is performed. .

Table 3. Percentage flow error against measured data for PROTEGO® VD/SV valves

		VD/SV DN50 (2 inch)			VD/SV DN80 (3 inch)		
Qdata (gpm)	Qdata (m3 / hr)	% OP	Qerror (USCS)	Qerror (Metric)	%OP	Qerror (USCS)	Qerror (Metric)
44	10	20%	-57%	53%	25%	35%	40%
88	20	90%	7%	-6%	30%	-14%	-11%
132	30	285%	2%	-1%	45%	-8%	-8%
176	40	575%	1%	0%	60%	-11%	-11%
220	50	1105%	8%	-7%	90%	-6%	-7%
264	60	1390%	0%	1%	140%	-12%	-13%
308	70	1925%	-0.1%	1%	220%	-13%	-14%
352	80	2595%	1%	0%	315%	-13%	-14%
396	90	3185%	-1%	2%	425%	-13 %	-14%
440	100	3960%	-1%	2%	545%	-13%	-14%

The method proposed here seems to be a quick, accurate, and easy technique that can be easily adopted by process engineers for calculating liquid flow capacities through low pressure relief valves. The reader is cautioned not to use the above method in the range of overpressures below 30% as less conservative values are obtained. The estimated capacities for overpressures above

30% are within reasonable tolerances. The user is cautioned that this provides the relief capacity of the valve only and effects of static and velocity head must be accounted for in determining the adequacy of the entire relief system.

4. Approach using manufacturer's relief valve air capacity data

This experimental rule-of-thumb consists of finding a relationship between the capacity of air and water flowing through the valve.

In order to develop such a relationship a connection between the flow rates and the pressure drop through the device for both media must be derived. By a cross comparison among several manufacturers a polynomial relationship like the one in Eq. 13 between air capacity and pressure drop seems to fit the curves at best. In that equation the parameter K_{air} can be treated as the flow coefficient for air flows and the safety factor φ is a fitting parameter to consider the ratio between the certified and the measured flow capacity. If no exact value for φ is given by the manufacturer for the specific valve, it can be assumed equal to 1.1.

$$Q_{air} = \varphi \cdot N_{air} \cdot K_{air} \cdot \Delta p^{a} \quad \text{with} \quad N_{air} = 1\, bar^{-a} \quad \text{[Eq. 13]}$$

For water flows a similar polynomial relationship can be derived by adjusting Eq. 1 as shown in Eq. 14. For sake of simplicity, the flow coefficient can be assumed roughly constant and equal to the asymptotic value extracted from Table 1.

$$Q_{water} = N_{water} \cdot K_{water} \cdot \Delta p^{0.5} \quad \text{with} \quad N_{water} = 1 bar^{-0.5} \quad \text{[Eq. 14]}$$

In this case the flow coefficient for water is measured but that is not the case in the normal practice. The simplest method to estimate it is to consider that at near atmospheric pressures air tends to behave as a weakly compressible or almost incompressible medium. Therefore, on behalf of the ideal nozzle theory applied to safety valves as in ISO 4126 [4] or API 520 [8] the ratio of the flow coefficients is equal to the square root of the inverse of the density ratio, Eq. 15.

$$\begin{aligned} K_{water}/K_{air} &\approx N_{air}/N_{water} \cdot \varphi \cdot Q_{water}/Q_{air} \cdot \Delta p^{a-0.5} \\ &\approx N_{air}/N_{water} \cdot \varphi \cdot \sqrt{\rho_{air}/\rho_{water}} \cdot \Delta p^{a-0.5} \\ &\approx (\Delta p/bar)^{a-0.5} \cdot \varphi \cdot 0.03165 \quad \text{[Eq. 15]} \end{aligned}$$

For the two valves VD/SV DN50 and DN80 based on Eq. 15 the approximated water flow coefficients obtained from the TÜV certified air flow curves are respectively 105.7 and 231.2 Nm³/h, assuming the parameter *a* close to 0.5. The roughly estimated water flow coefficients are rather close to the measured ones, respectively 111 and 278 Nm³/h. based on the obtained water flow coefficients the water flow capacities are calculated using Eq. 3 and compared against the measured values of Table 1 in Table 4.

From Table 4 it can be easily seen that the proposed rule of thumb results in reasonable agreement with the measured water flow rates except for the range of very low opening pressures. The authors recommend for very low capacities to modify the control valve equation in Eq. 3 by considering a low capacity correction factor K_v, postulated in API 520 [8] or by Darby and Molavi [8] as shown in Eq. 16. A validation of this formula is still ongoing.

$$Q_{water} = K_{water} \cdot K_v \cdot \Delta p^{0.5} \quad \text{with} \quad N_{water} = 1 bar^{-0.5} \quad \text{[Eq. 16]}$$

Table 4. Measured vs. calculated water flow rates at several opening pressures for PROTEGO® valves VD/SV DN50 and DN80 at the set pressure of 20 mbar-g (8 in. WC-g).

	VD/SV DN50			VD/SV DN80		
Measured Water capacity [m³/h]	Opening pressure [mbar]	Calculated Water capacity [m³/h]	Error [%]	Opening pressure [mbar]	Calculated Water capacity [m³/h]	Error [%]
10	24	16.37	63.7%	25	36.56	265.6%
20	38	20.60	3.0%	26	37.28	86.4%
30	77	29.33	2.2%	29	39.37	31.2%
40	135	38.84	2.9%	32	41.36	3.4%
50	241	51.89	3.8%	38	45.07	9.9%
60	298	57.70	3.8%	48	50.65	15.6%
70	405	67.27	3.9%	64	58.49	16.4%
80	539	77.60	3.0%	83	66.61	16.7%
90	657	85.68	4.8%	105	74.92	16.8%
100	812	95.25	4.8%	129	83.04	17.0%

	VD/SV DN50			VD/SV DN80		
Measured Water capacity [gpm]	Opening pressure [psi]	Calculated Water capacity [gpm]	Error [%]	Opening pressure [psi]	Calculated Water capacity [gpm]	Error [%]
44.03	0.348	72.07	63.7%	0.363	160.97	265.6%
88.06	0.551	90.70	3.0%	0.377	164.14	86.4%
132.09	1.117	129.14	2.2%	0.421	173.34	31.2%
176.11	1.958	171.01	2.9%	0.464	182.10	3.4%
220.14	3.495	228.46	3.8%	0.551	198.44	9.9%
264.17	4.322	254.05	3.8%	0.696	223.01	15.6%
308.20	5.874	296.18	3.9%	0.928	257.52	16.4%
352.23	7.818	341.66	3.0%	1.204	293.28	16.7%
396.26	9.529	377.24	4.8%	1.523	329.86	16.8%
440.29	11.777	419.37	4.8%	1.871	365.61	17.0%

5. Conclusion

In this paper two approaches for the prediction of water capacity in case of overfilling are presented, either assuming the availability of certified or published values for the air capacity of pressure vacuum valves or using literature data. Both methods have been compared with measurements of water capacity done with two PROTEGO® pressure relief valves and both approaches delivered reasonable agreement. The user is cautioned that calculation of the venting capacity at the maximum tank venting pressure must include the static and velocity head due to the flow of the fluid. The limits of application of the two methods proposed here are at the moment under investigation.

Future work would be to further test both approaches with additional types of pressure relief valves to broaden the range of applications. Nevertheless, the authors still recommend to contact the valve manufacturer for dedicated certified water capacity measurements.

6 Notation

Notation	USCS Units	Metric Units
Mass flow rate, W	Lbs_m/hr	Kg/h
$F\gamma$, Specific heat ratio factor	Dimensionless	Dimensionless
X_T, Pressure differential ratio factor	Dimensionless	Dimensionless
Upstream pressure, P_{1a}	Psia	Pa
Static pressure at valve inlet, P_1	psig	Pa-g
Flow coefficient	Cv = GPM of water per psi pressure drop	Kv = cubic meters per hour at a pressure drop of one kilogram per square centimeter.
Pressure drop, ΔP	Psi	Pa
Resistance Coefficient, K	Dimensionless	Dimensionless
Volumetric flow rate, Q	Gpm (US)	Liters per minute (lpm)
Density of fluid, ρ	Lb_m/ft^3	Kg/m^3
Diameter of piping system, d	Inches	Millimeter
Overpressure correction factor	Dimensionless	Dimensionless

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