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Comparison of different methods to predict chattering in pressure relief valves

Master Thesis submitted to the Universitat Rovira i Virgili
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Industrial Engineering Master

UNIVERSITAT ROVIRA I VIRGILI

Tarragona
January 2017

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1 Aim of the project

1.1 Purpose of the project

This master thesis is aimed at comparing different methods to predict chattering possibilities of Pressure Relief Valves (PRV). The study work will be based on the published work of Smith / Burgess / Powers (2011), Melhem (2016) and the Southern Research Institute (2016).

Some critical pressure relief valves of the polypropylene plants from a worldwide petrochemical company located in Tarragona will be analyzed. The study will include prediction of chattering possibilities for each pressure relief valve and a list of mitigation measures.

1.2 Editor team

The writting team is formed by the student of 2nd course of Industrial Engineering Master at Universitat Rovira i Virgili. With the following data:

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2 Introduction

In this section pressure relief valves will be defined. In addition there will be described the flaws that pressure relief valves can present. This will help to understand the later sections.

2.1 Pressure relief valves

A pressure relief valve is a safety device designed to protect a system or a pressurized vessel during an overpressure event. An overpressure event occurs when the pressure in a vessel or system increase beyond the specified design pressure or Maximum Allowable Working Pressure (MAWP).

Many Codes and Standards exist to control their design and application for being an important safety element.

There are many electronic, pneumatic and hydraulic systems to control fluid system variables, such as pressure, temperature and flow. Power sources of some type are required by these systems in order to operate, such as electricity or compressed air. A pressure relief valve must be capable of operating always, especially during when system controls are nonfunctional.

When a condition occurs that causes the pressure in a system or vessel to increase approaching to MAWP, the pressure relief valve is installed in order to prevent a catastrophic failure. Since reliability is directly related to the complexity of the device, it is important that the design of the pressure relief valve be as simple and robust as possible.

The pressure relief valve must open at a predetermined set pressure, flow a rated capacity at a specified overpressure, and close when the system pressure has returned to a safe level. Is important take into account that pressure relief valves material must be compatible with the process fluid. They must also be designed to operate in a consistently smooth and stable manner on a variety of fluids and fluid phases.

In another words, the spring holds the valve closed while the pressure in the vessel is below the set pressure of the relief device. When the pressure in the system or vessel approaches the set pressure of the relief device, the pressure relief valve opens, allowing fluid to leave the system, so the PRV will either keep the pressure from rising above the MAWP or will depressure it. The PRV will close when overpressure event is finished, that means that the set pressure at the inlet of the relief device drops below its blowdown pressure.

Following are the main relief valve types commonly used in the industry. Before getting into the relief valve types, some terms need to be described.

Superimposed back pressure is the static backpressure that exists on the outlet of the pressure relief valve, when the valve is closed. This pressure can be constant or variable depending on the conditions in the flare system before the relief valve can discharge.

Built-up back pressure is the backpressure generated due to pressure losses at the outlet of an open relief valve when it is discharging. This pressure depends on the downstream pressure in the flare header to which the relief valve is discharging and the relieving flowrate which is being discharged.

When the relief valve is discharging, effects of superimposed and built-up back pressure exist together and felt as the combined back pressure.

According to API 520 (Part I, 2008) there are different types of pressure relief valves:

Pressure relief valve (PRV): a pressure relief device designed to open and relieve excess pressure and to reclose and prevent the further flow of fluid after normal conditions have been restored.

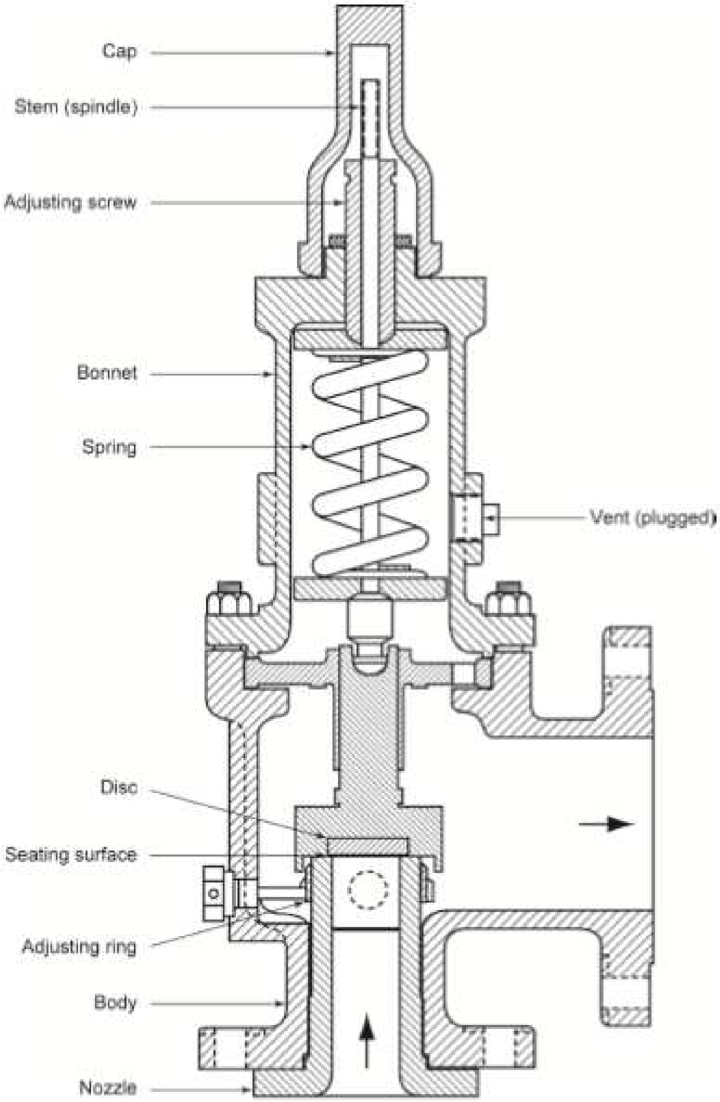


Figure 2.1: Conventional relief valve (taken from API 520-I-2008)

Safety valve (SV): a spring-loaded pressure relief valve actuated by the static pressure upstream of the valve and characterized by rapid opening or pop action. A safety valve is normally used with compressible fluids.

Relief valve (RV): a spring-loaded pressure relief valve actuated by the static pressure upstream of the valve. The valve opens normally in proportion to the pressure increase over the opening pressure. A relief valve is used primarily with incompressible fluids.

Safety relief valve (SRV): a spring-loaded pressure relief valve that may be used as either a safety or relief valve depending on the application.

Pilot-operated pressure relief valve (POPRV): A pressure relief valve in which the major relieving device or main valve is combined with and controlled by a self-actuated auxiliary pressure relief valve (pilot).

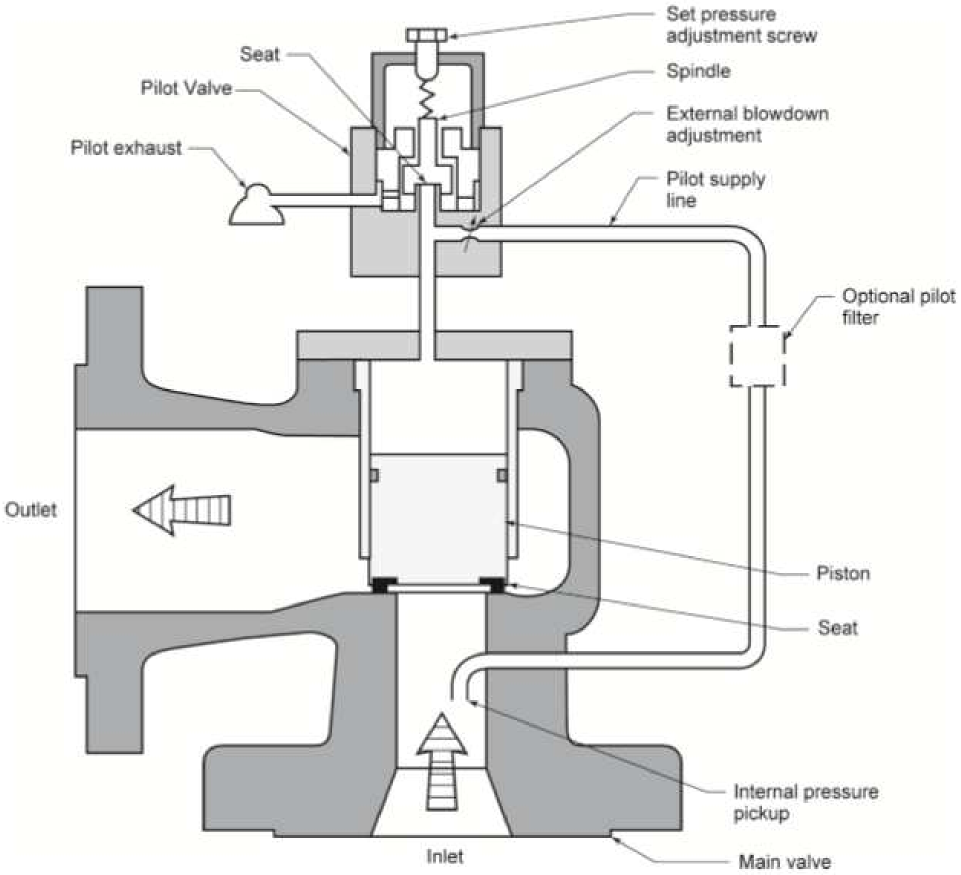


Figure 2.2: Pilot operated pressure relief valve (taken from API 520-I-2008)

However, the European Pressure Equipment Directive (PED, 1997) uses the overall term “safety valve” for every pressure-relieving device subject to the PED code (Hellemans, 2009). In this master thesis the terms pressure relief valve and safety valve are interchangeable.

2.2 Flaws in installed pressure relief valves

A historic survey on accidents related to safety valves has been performed. Historic surveys of accidents have been used in the chemical industry as a source of information about the hazards associated with a specific chemical process (Vilchez et al., 1995). A survey was performed (Basco, 2015) on accidents that could be attributed to overpressure plus the simultaneous failure of a safety valve. Among the 48 cases found from 1944 to 2005 (MHIDAS, 2007), 35 were associated with "mechanical failure of a safety valve", with considerable associated damage: 56 fatalities, 292 injured and more than 8000 evacuated. Consequently, the correct engineering of safety valves is obviously an important issue for any industrial plant.

Of course, most latent failures do not lead to accidents; some safety valves will never need to actuate under an overpressure situation in their entire life. However, such failures can be decisive in certain circumstances. The DIERS Institute (CCPS, 1998) observed that, amongst the 100 worst major accidents that occurred in the process industry between 1956 and 1986, twenty-five could be attributed, at least partly, to the inadequate design or maintenance of pressure relief systems. Several authors have studied these aspects and the results, showed here, have been divided between design and maintenance faults.

Technical design faults

Berwanger et al. (2000) analyzed the adequacy of pressure relief systems in 272 process plants in the US. In this important study, 14,873 devices were analyzed and the main conclusion was that: approximately 40% of process equipment has at least one error in its pressure relief system (no relief device 15%; undersized device 7%; improper installation 17%; undersized and improperly installed device 2%). Kumana and Aldeeb (2014) in a very wide study comprising 80,372 pressure relief devices, taken over 1,197 audits performed between 2005 and 2014, have found that: the number of relief devices with at least one major issue is 47% and 13,4% of the equipment was unprotected. In Europe, Westphal and Köper (2003), performed a survey of 4,000 safety valves, and found faults in 17%, including undersizing, pressure drop in the inlet pipe higher than 3%, and total backpressure higher than 15% for conventional safety valves.

Technical maintenance faults

Aird (1982) observed that 44% of safety valves opened outside the range +/- 10% of the set pressure in the pre-test. Smith (1995) analyzed the behavior of 13,000 safety valves: 18% opened at a pressure higher than 110% of the set pressure and 3% did not open at a pressure of twice the set pressure. On the basis of an analysis of 750 complaints concerning faulty operation of safety valves, Hellemans (2009) found that 10% were due to under- or over-sizing, 8% to bad maintenance, 33% to incorrect installation, 29% to incorrect transportation or handling, 12% to a manufacturing default and 7% to various other reasons. In a pre-test inspection of 292 valves, Chien et al. (2009) found that 4% opened at a pressure higher than 119% of the set pressure.

As pointed out before, the majority of these deficiencies will never be discovered because the valve will never need to open.

3 Statistical analysis of instability of pressure relief valves

In section 3 some incidents due to instability of pressure relief valves will be analyzed.

3.1 Shell Process Safety Incident Database

Otis (2011), performed a review of the existing incidents in safety relief valves due to chattering. A summary of the review is pointed out in table 3.1

Table 3.1: Shell PRV Chatter Incident Data

Year	PRV design service	Phase during incident	Liquid certified valve	Inlet loss >3%	High back pressure	Valve oversized	Other	Incident severity	Consequences
1964	Vapor	Liquid	No					4	4” line failure and fire
1974	Liquid	Liquid	No					3	Flange leak and fire
1976	Liquid	Liquid	No	Yes		Yes		3	Flange leak and fire
1978	Vapor	Liquid	No	Yes				5	2” propane line failure: VCE
1980	Liquid	Liquid	No					3	Flange leak and fire
1981	Liquid	Liquid	No				Relocated PRV	1	Flange leak
1981	Vapor	Liquid	No					1	Flange leak
1982	Vapor	???	No				Revised piping	1	Flange leak

1983	Liquid	Liquid	No				Improved supports	1	Small bore pipe failure
1983	Vapor	Vapor	No				Improved supports	2	Pipe failure
1983	Liquid	Liquid	No					1	Flange leak
1983	Liquid	Liquid	No				Changed pipe thk	1	Fitting failure
1983	Liquid	Liquid	No				Piping revisions	1	Flange leak
1983	Vapor	???	No	Yes	Yes	No		1	Flange leak
1986	Liquid	Liquid	No	No	Yes			1	Flange leak
1986	Vapor	???	No					1	Flange leak
1987	Liquid	Liquid	No				Replaced w liquid certificate	5	4" propane line failure: VCE
1998	Liquid	Liquid	No	No	No	Yes		2	Flange leak and fire
2002	Vapor	Liquid	No	No	No	Yes		1	Small bore pipe failure
2005	Vapor	Vapor	No	No	No	No	Acoustics	3	Large piping failure
2009	Liquid	Liquid	unknown	No	No			2	Flange leak
2009	Liquid	Liquid	unknown				Revised pipe fitting	1	Fitting failure
2009	Liquid	Liquid	Yes	Yes	Yes	No		1	3/4" gate valve leak
2010	Liquid	Liquid	No	No	No	Yes		1	Small bore pipe failure
2010	Liquid	Liquid	No	No	No	No		1	Pipe leak

Otis (2011) remarked the following parts based on table 3.1:

20 out of 25 incidents involved liquid relief:

- 17 were vapor trim PRVs relieving liquid
- 1 involved a liquid trim (ASME Liquid Certified) PRV
- 4 cases PRVs in vapor service with liquid relief scenario
- Contributing causes of liquid PRV chatter:
    - Use of vapor trim valves is a significant factor
        - Likely that all but one PRV were vapor only certified valves (ASME liquid certified valves were not available prior to 1985)
    - Inlet pressure drop not a significant factor
        - 2 cases where inlet losses were found to be high
        - 7 cases where inlet losses were not high
    - Over-sizing is not a major factor
        - 4 cases where PRV was grossly oversized
- Only 2 incidents involved are known to be vapor relief

    - Steam PRV inlet line broke
        - better PRV support was installed as a result of the incident
        - Implies inlet line pressure drop was NOT an issue
    - PRV bonnet failure due to acoustic phenomenon
        - Confirmed inlet losses <3% of set
        - Process was super-critical

3.2 Other process safety incidents

Following three more incidents are described:
The first example is the 1978 Commerce City Incident (Otis 2011)

Description:

- 10/3/78 the Conoco Refinery in Commerce City, Colorado experienced a vapor cloud explosion causing extensive damage
- Piping failure in a propane/butane splitter unit was believed to have been caused by relief valve chatter

Background:

- Butane/propane splitter (design pressure 310 psig) protected by 2 PRVs
    - PRV on the overhead (for cooling water failure)
    - PRV on the accumulator (for the fire case only)
- PRV Inlet Piping
    - 4x6 PRV on the overhead had an a 4" inlet line 31 feet in length with 4 ells. The pressure drop while relieving liquid exceeded 5%
    - 2x3 PRV on the accumulator had an 2" inlet line 16 feet in length with three ells.

Incident:

- Upset caused both PRVs to relieve and chatter
- 30 seconds after RV's started chattering there was a loud roar (vapor release) within the unit.

Conoco Investigation:

- Found the 2" inlet on the accumulator RV had failed from fatigue.
    - The natural frequency of the inlet line was calculated to be 10 Hz.
    - The RV manufacturer stated the RV chatter was between 5 and 15 Hz.
    - The inlet line was not braced well to dampen any induced vibrations.

- 2" PRV on accumulator was relieving liquid propane
- Portion of the flare lateral failed (brittle fracture) as a result the VCE blast loading

Current Speculation:

- Accumulator liquid relief caused by accumulator flooding
- Condenser PRV (assumed upstream) might pass liquid if located close to condenser

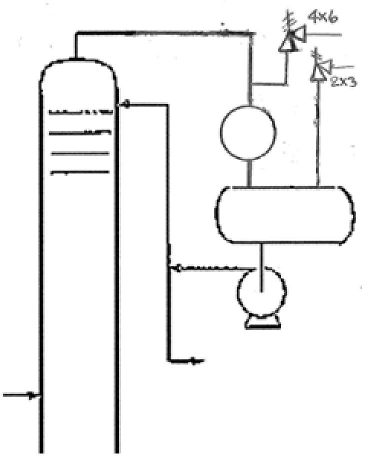


Figure 3.1: P&ID extraction from Commerce city incident

The second example is the accident in Colonia, Germany, 05/06/2011. (Umweltbundesamt, 2014)

A short summary about the incident:

- Unnoticed valve chattering for a long period of time
- Caused by flash evaporation (oil/water mixture) in an overflow valve
- Because of the vibration of valve chattering the adjusting screw for the set pressure has become loose.
- So the set pressure has unnoticed shifted to a lower set pressure.
- Consequently the safety valve did open several times at a lower pressure level.
- Crude oil was released into the environment because of a pipe break at a weldseam
- Costs caused by environmental damage: 500000 Euro
- Nobody was injured or killed

The third example is the accident reported by Politz (1985), he reported a case of chattering of safety valves, which produced severe vibration of the piping causing a failure in the inlet flange of the valve, spraying hot crude oil on nearby equipment. The root cause was the oversizing of the relieving capacity, i.e. two valves were installed in parallel with a very similar set pressure (470 and 475 psig) ignoring the fact that for the required flow in this blocked outlet scenario, only one valve would be necessary.

4 Thesis objectives

The objectives of this thesis are presented as general and specific.

4.1 General objetives

To compare rigorously the different static and dynamic methods to predict chattering in pressure relief valves in order to know its reliability.

4.2 Specific objectives

- To study rigorously each existing method including its constraints.
- To analyze the best static methods for calculating the instability of pressure relief valves.
- To recommend the best static method to the scientific community.
- Analyze some critical safety valves of the polypropylene plants from a worldwide petrochemical company located in Tarragona.
- To use a dynamic screening tool to predict chattering possibilities of PRV’s.

4.3 Justification of the thesis

Good engineering practices have long specified that inlet piping pressure drop from the protected vessel to the pressure relief valve should be limited to no greater than 3% of the set pressure.

Many companies have taken a more lenient approach to the inlet pressure loss limits; consequently, many installations do not meet the 3% design guideline. However OSHA (USA) has now begun levying fines against companies violating this 3% rule (Smith et al, 2011)

5 Literature survey on valve instability

In this section the dynamic responses of pressure relief valves will be described. Thereafter a description of the potential causes that cause this instability. Finally, the existing calculation methods are presented, both static and dynamic methods.

5.1 Introduction

A pressure relieve valve may experience three types of dynamic responses:

- Cycling
- Flutter
- Chatter

5.1.1 Cycling

The pressure relief valve experiments cycling when an opening and closing at relatively low frequency is produced. This most often occurs when the relief requirement of the valve is small compared to their relief capacity. In this case, when the pressure relief valve opens, the valve may flow more than what the system can provide, causing a depressure to the pressure relief valve reseating pressure. Once the PRV is closed, the system pressure rebuilds to the PRV set pressure. This cycle is repeated continuously, and this phenomenon is called cycling.

Generally, cycling does not cause harmful valve damage. However it may cause some wear over time and the valve’s ability to reseat tightly may be affected.

When capacity variations are frequently encountered in normal operation, one alternative is the use of multiple, smaller PRVs with staggered settings. With this arrangement, the PRV with the lowest setting will be capable of handling minor upsets, and additional PRVs will open as the capacity requirement increases.

An alternative to the use of multiple PRVs with staggered settings is the use of a modulating pilot-operated relief valve.

Summarizing, cycling can be defined as the non-destructive opening and closing of a relief device (< 1 hz). Cycling may result in damage to the safety relief valve internals but not expected to result in a loss of containment.

5.1.2 Flutter

Flutter is a phenomenon that occurs with the PRV opened. The pressure relief valve experiments a rapid reciprocating motion of the moveable parts because of the dynamics of the system that produce this instability. The disk reciprocates near the natural frequency of the valve. An important difference against the other two types of instability is that, during fluttering, the disk does not contact the seat.

Flutter may lead to rapid wear of any moveable member that is in contact with a stationary member of the PRV and has a higher probability of causing the PRV to become stuck in a full or partially open position. Flutter can also lead to a reduction in capacity.

Spring/mass systems that are used in spring loaded PRVs create a higher potential for flutter than pilot-operated PRVs.

Summarizing, flutter can be defined as the cycling of a valve open and closed without the seat contacting disk. Flutter may result in damage to the safety relief valve internals but not expected to result in a loss of containment.

5.1.3 Chatter

The pressure relief valve experiments chattering when opens and closes at a very high frequency. Spring/mass system that is used in spring loaded PRVs are susceptible to dynamic interaction with the system. Loss of containment is one of the concerns, e.g. loosening of flange bolts, another concern is the failure possibility of piping components due to fatigue. These concerns are caused by the impact loading from rapid hammering of the valve disk onto the valve seat. Chattering may lead to significantly reduced PRV flow capacity. Another concern is that chattering can cause valve seat damage and mechanical failure of valve internals. Spring loaded PRVs can experience chatter (modulating pilot-operated PRVs are less likely to chatter).

In liquid service the forces and velocity changes are much more severe than in vapor service due to the higher densities associated with liquids. Thus, damages caused by chatter phenomena are much more severe in liquid service. This is supported by analysis that shows that the pressure change as a result of fluid acceleration is typically small in inlet piping applications in vapor service. This is also supported by operating experience, which shows that loss of containment incidents due to chatter are primarily in liquid service.

Summarizing, chatter can be defined as the rapid cycling (> 1 hz) of a pressure relief valve. Chattering may lead to the loss of containment, a mechanical failure or welding of the relief device (either open or closed).

If a valve is improper installed, there is no way to confirm that the relief device will not chatter. Regardless of whether it is liquid or vapor:

- The installation may chatter if the minimal inlet line flow area is less than the sum of the area of the inlet nozzles of the valve.
- The installation may chatter if the minimal outlet line flow area is less than the sum of the area of the outlet nozzles of the valve.
- Installations may chatter if backpressure is greater than the limits specified by the valve manufacturer.

Dannenmaier et al. (2016) presents in their paper a selection of contradictory experimental results about the influence of inlet piping on safety valve stability. These results are presented in table 5.1.

The conclusions of table 5.1 show that the stability prediction of PRVs is not yet a solved issue.

Table 5.1: Selection of contradictory experimental results about the influence of inlet piping on safety valve stability

Author	**Valve / Medium**	**Conclusion**
ERPI (1982)	3 API valves / water	3% rule is not always conservative for large sized valves
Bommes (1984)	DN25/40 / water	Test setups with local pressure losses are not representative
Kastor (1986)	API DN 25/50 /air	3% rule is overly conservative
Stremme (1993)	DN50/80 / water	Pressure surge rule – improper replacement for the 3% rule
Schmidt (2011)	DN25/40 / nitrogen	3% rule is conservative
Cremers (2000)	DN25/40 / gases	Pressure surge rule as suitable replacement for the 3% rule
Izuchi (2010)	API 1E2, 1.5F2 /gas	Inlet piping: 1m to 5m (unstable); and >10m (stable)
Smith et al. (2011)	550 API valves	Some valves in practice operate stable while 3% rule is violated
Hös et al. (2014)	3 API valves /gas	3% rule is nt conservative

5.2 Potential causes for pressure relief valve instability

Many causes may lead into pressure relief device instability. Hereinafter a description of the causes considered in API 520 part II 2015.

5.2.1 Excessive inlet pressure losses

A pressure relief valve will start to open at its set pressure. Must be considered that in flow conditions, the amount of the pressure drop through the inlet piping and fittings will reduce the pressure acting on the valve disc. If this pressure drop is large enough, the valve inlet pressure may fall below reseating pressure. So the PRV will close, and it will reopen immediately when the static pressure reaches set pressure again.

Research of Izuchi (2008) and Melhem (2011) and Zahorsky (1982), cited in API 520-II-2015 indicate that the instability associated with excessive inlet losses relative to the blowdown may lead to cycling, flutter or chattering.

5.2.2 Excessive built-up backpressure

Built-up backpressure resulting from discharge flow through the outlet system of a conventional PRV results in a force on the valve disc that tends to return it to the closed position. If this returning force is sufficiently large, it may cause the valve to close completely, only to reopen immediately when the discharge flow has stopped and built-up backpressure has dissipated. Instability results from the rapid repetition of this cycle.

To prevent instability from this mechanism, historical design practices for conventional PRV discharge systems have been to limit the built-up backpressure to the valve’s allowable overpressure. Allowable valve overpressures are described in API 520 Part I. Where built-up backpressure exceeds these criteria, then decreasing the flow resistance of the discharge system or using a balanced PRV, restricted lift PRV or pilot-operated PRV are alternatives.

5.2.3 Acoustic interaction

When the PRV opens rapidly, the pressure just upstream of the valve disc drops and a pressure wave travels upstream at the speed of sound in the fluid. The pressure reduction at the PRV inlet will tend to return the valve disc to its closed position. When the pressure reduction wave reaches a large reservoir a pressure wave reflection occurs. If the pressure wave returns quickly, then the PRV will stay open and should flow in a stable manner or may flutter. If, on the other hand, the PRV closes before the pressure wave returns, then the PRV may cycle or chatter. The acoustic pressure waves are recoverable, so the PRV inlet pressure would rapidly build back up and the process would repeat. This phenomenon may contribute to instability in all fluid regimes; however, the effects of acoustic interaction are more pronounced with liquid reliefs as described in Melhem research (2016).

Pilot-operated PRV are less prone to instability by acoustic interaction because of their quicker response.

As per API 520 part II 2015, pressure wave reflection point, depends on the installation configuration.

An example of an acoustic reflection point is an abrupt cross sectional area change where the upstream piping cross sectional area is at least 10 times larger than the downstream piping cross sectional area and the length of the upstream piping is more than 20 times the diameter of the downstream piping (e.g. 4” diameter pipe connected to a 12” diameter pipe that is greater than 80 inches long).

5.2.4 Inlet retrograde condensation

In the case that the fluid to be relieved in a process upset is at supercritical condition and the pressure increases up to the set pressure of the valve, the inlet pressure of the valve can decrease and retrograde condensation can occur. This condensation could originate a volumetric contraction that might force the valve to close. Once the valve closed, the condensate would flash and the cycle would repeat. This phenomenon can cause chattering. This can be avoided in the process design phase. Increasing operation pressure retrograde condensation will occur downstream of the PRV instead in inlet. Figure 5.1 presents an example of retrograde condensation represented in a Mollier diagram.

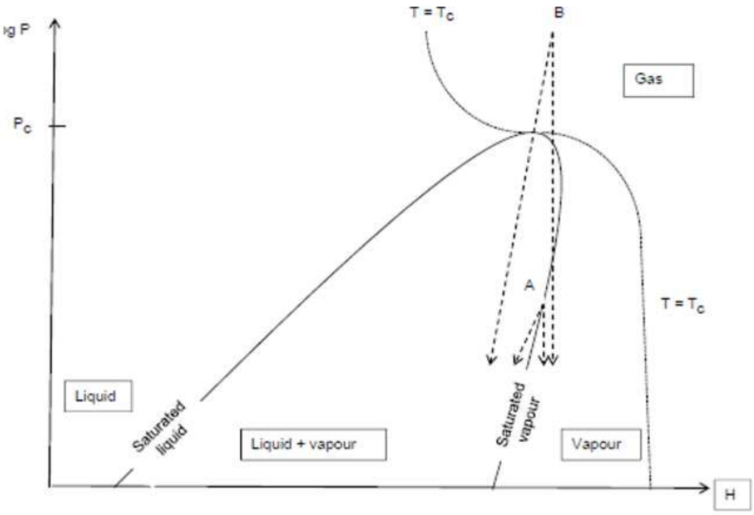


Figure 5.1: Retrograde condensation process (taken from Egan, 2011)

5.2.5 Acoustic induced vibration

The phenomenon of Acoustic Induced Vibration (AIV) is caused by fluid turbulence, and is further enhanced by a flow restriction device such as a safety valve. Problems have been encountered with gaseous systems, since sound energy propagates most easily in compressible media. Liquid relieving systems tend to dampen vibrations and, as a result, have not had any failures to date (Melhem, 2012).

The sound Power Level (PWL) quantifies the amount of acoustic energy emitted immediately downstream of the restriction and is calculated using process data such as flowrate, temperature, molecular weight and the pressure ratios across the valve. This energy is usually in the form of a standing wave, which causes vibrations when discontinuities in the piping system are encountered. The piping system response to these vibrations depends on the mechanical natural frequency of the system, which is a function of the material properties, pipe size, support fixity, etc. If the frequency of the vibrations in the system approaches the natural frequency, a resonant condition will cause severe amplification of the vibration. This vibration produces a cycling effect that may result in a fatigue failure. The areas most susceptible to it are branch connections, welded support attachments and other areas of stress intensification (geometric discontinuities).

Acceptable PWL’s have been documented based on industry-wide failure data and operating experience. Design of a piping system within these acceptable limits will greatly reduce the risk of a fatigue failure from AIV.

Reviews of the state of the art have been made by Melhem (2012) and Swindell (2013). Melhem reported that “According to the UK Health and Safety Executive (HSE), 21% of all piping failures offshore are caused by fatigue/vibration”

5.2.6 Improper valve selection (trim, seat and obturator design)

Safety valve selection trim is a very important factor in designing relief systems, in order to avoid possible instability problems.

There are three trims: vapor certified, liquid certified and trims that are dual certified either in ASME Code or in PED Code. See figure 5.2.

It is known that gas and vapors have different relief characteristics. Until 1985, the ASME code allowed an overpressure of 25% for liquid applications and manufacturers provided the same trim for both gases and liquids resulting in an opening/closing curve as represented in Figure 5.3.

Characteristic	Vapor Certified PRV	Liquid Certified PRV	Dual Certified PRV (Note 1)
Liquid Relief	Capacity is not certified but can be estimated using guidance in API 520 Part I (may need up to 25 % overpressure to achieve full lift)	Capacity is Certified	Capacity is Certified
Vapor Relief	Capacity is Certified	Capacity is not certified, and is not addressed by API 520 Part I. See manufacturer for estimated capacity.	Capacity is Certified
Range of blowdown available (see manufacturer for PRV specific blowdown values, see Note 2)	Up to 10 % for vapor, and Up to 15 % for liquid	Up to 20% for vapor or liquid	Up to 20 % for vapor or liquid
Tendency to chatter in liquid relief relative to liquid trim PRV	Increased	Neutral	Neutral
Effect of setting medium on the opening characteristic	PRV set on gas or vapor but relieving liquid may open 3 % to 5 % higher	PRV set on liquid but relieving vapor may open 3 % to 5 % lower	Minor effect (i.e. within Code tolerances)
Effect of required valve overpressure vs. set medium	Any shift up or down in the opening point may result in a similar shift in the point at which full lift is achieved		

NOTE 1 The term Dual Certified covers PRVs that are both vapor flow certified and liquid flow certified where this dual certification is achieved without making trim changes when switching fluids during the flow testing.

NOTE 2 These are typical values obtained from valve manufacturers. User is cautioned to fully understand the impact on operations when blowdown exceeds the operating margin.

Figure 5.2: Performance differences with PRV Trim (taken from API 520 part II 2015)

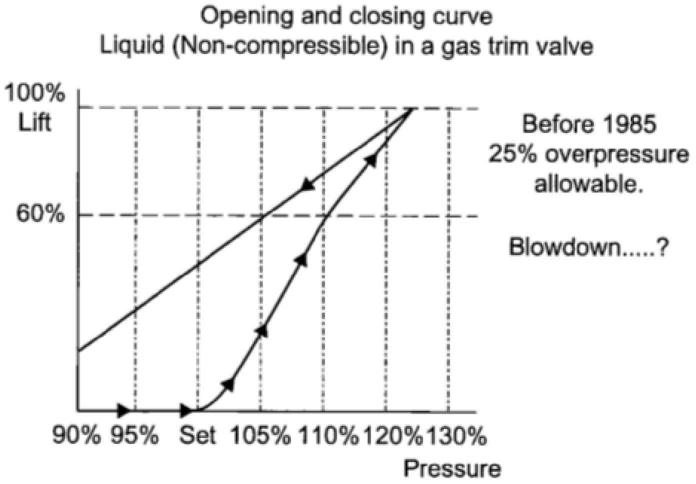


Figure 5.3: Characteristic curve of a relieving liquid in a gas/liquid trim before 1985 (taken from Hellemans, 2009)

On figure 5.3 see how the allowable overpressure was 25% and the blowdown was not defined.

However, since 1985 ASME has also required a maximum overpressure of 10 % on liquid valves. Actually most manufacturers have valves that fit for gases/vapors and liquids.

The problem concerning chattering is related essentially to the case when a valve with a gas trim releases a liquid (Figure 5.4)

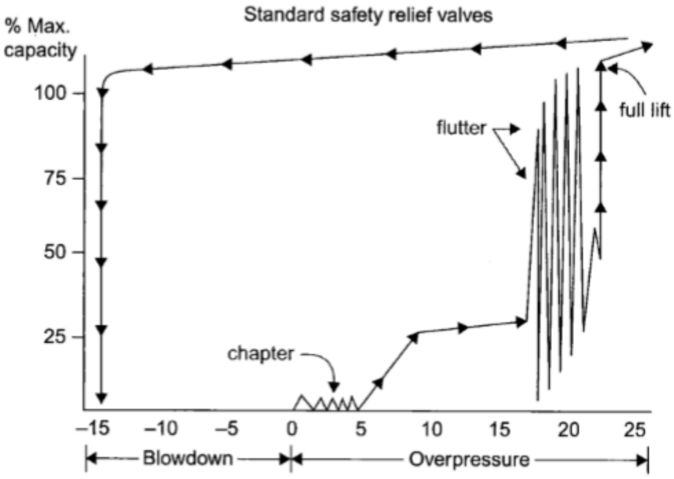


Figure 5.4: Characteristic of a valve gas trim relieving liquid (taken from Hellemans, 2009)

Liquid relief through a vapor certified valve should be analyzed for flows that imply 10% overpressure on the valve. Such relief does not achieve stability up to 10% overpressure and the valve does not achieve full lift up to 25% overpressure (see Figure 5.5). Operation below 10% overpressure has been demonstrated to be unstable. Liquid relief through vapor certified valves experiences little to no blowdown, and these scenarios have been noted as the cause for many of the incidents attributed to relief valve instability within the industry.

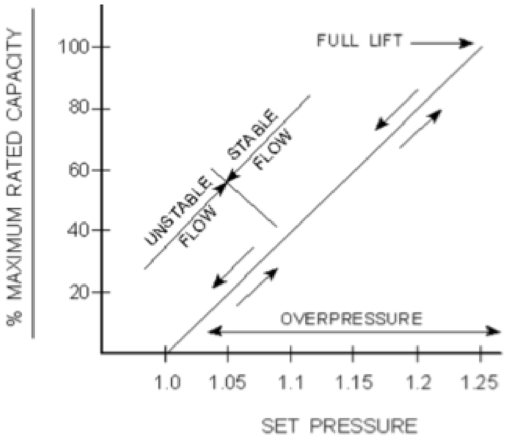


Figure 5.5: Characteristic of a liquid relief through a vapor certified valve

5.2.7 *Oversized pressure relief valves*

Oversized PRVs may lead to cycling. Oversizing of pressure-relief devices is frequently unavoidable. This is because the sizing case for a given relief device is often significantly larger than other relief cases. This is partly due to the conservative assumptions used in determining relief loads. For example, credit is not allowed for control system response that would reduce the relief load.

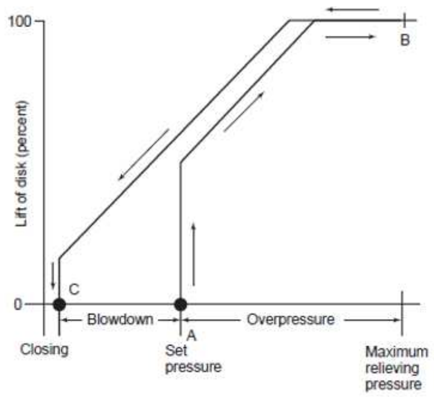


Figure 5.6: Behavior of a gas valve when the required flow is less than 25% of its rated capacity. (taken from API 520 part I, 2008)

5.2.8 *Ratio outlet area/orifice area.*

According to API 526 (2009), the ratio output area/orifice area for 4P6 and 6R8 are 4.3 and 3.0, respectively. Due to these small ratios, the build-up back pressure for conventional valves is higher than in other smaller safety valves, giving the same problem of chattering as "Excessive built-up back pressure" presented before in paragraph 5.2.2. The problem arises because once the valve open, the build-up back pressure resulting from discharge flow results in a force upon the valve disc, forcing the valve to close if the force is sufficiently large, and it will reopen again when the discharge flow has stopped. Instability comes with the repetition of this cycle.

5.2.9 *Body bowl choking.*

Body bowl choking occurs when the pressure safety valve body causes a critical flow condition at the valve body outlet (D'Alessandro 2011).

In 1983 Huff wrote "A secondary pressure in excess of the external back pressure can develop in the body of safety valves if the maximum flow condition is attained in the body outlet, the contribution of this choking effect to the true back pressure on the disk of unbalanced valves with closed bonnets is not generally recognized"

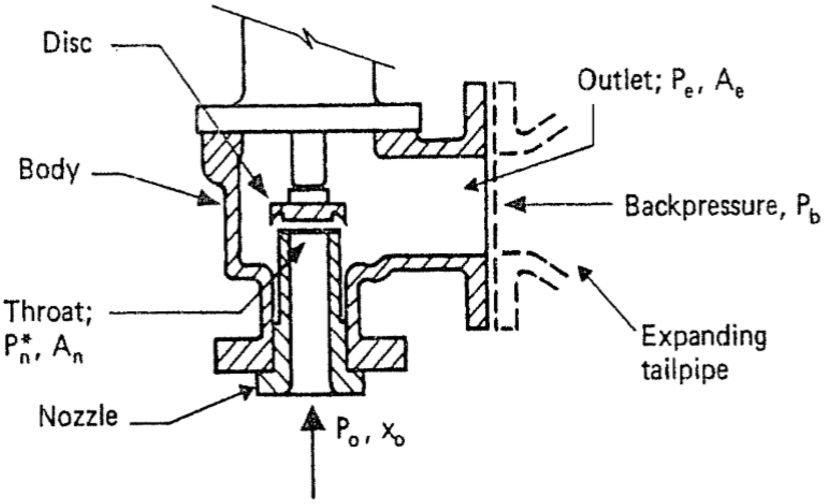


Figure 5.7: Valve schematic (taken from D'Alessandro 2011)

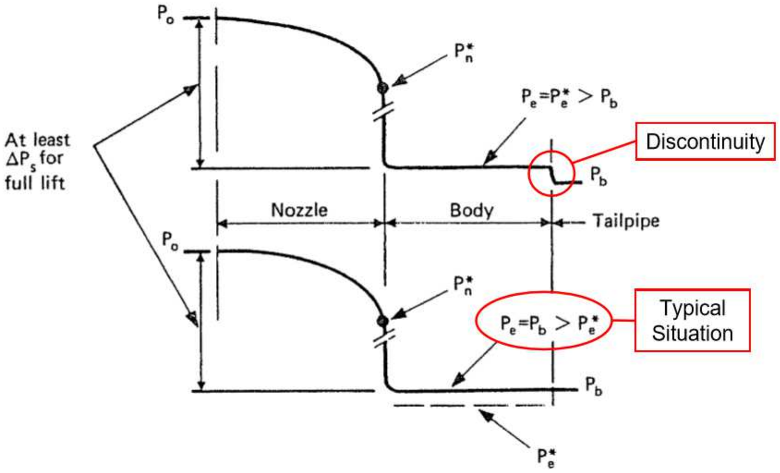


Figure 5.8: Pressure profile (taken from D'Alessandro 2011)

The key concept of figure 5.8 is that the minimum body bowl exit pressure Pe* is:

- Intrinsic to the valve geometry
- Dependent on the stagnation pressure only
- Independent of the tailpipe
- Not necessarily equal to the back pressure

For stable operation, the stagnation pressure (relieving pressure) should be less than the value given by the following equations (D'Alessandro, 2011):

$$P_0 < \frac{P_C}{(1+F_0)\cdot\frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

The fractional overpressure is defined by:

$$F_0 = fractional\ overpressure = \frac{P_0 - P_S}{P_S - P_C} \qquad \text{(Eq.5.2)}$$

Where,

$P_0 = relieving\ pressure\ (bara)$

$P_s = set\ pressure\ (bara)$

$P_C = superimposed\ backpressure\ (bara)$

$A_n = throat\ area\ (mm^2)$

$A_e = outlet\ area\ (mm^2)$

$K = heat\ capacity\ ratio\ for\ ideal\ gas$

5.3 Engineering analysis

Engineering Analysis concept appeared in the 1994 version of API 520 Part II for pressure relief valves with an inlet pressure drop greater than 3%. However, no guidance was given on how to perform this analysis.

ASME code Section VIII, ISO 4126-9 and in API 520, specify that inlet piping pressure drop from the vessel to the safety relief valve should be less than 3% of the safety relief valve's set pressure.

The design requirement of "limit the inlet losses to 3%" has been taken as a rule to design safety relief device inlet piping for these two following reasons:

1. Ensure that the pressure in the vessel will not increase beyond the MAWP of the protected vessel.
2. Ensure that the valve will operate stably.

The first concern can easily be solved resetting the relief valve to lower set pressure.

The second concern is more complicated to solve. It is related to the opening of a relief device from a closed position and operate stably.

As per API 520 Part II, 2015, "experience has shown that many PRV installations with calculated inlet pressure drop greater than 3% of set pressure have not resulted in failures due to relieving events. Because the relationship between inlet pressure loss and PRV chatter is not definitively understood, detailed requirements for an engineering analysis are the responsibility of the user. This may be a qualitative or quantitative assessment. Note that an engineering analysis should not be used to validate a PRV installation that has experienced chatter."

In this master thesis the proposed engineering analysis consists of answering and demonstrating the following questions:

1. According to the inspection records is there any evidence of past chattering?

2. Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

3. Is the inlet piping and fittings at least as large as the PRV inlet?

4. Is there at least a 2% SP margin between PRV blowdown and the inlet pressure loss?

5. Does excessive built-up backpressure occur according to the specific PRV?

6. Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

7. Does the PRV fulfill API 520 II - 2015 Simple Force Balance (Melhem)?

8. Is the risk of relieving of the existing pressure safety valve quantified?

The following table shows the required answers to avoid chattering

Table 5.2: Screening test to detect chattering possibilities

QUESTION	ANSWER TO AVOID CHATTERING	COMMENTS
According to the inspection records is there any evidence of past chattering?	No	
Is the PRV well installed according to API 520, ISO 4126-9, etc?	Yes	Consider the manufacturers recommendations as well
Is the inlet piping and fittings at	Yes	

least as large as the PRV inlet?		
Is there at least a 2% Set Pressure margin between PRV blowdown and the inlet pressure loss?	Yes	
Does the excessive built-up backpressure occur according to the specific PRV?	No	Conventional 10% of set pressure. Balanced 30-50% of set pressure
Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?	Yes	
Does the PRV fulfill API 520 II-2015 simple force balance?	Yes	
Is the risk of relieving of the existing pressure relief valve quantified?	Yes (acceptable)	Reference is made to the relieving to flare or atmosphere

If only one question does not conform to those in the table, chattering has to be considered and mitigation measures have to be implemented.

The typical mitigation actions for the case that a pressure relief valve has an inlet pressure drop greater than 3% and failed the engineering analysis, are:

- Increasing the diameter of the inlet pipe of the valve.
- Reduction of the distance between pressure relief valve and protected equipment.
- Restriction of the lift of the pressure relief valve considering the required flow.
- Changing the valve for another with the same size but with less area.
- Changing to remote sensing pop-action pilot PRV.
- Installation of a vibration damper.
- Others.

5.4 Simplified methods

Hereafter two simplified existing methods will be detailed:

- Smith / Burgess / Powers (2011)
- Simple force balance method (Melhem 2016)

5.4.1 Smith / Burgess / Powers (2011)

A procedure to ensure that some pressure relief devices installed in systems with inlet losses greater than 3% will not chatter is detailed.

The methodology developed in this paper has been used in an entire refinery, and it was found that over 50% of the installations that have inlet pressure losses greater than 3% will not chatter.

With this methodology the safety relief devices can be grouped into "those that will not chatter" and "those that may chatter". Then, with devices grouped, companies can put their effort only on the pressure relieve valves that may chatter. This will involve a reduction of costs.

The methodology consists into analyze and eliminate these following known causes of high frequency chatter:

- Excessively long inlet lines
- Excessive inlet pressure losses
- Frequency matching / harmonics
- Oversized relief devices
- Improper installation

For most of these causes that can produce chatter, the analysis for liquid filled systems and for vapor filled systems are different.

However, if the engineer performs the analysis and complies the conditions stablished, destructive valve operation is not expected and the inlet piping does not need to be modified.

Excessively long inlet lines

The pressure wave generated when the safety relief valve opens must travel from the seat of the disk to the pressure vessel and be reflected back to the disk inlet prior to the relief valve beginning to close, if not, the disk will close.

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

Where,

$t_0 = opening\ time\ of\ the\ valve\ (s)$

$L = inlet\ line\ acoustic\ length\ (ft)$

$c = speed\ of\ sound\ in\ the\ fluid\ \left(\frac{ft}{s}\right)$

The following correlation, equation 5.4, was developed to predict the opening times. .

$$t_0 \approx \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_S}{P_{atm}}\right)^{\frac{2}{3}} \cdot \left(1 - \frac{P_{atm}}{P_S}\right)^2} \right] \cdot \left(\frac{h}{h_{max}}\right)^{0.7} \qquad \text{(Eq.5.4)}$$

Where,

$d_{psvi} = inlet\ PRV\ flange\ diameter\ (in)$

$P_s = set\ pressure\ (psi)$

$P_{atm} = atmospheric\ pressure\ (psi)$

$\frac{h}{h_{max}} = fraction\ of\ total\ travel\ when\ relief\ device\ open$

Regarding the term $\frac{h}{h_{max}}$, several researchers have indicated that can range between 40% and 100% of their full lift. Here 60% value will be used.

Considering compressible fluids, for a perfect gas, the maximum acceptable length for the inlet piping can be determined as follows:

Equation 5.5 was obtained from API STD 521 to calculate the speed of sound in a perfect gas.

$$c = 223\sqrt{\frac{kT}{MW}} \qquad \text{(Eq.5.5)}$$

Where,

$k = isentropic\ expansion\ factor;\ \frac{Cp}{Cv}\ for\ an\ ideal\ gas$

$T = Temperature\ of\ the\ gas\ (°R)$

$MW = molecular\ weight\ of\ the\ gas\ \left(\frac{g}{mol}\right)$

$c = speed\ of\ sound\ in\ the\ fluid\ \left(\frac{ft}{s}\right)$

Equation 5.6 was obtained by substituting equation 5.5 into equation 5.3 for the speed of sound and solving for length.

$$L < 111.5 \cdot t_{open}\sqrt{\frac{kT}{MW}} \tag{Eq.5.6}$$

For the maximal length of the inlet pipe, Smith et al. (2011), apply a rearranged equation developed by Fromman and Friedel (1998) assuming that the sudden reduction in pressure is 20% of the set pressure.

$$\mathrm{L}_i < 9078 \cdot \frac{{d_i}^2}{w_{\%O}}(P_s - P_B)t_0 \tag{Eq.5.7}$$

Where,

$d_i = internal\ diameter\ (in)$

$w_{\%O} = mass\ flow\ rate\ at\ the\ valve\ percent\ open\ \left(\frac{lb}{s}\right)$

$P_B = back\ pressure\ (psi)$

For the maximal length of the inlet pipe, Smith et al. (2011), applies another rearranged equation developed by Fromman and Friedel (1998) assuming that the sudden reduction in pressure is the blowdown.

$$\mathrm{L}_i < 45390 \cdot \frac{{d_i}^2}{W_{\%O}}\left(\frac{P_S - P_{RC}}{P_S}\right)(P_s - P_B)t_0 \tag{Eq.5.8}$$

Where,

$P_{RC} = valve\ reclosing\ pressure\ (psi)$

Considering incompressible fluids, for liquid the speed of sound is calculated as:

$$\mathrm{c} = 1.09\sqrt{\frac{K_s}{\rho}} \tag{Eq.5.9}$$

Where,

$K_s = isentropic\ bulk\ modulus\ of\ elasticity\ (psi)$

$\rho = fluid\ density\ \left(\frac{lb}{ft^3}\right)$

Chattering is not expected if the length of the inlet line complies with equation 5.10.

$$\mathrm{L}_i < 0.55 \cdot t_o \sqrt{\frac{K_S}{\rho}} \quad \text{(Eq.5.10)}$$

Excessive inlet pressure losses

Considering compressible fluids, is specified that the system may chatter if the sum of the acoustic and frictional inlet pressure losses is greater than the blowdown of the relief device

Following equation 5.11 is used to estimate the acoustic pressure losses, and will be required by constraint expressed in equation 5.12 for the length of the inlet piping.

$$\Delta P_{Acoustic} = \frac{L \cdot w_{PSV}}{12.6 \cdot {d_i}^2 \cdot t_0} + \frac{1}{10.5 \cdot \rho}\left(\frac{w_{PSV} \cdot L}{c \cdot d_i \cdot t_0}\right)^2 \quad \text{(Eq.5.11)}$$

Where,

$w_{PSV} = mass\ flow\ rate\ of\ PSV\ \left(\frac{lb}{s}\right)$

Following equation 5.12, coming from the work of Singh (1982-1983), must fulfills in order to avoid chattering.

$$(P_s - P_{RC}) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic} \quad \text{(Eq.5.12)}$$

Equations 5.11 and 5.12 should be verified for opening, full flow and closing conditions.

Considering incompressible fluids, the equation 5.14 must fulfills in order to avoid chattering.

$$\Delta P_{Wave} = \frac{c\rho}{4636.8}(V_0 - V_F) \quad \text{(Eq.5.13)}$$

$$(P_s - P_{RC}) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Wave} \quad \text{(Eq.5.14)}$$

As with compressible fluids, equations 5.13 and 5.14 have to be verified for opening, full flow and closing conditions.

Oversized relief valves

Considering compressible fluids, in order to chatter, an oversized valve for gas/vapor service must have a system capable of increasing the pressure in a cycle time of 1 second or less. Assuming a safety factor of 500%, that means a system cycling time of 5 seconds instead of one second:

$$W_{PSV} > 0.20\, V_{System}(\rho_{Set} - \rho_{Shut}) + W_{required} \qquad \text{(Eq.5.15)}$$

Where,
$V_{system} = volume\ protected\ (ft^3)$
$\rho_{Set} = density\ at\ the\ set\ pressure\ \left(\frac{lb}{ft^3}\right)$
$\rho_{Shut} = density\ at\ set\ minus\ blowdown\ pressure\ \left(\frac{lb}{ft^3}\right)$
$W_{required} = required\ mass\ flow\ rate\ \left(\frac{lb}{s}\right)$

As safety relief device closes at 20-25 % of its rated capacity; thus, another condition for stability is:

$$W_{PSV} < 4W_{required} \qquad \text{(Eq.5.16)}$$

Considering incompressible fluids equation 5.16 have to be satisfied in order to avoid chattering.

5.4.2 Simple force balance method (Melhem, 2016)

Melhem has published a paper "Analysis of PRV Stability in Relief Systems" in 2 parts, in part I a dynamic methodology calculation is developed (ref. to 5.5.1), while in part II a simplified model calculation is provided. API 520 part II 2015 includes a simplified form of the force balance developed by Melhem. The purpose of this method, in the same way as the previous one presented in section 5.4.1, is to know if a pressure relief valve will work in stable manner during fluid conditions. In order to avoid instability, the following equations regarding force balance should be satisfied:

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

$$\left(1 + \frac{\%OP}{100}\right) P_{set} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \left(1 + \frac{\%BD}{100}\right) P_{set} \qquad \text{(Eq.5.18)}$$

$$100\left(\frac{\Delta P_{back} + \Delta P_{f,wave} + \Delta P_{wave}}{P_{set}}\right) < \%BD + \%OP \qquad \text{(Eq.5.19)}$$

$$\%BP + \%FPL + \%WPL < \%BD + \%OP \tag{Eq.5.20}$$

Where,

$P_{source} = source\ pressure\ (psi)$

$\Delta P_{f,wave} = pressure\ losses\ due\ to\ friction\ (psi)$

$\Delta P_{wave} = wave\ pressure\ losses\ (psi)$

$\Delta P_{back} = backpressure\ (psi)$

If the PRV have bellows to protect against backpressure and considering that, as per manufacturing tolerance, the bellows only protect 90 % of the disk surface, the following equations can be used.

$$100\left(\frac{0.1\Delta P_{back}+\Delta P_{f,wave}+\Delta P_{wave}}{P_{set}}\right) < \%BD + \%OP \tag{Eq.5.21}$$

$$\frac{\%BP}{10} + \%FPL + \%WPL < \%BD + \%OP \tag{Eq.5.22}$$

ΔP wave can be estimated as follows:

$$t_{wave} = \frac{2L_p}{c_o} \tag{Eq.5.23}$$

Where,

$L_p = inlet\ line\ length\ (ft)$

$c_o = speed\ of\ sound\ in\ the\ fluid\ \left(\frac{ft}{s}\right)$

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) \tag{Eq.5.24}$$

$$\Delta P_{wave} = \tau\frac{c_0 M_{close}}{A_p} + \tau^2\frac{M_{close}^2}{2\rho_0 A_p^2} \tag{Eq.5.25}$$

$\tau\frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$

$\tau^2\frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$

$$\Delta P_{wave} = \tau\frac{c_0 M_{close}}{A_p} + \tau^2\frac{M_{close}^2}{2\rho_0 A_p^2} \tag{Eq.5.26}$$

$$\Delta P_{wave} = \tau \rho u c_0 \left[1 + \frac{\tau \rho u}{2\rho_0 c_0}\right] \qquad \text{(Eq.5.27)}$$

Where,

$M_{close} = mass\ \text{flow}\ rate\ during\ closing\ \left(\frac{lb}{ft^3}\right)$

$t_{valve} = PRV\ opening\ or\ closing\ time(s)$

$\Delta P_{wave} = fluid\ inertia\ term$

$c_0 = speed\ of\ sound\ \left(\frac{ft}{s}\right), for\ an\ ideal\ gas = \sqrt{\gamma \frac{P_0}{\rho_0}}$

The pressure drop due to friction during opening or closing of the PRV can be estimated using equation 5.28:

$$P_{f,wave} = \tau^2 \Delta P_f = \tau^2 \frac{M^2 (K + \frac{4fL_p}{D_p})}{2\rho_0 {A_p}^2} \qquad \text{(Eq.5.28)}$$

Where,

$K = velocity\ heads\ loss$

$f = fanning\ friction\ factor$

$D_p = pipe\ diameter\ (in)$

$L_p = pipe\ length\ (in)$

$A_p = pipe\ length\ (in^2)$

Equation 5.29 is developed in Melhem part I (2016) using partial differential equations. Specifies the round trip travel time of the pressure wave.

$$\Delta t = \frac{4L}{c_0} \qquad \text{(Eq.5.29)}$$

Speed of Sound Estimates

The speed of sound is calculated as follows:

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

Where,

$k_s = isentropic\ compressibility\ (psi)$

$\rho = fluid\ mass\ density\ \left(\frac{lb}{ft^3}\right)$

$C_p = \text{fluid}\ heat\ capacity\ at\ constant\ pressure$

$C_v = \text{fluid}\ heat\ capacity\ at\ constant\ volume$

Estimation of Ks and mD

Grolmes (2013) provides the following equation for the estimation of the PRV spring constant:

$$K_s = C_1 \left[\frac{P_{set}A_N}{x_{max}}\right] = C_2 C_3 \left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

Where,

$C_1,\ C_2, C_3 = dimensionless\ constants\ close\ to\ 1\ in\ magnitude$

Weight in motion is calculated using formula 5.32:

$$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV} \qquad \text{(Eq.5.32)}$$

Where,

$M_{PRV} = valve\ body\ weight\ including\ a\ 150\#\ flange\ (pounds)$

Knowing Ks and mD, the undamped natural frequency of the valve is calculated with formula 5.33:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} \qquad \text{(Eq.5.33)}$$

PRV Opening and Closing Time

Grolmes (2013) provides the following equation for the estimation of the pressure relief valve opening time:

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N-1}}}} \approx \frac{1}{2f_n} \qquad \text{(Eq.5.34)}$$

Recent analysis performed by Darby (2013-2014) suggest that the damped valve opening time can be approximated by:

$$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} \qquad \text{(Eq.5.35)}$$

Where,

$\varsigma = damping\ coeficient,$ well represented by a value around 0.5

Acoustic analisis

Izuchi (2010) simplifies his detailed modeling analysis to restrict the inlet line length for stable PRV operation as follows:

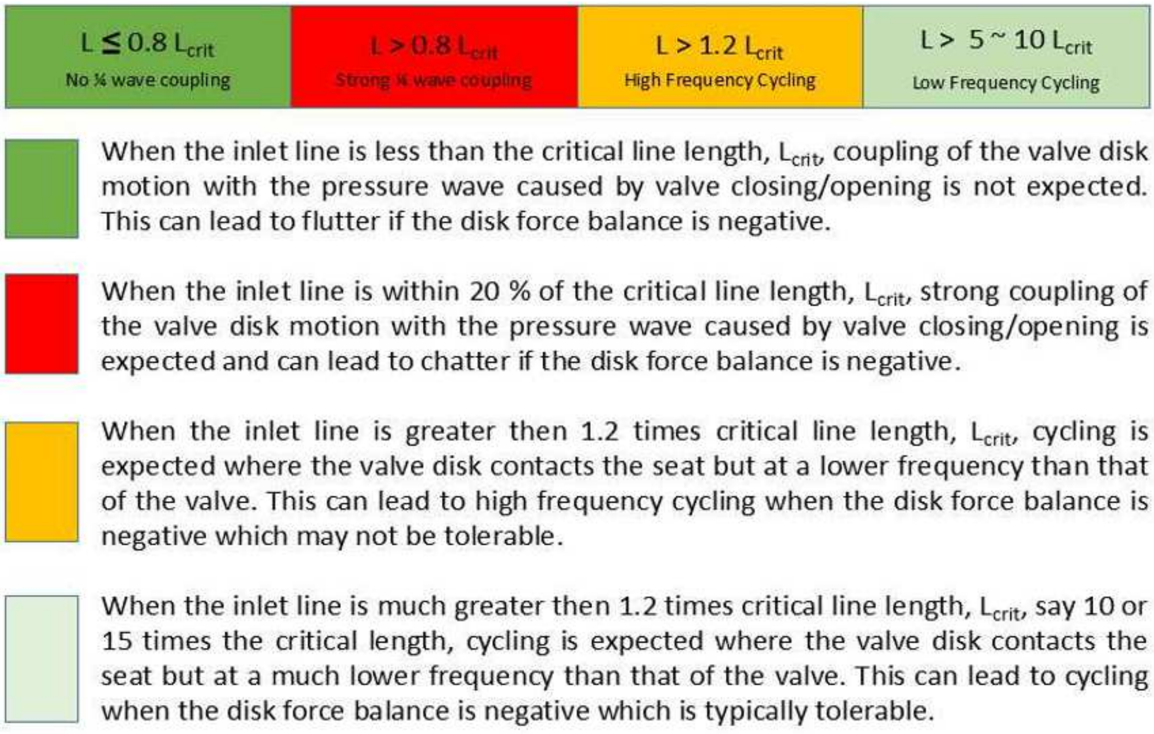
$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Where,

$x = disc\ lift\ (in)$

$f_n = frequency\ (hz)$

In order to determine the kind of instability that suffers the PRV, figure 5.9 can be used in conjunction with the force balance.



$L \leq 0.8\ L_{crit}$	$L > 0.8\ L_{crit}$	$L > 1.2\ L_{crit}$	$L >\ 5 \sim 10\ L_{crit}$
No ¼ wave coupling	Strong ¼ wave coupling	High Frequency Cycling	Low Frequency Cycling

🟩 When the inlet line is less than the critical line length, L_{crit}, coupling of the valve disk motion with the pressure wave caused by valve closing/opening is not expected. This can lead to flutter if the disk force balance is negative.

🟥 When the inlet line is within 20 % of the critical line length, L_{crit}, strong coupling of the valve disk motion with the pressure wave caused by valve closing/opening is expected and can lead to chatter if the disk force balance is negative.

🟨 When the inlet line is greater then 1.2 times critical line length, L_{crit}, cycling is expected where the valve disk contacts the seat but at a lower frequency than that of the valve. This can lead to high frequency cycling when the disk force balance is negative which may not be tolerable.

🟩 When the inlet line is much greater then 1.2 times critical line length, L_{crit}, say 10 or 15 times the critical length, cycling is expected where the valve disk contacts the seat but at a much lower frequency than that of the valve. This can lead to cycling when the disk force balance is negative which is typically tolerable.

Figure 5.9: Critical length multiplier PRV guidance (Melhem 2016)

5.5 Rigorous/dynamic Methods

The dynamic models (Darby et al., 2013-2014; Melhem, 2016; Hös et al., 2012-2015; Izuchi, 2010) requires to know characteristic parameters of the valve that hardly have, like spring constant, mass of the moving parts, damping factor and geometric parameters (Darby et al. 2013-2014).

Additionally calculations are too much complicated without dedicated software.

5.5.1 Darby (2013-2014)

Valve instability is influenced by factors such as the dynamic response of the valve disk to the unstable pressures and forces exercised by the fluid on the disk. Guidelines recommended by API, regarding the maximum inlet pressure losses of 3% of the set pressure, consider steady-state operating conditions and a typical blow-down pressure for the valve of about 7% of the set pressure. Thus, more reliable guidelines are required.

Darby, developed a mathematical model to predict the position of the valve disk. This mathematical model use this following set of five coupled nonlinear algebraic/differential equations.

$$x = fn(F_x, t) \quad \text{(Eq.5.37)}$$
$$F_x = fn(P_N, P_B, w_N) \quad \text{(Eq.5.38)}$$
$$P_N = fn(w_0, w_N, t) \quad \text{(Eq.5.39)}$$
$$P_B = fn(w_N, t) \quad \text{(Eq.5.40)}$$
$$w_N = fn(x, P_N, P_B) \quad \text{(Eq.5.41)}$$

Where,

$F_x = net\ force\ exerted\ on\ the\ disk$

$P_N = dynamic\ pressure\ acting\ on\ the\ disk\ at\ the\ nozzle\ discharge$

$P_B = backpressure\ on\ the\ disk$

$w_N = \ instantaneous\ mass\ \text{flow}\ rate\ through\ the\ nozzle$

$w_0 = \ mass\ \text{flow}\ rate\ leaving\ the\ vessel$

$t = \ time$

$x = \ valve - disk\ lift\ position$

This methodology is difficult to apply without software. The method takes into account the influence of the various parameters on the stable/unstable nature of the disk response, such:

- The spring-mass-damping characteristics of the moving parts of the valve.
- The net forces acting on the disk, which are primarily the pressure and momentum forces exerted by the fluid on the disk
- The setting of the blow-down ring, which determines the reclosure conditions for the valve
- The dynamics of the fluid in the piping upstream of the valve
- The fluid dynamics and the pressure drop in the valve discharge line
- The disk-lift versus flow characteristic of the relief valve at and below the design capacity.

Some required data is often not provided by manufacturer, and is difficult to stablish, such damping factor and deflection angle of the fluid path leaving the disk.

5.5.2 Melhem (2016)

Nowadays some organizations and companies, such American Petroleum Institute, ioMosaic, Pentair, etc. are working on the development of tools on how to perform an Engineering Analysis to validate systems where 3 % rule is exceeded.

As pointed before in 5.5.1, it is clear that PRV stability is a dynamics problem. Melhem remark that the calculation requires an understanding and coupling of the dynamics of the following components:

- Pressure Source
- Inlet Line
- Pressure relief valve
- Discharge Line

Is critical the interaction of pressure wave phenomena in the inlet line with the valve disk motion.

The dynamics of the pressure source are well understood, and the dynamics of flow in relief lines have also been well understood, by the other hand, the dynamics of the PRV itself are currently thought to be well represented with a single degree of freedom representation.

Is in the dynamics of the PRV itself where problems appear. As method developed by Darby (2013-2014), data regarding the geometry of the valve, such disk area, spring constants, mass of the moving parts and damping factor, must be known or need to be approximated.

5.5.3 Hös et al. (2012-2015)

A new mathematical model has been developed by Hös et al. doing a synthesis of previous literature and focusing specifically into instability due to interaction between the valve and the inlet pipe. The model demonstrate that effects of line pressure loss are not critical regarding instability.

The papers present experiments, with different flow rates and length of pipe, done with different commercially available values.

Hös demonstrate that instabilities presented in their experiments are not alleviated by the 3% inlet line loss criterion. But evidence for the existence of a fundamental quarter-wave instability due to a coupling between valve motion and an acoustic quarter-wave in the inlet pipe.

5.5.4 Southern research institute (2016)

A model has been developed by SWRI (2016) that delivers a stability map for pressure relief valve applications. The model is presented with an Excel interface for ease of use. Excel spreadsheet is protected and no details about the calculations done have been provided by SWRI. A User's Manual describes the capabilities of this computational tool to predict the stability of pressure relief valves. The model can be used for applications involving gases and vapors. It is not meant for use with liquid or two-phase applications.

5.5.5 Izuchi (2010)

As Hös et al. (2012-2015), Izuchi investigation found that the interaction effect between the pressure wave propagation through the inlet pipe and the valve disc motion was the cause of a dynamic instability. The longer the inlet pipe is, more mitigated is this king of instability, because oscillating motion of the valve disc is attenuated before the pressure wave returns back.

Comparing with static stability it seems contradictory. Because the mitigation of the dynamic instability presented by Izuchi requires long inlet pipe lines and the 3% rule requires short inlet pipe lines.

In this paper is also studied the effect of the outlet area ratio to the orifice area for the safety valve. And determines that instability increase when the outlet area ratio is lower than 6.0.

6 Used methods in the comparison study

Three calculation methods will be used on the 6 case studies developed in section 7. These 2 following can be grouped as they are considered as simplified methods:

- Smith / Burgess / Powers (2011)
- Simple force balance method (Melhem, 2016)

By the other hand, a dynamic method will be applied. Results will be obtained from a software developed by the Southern Research Institute. From now called as follows:

- SWRI (2016)

7 Case studies

In this section a total of 6 critical pressure relief valves of the polypropylene plants from a worldwide petrochemical company located in Tarragona have been analyzed. The study includes prediction of chattering for each pressure relief valve.

7.1 PRV YS-700-01(K700)

A case study will be presented applying the two different calculation methods. It corresponds to the valve YS700-01 with an inlet pressure drop of 4.18% of the set pressure (not fulfill the 3% rule).A scheme for the installation of the valve is presented in figure 7.1, a picture of the valve and the protected equipment is presented in figure 7.2 and two isometric drawings are presented in figure 7.3 and 7.4.

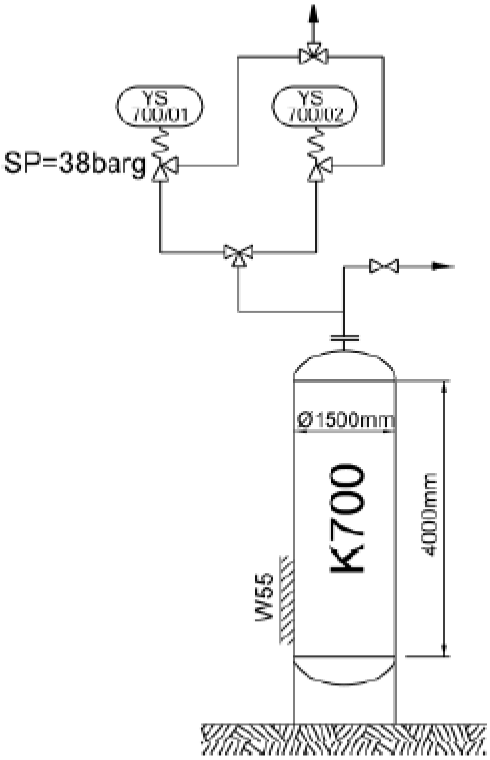


Figure 7.1: Scheme of YS700-01 installation

Figure 7.2: Picture of YS700-01 and protected equipment.

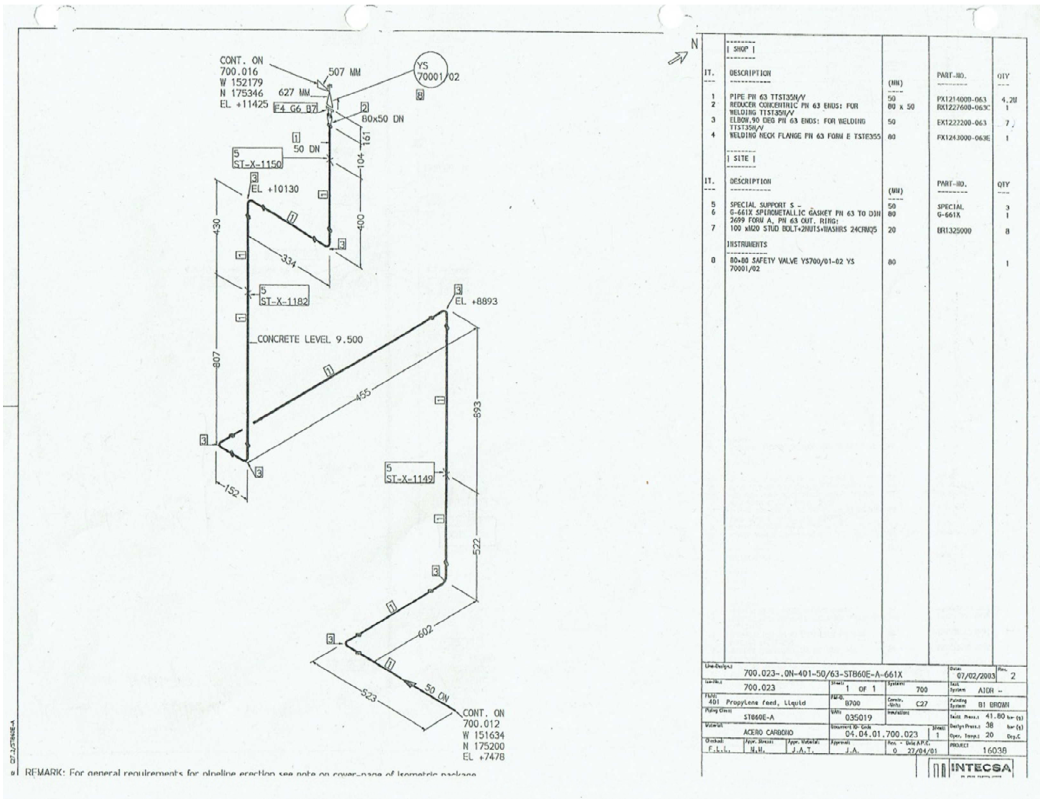


Figure 7.3: Isometric drawing of YS700-01 sheet 1.

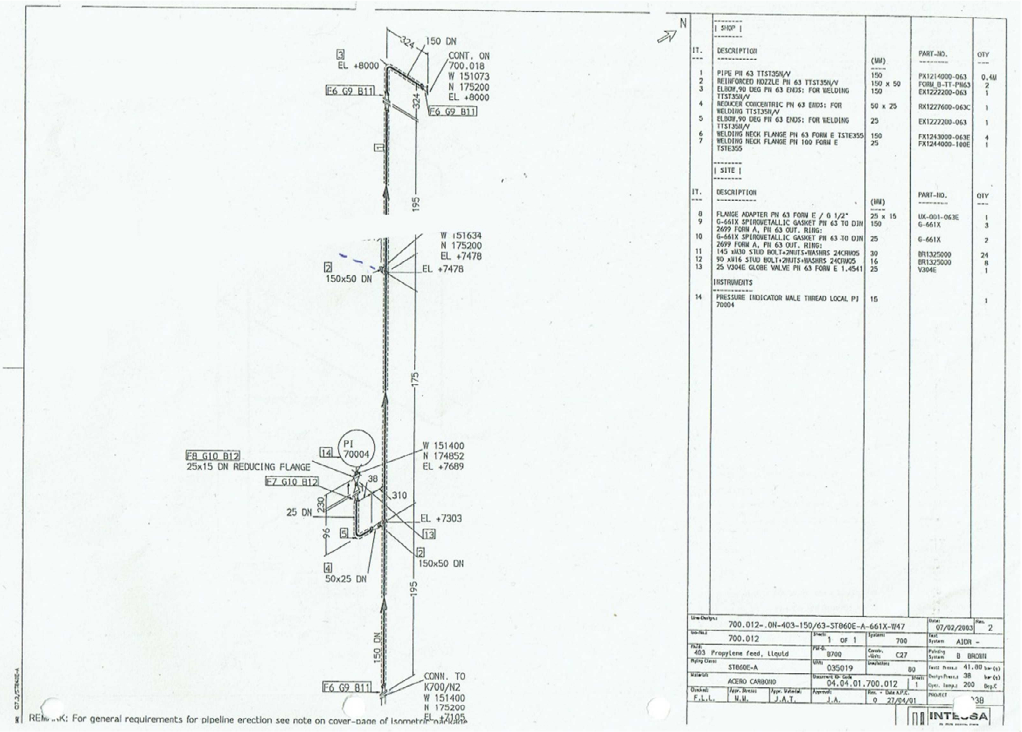


Figure 7.4: Isometric drawing of YS700-01 sheet 2.

YS700-01 protects the liquid propylene dryer (removes water from a liquid propylene) from two relieving scenarios: fire and thermal expansion according to the contingency analysis done. See figure 7.5. The dryer is full of propylene liquid at 23 ºC and 16 bara in operating conditions, which corresponds to a lightly subcooled propylene.

Table 7.1: Results of the contingency analysis for YS700-01.

CONTINGENCY		COMMENTS	JUSTIFICATION
1	Blocked outlets	Not applicable	
2	Abnormal heat input	Not applicable	
3	Exachanger tube breakage	Not applicable	
4	Auto control failure	Not applicable	
5	Reflux failure	Not applicable	
6	Fire	See calculations below	
7	Cooling water failure	Not applicable	
8	Power failure	Not applicable	
9	Instrument air failure	Not applicable	
10	Inadvertent VA open/close	Not applicable	
11	Mechanical equip.failure	Not applicable	
12	Heat loss	Not applicable	
13	Thermal	Applicable	Calculate with a T=25°C (difference between night and day)
14	Loss of quench/cold feed	Not applicable	
15	Chemical reaction	Not applicable	
16	Steam out	Not applicable	

The relieving loads for fire scenario has been calculated.

The design conditions for the pressure relief valve according to the original specification sheet are in the following table:

Table 7.2: Design conditions for YS700-01.

Variable	Value	Units
SP	38	$barg$
P_R	42.813	$bara$
T_R	86	$°C$
$Leser\ valve$	typ 4564.6062	$-$
$Fluid$	$propylene\ gas$	$-$
W_R	15000	$\frac{Kg}{h}$
W_{max}	21007	$\frac{Kg}{h}$
$Area$	1256.6	mm^2
$Valve\ weight$	46	Kg
$\alpha_{d,DG}(certified)$	0.28	$-$
$\alpha_{d,DG}\ (Full\ lift)$	0.8	$-$
$\alpha_{d,F}\ (certified)$	0.24	$-$
$\alpha_{d,F}\ (Full\ lift)$	0.54	$-$
d_0	40	mm
$DN\ inlet$	50	mm
$DN\ outlet$	80	mm
$PN\ inlet$	63	bar
$PN\ outlet$	16	bar
$lift\ restriction$	4.5	mm
$\frac{h}{d_0}\ (full\ lift)$	0.313	$-$
$\frac{h}{d_0}(restricted)$	0.1125	$-$
$\Delta P_{friction\ inlet}$	1.588	bar
P_B	3.13	$barg$
$Blowdown$	10% $(from\ manufacturer)$	$-$

However, the relieving load, in case of fire, depends on the moment of the process. Once the fire begins, the phenomenon that happens is:

→ Isochoric transformation (thermal expansion) of the trapped liquid propylene from 23 ºC and 16 bara (normal operating conditions) to 42.8 bara (relieving pressure)

→ When the valve opens, it relieves propylene liquid which vaporizes following an isentropic transformation until the total backpressure is 4.14 bara (this total backpressure was obtained from the petrochemical company)

→When the liquid reaches 88 ºC, it begins to boil with formation of bubbles at the wall and the valve releases two-phase flow at the inlet and at the outlet, and only after the disengagement of the vapor/liquid phases, begins the release of vapor

→ After the boiling phase an expansion of the gas begins with the possibility of retrograde condensation.

The relieving process can be represented by the following Mollier Diagram, figure 7.3. Although it is a dynamic process some singular points are representative of the phenomenon and have been represented on it.

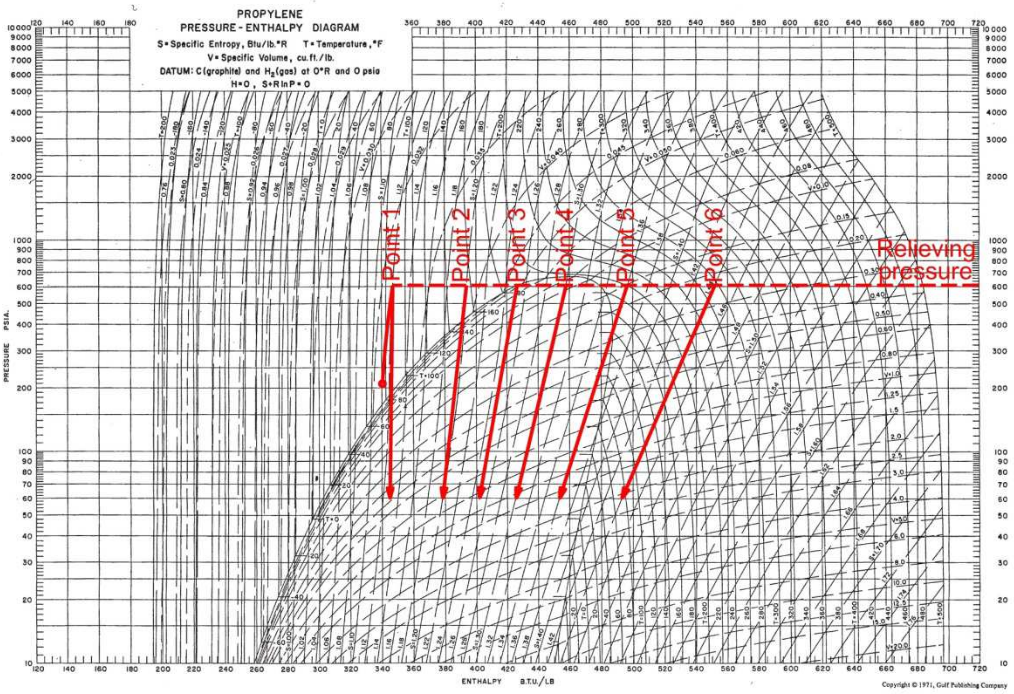


Figure 7.5: Representation (Mollier Diagram) of the relieving process of YS700-01 in case of fire.

7.1.1 *Smith / Burgess / Powers (2011)*

Following the paper of D. Smith, J. Burgess, and C. Powers, Relief device inlet piping: beyond the 3% rule, HP, November 2011, pp59-66

A) Inlet line length (Cremer/Friedel/Pallaks, 2001, 2003)

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.6)}$$

$$d_{psvi} = 40mm = 1.575in$$

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.5)}$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_s}{P_{atm}}\right)^{\frac{2}{3}} \cdot (1 - \frac{P_{atm}}{P_s})^2}\right] \cdot (\frac{h}{h_{max}})^{0.7} \qquad \text{(Eq.5.4)}$$

Full lift has been restricted to 4.5 mm

Thus,

$$\frac{h}{h_{max}} = \frac{4.5}{12.52} = 0.359$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot 1.575}}{\left(\frac{565.8}{14.696}\right)^{\frac{2}{3}} \cdot (1 - \frac{14.696}{565.8})^2}\right] \cdot \left(\frac{4.5}{12.52}\right)^{0.7} = 0.009s$$

$$K = \frac{Cp}{Cp - Cv} \qquad \text{(Eq.7.1)}$$

$$K = \frac{Cp}{Cp - 1.986} = \frac{17.5}{17.5 - 1.986} = 1.13$$

Cp from API Technical Data Book (1997),

Temperature considered 86ºC = 647ºR

$$C = 223 \cdot \sqrt{\frac{1.13 \cdot 647}{42}} = 930 \frac{ft}{s} = 283 \frac{m}{s}$$

t wave (go and return)

$$t_{wave} = \frac{2L}{C} > \frac{2 \cdot 5.66}{283} = 0.04s$$

According to annex C of API 520-11-2015 there is not an acoustic reflection point because:

Area DN 50 = 0.00233m²

Area DN 150 = 0.0194m²

$0.0194 < 10 \cdot 0.00233 \rightarrow No\ check$

$L\ upstream = 0.4m > 20 \cdot 0.0545 \rightarrow No\ check$

So, there is not acoustic reflection point in connection between DN 150 to DN50

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} = 111.5 \cdot 0.009 \cdot \sqrt{\frac{1.13 \cdot 647}{42}} = 4.19ft = 1.28m$$

B) Inlet line length (Froman/Friedel, 1998) ΔP:20%

$L_{100\%} < 9078 \cdot \frac{{d_i}^2}{W_{100\%}} \cdot (P_s - P_B) \cdot t_0$ (Eq.5.8)

$W_{100\%} = 21007Kg/h = 46312\ lb/h$

$P_s = 38barg \cdot 14.5038 = 551psig$

$P_B = 3.13barg \cdot 14.5038 = 45psig$

$L_{100\%} < 9078 \cdot \frac{2.146^2}{46312} \cdot (551 - 45) \cdot 0.009 = 4.11ft = 1.25m$

C) Inlet line length (Froman/Friedel, 1998) ΔP:blowdown

$\mathrm{L} < 45390 \cdot \frac{{d_i}^2}{W_{\%}} \cdot \left(\frac{P_s - P_{RC}}{P_S}\right) \cdot (P_s - P_B) \cdot t_0$ (Eq.5.8)

Blowdown=10% from LESER catalog

P_B from Aspen Flare analyzer (given by the petrochemical company)

$$\mathrm{L} < 45390 \cdot \frac{2.146^2}{46312} \cdot (0.1) \cdot (551 - 45) \cdot 0.009 = 2.06ft = 0.63m$$

D) Required flow > 25% Maximal flow

$$\mathrm{Req.\,flow} > 0.25 \cdot Maximal\ flow \tag{Eq.5.16}$$

$$15000\frac{kg}{h} > 0.25 \cdot 21007 = 5252\frac{kg}{h} \rightarrow OK$$

E) Acoustic pressure losses

$$\Delta P_{Acoustic} = \frac{L \cdot W_{PSV}}{12.6 \cdot {d_i}^2 \cdot t_0} + \frac{1}{10.5 \cdot \rho}\left(\frac{W_{PSV} \cdot L}{c \cdot d_i \cdot t_0}\right)^2 \tag{Eq.5.11}$$

$$\rho = \frac{P_{SET} \cdot MW}{zRT} = \frac{565.8 \cdot 42}{0.55 \cdot 10.731 \cdot 647} = 6.85\frac{lb}{ft^3}$$

$$\Delta P_{Acoustic} = \frac{18.6 \cdot \frac{46312}{3600}}{12.6 \cdot 2.146^2 \cdot 0.009} + \frac{1}{10.5 \cdot 6.85}\left(\frac{\frac{46312}{3600} \cdot 18.6}{930 \cdot 2.146 \cdot 0.009}\right)^2 = 458 + 2 = 460psi = 31.7bar$$

$$\Delta P_{friction} = 1.6bar$$

$$\Delta P_{total} = 31.7bar + 1.6bar = 33.3\ bar$$

$$(P_s - P_{RC}) = \ (P_s * BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic} \tag{Eq.5.12}$$

$$(P_s \cdot BD) = 3.8 > 33.3 \rightarrow No\ check!$$

The above equation (5.12) is for the case that

$$L < \frac{ct}{2}$$

But in this case $L > \frac{ct}{2}$, then the correct equation to use according Darby publication (2013, pg 1264)

$$\Delta P_{Acoustic} = \frac{C \cdot W_{PSV}}{A_i \cdot g_c} + \frac{{W_{PSV}}^2}{2 \cdot \rho_0 \cdot {A_i}^2 g_c}$$

$$\Delta P_{Acoustic} = \frac{930 \cdot 12.86}{\frac{\pi \cdot 0.1788^2}{4} \cdot 32.2} + \frac{12.86^2}{2 \cdot 6.85 \cdot \frac{\pi \cdot 0.1788^2}{4}^2 \cdot 32.2} = 14792 + 595 = 15387 \frac{lb}{ft^3} = 107 psi = 7.4 bar$$

$\Delta P_{friction} = 1.6 bar$ (NOTE 1)

$\Delta P_{total} = 7.4 bar + 1.6 bar = 9\ bar$

$(P_s - P_{RC}) = \ (P_s \cdot BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic}$ (Eq.5.12)

$(P_s \cdot BD) = 3.8 > 9 \rightarrow No\ check!$

Rigorous calculation of the inlet pressure drop

NOTE: Rigorous inlet pressure loss calculation is write down done for case study 1 only.

Process data:

Ps: 38 barg

Temperature: 86°C

K= 1.23

Z= 0.5 @ 38 barg

Overpressure: 10%

Leser valve typ: 4564.6062

Wmax: 21007 Kg/h (from leser specification sheet)

Pr: 42.813 bara (=1.1·38+1.013)

μ= 0.0103Cp= 0.0000103Kg/ms

Reynolds Nº calculation, in order to obtain K value for piping:

- Vapor density

$\frac{P \cdot MW}{zRT} = \frac{42.24 \cdot 42}{0.5 \cdot 0.082 \cdot 359.15} = 120.5 \frac{Kg}{m^3}$ (Eq.7.2)

- Volumetric flow

$$\frac{W}{\rho} = \frac{21007}{120.5 \cdot 3600} = 0.0484 \frac{m^3}{s} \quad \text{(Eq.7.3)}$$

- Velocity

$$\frac{Q}{\frac{\pi D^2}{4}} = \frac{0.0484}{\frac{\pi \cdot 0.0545^2}{4}} = 20.74 \frac{m}{s} \quad \text{(Eq.7.4)}$$

- Reynolds Nº

$$\frac{DV\rho}{\mu} = \frac{0.0545 \cdot 20.74 \cdot 120.5}{0.0000103} = 13.2 \cdot 10^6 \quad \text{(Eq.7.5)}$$

- Friction factor (Moody) for slightly corroded pipe

$$\frac{\varepsilon}{D} = \frac{0.3\ mm}{54.5\ mm} = 0.0055 \quad \text{(Eq.7.6)}$$

$$f = 0.031$$

DN 50 is set as reference (ID =54.5 mm), that is the inlet PRV diameter.

Table 7.3: Total K calculations

Equivalent lenght	$\boldsymbol{Ki = \frac{fL}{D}}$	$\boldsymbol{\beta^4 = (\frac{d_1}{d_2})^4}$	$\boldsymbol{\Sigma Ki}$
Outlet K700	0.5	$\left(\frac{54.5}{157.1}\right)^4 = 0.0145$	0.0072
0.37m pipe DN150 (ID157.1mm) with f=0.031 (fL/D)	0.073	0.0145	0.0011
1 Tee (ID157.1) with f=λ=0.0165	0.75	0.0145	0.0109
1 reduction 157.1x54.5 $K_1 = 0.5 \cdot (1 - \beta^2)$ Crane pag A-46	0.5	-	0.5
4,2m pipe DN50 (54.5mm) with f=0.031 (fL/D)		-	2.3890
7 90° elbow (3D) (r/d=1.26)	0.28		1.960
1 reduction 50x80 α =30°C (Almesa catalogue) $K_1 = 2.6\,sin 15° \,(1 - \beta^2)^2$	0.6726	-	0.6726

Crane pag A-46			
1 changeover valve DN 80 (K=2 from Leser catalog)	2	$\left(\frac{54.5}{81.7}\right)^4 = 0.1980$	0.3960
1 reduction 80x50 α=30°; $K_1 = 0.8 \cdot (1-\beta^2)$	0.199	-	0.1990
TOTAL K			6.136

Assuming isothermic flow, according to API 521-2014

$$\frac{fL}{D} = \frac{1}{{M_a}^2}\left[\left(\frac{P_1}{P_2}\right)^2 - 1\right] - \ln\left(\left(\frac{P_1}{P_2}\right)^2\right) \quad \text{(Eq.7.7)}$$

M_a number in DN 50 valve inlet is:

$$M_{a_2} = 3.23 \cdot 10^{-5} \cdot \left(\frac{q_m}{p_2 d^2}\right) \cdot \left(\frac{zT}{M}\right)^{0.5} \quad \text{(Eq.7.8)}$$

$$M_{a_2} = 3.23 \cdot 10^{-5} \cdot \left(\frac{21007}{4281 \cdot 0.0545^2}\right) \cdot \left(\frac{0.5 \cdot 359.15}{42}\right)^{0.5}$$

Replacing

$$6.136 = \frac{1}{0.1103^2}\left[\left(\frac{P_1}{P_2}\right)^2 - 1\right] - \ln\left(\left(\frac{P_1}{P_2}\right)^2\right)$$

By trial and error

$$\frac{P_1}{P_2} = 1.0371$$

$$P_1 = 1.0371 \cdot 42.813 = 44.401$$

$$\Delta P = 44.401 - 42.813 = 1.588\ bar$$

$$\frac{1.588}{38} \cdot 100 = 4.18\%$$

3% rule is not fulfilled.

F) Body bowl choking (D'Alessandro Method)

$$P_0 < \frac{P_C}{(1+F_0)\cdot\frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

$$A_n = \text{throat area} = \frac{\pi \cdot 40^2}{4} = 1256.6mm^2$$

$$A_e = \text{outlet area} = \frac{\pi \cdot 81.7^2}{4} = 5242.4mm^2$$

K=1.13(ideal gas)

$$P_C = 0.15barg = 16.9psia = superimposed\ backpressure$$

$$P_0 < \frac{16.9}{(1+0.1)\cdot\frac{1256.6}{5242.4}} \cdot \frac{1}{\left(\frac{2}{1.13+1}\right)^{\frac{1.13}{1.13+1}} - 0.1} = 322psia$$

$$P_0 = 42.813barg = 620.9psia$$

$$620.9psia < 322psia \rightarrow No\ check \rightarrow Possibility\ of\ body\ bowl\ chocking$$

G) Compressible vapors criteria (Oversizing)

$$W_{PSV} > 0.2 \cdot V_{system} \cdot (\rho_{set} - \rho_{shut}) + W_{required} \qquad \text{(Eq.5.15)}$$

If this equation fulfills the valve can chatter.

During the boiling process:

Pset at 38barg and 86°C = 6.353$\frac{lb}{ft^3}$

Pshut at 34.2barg and 86°C = 4.993$\frac{lb}{ft^3}$ (webbook nist)

Vsystem=476ft^3 (from datasheet of K700 excluding internals)

Vsystem=476ft^3-205ft^3 (Grace catalyst)= 271ft^3

Thus,

$$12.9\frac{lb}{s} > 0.2 \cdot 271 \cdot (6.353 - 4.993) + 9.2\frac{lb}{s}$$

$$12.9\frac{lb}{s} > 83 \rightarrow No\ fullfills!\ No\ chattering\ possibilities$$

7.1.2 Melhem (2016)

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \quad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \quad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \quad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using ASPEN HYSYS v8.6 TM with Peng Robinson as EOS

Table 7.4: Inlet to pipe/inlet to PRV properties for YS700-01.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	86	41.8 (1)	8.213	1.025
Inlet to PRV	86	40.3 (6% SP)	7.930	1.029

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 38 = 41.8 barg

So, the following table can be created

Table 7.5: Isothermal properties for YS700-01.

Temperature, ºC	P psig (barg)	Density lb/ft^3

86	583.1 (40.2)	7.482
86	586.0 (40.4)	8.023
86	588.9 (40.6)	8.227
86	(40.8)	Liquid

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.066\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.025}{0.066}\cdot\ 32.174\cdot\ 144}\ = 268.2\ ft/s$$

→Speed of sound at PRV inlet

$$c = \sqrt{\frac{1.029}{0.066}\cdot\ 32.174\cdot\ 144}\ = 268.8\ ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N-1}}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \qquad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_s}{m_D}} \qquad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$

$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2\ \text{(assumed)}$

The full lift has a length of 0.313·40 =12.52mm

The lift has been restricted to 4.5mm

Thus,

$\frac{h}{h_{max}} = \frac{4.5}{12.52} = 0.359$

The parameters for a LESER 4564.6062 safety valve, are:

$AN = \pi \frac{1.575^2}{4} = 1.948\ in^2$

$xmax$ = 4.5mm

$Pset$ = 38 barg = 551.1 psig = 565.8 psia

$K_s = 1.1 \cdot 1.2 \cdot \frac{551.1 \cdot\ 1.948}{0.177\ \text{in}} = 8006\ \frac{lb_f}{in}$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV} \qquad \text{(Eq.5.32)}$$

$m_D = 0.018x101 + 0.00022x101^2 = 4.06lbm$

→Natural frequency of the valve

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{8006}{2.59\ lb_m 4.06}x32.174x12} = 138.9Hz$$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2\cdot 138.9s^{-1}} = 0.0036\ s = 3.6\ ms$ (NOTE 1)

NOTE1: the calculation of the t_{open} with the equation of Cremer/Friedel/Pallacks gives 0,009s=9ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{3.6\ ms}{\sqrt{1-0.5^2}} = 4.2\ ms \qquad \text{(Eq.5.35)}$$

Step 3: Force Balance

→PRV Stability Part II

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

→Need tau (Ꞇ)

$$t_{wave} = \frac{2L_p}{c_o} \qquad \text{(Eq.5.23)}$$

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) = min\left(\frac{\frac{2xLp}{c}}{t_{open\ /\ close,d}}, 1\right) = min\left(\frac{\frac{2x18.57ft}{268.2fts^{-1}}}{0.0042}, 1\right) = 1 \qquad \text{(Eq.5.24)}$$

→dPwave (PRV Stability Pt II Eqn 21)

$$\Delta P_{wave} = \tau\frac{c_0 M_{close}}{A_p} + \tau^2\frac{M_{close}^2}{2\rho_0 A_p^2} \text{ NOTE 2} \qquad \text{(Eq.5.25)}$$

$\tau\frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$

$\tau^2\frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$

→Ap is constant → No reflection point!

NOTE 2: Although there is a champeover valve and a 150 to 50 intersection, it is assumed no reflection point (see calculations)

→Assume Mclose = 80% of capacity

0.8 · 21007 Kg/h = 37050 lb/h

→c_0= 268.2 ft/s

→ρ_0 = 8.213 lb/ft3

→Dpipe = 54.5 mm = 2.145 in

$$\Delta P_{wave,open} = 1 \cdot \frac{268.2 fts^{-1} \cdot 46312.5 lb_m h^{-1} \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(46312.5h^{-1} \cdot \frac{h}{3600s})^2}{2x8.213 lb_m ft^{-3} \cdot ((2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 137490\ lb_m ft^{-1} s^{-2} + 15999\ lb_m ft^{-1} s^{-2}\ = 153489\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,open} = 153489\ lb_m ft^{-1} s^{-2} \cdot\ \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 33.1 lb_f in^{-2}$$

$$\Delta P_{wave,close} = 1 \cdot \frac{268.2 fts^{-1} \cdot 37050 \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(37050h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 8.213 lb_m ft^{-3} \cdot ((2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 109992\ lb_m ft^{-1} s^{-2} + 10239\ lb_m ft^{-1} s^{-2}\ = 120231\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,close} = 120231\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 25.9 lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 1^2 \cdot\ 1.588\ bar = 23.03\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2 \tau^2 \Delta P_{f,opening} = 0.8^2 1^2 1.588\ bar = 1.016\ bar = 14.73\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$606.26 - 33.1 - 23.03 - 45.4\ - 496.03 = 8.7$$

Closing:

$$606.26 - 25.9 - 14.73 - 45.4 \ - 496.03 = 24.2$$

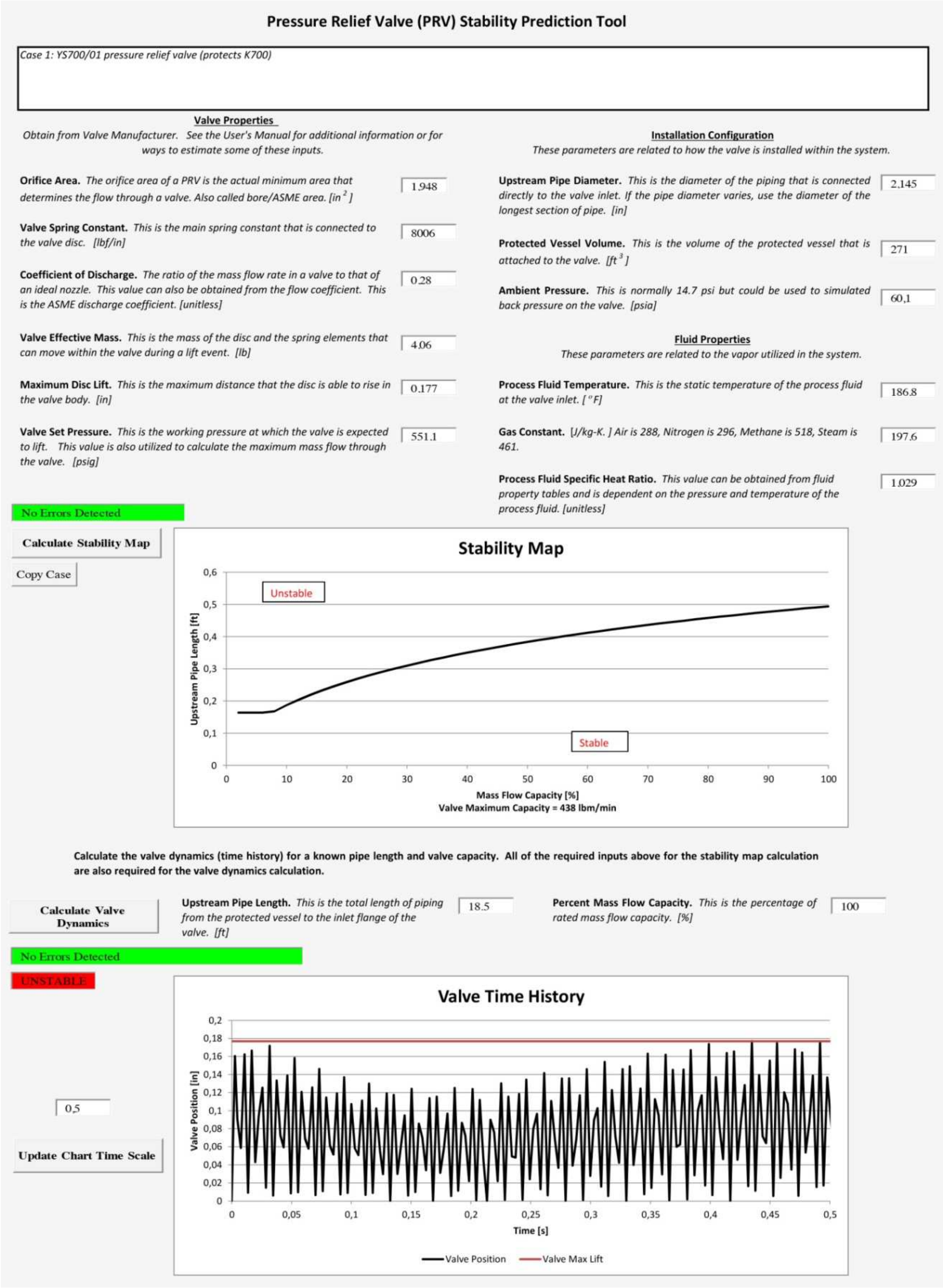
→Force balance is positive → **NO chattering**

Step 4: Acoustic Analysis

Acoustic analysis is not required because force balance is positive

7.1.3 SWRI (2016)

The SWRI software consists of a spreadsheet (visual basic), which gives the stability results in a very graphical view. A screenshot is presented:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 1: YS700/01 pressure relief valve (protects K700)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in^2]* 1.948

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 8006

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.28

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 4.06

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.177

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 551.1

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2.145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft^3]* 271

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 60,1

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 186.8

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 18.5

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0,5

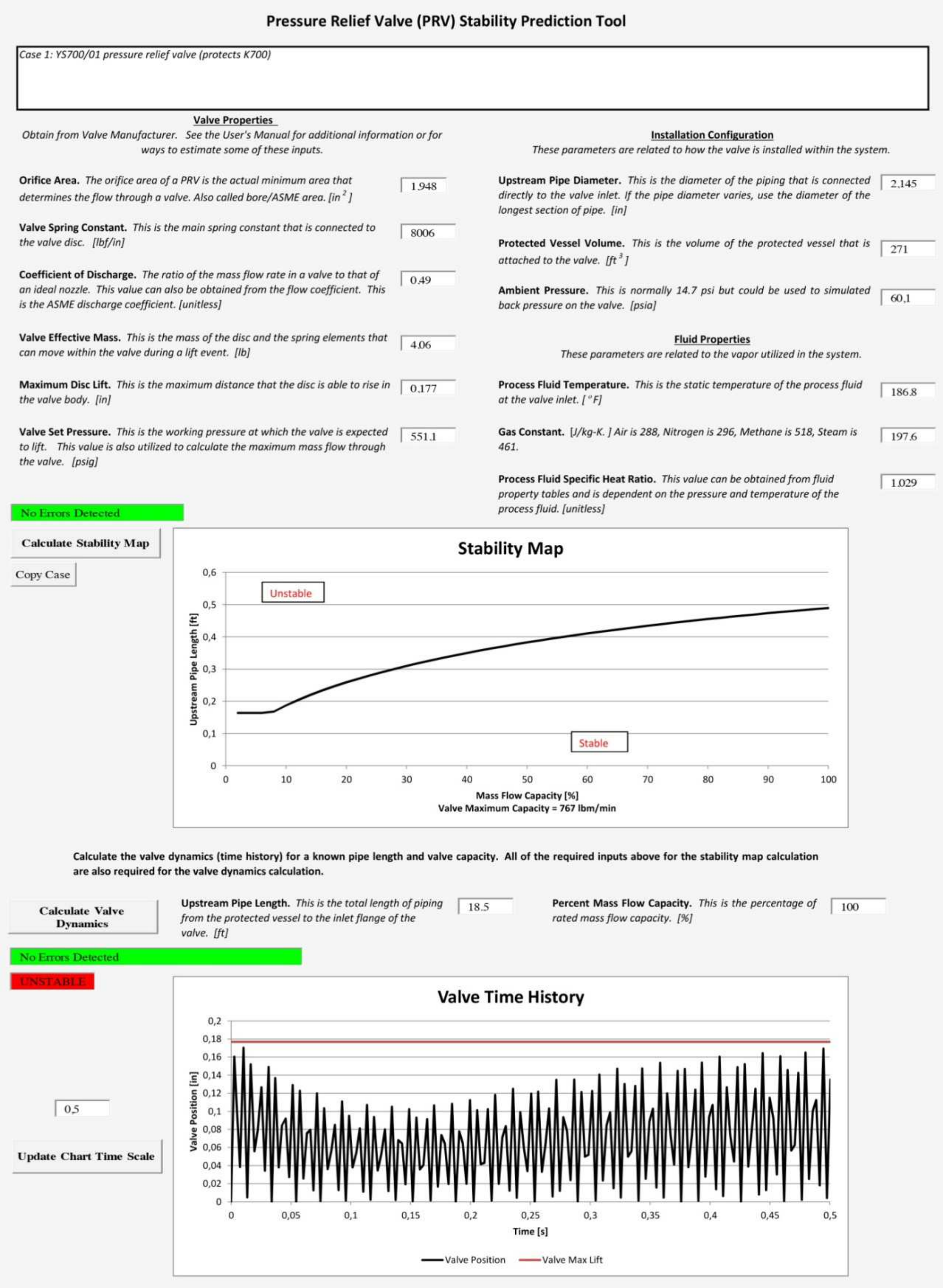
Figure 7.6: Stability results of SWRI software for YS700-01 (unreal flow).

However the software calculate a maximal flow of $438\,\frac{lb}{min}$ but the real value is $772\,\frac{lb}{min}$.

One way to solve this problem is by changing the discharge coefficient proportionally:

$$\frac{0.28}{438\frac{lb}{min}} \cdot 772\,\frac{lb}{min} = 0.49$$

Thus, the new result is:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 1: YS700/01 pressure relief valve (protects K700)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in ^{2}]* 1.948

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 8006

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.49

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 4.06

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.177

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 551.1

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2,145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft ^{3}]* 271

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 60,1

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 186.8

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

🟩 No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 18.5

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

🟩 No Errors Detected

🟥 UNSTABLE

0,5

Figure 7.7: Stability results of SWRI software for YS700-01 (real flow).

The stability map shows that the safety valve operates in the unstable region. The valve time history shows instability. It is observed that the disc strikes in the seats at a frequency of 140 Hz approximately. Therefore PRV suffers chattering.

7.1.4 Engineering analysis summary

According to the engineering analysis procedure described section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? Yes

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

38-(34.2+0.76)>1.59

5) Does excessive built-up backpressure occur according to the specific PRV?

No, the built-up back backpressure is 3.13 barg, thus

(3.13/38)·100=8.2%<10%, OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table, 7.6:

Table 7.6: Stability analysis results for YS700-01

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	5.7	1.3	No	Yes
Inlet line length (Frommann and Friedel, 1998) ΔP 20%	5.7	1.3	No	Yes

Inlet line length (Frommann and Friedel, 1998) ΔP blowdown	5.7	0.6	No	Yes
Required flow > 25% rated flow (oversizing)			Yes	No
Compressible vapors criteria (oversizing)			No	No
Total backpressure for a conventional valve < 10% SP			Yes	No
Body bowl choking			No	Unknown
Acoustic pressure losses			No	Yes
API Simple Force Balance (Melhem, 2016)			Yes	No

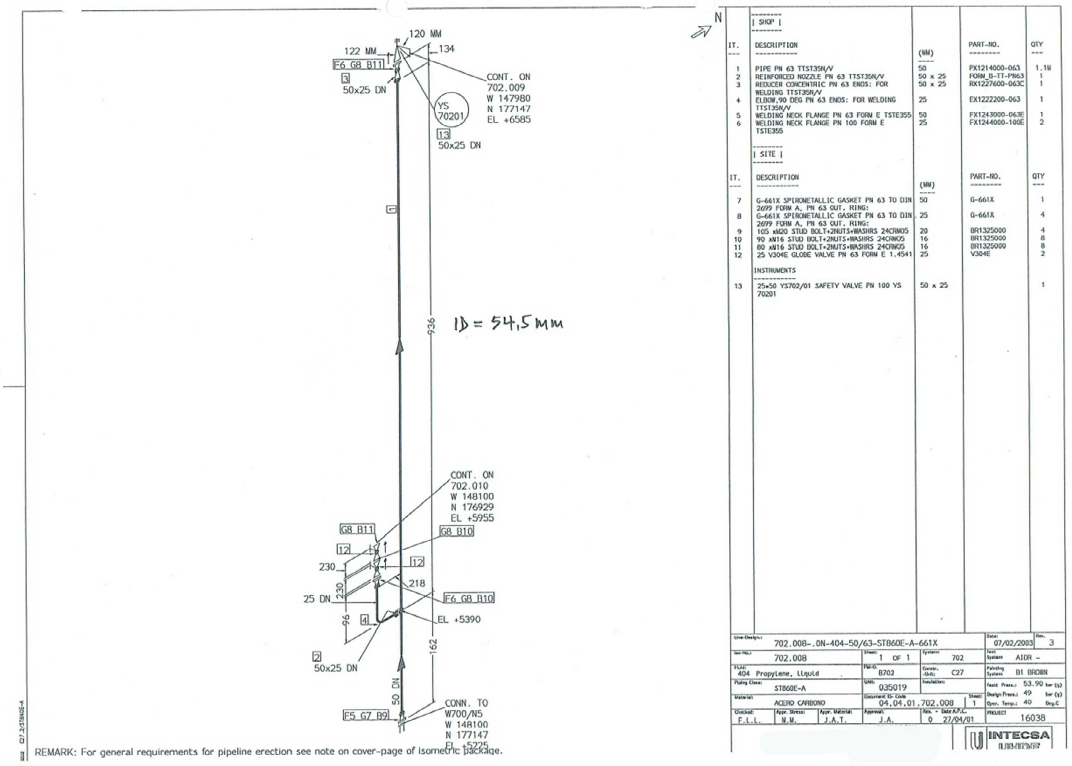
8) Is the risk of relieving of the existing pressure relief valve quantified?

Yes, very low risk. It discharges to flare.

7.2 PRV YS-702-01(W700)

The second case study corresponds to the valve YS702-01 with an inlet pressure drop greater than 3% of the set pressure (not fulfill the 3% rule). A picture of the valve and the protected equipment is presented in figure 7.6 and an isometric drawing is presented in figure 7.7.

Figure 7.8: Picture of YS702-01 and protected equipment.



REMARK: For general requirements for pipeline erection see note on cover-page of isometric package.

SHOP				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
1	PIPE PN 63 TTST35N/V	50	PX1214000-063	1.1M
2	REINFORCED NOZZLE PN 63 TTST35N/V	50 x 25	FORM_B-TT-PN63	1
3	REDUCER CONCENTRIC PN 63 ENDS: FOR WELDING TTST35N/V	50 x 25	RX1227600-063C	1
4	ELBOW,90 DEG PN 63 ENDS: FOR WELDING TTST35N/V	25	EX1222200-063	1
5	WELDING NECK FLANGE PN 63 FORM E TSTE355	50	FX1243000-063E	1
6	WELDING NECK FLANGE PN 100 FORM E TSTE355	25	FX1244000-100E	2

SITE				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
7	G-661X SPIRONETALLIC GASKET PN 63 TO DIN 2699 FORM A, PN 63 OUT. RING:	50	G-661X	1
8	G-661X SPIRONETALLIC GASKET PN 63 TO DIN 2699 FORM A, PN 63 OUT. RING:	25	G-661X	4
9	105 xM20 STUD BOLT+2NUTS+WASHRS 24CRMO5	20	BR1325000	4
10	90 xM16 STUD BOLT+2NUTS+WASHRS 24CRMO5	16	BR1325000	8
11	80 xM16 STUD BOLT+2NUTS+WASHRS 24CRMO5	16	BR1325000	8
12	25 V304E GLOBE VALVE PN 63 FORM E 1.4541	25	V304E	2
	INSTRUMENTS			
13	25x50 YS702/01 SAFETY VALVE PN 100 YS 70201	50 x 25		1

Line-Design.: 702.008-.0N-404-50/63-ST860E-A-661X		Date: 07/02/2003	Rev. 3
Iso-No.: 702.008	Sheet: 1 OF 1	System: 702	Test System AIDR -
Fluid: 404 Propylene, Liquid	P&I-D: B702	Constr.-Unit: C27	Painting System B1 BROWN
Piping Class: ST860E-A	UAN: 035019	Insulation:	Test Press.: 53.90 bar (g)
Material: ACERO CARBONO	Document ID-Code 04.04.01.702.008	Sheet: 1	Design Press.: 49 bar (g) Oper. Temp.: 40 Deg.C
Checked: F.L.L. Appr. Stress: N.M. Appr. Material: J.A.T.	Approval: J.A.	Rev. - Date A.P.C. 0 27/04/01	PROJECT 16038

INTECSA

Figure 7.9: Isometric drawing of YS702-01.

The relieving process can be represented by the following Mollier Diagram, figure 7.8. Although it is a dynamic process some singular points are representative of the phenomenon and have been represented on it.

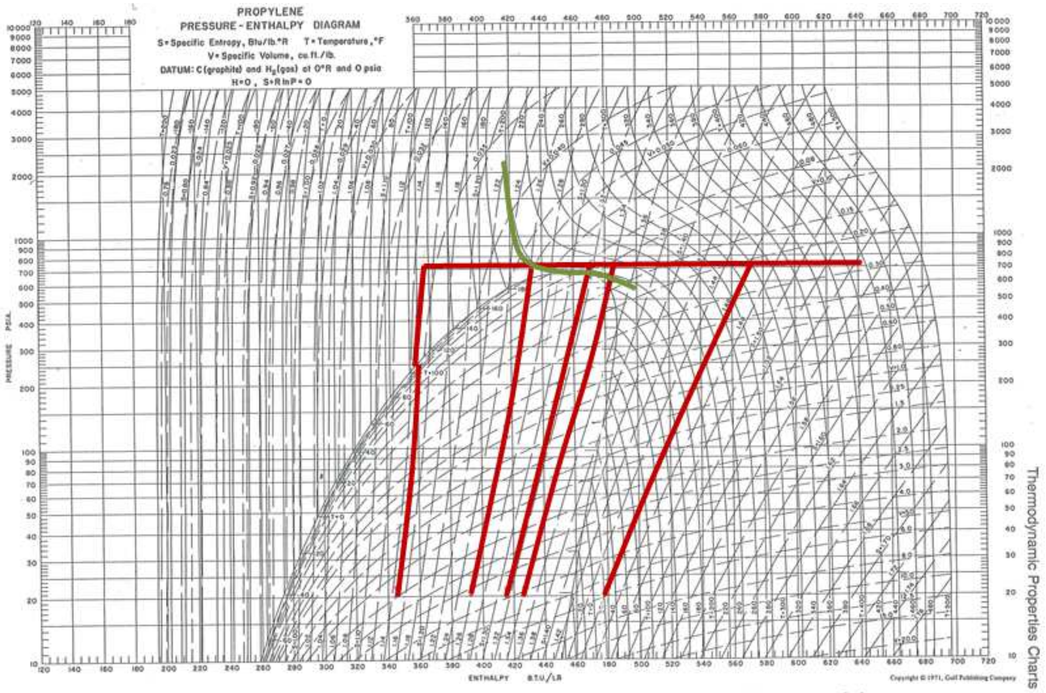


Figure 8.6. Propylene pressure-enthalpy diagram. Note: Add −362.0 Btu/lb to chart readings to get enthalpy

Figure 7.10: Representation of the relieving process of YS702-01 in case of fire.

The relieving loads for fire scenario has been calculated.

The design conditions for the pressure relief valve according to the original specification sheet are in the following table:

a) Gas phase

Table 7.7: Design conditions for YS702-01.

Variable	Value	Units
SP	45	$barg$
T_R	100	$°C$
$Leser\ valve$	typ 4564.6052	$-$
$Fluid$	$propylene\ gas$	$-$
W_R	10000	$\frac{Kg}{h}$
W_{max}	15826.9	$\frac{Kg}{h}$
$Area$	314.16	mm^2

$Valve\ weight$	20	Kg
$\alpha_{d,DG}$	0.8	$-$
$\alpha_{d,F}$	0.6	$-$
d_0	20	mm
$DN\ inlet$	25	mm
$DN\ outlet$	50	mm
$PN\ inlet$	100	bar
$PN\ outlet$	40	bar
$\Delta P_{friction\ inlet}$	0.646	bar
P_B	3.43	$barg$
$Blowdown$	10% $(from\ manufacturer)$	$-$

b) Liquid phase

$P_R = 50.513\ bara = 732.6\ psia$

$T_R = 45.5\ °C$

7.2.1 Smith / Burgess / Powers (2011), gas phase

Following the paper of D. Smith, J. Burgess, and C. Powers, Relief device inlet piping: beyond the 3% rule, HP, November 2011, pp59-66

A) Inlet line length (Cremer/Friedel/Pallaks, 2001, 2003)

$$L < 111{,}5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.6)}$$

$d_{psvi} = 20mm = 0.787in$

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.5)}$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_s}{P_{atm}}\right)^{\frac{2}{3}} \cdot (1 - \frac{P_{atm}}{P_s})^2}\right] \cdot (\frac{h}{h_{max}})^{0.7} \qquad \text{(Eq.5.4)}$$

$\frac{h}{h_{max}} = 0.6$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot 0.787}}{\left(\frac{46.013}{1.013}\right)^{\frac{2}{3}} \cdot (1 - \frac{1.013}{46.013})^2}\right] \cdot (0.6)^{0.7} = 0.012s$$

$$K = \frac{Cp}{Cp - 1.986} = \frac{15.226}{15.226 - 1.986} = 1.13 \qquad \text{(Eq.7.1)}$$

Cp from API Technical Data Book (1997),

Temperature considered 100ºC = 672ºR

$$C = 223 \cdot \sqrt{\frac{1.15 \cdot 672}{42}} = 956\frac{ft}{s} = 291.6\frac{m}{s}$$

t wave (go and return)

$$t_{wave} = \frac{2L}{C} > \frac{2 \cdot 1.1}{291.6} = 0.0075s$$

$$L < 111{,}5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} = 111.5 \cdot 0.012 \cdot \sqrt{\frac{1.15 \cdot 672}{42}} = 5.74ft = 1.74m$$

B) Inlet line length (Froman/Friedel, 1998) ΔP:20%

Assuming initial lift is 60%

$$L < 9078 \cdot \frac{{d_i}^2}{W_{60\%}} \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

$$W_{100\%} = 15827Kg/h = 34892\ lb/h$$

Assuming that 60% lift corresponds to a 60% maximal flow

$$W_{60\%} = 20935\ lb/h$$

$$P_s = 45barg \cdot 14.5038 = 652.67psig$$

As per flarenet: 7.63% of SP

$$P_B = 3.43barg \cdot 14.5038 = 49.8psig$$

$$L < 9078 \cdot \frac{2.146^2}{20935} \cdot (652.67 - 49.8) * 0.012 = 14.4ft = 4.4m$$

C) Inlet line length (Fromman/Friedel) ΔP:blowdown

$$\mathrm{L} < 45390 \cdot \frac{d_i^{\,2}}{W_{\%}} \cdot \left(\frac{P_s - P_{RC}}{P_S}\right) \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

Blowdown=10% from LESER catalog

P_B from Aspen Flare analyzer (given by the petrochemical company)

$$\mathrm{L} < 45390 \cdot \frac{2.146^2}{20935} \cdot (0.1) \cdot (652.67 - 49.8) \cdot 0.012 = 7.22ft = 2.2m$$

D) Required flow > 25% Maximal flow

$$\mathrm{Req.\,flow} > 0.25 \cdot Maximal\ flow \qquad \text{(Eq.5.16)}$$

$$10000\,\frac{kg}{h} > 0.25 \cdot 15826.9 = 3956.7\ \frac{kg}{h} \rightarrow OK$$

E) Acoustic pressure losses

$$\Delta P_{Acoustic} = \frac{L \cdot W_{PSV}}{12.6 \cdot d_i^{\,2} \cdot t_0} + \frac{1}{10.5 \cdot \rho}\left(\frac{W_{PSV} \cdot L}{c \cdot d_i \cdot t_0}\right)^2 \qquad \text{(Eq.5.11)}$$

$$\rho = \frac{P_{SET} \cdot MW}{zRT} = \frac{667 \cdot 42}{0.42 \cdot 10.731 \cdot 672} = 9.25\,\frac{lb}{ft^3}$$

$$\Delta P_{Acoustic} = \frac{3.6 \cdot \frac{20935}{3600}}{12.6 \cdot 2.146^2 \cdot 0.012} + \frac{1}{10.5 \cdot 9.25}\left(\frac{\frac{20935}{3600} \cdot 3.6}{956 \cdot 2.146 \cdot 0.012}\right)^2 = 30.1 + 0 = 30.1psi = 2.1bar$$

$$\Delta P_{friction} = 0.646bar \cdot 0.6^2 = 0.2bar(is\ assumed\ 60\%\ lift \rightarrow 60\% \max flow)$$

$$\Delta P_{total} = 2.1bar + 0.2bar = 2.3\ bar$$

$$(P_s - P_{RC}) = \ (P_s \cdot BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic} \qquad \text{(Eq.5.12)}$$

$$(4.5 \cdot 0.1) = 4.5 > 2.3 \rightarrow check!$$

F) Body bowl choking (D'Alessandro Method)

$$P_0 < \ \frac{P_C}{(1+F_0) \cdot \frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

$$A_n = \text{throat area} = \frac{\pi \cdot 20^2}{4} = 314.159\, mm^2$$

$$A_e = \text{outlet area} = \frac{\pi \cdot 54.5^2}{4} = 2332.8\, mm^2$$

$$F_0 = \frac{P_0 - P_s}{P_s - P_c} = \frac{50.513 - 46.013}{46.013 - 1.013} = 0.1$$

$P_0: Relieving\ pressure$

$P_S: Set\ Pressure$

$P_C: Superimposed\ back\ pressure$

K=1.15 (ideal gas)

$$P_0 < \frac{1.013}{(1+0.1)\cdot\frac{314.159}{2332.8}} \cdot \frac{1}{\left(\frac{2}{1.15+1}\right)^{\frac{1.15}{1.15+1}} - 0.1} = 7.93$$

$$P_0 = 50.513 barg$$

$$P_0 = 50.513 barg < 7.93\ barg \rightarrow Check!$$

There is no possibility of secondary back pressure!

G) Compressible vapors criteria (Oversizing)

$$W_{PSV} > 0.2 \cdot V_{system} \cdot \left(\rho_{set} - \rho_{shut}\right) + W_{required} \qquad \text{(Eq.5.15)}$$

If this equation is fulfilled the safety valve can chatter.

During the boiling process:

Pset at 45barg and 100°C = 7.304$\frac{lb}{ft^3}$

Pshut at 40.5barg and °C = 5.761$\frac{lb}{ft^3}$ (webbook nist)

Vsystem=24.3ft^3

Vsystem=24.3ft^3-6.2ft^3 (Grace tubes)= 18.1ft^3

Thus,

$$9.7\,\frac{lb}{s} > 0.2 \cdot 18.1 \cdot (7.304 - 5.761) + 6.1\,\frac{lb}{s}$$

$9.7\,\frac{lb}{s} > 11.7 \rightarrow No\ fullfills!\ No\ chattering\ possibilities$

7.2.2 Melhem (2016), gas phase

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using webbook NIST

Table 7.8: Inlet to pipe/inlet to PRV properties for YS702-01.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	100	49.5 (1)	9.3023	1.025
Inlet to PRV	100	47.7 (6% SP)	8.1202	1.029

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 45 = 49.5 barg

So, the following table can be created

Table 7.9: Isothermal properties for YS702-01.

Temperature, ºC	P psig (barg)	Density lb/ft^3
100	691.8 (47.7)	8.1202 Supercritical
100	699.1 (48.2)	8.4071 Supercritical
100	706.3 (48.7)	8.7222 Supercritical
100	717.9 (49.5)	9.3023 Supercritical

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.045\,\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.025}{0.045}\cdot 32.174\cdot 144} = 324.85\,ft/s$$

→Speed of sound at PRV inlet32174

$$c = \sqrt{\frac{1.029}{0.045}\cdot 32.174\cdot 144} = 325.48\,ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N-1}}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \qquad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_s}{m_D}} \qquad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

$$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$$

$$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2\ \text{(assumed)}$$

Assuming initial lift is 60%

Thus,

$$\frac{h}{h_{max}} = 0.6$$

The parameters for a LESER safety valve, are:

$$AN = \pi\frac{0.7874^2}{4} = 0.487\ in^2$$

$xmax$ = 3.76mm (0.313·20·60%)=0.148 in

$Pset$ = 45 barg = 652.62 psig

$$K_s = 1.1 \cdot 1.2 \cdot \frac{652.62 \cdot 0.487}{0.148\ \mathrm{in}} = 2834.7\ \frac{lb_f}{in}$$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV} \qquad \text{(Eq.5.32)}$$

$$m_D = 0.018 \cdot 44.1 + 0.00022 \cdot 44.1^2 = 1.22lbm$$

→Natural frequency of the valve

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{2834.7}{2.59\ lb_m 1.22}\cdot 32.174\cdot 12} = 93.66Hz$$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2\cdot 93.66s^{-1}} = 0.0053\ s = 5.3\ ms$ (NOTE 1)

NOTE1: the calculation of the t_{open} with the equation of Cremer/Friedel/Pallacks gives 0,0075s=7.5ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{5.3\ ms}{\sqrt{1-0.5^2}} = 6.11\ ms$ (Eq.5.35)

Step 3: Force Balance

→PRV Stability Part II

$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$ (Eq.5.17)

→Need tau (Ꞇ)

$t_{wave} = \frac{2L_p}{c_o}$ (Eq.5.23)

$$\tau = min\left(\frac{t_{wave}}{t_{valve}},1\right) = min\left(\frac{\frac{2\cdot L_p}{c}}{t_{open\ /\ close,d}},1\right) = min\left(\frac{\frac{2\cdot 3.61ft}{324.85\ fts^{-1}}}{0.00611},1\right) = \min(3.63,1) = 1$$

→dPwave (PRV Stability Pt II Eqn 21)

$\Delta P_{wave} = \tau\frac{c_0 M_{close}}{A_p} + \tau^2\frac{M_{close}^2}{2\rho_0 A_p^2}$ NOTE 2 (Eq.5.25)

$\tau\frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$

$\tau^2\frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$

→Ap is constant → No reflection point!

NOTE 2: Although there is a champeover valve and a 50 to 25 intersection, it is assumed no reflection point (see calculations)

→Assume Mclose = 80% of capacity

0.8·15826.9 Kg/h = 27914 lb/h

→c_0 = 324.85 ft/s

→ρ_0 = 9.3023lb/ft3

→Dpipe = 54.5 mm = 2.145 in

$$\Delta P_{wave,open} = 1 \cdot \frac{324.85fts^{-1}\cdot 34892.5lb_m h^{-1}\cdot \frac{h}{3600s}}{(2.145in)^2\pi\cdot 0.25\cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(34892.5h^{-1}\cdot \frac{h}{3600s})^2}{2\cdot 9.3023lb_m ft^{-3}\cdot ((2.145in)^2\pi\cdot 0.25\cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 125467\ lb_m ft^{-1}s^{-2} + 8018.2\ lb_m ft^{-1}s^{-2}\ = 133485.2\ lb_m ft^{-1}s^{-2}$$

$$\Delta P_{wave,open} = 133485.2\ lb_m ft^{-1}s^{-2} \cdot \frac{lb_f}{32.174lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 28.8lb_f in^{-2}$$

$$\Delta P_{wave,close} = 1 \cdot \frac{324.85fts^{-1}\cdot 27914\cdot \frac{h}{3600s}}{(2.145in)^2\pi\cdot 0.25\cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(27914h^{-1}\cdot \frac{h}{3600s})^2}{2\cdot 9.3023lb_m ft^{-3}\cdot ((2.145in)^2\pi\cdot 0.25\cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 100374\ lb_m ft^{-1}s^{-2} + 5132\ lb_m ft^{-1}s^{-2}\ = 105497\ lb_m ft^{-1}s^{-2}$$

$$\Delta P_{wave,close} = 105497\ lb_m ft^{-1}s^{-2} \cdot \frac{lb_f}{32.174lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 22.77lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 1^2 \cdot 0.646\ bar = 9.37\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2\tau^2\Delta P_{f,opening} = 0.8^2 1^2 0.646\ bar = 0.41344\ bar = 6\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$717.94 - 28.8 - 9.37 - 45.4 - 522.14 = 112.23$$

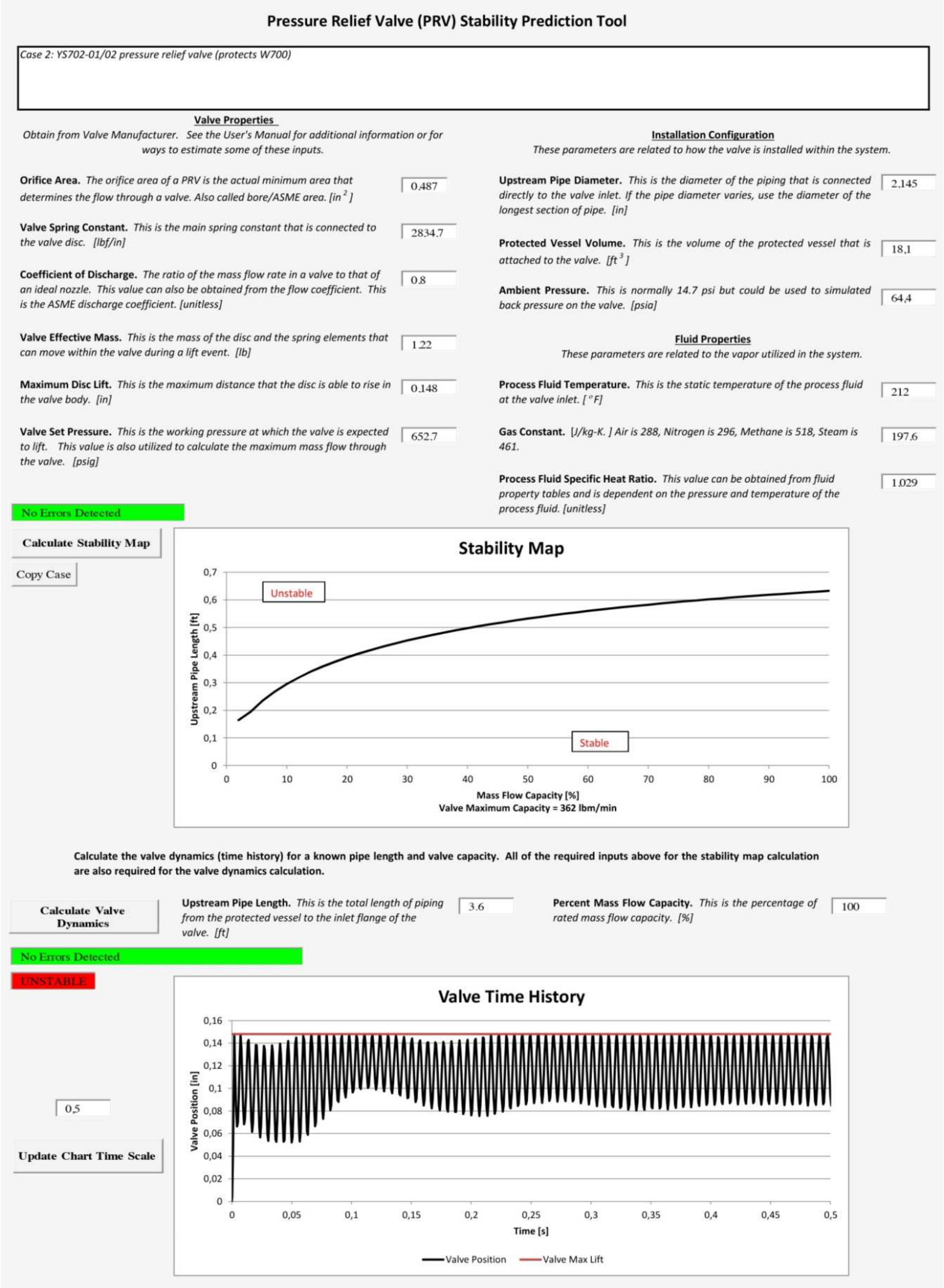
Closing:

$$717.94 - 22.77 - 14.736 - 45.4 - 522.14 = 121.63$$

→Force balance is positive → **NO chattering**

7.2.3 SWRI (2016)

The screenshot of the results with the software is as following:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 2: YS702-01/02 pressure relief valve (protects W700)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in^2]* 0.487

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 2834.7

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.8

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 1.22

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.148

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 652.7

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2,145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft^3]* 18,1

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 64,4

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 212

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 3.6

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0,5

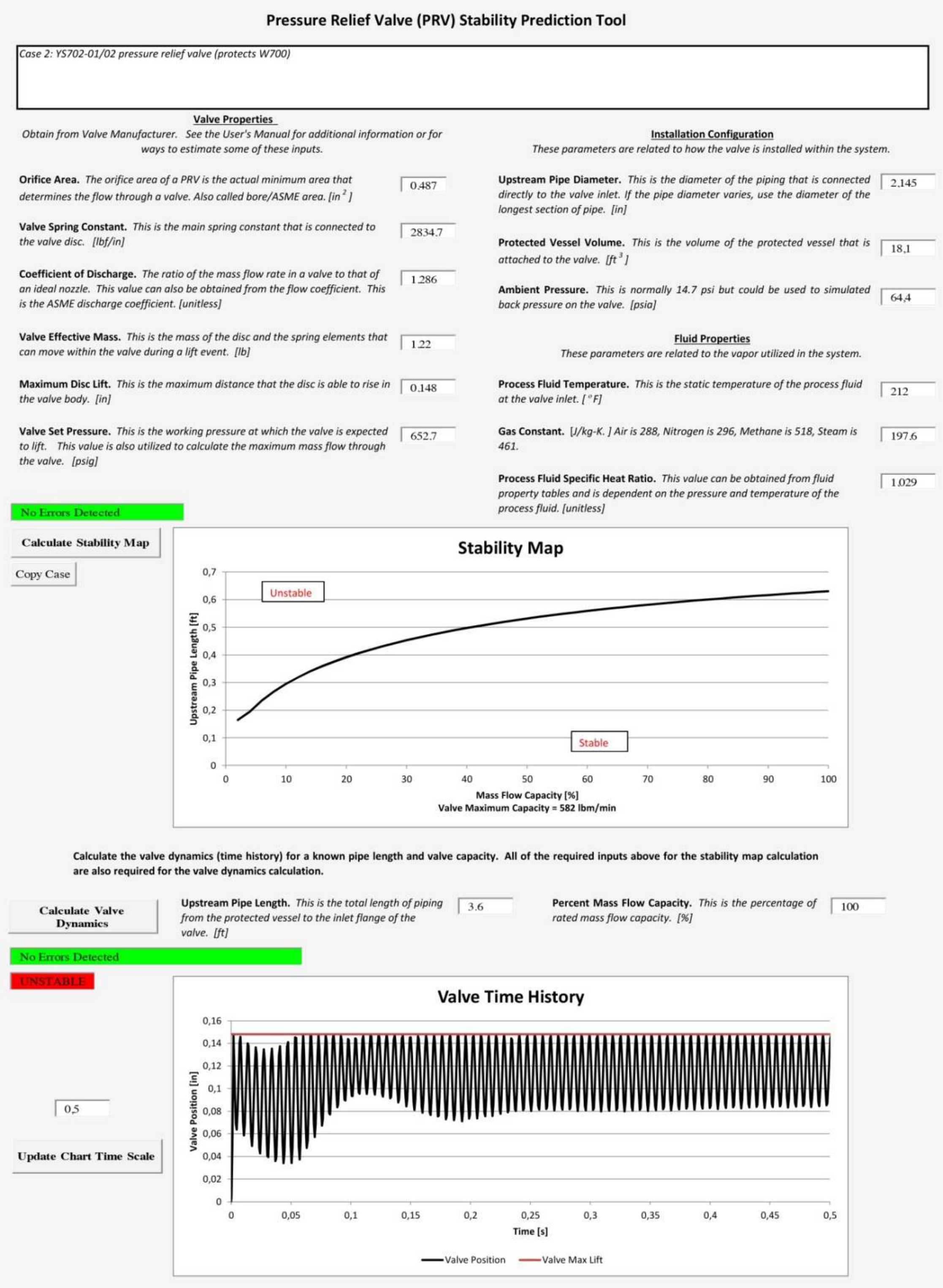
Figure 7.11: Stability results of SWRI software for YS702-01 (unreal flow).

However the software calculate a maximal flow of $362\frac{lb}{min}$ but the real value is $582\frac{lb}{min}$.

Thus as with the case of valve Y700-01:

$$\frac{0.8}{362\frac{lb}{min}} \cdot 582\frac{lb}{min} = 1.286$$

Thus, the new result is



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 2: YS702-01/02 pressure relief valve (protects W700)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in ^{2}]* 0.487

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 2834.7

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 1.286

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 1.22

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.148

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 652.7

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2,145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft ^{3}]* 18,1

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 64,4

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 212

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 3.6

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0.5

Figure 7.12: Stability results of SWRI software for YS702-01 (real flow).

The stability map shows that the safety valve operates in the unstable region. The valve time history shows instability. It is observed that the disc strikes at the top of its path at a frequency of 160 Hz approximately. Therefore PRV suffers fluttering.

7.2.4 Engineering analysis summary

According to the engineering analysis procedure described in section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? Yes

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

45-(40.5+0.9)>0.646

5) Does excessive built-up backpressure occur according to the specific PRV?

No, the built-up back backpressure is 3.43 barg, thus

(3.43/45)·100=7.6%<10%, OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table 7.10:

Table 7.10: Stability analysis results for YS702-01

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	1.1	1.74	Yes	No
Inlet line length (Frommann and Friedel, 1998) ΔP 20%	1.1	4.4	Yes	No

Inlet line length (Frommann and Friedel, 1998) ΔP blowdown	1.1	2.2	Yes	No
Required flow > 25% rated flow (oversizing)			Yes	No
Compressible vapors criteria (oversizing)			No	No
Total backpressure for a conventional valve < 10% SP			Yes	No
Body bowl choking			Yes	Unknown
Acoustic pressure losses			Yes	No
API Simple Force Balance (Melhem, 2016)			Yes	No

8) Is the risk of relieving of the existing pressure relief valve quantified?
Yes, very low risk. It discharges to flare.

7.2.5 Smith / Burgess / Powers (2011), liquid phase

Scenario

Before the propylene liquid reaches its critical temperature due to the fire, the input f the safety valve is a subcooled liquid.

The stability at this situation must be also calculated.

Design Basis

The equations 5.3, 5.9, 5.13 and 5.14 of paragraph 5.4.1 will be used.

Relieving pressure = 50.513 barg = 732.6 psia

Relieving temperature = 45.5°C = 113.9°F

$t_0 = 0.012s$ (60% open) see STABILITY CALCULATION_YS702-01_GAS PHASE

$C = 1.09 \cdot \sqrt{\frac{K_S}{\rho}}$ (Eq.5.9)

Ks: the isoentropic bulk modulus of elasticity (psi)

ρ: fluid density (lb/ft^3)

c: speed of sound (ft/s)

As per http://webbook.nist.gov:
- ρ = 481 Kg/m³ = 30 lb/ft³
- c = 633.7 m/s = 2079 ft/s
- Cp = 0.66126 cal/g°K
- Cv = 0.38649 cal/g°K
- μ = 0.38649 cal/g°K

Applying formula 5.3 of paragraph 5.4.1:

$L_i < \frac{t_0 c}{2} = \frac{0.012 \cdot 2079}{2} = 12.4\, ft = 3.8\, m$ (Eq.5.3)

$1.1\, m < 3.8\, m$

CHECK!

Applying formula 5.13 of paragraph 5.4.1:

$\Delta P_{wave} = \frac{c\rho}{4636.8}(V_0 - V_F)$ (Eq.5.13)

Considering

$V_F = 0$

$A \cdot V_0 = Relieving\ load = 4.69\ \mathrm{m^3/h}$

$$\frac{\pi \cdot 0.0545^2}{4} \cdot V_0 = \frac{4.69}{3600}$$

$V_0 = 0.56\, m/s = 1.8\, ft/s$

Thus,

$\Delta P_{wave} = \frac{2079 \cdot 30}{4636.8}(1.8 - 0) = 24.2\, psi$

Applying formula 5.14 of paragraph 5.4.1:

$$P_s - P_{RC} > \Delta P_{total} = \Delta P_{frictional} + \Delta P_{wave} \qquad \text{(Eq.5.14)}$$

$\Delta P_{friction} = 0.00000336 \frac{f \cdot L \cdot W^2}{\rho d^5}$ (obtained from Crane book)

$$Re = \frac{D \cdot v \cdot \rho}{\mu} = \frac{0.0545 \cdot 0.56 \cdot 481}{0.0000839} = 1.75 \cdot 10^5$$

(Data from http://webbook.nist.gov)

$\frac{\varepsilon}{D} = \frac{0.03mm}{54.5mm} = 0.0055$

f=0.031 (Darcy factor) (Crane, 1999)

k=3.52 (see STABILITY CALCULATION_YS702-01_GAS PHASE)

$$L_{eq=} \frac{k \cdot D}{f} = \frac{3.52 \cdot 0.0545}{0.031} = 6.19m = 20.3ft$$

So,

$$\Delta P_{friction} = 0.00000336 \frac{0.031 \cdot 20.3 \cdot 4973^2}{30 \cdot 2.145^5} = 0.038\, psi$$

Giving values to formula 5.14 of Smith paper,

$652.7\, psi - 587.4\, psi > 0.038\, psi + 24.2\, psi$→OK!

7.2.6 Melhem (2016), liquid phase

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \le \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using webbook NIST

Table 7.11: Inlet to pipe/inlet to PRV properties for YS702-01.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	45.5	49.5 (1)	61.935	1.033
Inlet to PRV	45.5	47.7 (6% SP)	61.931	1.033

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 45 = 49.5 barg

So, the following table can be created

Table 7.12: Isothermal properties for YS702-01.

Temperature, ºC	P psig (barg)	Density lb/ft^3
45.5	691.8 (47.7)	61.931 liquid
45.5	699.1 (48.2)	61.932 liquid
45.5	706.3 (48.7)	61.933 liquid
45.5	717.9 (49.5)	61.935 liquid

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.0022\,\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.033}{0.0022}\cdot 32.174\cdot 144} = 1474.93\ ft/s$$

→Speed of sound at PRV inlet32174

$$c = \sqrt{\frac{1.033}{0.0022}\cdot 32.174\cdot 144} = 1474.93\ ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N-1}}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \qquad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_s}{m_D}} \qquad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

$$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$$

$$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2\ \text{(assumed)}$$

Assuming initial lift is 60%

Thus,

$\frac{h}{h_{max}} = 0.6$

The parameters for a LESER safety valve, are:

$AN = \pi \frac{0.7874^2}{4} = 0.487\ in^2$

$xmax$ = 3.76mm (0.313·20·60%)=0.148 in

$Pset$ = 45 barg = 652.62 psig

$K_s = 1.1 \cdot 1.2 \cdot \frac{652.62 \cdot 0.487}{0.148\ \text{in}} = 2834.7\ \frac{lb_f}{in}$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV}$ (Eq.5.32)

$m_D = 0.018 \cdot 44.1 + 0.00022 \cdot 44.1^2 = 1.22lbm$

→Natural frequency of the valve

$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{2834.7}{2.59\ lb_m 1.22} \cdot 32.174 \cdot 12} = 93.66Hz$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2 \cdot 93.66s^{-1}} = 0.0053\ s = 5.3\ ms$ (NOTE 1)

NOTE1: the calculation of the t_{open} topen with the equation of Cremer/Friedel/Pallacks gives 0.0075s=7.5ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{5.3\ ms}{\sqrt{1-0.5^2}} = 6.11\ ms \qquad \text{(Eq.5.35)}$$

Step 3: Force Balance

→PRV Stability Part II

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

→Need tau (Ꞇ)

$$t_{wave} = \frac{2L_p}{c_o}$$

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) = min\left(\frac{\frac{2\cdot L_p}{c}}{t_{open\ /\ close,d}}, 1\right) = min\left(\frac{\frac{2\cdot 3.61 ft}{1474.93\ fts^{-1}}}{0.00611}, 1\right) = \min(0.8, 1) = 0.8$$

→dPwave (PRV Stability Pt II Eqn 21)

$$\Delta P_{wave} = \tau \frac{c_0 M_{close}}{A_p} + \tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \ \text{ NOTE 2} \qquad \text{(Eq.5.25)}$$

$$\tau \frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$$

$$\tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$$

→Ap is constant → No reflection point!

NOTE 2: Although there is a champeover valve and a 50 to 25 intersection, it is assumed no reflection point (see calculations)

→Assume Mclose = 80% of capacity

0.8 · 15826.9 Kg/h = 27914 lb/h

→c_0 = 324.85 ft/s

→ρ_0 = 9.3023lb/ft3

→Dpipe = 54.5 mm = 2.145 in

$\Delta P_{wave,open} =$

$$0.8 \cdot \frac{1494.93 fts^{-1} \cdot 34892.5 lb_m h^{-1} \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 0.8^2 \cdot \frac{(34892.5h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 9.3023 lb_m ft^{-3} \cdot ((2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 461911.15\ lb_m ft^{-1} s^{-2} + 23610\ lb_m ft^{-1} s^{-2}\ = 485521.6\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,open} = 485521.6\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 104.8 lb_f in^{-2}$$

$$\Delta P_{wave,close} = 0.8 \cdot \frac{1494.93 fts^{-1} \cdot 27914 \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 0.8^2 \cdot \frac{(27914h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 9.3023 lb_m ft^{-3} \cdot (2.145in^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 369528.9\ lb_m ft^{-1} s^{-2} + 15110\ lb_m ft^{-1} s^{-2}\ = 304638.9\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,close} = 304638\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 83.02 lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 0.8^2 \cdot 0.646\ bar = 6\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2 \tau^2 \Delta P_{f,opening} = 0.8^2 0.8^2 0.646\ bar = 0.41344\ bar = 3.84\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$717.94 - 104.8 - 6 - 45.4\ - 522.14 = 39.6$$

Closing:

$$717.94 - 83.02 - 3.84 - 45.4\ - 522.14 = 67.4$$

→Force balance is positive → **NO chattering**

7.2.7 Engineering analysis summary

According to the engineering analysis procedure described in section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? Yes

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

45-(40.5+0.9)>0.646

5) Does excessive built-up backpressure occur according to the specific PRV?

No, the built-up back backpressure is 3.43 barg, thus

(3.43/45)·100=7.6%<10%, OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table 7.13:

Table 7.13: Stability analysis results for YS702-01

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	1.1	3.8	Yes	No
Required flow > 25% rated flow (oversizing)			Yes	No
Total backpressure for a conventional			Yes	No

valve < 10% SP				
Acoustic pressure losses			Yes	No
API Simple Force Balance (Melhem, 2016)			Yes	No

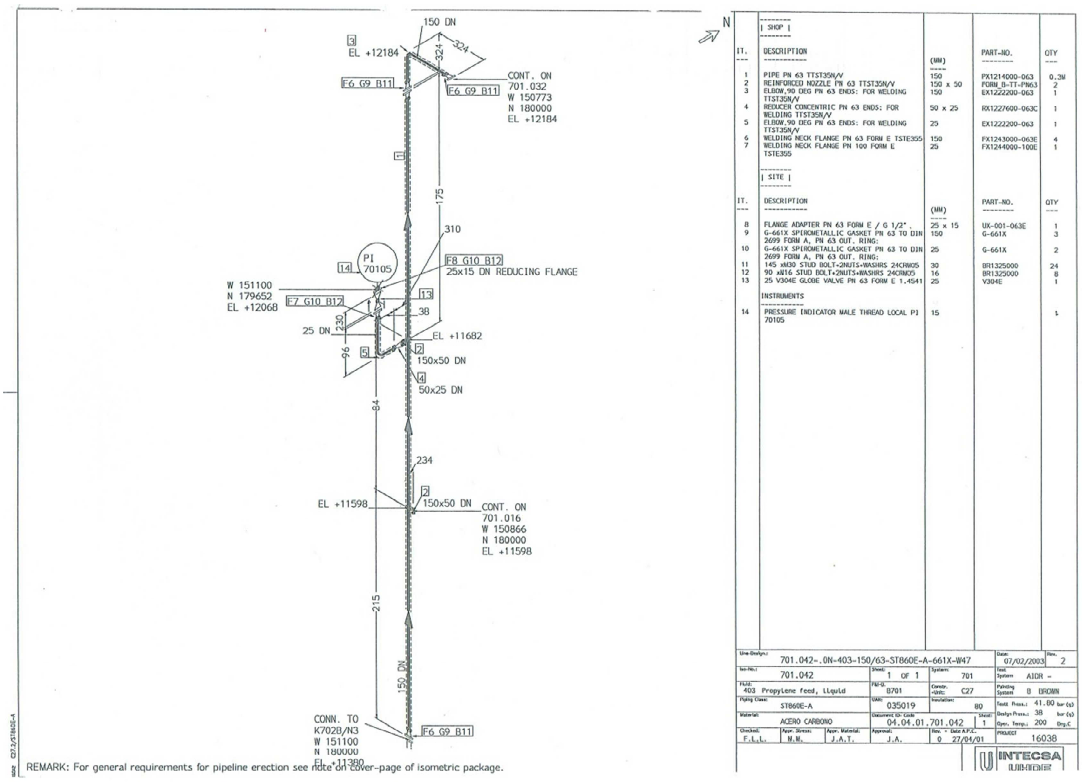
8) Is the risk of relieving of the existing pressure relief valve quantified?

Yes, very low risk. It discharges to flare.

7.3 PRV YS-701-01(K702B)

The third case study corresponds to the valve YS701-01/02 with an inlet pressure drop greater than 3% of the set pressure (not fulfill the 3% rule).A picture of the valve and the protected equipment is presented in figure 7.9 and two isometric drawings are presented in figures 7.10 and 7.11.

Figure 7.13: Picture of YS701-01/02 and protected equipment.

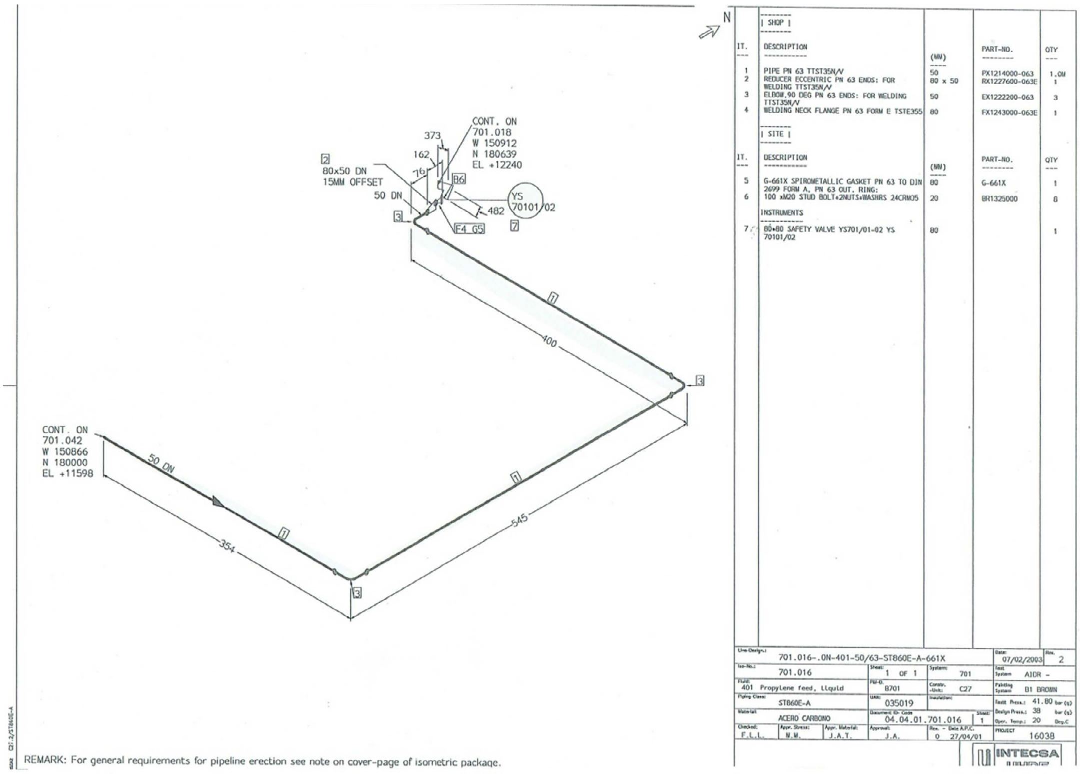


SHOP				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
1	PIPE PN 63 TTST35N/V	150	PX1214000-063	0.3M
2	REINFORCED NOZZLE PN 63 TTST35N/V	150 x 50	FORM_B-TT-PN63	2
3	ELBOW,90 DEG PN 63 ENDS: FOR WELDING TTST35N/V	150	EX1222200-063	1
4	REDUCER CONCENTRIC PN 63 ENDS: FOR WELDING TTST35N/V	50 x 25	RX1227600-063C	1
5	ELBOW,90 DEG PN 63 ENDS: FOR WELDING TTST35N/V	25	EX1222200-063	1
6	WELDING NECK FLANGE PN 63 FORM E TSTE355	150	FX1243000-063E	4
7	WELDING NECK FLANGE PN 100 FORM E TSTE355	25	FX1244000-100E	1

SITE				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
8	FLANGE ADAPTER PN 63 FORM E / G 1/2" .	25 x 15	UX-001-063E	1
9	G-661X SPIROMETALLIC GASKET PN 63 TO DIN 2699 FORM A, PN 63 OUT. RING:	150	G-661X	3
10	G-661X SPIROMETALLIC GASKET PN 63 TO DIN 2699 FORM A, PN 63 OUT. RING:	25	G-661X	2
11	145 xM30 STUD BOLT+2NUTS+WASHRS 24CRMO5	30	BR1325000	24
12	90 xM16 STUD BOLT+2NUTS+WASHRS 24CRMO5	16	BR1325000	8
13	25 V304E GLOBE VALVE PN 63 FORM E 1.4541	25	V304E	1
	INSTRUMENTS			
14	PRESSURE INDICATOR MALE THREAD LOCAL PI 70105	15		1

Line-Design.: 701.042-.0N-403-150/63-ST860E-A-661X-W47
Date: 07/02/2003
Rev.: 2
Iso-No.: 701.042
Sheet: 1 OF 1
System: 701
Test System: AIDR -
Fluid: 403 Propylene feed, Liquid
P&I-D.: B701
Constr.-Unit: C27
Painting System: B BROWN
Piping Class: ST860E-A
UAN: 035019
Insulation: 80
Testt Press.: 41.80 bar (g)
Design Press.: 38 bar (g)
Oper. Temp.: 200 Deg.C
Material: ACERO CARBONO
Document ID- Code: 04.04.01.701.042
Sheet: 1
Checked: F.L.L.
Appr. Stress: M.M.
Appr. Material: J.A.T.
Approval: J.A.
Rev. - Date A.P.C.: 0 27/04/01
PROJECT: 16038
INTECSA UHDE

Figure 7.14: Isometric drawing of YS701-01/02 sheet 1.



SHOP				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
1	PIPE PN 63 TTST35N/V	50	PX1214000-063	1.0M
2	REDUCER ECCENTRIC PN 63 ENDS: FOR WELDING TTST35N/V	80 x 50	RX1227600-063E	1
3	ELBOW,90 DEG PN 63 ENDS: FOR WELDING TTST35N/V	50	EX1222200-063	3
4	WELDING NECK FLANGE PN 63 FORM E TSTE355	80	FX1243000-063E	1

SITE				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
5	G-661X SPIROMETALLIC GASKET PN 63 TO DIN 2699 FORM A, PN 63 OUT. RING:	80	G-661X	1
6	100 xM20 STUD BOLT+2NUTS+WASHRS 24CRMO5	20	BR1325000	8
	INSTRUMENTS			
7	80+80 SAFETY VALVE YS701/01-02 YS 70101/02	80		1

Line-Design.: 701.016-.0N-401-50/63-ST860E-A-661X
Date: 07/02/2003
Rev.: 2
Iso-No.: 701.016
Sheet: 1 OF 1
System: 701
Test System: AIDR -
Fluid: 401 Propylene feed, Liquid
P&I-D.: B701
Constr.-Unit: C27
Painting System: B1 BROWN
Piping Class: ST860E-A
UAN: 035019
Insulation:
Testt Press.: 41.80 bar (g)
Design Press.: 38 bar (g)
Oper. Temp.: 20 Deg.C
Material: ACERO CARBONO
Document ID- Code: 04.04.01.701.016
Sheet: 1
Checked: F.L.L.
Appr. Stress: M.M.
Appr. Material: J.A.T.
Approval: J.A.
Rev. - Date A.P.C.: 0 27/04/01
PROJECT: 16038
INTECSA UHDE

Figure 7.15: Isometric drawing of YS701-01/02 sheet 2.

The relieving loads for fire scenario has been calculated.

The design conditions for the pressure relief valve according to the original specification sheet are in the following table:

Table 7.14: Design conditions for YS701-01/02.

Variable	Value	Units
SP	38	$barg$
T_R	86	$°C$
$Leser\ valve$	$typ\ 4564.6062$	$-$
$Fluid$	$propylene\ gas$	$-$
W_R	20000	$\frac{Kg}{h}$
W_{max}	24008	$\frac{Kg}{h}$
$Area$	1256.6	mm^2
$Valve\ weight$	46	Kg
$\alpha_{d,DG}$	0.32	$-$
$\alpha_{d,F}$	0.27	$-$
d_0	40	mm
$DN\ inlet$	50	mm
$DN\ outlet$	80	mm
$PN\ inlet$	63	bar
$PN\ outlet$	16	bar
$lift\ restriction$	5	mm
$\frac{h}{d_0}\ (full\ lift)$	0.313	$-$
$\Delta P_{friction\ inlet}$	1.117	bar
P_B	4.15	$barg$
$Vessel\ volume$	11	m^3
$Fill\ Volume$	6.5	m^3

7.3.1 Smith / Burgess / Powers (2011)

Following the paper of D. Smith, J. Burgess, and C. Powers, Relief device inlet piping: beyond the 3% rule, HP, November 2011, pp59-66

A) Inlet line length (Cremer/Friedel/Pallaks, 2001, 2003)

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.6)}$$

$$d_{psvi} = 40mm = 1.575in$$

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.5)}$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_S}{P_{atm}}\right)^{\frac{2}{3}} \cdot (1-\frac{P_{atm}}{P_S})^2}\right] \cdot (\frac{h}{h_{max}})^{0.7} \qquad \text{(Eq.5.4)}$$

Full lift has been restricted to 5 mm

Thus,

$$\frac{h}{h_{max}} = \frac{5}{12.52} = 0.4$$

$$t_0 = \left[0.015 + 0.02 * \frac{\sqrt{2 \cdot 1.575}}{\left(\frac{565.8}{14.696}\right)^{\frac{2}{3}} \cdot (1-\frac{14.696}{565.8})^2}\right] \cdot \left(\frac{5}{12.52}\right)^{0.7} = 0.016s$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}}$$

$$K = \frac{Cp}{Cp-1.986} = \frac{17.5}{17.5-1.986} = 1.13 \qquad \text{(Eq.7.1)}$$

Cp from API Technical Data Book (1997),

Temperature considered 86ºC = 647ºR

$$C = 223 \cdot \sqrt{\frac{1.13 \cdot 647}{42}} = 930 \frac{ft}{s} = 283 \frac{m}{s}$$

t wave (go and return)

$$t_{wave} = \frac{2L}{C} > \frac{2 \cdot 1.5}{283} = 0.01s$$

According to annex C of API 520-11-2015 there is not an acoustic reflection point because:

Area DN 50 = 0.00233m²

Area DN 150 = 0.0194m²

$0.0194 < 10 \cdot 0.00233 \rightarrow No\ check$

$Upstream = 0.4m > 20 \cdot 0.0545 \rightarrow No\ check$

So, there is not acoustic reflection point in connection between DN 150 to DN50

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} = 111.5 \cdot 0.009 \cdot \sqrt{\frac{1.13 \cdot 647}{42}} = 4.19ft = 1.28m$$

B) Inlet line length (Froman/Friedel, 1998) ΔP:20%

$$L_{100\%} < 9078 \cdot \frac{{d_i}^2}{W_{100\%}} \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

$W_{100\%} = 24008Kg/h = 52929\ lb/h$

$P_s = 38barg \cdot 14.5038 = 551psig$

$P_B = 3.13barg \cdot 14.5038 = 45psig$

$$L_{100\%} < 9078 \cdot \frac{2.146^2}{52929} \cdot (551 - 45) \cdot 0.016 = 6.39ft = 1.95m$$

C) Inlet line length (Froman/Friedel, 1998) ΔP:blowdown

$$\mathrm{L} < 45390 \cdot \frac{{d_i}^2}{W_{\%}} \cdot \left(\frac{P_s - P_{RC}}{P_S}\right) \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

Blowdown=10% from LESER catalog

P_B from Aspen Flare analyzer (given by the petrochemical company)

$$\mathrm{L} < 45390 \cdot \frac{2.146^2}{52929} \cdot (0.1) \cdot (551 - 45) \cdot 0.016 = 3.197ft = 0.98m$$

D) Required flow > 25% Maximal flow

$$\text{Req. flow} > 0.25 \cdot Maximal\ flow \qquad \text{(Eq.5.16)}$$

$$20000 \frac{kg}{h} > 0.25 \cdot 24008 = 6002 \frac{kg}{h} \rightarrow OK$$

E) Acoustic pressure losses

$$\Delta P_{Acoustic} = \frac{L \cdot W_{PSV}}{12.6 \cdot {d_i}^2 \cdot t_0} + \frac{1}{10.5 \cdot \rho} \left(\frac{W_{PSV} \cdot L}{c \cdot d_i \cdot t_0} \right)^2 \qquad \text{(Eq.5.11)}$$

$$\rho = \frac{P_{SET} \cdot MW}{zRT} = \frac{565.8 \cdot 42}{0.5 \cdot 10.731 \cdot 647} = 6.85 \frac{lb}{ft^3}$$

$$\Delta P_{Acoustic} = \frac{4{,}92 \cdot \frac{52929}{3600}}{12.6 \cdot 2.146^2 \cdot 0.016} + \frac{1}{10.5 \cdot 6.85} \left(\frac{\frac{52929}{3600} \cdot 4{,}92}{930 \cdot 2.146 \cdot 0.016} \right)^2 = 77.98 psi = 5.38 bar$$

$$\Delta P_{friction} = 1.18 bar$$

$$\Delta P_{total} = 5.38 bar + 1.18 bar = 6.56\ bar$$

$$(P_s - P_{RC}) = \ (P_s \cdot BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic} \qquad \text{(Eq.5.12)}$$

$$(P_s \cdot BD) = 3.8 > 6.56 \rightarrow No\ check!$$

F) Body bowl choking (D'Alessandro Method)

$$P_0 < \ \frac{P_C}{(1+F_0) \cdot \frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1} \right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

$$A_n = \text{throat area} = \frac{\pi \cdot 40^2}{4} = 1256.6 mm^2$$

$$A_e = \text{outlet area} = \frac{\pi \cdot 81.7^2}{4} = 5242.4 mm^2$$

K=1.13(ideal gas)

$$P_C = 0.15 barg = 2.18 psia = superimposed\ backpressure$$

$$P_0 < \ \frac{2.18}{(1+0.1) \cdot \frac{1256.6}{5242.4}} \cdot \frac{1}{\left(\frac{2}{1.13+1} \right)^{\frac{1.13}{1.13+1}} - 0.1} = 9.98 psia$$

$$P_0 = 42.813 barg = 620.9 psia$$

$$620.9 psia < 9.98 psia \rightarrow No\ check \rightarrow Possibilityof\ body\ bowl\ chocking$$

G) Compressible vapors criteria (Oversizing)

$$W_{PSV} > 0.2 \cdot V_{system} \cdot \left(\rho_{set} - \rho_{shut}\right) + W_{required} \qquad \text{(Eq.5.15)}$$

If this equation fulfills the valve can chatter.

During the boiling process:

Pset at 38barg and 86°C = 6.353$\frac{lb}{ft^3}$

Pshut at 34.2barg and 86°C = 4.993$\frac{lb}{ft^3}$ (webbook nist)

Vsystem=388.5ft^3

Vsystem=388.5ft^3-229.5ft^3 (Grace catalyst)= 159ft^3

Thus,

$$14.7\frac{lb}{s} > 0.2 \cdot 159 \cdot \left(6.353 - 4.993\right) + 12.25\frac{lb}{s}$$

$$14.7\frac{lb}{s} > 55.5 \rightarrow No\ fullfills!\ No\ chattering\ possibilities$$

7.3.2 Melhem (2016)

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using ASPEN HYSYS v8.6 TM with Peng Robinson as EOS

Table 7.15: Inlet to pipe/inlet to PRV properties for YS701-01/02.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	86	41.8 (1)	8.213	1.025
Inlet to PRV	86	40.3 (6% SP)	7.930	1.029

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 38 = 41.8 barg

So, the following table can be created

Table 7.16: Isothermal properties for YS701-01/02.

Temperature, ºC	P psig (barg)	Density lb/ft^3
86	583.1 (40.2)	7.482
86	586.0 (40.4)	8.023
86	588.9 (40.6)	8.227
86	(40.8)	Liquid

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.066\,\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.025}{0.066}\cdot 32.174\cdot 144} = 268.2\ ft/s$$

→Speed of sound at PRV inlet

$$c = \sqrt{\frac{1.029}{0.066}\cdot 32.174\cdot 144} = 268.8\ ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N-1}}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \quad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_S}{m_D}} \quad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \quad \text{(Eq.5.31)}$$

$$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$$

$$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2\ \text{(assumed)}$$

The full lift has a length of 0.313·40 =12.52mm

The lift has been restricted to 5mm

Thus,

$$\frac{h}{h_{max}} = \frac{5}{12.52} = 0.399$$

The parameters for a LESER 4564.6062 safety valve, are:

$$AN = \pi\frac{1.575^2}{4} = 1.948\ in2$$

$xmax$ = 5mm

$Pset$ = 38 barg = 551.1 psig = 565.8 psia

$$K_s = 1.1 \cdot 1.2 \cdot \frac{551.1 \cdot 1.948}{0.197\ \text{in}} = 7197\ \frac{lb_f}{in}$$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV}$ (Eq.5.32)

$m_D = 0.018 \cdot 101 + 0.00022 \cdot 101^2 = 4.06lbm$

→Natural frequency of the valve

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{7197}{4.06} \cdot 32.174 \cdot 12} = 131.7Hz$$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2 \cdot 131.7s^{-1}} = 0.0038\ s = 3.8\ ms$ (NOTE 1)

(Eq.5.35)

NOTE1: the calculation of the t_{open} with the equation of Cremer/Friedel/Pallacks gives 0.016s=16ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{3.8\ ms}{\sqrt{1-0.5^2}} = 4.4\ ms$

Step 3: Force Balance

→PRV Stability Part II

$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$ (Eq.5.17)

→Need tau (Ꞇ)

$t_{wave} = \frac{2L_p}{c_o}$ (Eq.5.23)

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) = min\left(\frac{\frac{2 \cdot L_p}{c}}{t_{open\ /\ close,d}}, 1\right) = min\left(\frac{\frac{2 \cdot 4.9ft}{268.2fts^{-1}}}{0.0038}, 1\right) = \min(9.6, 1) = 1$$

→dPwave (PRV Stability Pt II Eqn 21)

$$\Delta P_{wave} = \tau \frac{c_0 M_{close}}{A_p} + \tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \text{ NOTE 2} \qquad \text{(Eq.5.25)}$$

$$\tau \frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$$

$$\tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$$

→Ap is constant → No reflection point!

NOTE 2: Although there is a champeover valve and a 150 to 50 intersection, it is assumed no reflection point (see calculations)

→Assume Mclose = 80% of capacity

0.8·24008 Kg/h = 42343 lb/h

→c_0 = 268.2 ft/s

→ρ_0 = 8.213 lb/ft3

→Dpipe = 54.5 mm = 2.145 in

$$\Delta P_{wave,open} = 1 \cdot \frac{268.2fts^{-1} \cdot 52929lb_m h^{-1} \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(52929h^{-1} \cdot \frac{h}{3600s})^2}{2x8.213lb_m ft^{-3} \cdot ((2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 157132\ lb_m ft^{-1} s^{-2} + 20897\ lb_m ft^{-1} s^{-2} = 178029\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,open} = 178029\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 38.4 lb_f in^{-2}$$

$$\Delta P_{wave,close} = 1 \cdot \frac{268.2fts^{-1} \cdot 42343 \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(42343h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 8.213lb_m ft^{-3} \cdot ((2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 125706\ lb_m ft^{-1} s^{-2} + 13374\ lb_m ft^{-1} s^{-2} = 139080\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,close} = 139080\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 30 lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 1^2 \cdot 1.177\ bar = 17.07\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2 \tau^2 \Delta P_{f,opening} = 0.8^2 1^2 1.177\ bar = 0.753\ bar = 10.92\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$606.26 - 17.07 - 38.4 - 60.19 - 496.03 = -5.4$$

Closing:

$$606.26 - 10.92 - 30 - 60.19 - 496.03 = 9.1$$

→Force balance is negative → **chattering**

Step 4: Acoustic Analysis

→PRV Stability Part II

$$L \leq \frac{C}{4f_n} \sqrt{\frac{x}{x + x_0}} \qquad \text{(Eq.5.36)}$$

$$L \leq \frac{C}{4f_n} \sqrt{\frac{1.32x}{1.32x + x_{max}}}$$

→Equation constant is:

$$\frac{A_{pop}}{A_N} \frac{P_{full}}{P_{set}} = 1.2 \cdot 1.1 = 1.32$$

$$L_{crit} = \frac{C_0}{4f_n}\sqrt{\frac{1.32x}{1.32x+x_{max}}} = \frac{268.2fts^{-1}}{4\cdot 131.7s^{-1}}\sqrt{\frac{1.32\cdot 0.197\ in}{1.32\cdot 0.197+0.197}} = 0.38ft = 0.17m$$

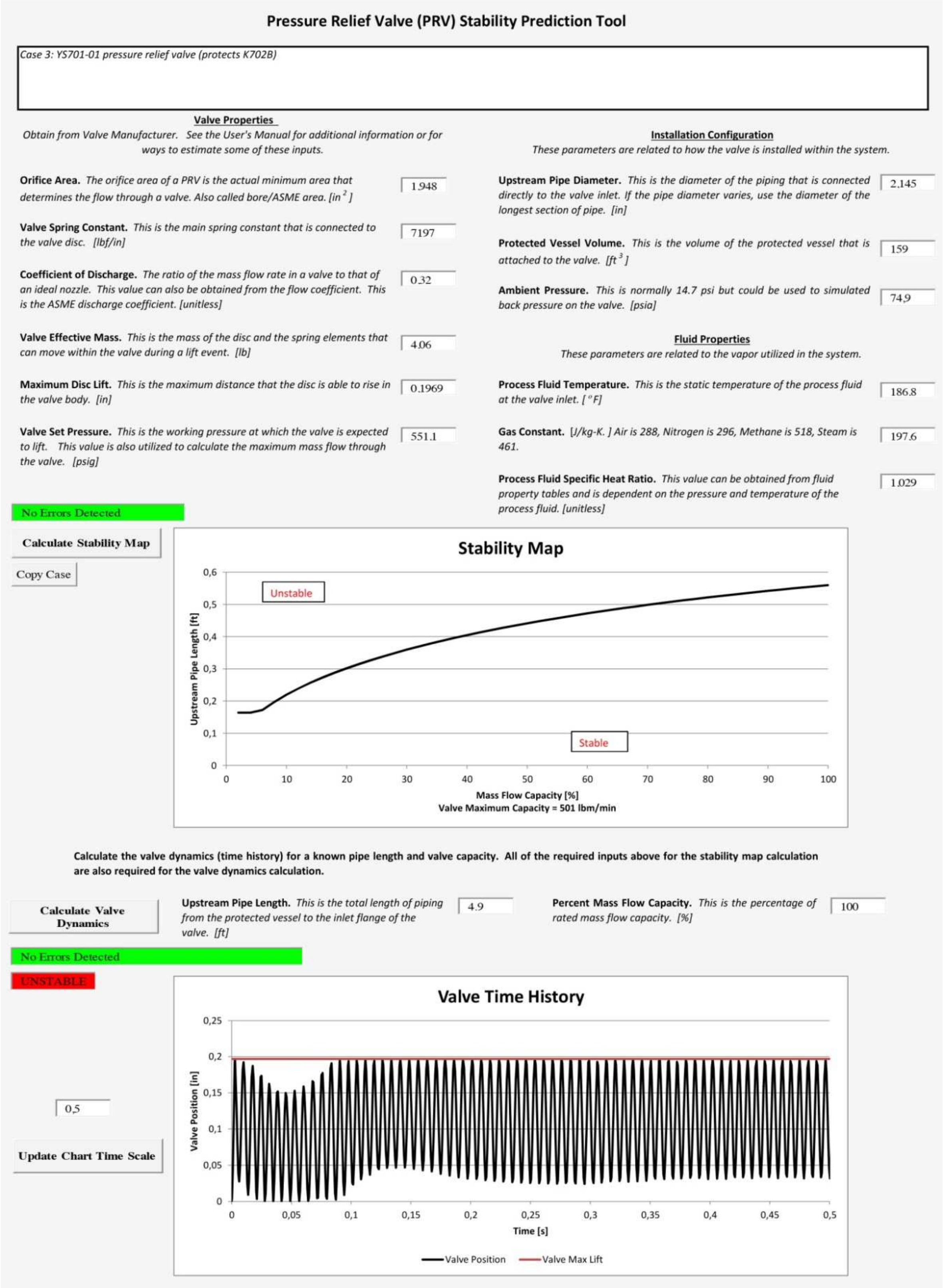
$$L_{crit} = 0.12m < L_p$$

$$L_{crit} = 0.12m < 1.5m$$

→PRV is likely to **low frequency cycling**

7.3.3 SWRI (2016)

The screenshot of the results with the software is presented here:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 3: YS701-01 pressure relief valve (protects K702B)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in ^{2}]* 1.948

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 7197

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.32

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 4.06

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.1969

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 551.1

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2.145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft ^{3}]* 159

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 74,9

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 186.8

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

🟩 No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 4.9

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

🟩 No Errors Detected

🟥 UNSTABLE

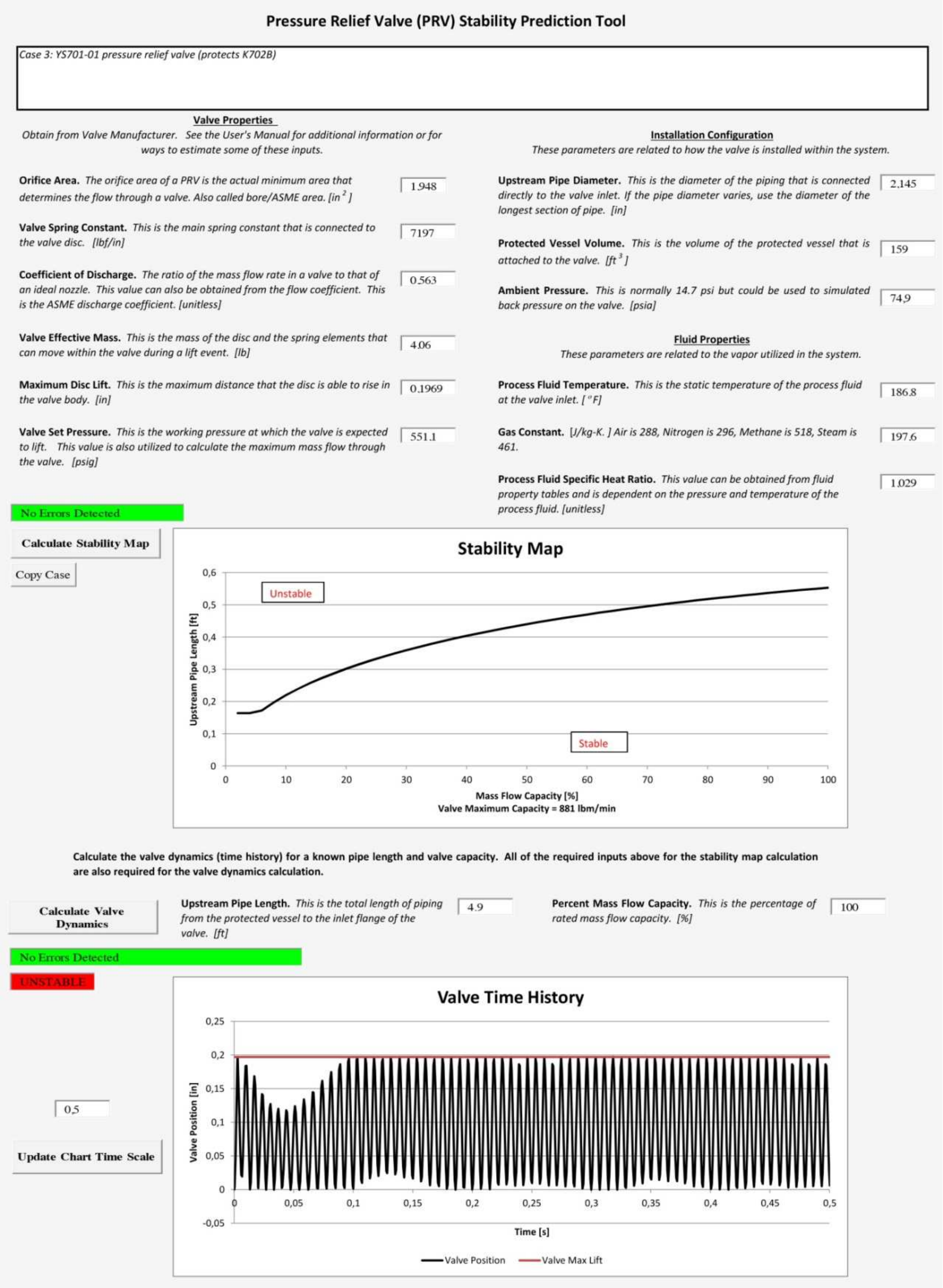
Figure 7.16: Stability results of SWRI software for YS701-01/02 (unreal flow).

However the software calculate a maximal flow of $501\,\frac{lb}{min}$ but the real value is $882\,\frac{lb}{min}$.

Thus as with the case of valve Y700-01:

$$\frac{0.32}{501\frac{lb}{min}}\cdot 882\,\frac{lb}{min}=0.563$$

Thus, the new result is



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 3: YS701-01 pressure relief valve (protects K702B)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in²]* 1.948

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 7197

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.563

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 4.06

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.1969

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 551.1

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2.145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft³]* 159

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 74.9

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 186.8

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 4.9

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0.5

Figure 7.17: Stability results of SWRI software for YS701-01/02 (real flow).

The stability map shows that the safety valve operates in the unstable region. The valve time history shows instability. It is observed that the disc strikes at the seats at a frequency of 160 Hz approximately. Therefore PRV suffers chattering.

7.3.4 Engineering analysis summary

According to the engineering analysis procedure described in section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? Yes

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

38-(34.2+0.76)>1.12

5) Does excessive built-up backpressure occur according to the specific PRV?

Yes, the built-up back backpressure is 4.15 barg, thus

(4.15/38)·100=10.92%>10%, NOT OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table 7.17:

Table 7.17: Stability analysis results for YS701-01/02

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	1.5	1.28	No	Yes
Inlet line length (Frommann and	1.5	1.95	Yes	No

Friedel, 1998) ΔP 20%				
Inlet line length (Frommann and Friedel, 1998) ΔP blowdown	1.5	0.95	No	Yes
Required flow > 25% rated flow (oversizing)			Yes	No
Compressible vapors criteria (oversizing)			No	No
Total backpressure for a conventional valve < 10% SP			No	Yes
Body bowl choking			No	Unknown
Acoustic pressure losses			No	Yes
API Simple Force Balance (Melhem, 2016)			No	Yes

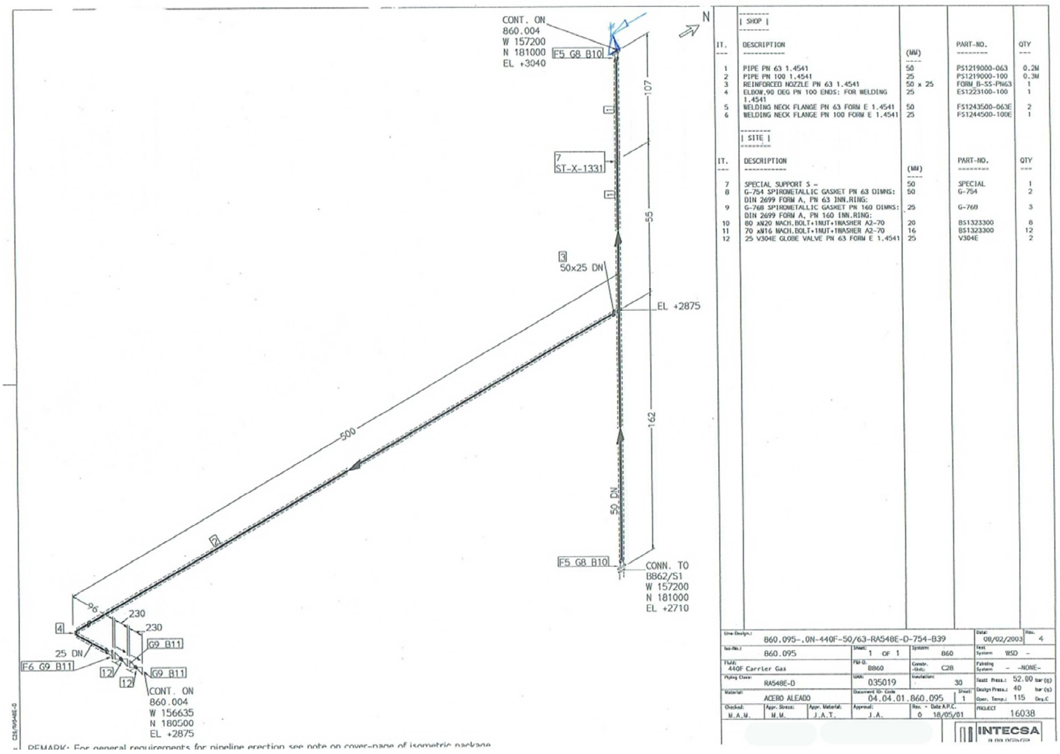
8) Is the risk of relieving of the existing pressure relief valve quantified?

Yes, very low risk. It discharges to flare.

7.4 PRV YS-860-01(B862)

The fourth case study corresponds to the valve YS860-01 with an inlet pressure drop greater than 3% of the set pressure (not fulfill the 3% rule). A picture of the valve and the protected equipment is presented in figure 7.12 and an isometric drawing is presented in figure 7.13.

Figure 7.18: Picture of YS860-01 and protected equipment.



| SHOP |

IT.	DESCRIPTION	(MM)	PART-NO.	QTY
1	PIPE PN 63 1.4541	50	PS1219000-063	0.2M
2	PIPE PN 100 1.4541	25	PS1219000-100	0.3M
3	REINFORCED NOZZLE PN 63 1.4541	50 x 25	FORM_B-SS-PN63	1
4	ELBOW,90 DEG PN 100 ENDS: FOR WELDING 1.4541	25	ES1223100-100	1
5	WELDING NECK FLANGE PN 63 FORM E 1.4541	50	FS1243500-063E	2
6	WELDING NECK FLANGE PN 100 FORM E 1.4541	25	FS1244500-100E	1

| SITE |

IT.	DESCRIPTION	(MM)	PART-NO.	QTY
7	SPECIAL SUPPORT S -	50	SPECIAL	1
8	G-754 SPIROMETALLIC GASKET PN 63 DIMNS: DIN 2699 FORM A, PN 63 INN.RING:	50	G-754	2
9	G-768 SPIROMETALLIC GASKET PN 160 DIMNS: DIN 2699 FORM A, PN 160 INN.RING:	25	G-768	3
10	80 xM20 MACH.BOLT+1NUT+1WASHER A2-70	20	BS1323300	8
11	70 xM16 MACH.BOLT+1NUT+1WASHER A2-70	16	BS1323300	12
12	25 V304E GLOBE VALVE PN 63 FORM E 1.4541	25	V304E	2

Line-Design.: 860.095-.0N-440F-50/63-RA548E-D-754-B39		Date: 08/02/2003	Rev. 4
Iso-No.: 860.095	Sheet: 1 OF 1	System: 860	Test System: WSD -
Field: 440F Carrier Gas	P&I-D: B860	Constr.-Unit: C28	Painting System: - -NONE-
Piping Class: RA548E-D	UAN: 035019	Insulation: 30	Test Press.: 52.00 bar (g) Design Press.: 40 bar (g) Oper. Temp.: 115 Deg.C
Material: ACERO ALEADO	Document ID- Code: 04.04.01.860.095	Sheet: 1	
Checked: M.A.M. Appr. Stress: M.M. Appr. Material: J.A.T.	Approval: J.A.	Rev. - Date A.P.C.: 0 18/05/01	PROJECT 16038

INTECSA

Figure 7.19: Isometric drawing of YS860-01.

The relieving loads for fire scenario has been calculated.

The design conditions for the pressure relief valve according to the original specification sheet are in the following table:

Table 7.18: Design conditions for YS860-01.

Variable	Value	Units
SP	40	$barg$
T_R	87	$°C$
$Leser\ valve$	typ 4564.6062	$-$
$Fluid$	$propylene\ gas$	$-$
W_R	15500	$\frac{Kg}{h}$
W_{max}	62629.1	$\frac{Kg}{h}$
$Area$	1256.6	mm^2
$Valve\ weight$	46	Kg
$\alpha_{d,DG}$	0.8	$-$
$\alpha_{d,F}$	0.54	$-$
d_0	40	mm
$DN\ inlet$	50	mm
$DN\ outlet$	80	mm
$PN\ inlet$	63	bar
$PN\ outlet$	16	bar
$\frac{h}{d_0}\ (full\ lift)$	0.313	$-$
$\Delta P_{friction\ inlet}$	2.192	bar
P_B	3.35	$barg$

7.4.1 Smith / Burgess / Powers (2011)

Following the paper of D. Smith, J. Burgess, and C. Powers, Relief device inlet piping: beyond the 3% rule, HP, November 2011, pp59-66

A) Inlet line length (Cremer/Friedel/Pallaks, 2001, 2003)

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.6)}$$

$$d_{psvi} = 40mm = 1.575in$$

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.5)}$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_S}{P_{atm}}\right)^{\frac{2}{3}} \cdot (1 - \frac{P_{atm}}{P_S})^2} \right] \cdot (\frac{h}{h_{max}})^{0.7} \qquad \text{(Eq.5.4)}$$

$$\frac{h}{h_{max}} = 0.6$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot 1.575}}{\left(\frac{594.7}{14.696}\right)^{\frac{2}{3}} \cdot (1 - \frac{14.696}{594.7})^2} \right] \cdot (0.6)^{0.7} = 0.012s$$

$$K = \frac{Cp}{Cp - 1.986} = \frac{17.5}{17.5 - 1.986} = 1.13 \qquad \text{(Eq.7.1)}$$

Cp from API Technical Data Book (1997),

Temperature considered 87ºC = 648ºR

$$C = 223 \cdot \sqrt{\frac{1.13 \cdot 648}{42}} = 931 \frac{ft}{s} = 284 \frac{m}{s}$$

t wave (go and return)

$$t_{wave} = \frac{2L}{C} > \frac{2 \cdot 0.33}{284} = 0.0023s$$

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} = 111.5 \cdot 0.012 \cdot \sqrt{\frac{1.13 \cdot 648}{42}} = 5.58ft = 1.7m$$

B) Inlet line length (Froman/Friedel, 1998) ΔP:20%

$$L_{100\%} < 9078 \cdot \frac{{d_i}^2}{W_{100\%}} \cdot (P_S - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

$$W_{100\%} = 62629 Kg/h = 138073\ lb/h$$

$P_s = 40barg \cdot 14.5038 = 580psig$

$P_B = 3.35barg \cdot 14.5038 = 48.6psig$

$L_{100\%} < 9078 \cdot \frac{2.146^2}{138073} \cdot (580 - 48.6) \cdot 0.012 = 1.93ft = 0.59m$

C) Inlet line length (Froman/Friedel, 1998) ΔP:blowdown

$$\mathrm{L} < 45390 \cdot \frac{{d_i}^2}{W_{\%}} \cdot \left(\frac{P_S - P_{RC}}{P_S}\right) \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

Blowdown=10% from LESER catalog

P_B from Aspen Flare analyzer (given by the petrochemical company)

$\mathrm{L} < 45390 \cdot \frac{2.146^2}{138073} \cdot (0.1) \cdot (580 - 48.6) \cdot 0.012 = 0.97ft = 0.29m$

D) Required flow > 25% Maximal flow

$$\mathrm{Req.\,flow} > 0.25 \cdot Maximal\ flow \qquad \text{(Eq.5.16)}$$

$21995\frac{kg}{h} > 0.25 \cdot 62629 = 15675\frac{kg}{h} \rightarrow OK$

E) Acoustic pressure losses

$$\Delta P_{Acoustic} = \frac{L \cdot W_{PSV}}{12.6 \cdot {d_i}^2 \cdot t_0} + \frac{1}{10.5 \cdot \rho}\left(\frac{W_{PSV} \cdot L}{c \cdot d_i \cdot t_0}\right)^2 \qquad \text{(Eq.5.11)}$$

$$\rho = \frac{P_{SET} \cdot MW}{zRT} = \frac{580 \cdot 42}{0.55 \cdot 10.731 \cdot 648} = 6.37\frac{lb}{ft^3}$$

$$\Delta P_{Acoustic} = \frac{5.58 \cdot \frac{138073}{3600}}{12.6 \cdot 2.146^2 \cdot 0.012} + \frac{1}{10.5 \cdot 6.37}\left(\frac{\frac{138073}{3600} \cdot 5.58}{931 \cdot 2.146 \cdot 0.012}\right)^2 = 307.3 + 0.012 = 307.3psi = 21.2bar$$

$\Delta P_{friction} = 1.06bar$

$\Delta P_{total} = 21.2bar + 1.06bar = 22.3\ bar$

$$(P_s - P_{RC}) = (P_s \cdot BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic} \qquad \text{(Eq.5.12)}$$

$(P_s \cdot BD) = 4 > 22.3 \rightarrow No\ check!$

F) Body bowl choking (D'Alessandro Method)

$$P_0 < \frac{P_C}{(1+F_0)\cdot\frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

$$A_n = \text{throat area} = \frac{\pi \cdot 40^2}{4} = 1256.6mm^2$$

$$A_e = \text{outlet area} = \frac{\pi \cdot 81.7^2}{4} = 5242.4mm^2$$

K=1.13(ideal gas)

$$P_C = 0.15barg = 16.9psia = superimposed\ backpressure$$

$$P_0 < \frac{16.9}{(1+0.1)\cdot\frac{1256.6}{5242.4}} \cdot \frac{1}{\left(\frac{2}{1.13+1}\right)^{\frac{1.13}{1.13+1}} - 0.1} = 322psia$$

$$P_0 = 45.013barg = 652.9psia$$

$$652.9psia < 322psia \rightarrow No\ check \rightarrow Possibilityof\ body\ bowl\ chocking$$

G) Compressible vapors criteria (Oversizing)

$$W_{PSV} > 0.2 \cdot V_{system} \cdot \left(\rho_{set} - \rho_{shut}\right) + W_{required} \qquad \text{(Eq.5.15)}$$

If this equation fulfills the valve can chatter.

During the boiling process:

Pset at 40barg and 87°C = 6.37$\frac{lb}{ft^3}$

Pshut at 36barg and 87°C = 4.993$\frac{lb}{ft^3}$ (webbook nist)

Vsystem=355.02ft^3 (from datasheet of B862)

Thus,

$$38.4\frac{lb}{s} > 0.2 \cdot 355.02 \cdot \left(6.37 - 4.993\right) + 9.5\frac{lb}{s}$$

$$38.4\frac{lb}{s} > 107.3 \rightarrow No\ fullfills!\ No\ chattering\ possibilities$$

7.4.2 Melhem (2016)

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using ASPEN HYSYS v8.6 TM with Peng Robinson as EOS

Table 7.19: Inlet to pipe/inlet to PRV properties for YS860-01.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	87	44 (1)	2.996	1.025
Inlet to PRV	87	41.4 (6% SP)	2.789	1.029

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 40 = 44 barg

So, the following table can be created

Table 7.20: Isothermal properties for YS860-01.

Temperature, ºC	P psig (barg)	Density lb/ft^3
87	600.46 (41.4)	2.792
87	609.16 (42)	2.839
87	617.86 (42.6)	2.885
87	626.56 (43.2)	2.933

87	638.17 (44)	2.997

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.078\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.025}{0.078}\cdot 32.174 \cdot 144} = 246.7\ ft/s$$

→Speed of sound at PRV inlet

$$c = \sqrt{\frac{1.029}{0.078}\cdot 32.174 \cdot 144} = 247.2\ ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N-1}}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \qquad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_s}{m_D}} \qquad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

$$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$$

$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2 \text{ (assumed)}$

Assuming initial lift is 60%

Thus,

$\frac{h}{h_{max}} = 0.6$

The parameters for a LESER safety valve, are:

$$AN = \pi \frac{1.575^2}{4} = 1.948\ in2$$

$xmax$ = 3.76mm (0.313·20·60%)=0.148 in

$Pset$ = 40 barg = 580.1 psig = 594.7 psia

$$K_s = 1.1 \cdot 1.2 \cdot \frac{594.7 \cdot 1.948}{0.148 \text{ in}} = 10332\ \frac{lb_f}{in}$$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV}$ (Eq.5.32)

$m_D = 0.018 \cdot 101 + 0.00022 \cdot 101^2 = 4.06lbm$

→Natural frequency of the valve

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{10332}{2.59\ lb_m 4.06} \cdot 32.174 \cdot 12} = 98.03Hz$$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2 \cdot 98.03s^{-1}} = 0.0051\ s = 5.1\ ms$ (NOTE 1)

NOTE1: the calculation of the t_{open} with the equation of Cremer/Friedel/Pallacks gives 0,012s=12ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{5.1\ ms}{\sqrt{1-0.5^2}} = 5.9\ ms \qquad \text{(Eq.5.35)}$$

Step 3: Force Balance

→PRV Stability Part II

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

→Need tau (Ƭ)

$$t_{wave} = \frac{2L_p}{c_o} \qquad \text{(Eq.5.23)}$$

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) = min\left(\frac{\frac{2\cdot L_p}{c}}{t_{open\ /\ close,d}}, 1\right) = min\left(\frac{\frac{2\cdot 1.1ft}{246.7fts^{-1}}}{0.0051}, 1\right) = \min(1.7, 1) = 1$$

→dPwave (PRV Stability Pt II Eq. 21)

$$\Delta P_{wave} = \tau \frac{c_0 M_{close}}{A_p} + \tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \qquad \text{(Eq.5.25)}$$

$$\tau \frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$$

$$\tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$$

→Ap is constant → No reflection point!

→Assume Mclose = 80% of capacity

0.8·62629 Kg/h = 110458 lb/h

→c_0 = 246.7 ft/s

→ρ_0 = 2.792 lb/ft3

→Dpipe = 54.5 mm = 2.145 in

$$\Delta P_{wave,open} = 1 \cdot \frac{246.7fts^{-1}\cdot 138073lb_m h^{-1}\cdot\frac{h}{3600s}}{(2.145in)^2\pi\cdot 0.25\cdot\frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(138073h^{-1}\cdot\frac{h}{3600s})^2}{2x2.792lb_m ft^{-3}\cdot((2.145in)^2\pi\cdot 0.25\cdot\frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 377045\ lb_m ft^{-1}s^{-2} + 418314\ lb_m ft^{-1}s^{-2} = 795359\ lb_m ft^{-1}s^{-2}$$

$$\Delta P_{wave,open} = 795359\ lb_m ft^{-1}s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 171.7 lb_f in^{-2}$$

$$\Delta P_{wave,close} = 1 \cdot \frac{246.7 fts^{-1} \cdot 110458 \cdot \frac{h}{3600s}}{(2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(110458h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 2.792 lb_m ft^{-3} \cdot ((2.145in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 301635\ lb_m ft^{-1}s^{-2} + 267719\ lb_m ft^{-1}s^{-2} = 569354\ lb_m ft^{-1}s^{-2}$$

$$\Delta P_{wave,close} = 569354\ lb_m ft^{-1}s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 122.9 lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 1^2 \cdot 1.06\ bar = 15.37\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2 \tau^2 \Delta P_{f,opening} = 0.8^2 1^2 1.06\ bar = 0.68\ bar = 9.86\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$638.2 - 171.7 - 15.37 - 48.6 - 522.1 = -119.6$$

Closing:

$$638.2 - 122.9 - 9.86 - 48.6 - 522.1 = -65.3$$

→Force balance is negative → **CHATTERING**

Step 4: Acoustic Analysis

→PRV Stability Part II

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

$$L \leq \frac{C}{4f_n}\sqrt{\frac{1.32x}{1.32x+x_{max}}}$$

→Equation constant is:

$$\frac{A_{pop}}{A_N}\frac{P_{full}}{P_{set}} = 1.2 \cdot 1.1 = 1.32$$

$$L_{crit} = \frac{C_0}{4f_n}\sqrt{\frac{1.32x}{1.32x + x_{max}}} = \frac{246.7fts^{-1}}{4x98.03s^{-1}}\sqrt{\frac{1.32 \cdot 0.148\ in}{1.32 \cdot 0.148 + 0.148}} = 0.47ft = 0.14m$$

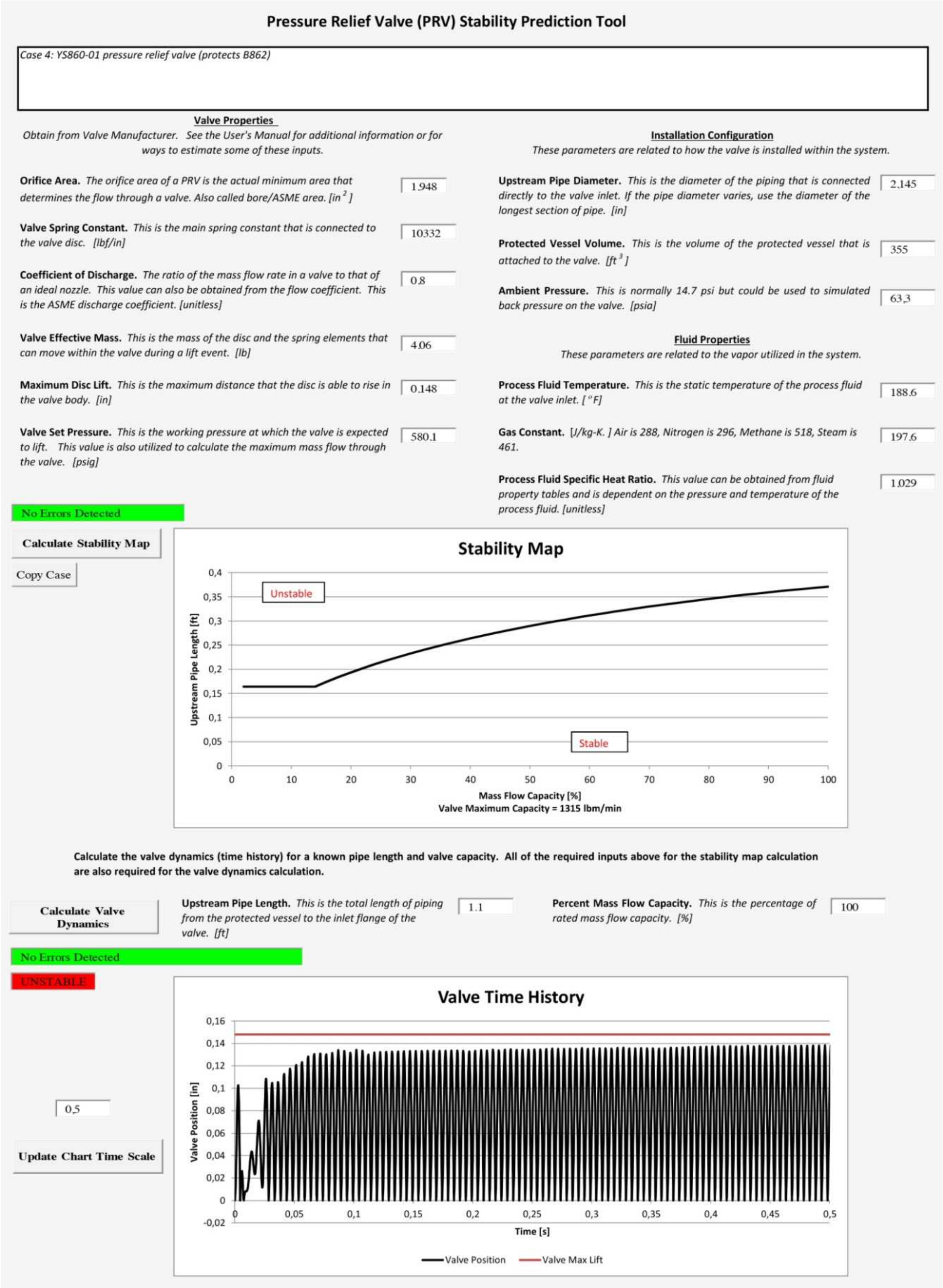
$$L_{crit} = 0.14m < L_p$$

$$L_{crit} = 0.14m < 1.1m$$

→PRV is likely to **low frequency cycling**

7.4.3 SWRI (2016)

The screenshot of the software results is:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 4: YS860-01 pressure relief valve (protects B862)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in^2]* 1.948

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 10332

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.8

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 4.06

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.148

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 580.1

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2.145

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft^3]* 355

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 63,3

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 188.6

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.029

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 1.1

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0,5

Figure 7.20: Stability results of SWRI software for YS860-01.

In this case the software is able to match the rated flow. The software gives $1315\frac{lb}{min}$ and the real value is $1368\frac{lb}{min}$.

The stability map shows that the safety valve operates in the unstable region. The valve time history shows instability. It is observed that the disc strikes at the seats at a frequency of 240 Hz approximately. Therefore PRV suffers chattering.

7.4.4 Engineering analysis summary

According to the engineering analysis procedure described in section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? Yes

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

40-(36+0.8)>2.19

5) Does excessive built-up backpressure occur according to the specific PRV?

No, the built-up back backpressure is 3.35 barg, thus

(3.35/40)·100=8.4%<10%, OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table 7.21:

Table 7.21: Stability analysis results for YS860-01

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	0.33	1.7	Yes	No
Inlet line length (Frommann and Friedel, 1998) ΔP 20%	0.33	0.59	Yes	No
Inlet line length (Frommann and Friedel, 1998) ΔP blowdown	0.33	0.29	No	Yes
Required flow > 25% rated flow (oversizing)			Yes	No
Compressible vapors criteria (oversizing)			No	No
Total backpressure for a conventional valve < 10% SP			Yes	No
Body bowl choking			No	Unknown
Acoustic pressure losses			No	Yes
API Simple Force Balance (Melhem, 2016)			No	Yes

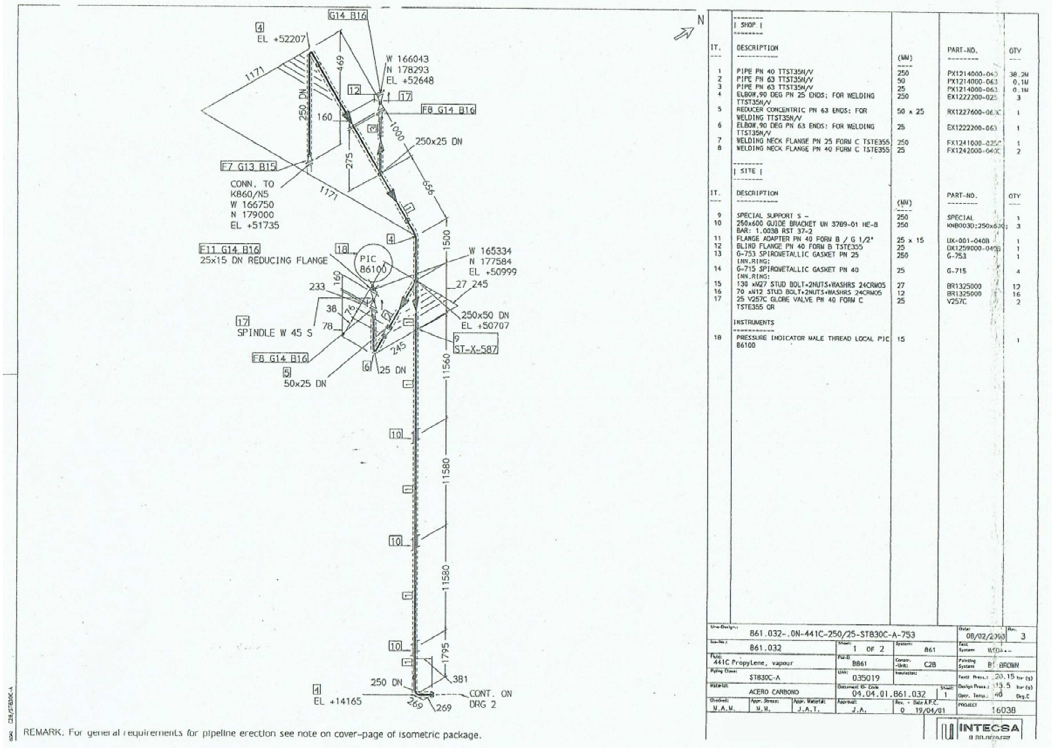
8) Is the risk of relieving of the existing pressure relief valve quantified?

Yes, very low risk. It discharges to flare.

7.5 PRV YS-861-04(K860)

The fifth case study corresponds to the valve YS861-04 with an inlet pressure drop greater than 3% of the set pressure (not fulfill the 3% rule). A picture of the valve and the protected equipment is presented in figure 7.14 and two isometric drawings are presented in figures 7.15 and 7.16.

Figure 7.21: Picture of YS861-04 and protected equipment.

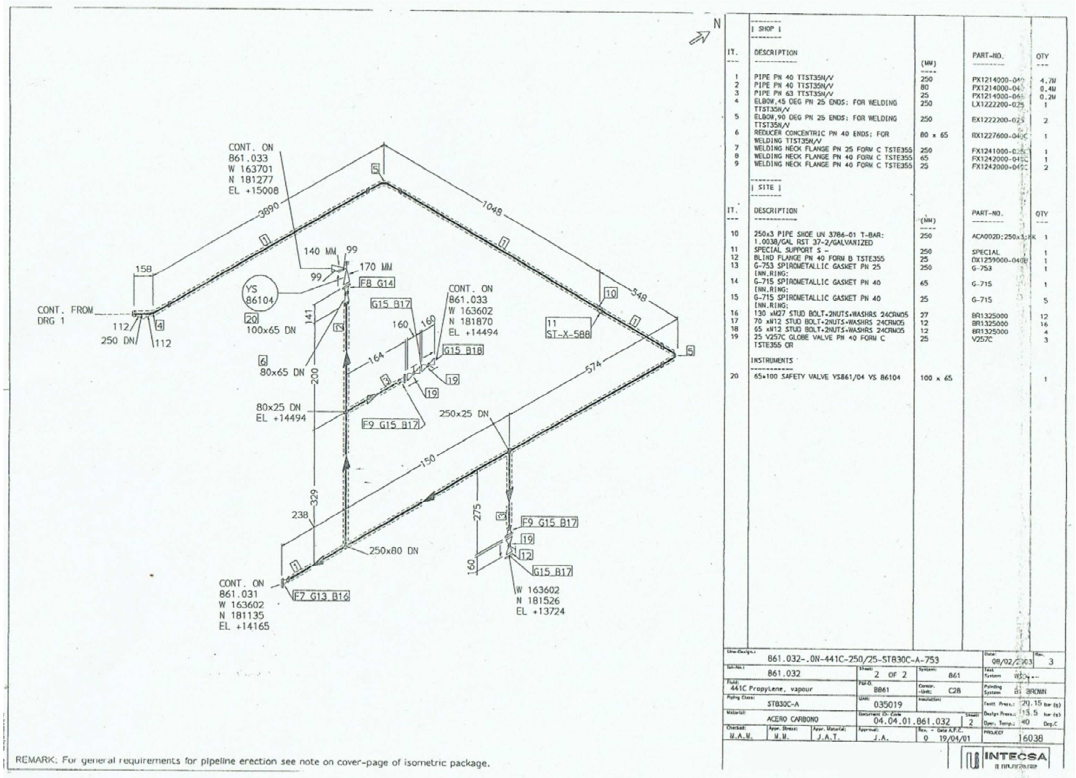


SHOP				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
1	PIPE PN 40 TTST35N/V	250	PX1214000-040	38.2M
2	PIPE PN 63 TTST35N/V	50	PX1214000-063	0.1M
3	PIPE PN 63 TTST35N/V	25	PX1214000-063	0.1M
4	ELBOW,90 DEG PN 25 ENDS; FOR WELDING TTST35N/V	250	EX1222200-025	3
5	REDUCER CONCENTRIC PN 63 ENDS: FOR WELDING TTST35N/V	50 x 25	RX1227600-063C	1
6	ELBOW,90 DEG PN 63 ENDS: FOR WELDING TTST35N/V	25	EX1222200-063	1
7	WELDING NECK FLANGE PN 25 FORM C TSTE355	250	FX1241000-025C	1
8	WELDING NECK FLANGE PN 40 FORM C TSTE355	25	FX1242000-040C	2

SITE				
IT.	DESCRIPTION	(MM)	PART-NO.	QTY
9	SPECIAL SUPPORT S -	250	SPECIAL	1
10	250x600 GUIDE BRACKET UN 3789-01 HE-B BAR: 1.0038 RST 37-2	250	KNB003D;250x600;	3
11	FLANGE ADAPTER PN 40 FORM B / G 1/2"	25 x 15	UX-001-040B	1
12	BLIND FLANGE PN 40 FORM B TSTE355	25	DX1259000-040B	1
13	G-753 SPIROMETALLIC GASKET PN 25 INN.RING:	250	G-753	1
14	G-715 SPIROMETALLIC GASKET PN 40 INN.RING:	25	G-715	4
15	130 xM27 STUD BOLT+2NUTS+WASHRS 24CRMO5	27	BR1325000	12
16	70 xM12 STUD BOLT+2NUTS+WASHRS 24CRMO5	12	BR1325000	16
17	25 V257C GLOBE VALVE PN 40 FORM C TSTE355 OR	25	V257C	2
	INSTRUMENTS			
18	PRESSURE INDICATOR MALE THREAD LOCAL PIC 86100	15		1

Line-Design.: 861.032-.0N-441C-250/25-ST830C-A-753		Date: 08/02/2003	Rev. 3
Iso-No.: 861.032	Sheet: 1 OF 2	System: 861	Test System:
Fluid: 441C Propylene, vapour	P&I-D: B861	Constr.-Unit: C28	Painting System: B: BROWN
Piping Class: ST830C-A	UAR: 035019	Insulation:	Test Press.: 20.15 bar (g)
Material: ACERO CARBONO	Document ID-Code: 04.04.01.861.032	Sheet: 1	Design Press.: 15.5 bar (g) Oper. Temp.: 40 Deg.C
Checked: M.A.M. / Appr. Stress: M.M. / Appr. Material: J.A.T.	Approval: J.A.	Rev. - Date A.P.C.: 0 19/04/01	PROJECT 16038

Figure 7.22: Isometric drawing of YS861-04 sheet 1.



SHOP

IT.	DESCRIPTION	(MM)	PART-NO.	QTY
1	PIPE PN 40 TTST35N/V	250	PX1214000-04	4.7M
2	PIPE PN 40 TTST35N/V	80	PX1214000-04	0.4M
3	PIPE PN 63 TTST35N/V	25	PX1214000-06	0.2M
4	ELBOW,45 DEG PN 25 ENDS: FOR WELDING TTST35N/V	250	LX1222200-025	1
5	ELBOW,90 DEG PN 25 ENDS: FOR WELDING TTST35N/V	250	EX1222200-025	2
6	REDUCER CONCENTRIC PN 40 ENDS: FOR WELDING TTST35N/V	80 x 65	RX1227600-040C	1
7	WELDING NECK FLANGE PN 25 FORM C TSTE355	250	FX1241000-025C	1
8	WELDING NECK FLANGE PN 40 FORM C TSTE355	65	FX1242000-040C	1
9	WELDING NECK FLANGE PN 40 FORM C TSTE355	25	FX1242000-040C	2

SITE

IT.	DESCRIPTION	(MM)	PART-NO.	QTY
10	250x3 PIPE SHOE UN 3786-01 T-BAR: 1.0038/GAL RST 37-2/GALVANIZED	250	ACA002D:250x3:HK	1
11	SPECIAL SUPPORT S -	250	SPECIAL	1
12	BLIND FLANGE PN 40 FORM B TSTE355	25	DX1259000-040B	1
13	G-753 SPIROMETALLIC GASKET PN 25 INN.RING:	250	G-753	1
14	G-715 SPIROMETALLIC GASKET PN 40 INN.RING:	65	G-715	1
15	G-715 SPIROMETALLIC GASKET PN 40 INN.RING:	25	G-715	5
16	130 xM27 STUD BOLT+2NUTS+WASHRS 24CRMO5	27	BR1325000	12
17	70 xM12 STUD BOLT+2NUTS+WASHRS 24CRMO5	12	BR1325000	16
18	65 xM12 STUD BOLT+2NUTS+WASHRS 24CRMO5	12	BR1325000	4
19	25 V257C GLOBE VALVE PN 40 FORM C TSTE355 OR	25	V257C	3

INSTRUMENTS

IT.	DESCRIPTION	(MM)	PART-NO.	QTY
20	65*100 SAFETY VALVE YS861/04 YS 86104	100 x 65		1

861.032-.0N-441C-250/25-ST830C-A-753
Date: 08/02/2003 Rev. 3
861.032
Sheet: 2 OF 2
System: 861
441C Propylene, vapour
B861
Constr.-Unit: C28
Painting System: BROWN
Piping Class: ST830C-A
Unit: 035019
Insulation:
Test Press.: 20.15 bar (g)
Material: ACERO CARBONO
Document ID-Code: 04.04.01.861.032
Sheet: 2
Design Press.: 15.5 bar (g)
Oper. Temp.: 40 Deg.C
Checked: M.A.M.
Appr. Stress: M.M.
Appr. Material: J.A.T.
Approval: J.A.
Rev. - Date A.F.C.: 0 19/04/01
PROJECT 16038
INTECSA

REMARK: For general requirements for pipeline erection see note on cover-page of isometric package.

Figure 7.23: Isometric drawing of YS861-04 sheet 2.

The relieving loads for fire scenario has been calculated.

The design conditions for the pressure relief valve according to the original specification sheet are in the following table:

Table 7.22: Design conditions for YS861-04.

Variable	Value	Units
SP	15.5	$barg$
T_R	40	$°C$
$Leser\ valve$	typ 4414.4682	$-$
$Fluid$	$propylene\ gas$	$-$
W_R	30800	$\frac{Kg}{h}$
W_{max}	42274	$\frac{Kg}{h}$
$Area$	2827.4	mm^2
$Valve\ weight$	32	Kg
$\alpha_{d,DG}$	0.7	$-$
$\alpha_{d,F}$	0.045	$-$

d_0	60	mm
$DN\ inlet$	65	mm
$DN\ outlet$	100	mm
$PN\ inlet$	40	bar
$PN\ outlet$	16	bar
$\Delta P_{friction\ inlet}$	0.567	bar
P_B	1.86	$barg$

7.5.1 Smith / Burgess / Powers (2011)

Following the paper of D. Smith, J. Burgess, and C. Powers, Relief device inlet piping: beyond the 3% rule, HP, November 2011, pp59-66

A) Inlet line length (Cremer/Friedel/Pallaks, 2001, 2003)

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.6)}$$

$$d_{psvi} = 65mm = 2.559in$$

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.5)}$$

$$t_0 = \left[0{,}015 + 0{,}02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_S}{P_{atm}}\right)^{\frac{2}{3}} \cdot (1 - \frac{P_{atm}}{P_S})^2}\right] \cdot (\frac{h}{h_{max}})^{0.7} \qquad \text{(Eq.5.4)}$$

$$\frac{h}{h_{max}} = 0.6$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot 2.559}}{\left(\frac{239.31}{14.5038}\right)^{\frac{2}{3}} \cdot (1 - \frac{14.5038}{239.31})^2}\right] \cdot (0.6)^{0.7} = 0.016s$$

$$K = \frac{Cp}{Cp - 1.986} = \frac{10.8}{10.8 - 1.986} = 1.23 \qquad \text{(Eq.7.1)}$$

Cp from API Technical Data Book (1997),

Temperature considered 40ºC = 563.7ºR

$$C = 223 \cdot \sqrt{\frac{1.23 \cdot 563.7}{42}} = 906 \frac{ft}{s} = 276.2 \frac{m}{s}$$

t wave (go and return)

$$t_{wave} = \frac{2L}{C} > \frac{2 \cdot 35.32}{276.2} = 0.256s$$

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} = 111.5 \cdot 0.016 \cdot \sqrt{\frac{1.23 \cdot 563.7}{42}} = 7.25ft = 2.21m$$

B) Inlet line length (Froman/Friedel, 1998) ΔP:20%

Assuming initial lift is 60%

$$L < 9078 \cdot \frac{{d_i}^2}{W_{60\%}} \cdot (P_s - P_B) \cdot t_0$$ (Eq.5.8)

$$W_{100\%} = 42274Kg/h = 93198\ lb/h$$

Assuming that 60% lift corresponds to a 60% maximal flow

$$W_{60\%} = 55919\ lb/h$$

$$P_s = 15.5barg \cdot 14.5038 = 224.81psig$$

$$P_B = 1.86barg \cdot 14.5038 = 26.98psig$$

$$L < 9078 \cdot \frac{2.559^2}{55919} \cdot (224.81 - 26.98) \cdot 0.016 = 3.36ft = 1.03m$$

C) Inlet line length (Fromman/Friedel) ΔP:blowdown

$$\mathrm{L} < 45390 \cdot \frac{{d_i}^2}{W_{\%}} \cdot \left(\frac{P_s - P_{RC}}{P_S}\right) \cdot (P_s - P_B) \cdot t_0$$ (Eq.5.8)

Blowdown=10% from LESER catalog

P_B from Aspen Flare analyzer (given by the petrochemical company)

$$\mathrm{L} < 45390 \cdot \frac{2.559^2}{55919} \cdot (0.1) \cdot (224.81 - 26.98) \cdot 0.016 = 1.68ft = 0.51m$$

D) Required flow > 25% Maximal flow

$$\mathrm{Req.\,flow} > 0.25 \cdot Maximal\ flow$$ (Eq.5.16)

$$30800\frac{kg}{h} > 0.25 \cdot 42274 = 10568.5\frac{kg}{h} \rightarrow OK$$

E) Acoustic pressure losses

$$\Delta P_{Acoustic} = \frac{L \cdot W_{PSV}}{12.6 \cdot {d_i}^2 \cdot t_0} + \frac{1}{10.5 \cdot \rho}\left(\frac{W_{PSV} \cdot L}{c \cdot d_i \cdot t_0}\right)^2$$ (Eq.5.11)

$$\rho = \frac{P_{SET} \cdot MW}{zRT} = \frac{239 \cdot 42}{0.45 \cdot 10.731 \cdot 564} = 3.81\frac{lb}{ft^3}$$

$$\Delta P_{Acoustic} = \frac{35.32 \cdot \frac{55919}{3600}}{12.6 \cdot 2.559^2 \cdot 0.016} + \frac{1}{10.5 \cdot 3.81}\left(\frac{\frac{55919}{3600} \cdot 35.32}{906 \cdot 2.559 \cdot 0.016}\right)^2 = 415.57 + 5.47 = 421.04psi =$$

$29.03bar$

$\Delta P_{friction} = 0.567bar \cdot 0.6^2 = 0.2bar(is\ assumed\ 60\%\ lift \rightarrow 60\% \max flow)$

$\Delta P_{total} = 29.03bar + 0.2bar = 29.23\ bar$

$(P_s - P_{RC}) = \ (P_s \cdot BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic}$ (Eq.5.12)

$(15.5 \cdot 0.1) = 1.55 > 29.23 \rightarrow no\ check!$

F) Body bowl choking (D'Alessandro Method)

$$P_0 < \ \frac{P_C}{(1+F_0) \cdot \frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

$$A_n = \text{throat area} = \frac{\pi \cdot 65^2}{4} = 3318.3mm^2$$

$$A_e = \text{outlet area} = \frac{\pi \cdot 104^2}{4} = 8494.9mm^2$$

K=1.13(ideal gas)

$P_C = 0.15barg = 16.9psia = superimposed\ backpressure$

$$P_0 < \ \frac{16.9}{(1+0.1) \cdot \frac{3318.3}{8494.9}} \cdot \frac{1}{\left(\frac{2}{1.13+1}\right)^{\frac{1.13}{1.13+1}} - 0.1} = 197.6psia$$

$P_0 = 45.013barg = 652.9psia$

$652.9psia < 197.6psia \rightarrow No\ check \rightarrow Possibility\ of\ body\ bowl\ chocking$

G) Compressible vapors criteria (Oversizing)

$W_{PSV} > 0.2 \cdot V_{system} \cdot \left(\rho_{set} - \ \rho_{shut}\right) + W_{required}$ (Eq.5.15)

If this equation is fulfilled the safety valve can chatter.

During the boiling process:

Pset at 15.5barg and 40°C = $2.227 \frac{lb}{ft^3}$

Pshut at 13.95barg and 40°C = $1.762 \frac{lb}{ft^3}$ (webbook nist)

Vsystem=105.9ft^3

Thus,

$$25.9\frac{lb}{s} > 0.2 \cdot 105.9 \cdot (2.227 - 1.762) + 18.9\frac{lb}{s}$$

$$25.9\frac{lb}{s} > 28.74 \rightarrow No\ fullfills!\ No\ chattering\ possibilities$$

7.5.2 Melhem (2016)

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using webbook NIST

Table 7.23: Inlet to pipe/inlet to PRV properties for YS861-04.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	40	17.05 (1)	2.2247	1.14
Inlet to PRV	40	16.43 (6% SP)	2.2108	1.14

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 15.5 = 17.05 barg

So, the following table can be created

Table 7.24: Isothermal properties for YS861-04.

Temperature, ºC	P psig (barg)	Density lb/ft^3
40	238.297 (16.43)	2.2108
40	238.4 (16.44)	2.2129
40	239.3 (16.45)	2.2247

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.013\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.14}{0.013}\cdot 32.174\cdot 144} = 637.4\ ft/s$$

→Speed of sound at PRV inlet:

$$c = \sqrt{\frac{1.14}{0.013}\cdot 32.174\cdot 144} = 637.4\ ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N}-1}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \qquad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_s}{m_D}} \qquad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$

$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2\ (\mathrm{assumed})$

Assuming initial lift is 60%

Thus,

$\frac{h}{h_{max}} = 0.6$

The parameters for a LESER safety valve, are:

$AN = \pi\frac{2.3622^2}{4} = 4.38\ in2$

$xmax$ = 8.75mm (0.24·60·60%)=0.34 in

$Pset$ = 15.5 barg = 224.8 psig

$K_s = 1.1\cdot 1.2\cdot\frac{224.8\cdot 4.38}{0.34\ \mathrm{in}} = 3822.66\ \frac{lb_f}{in}$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV} \qquad \text{(Eq.5.32)}$$

$m_D = 0.018\cdot 70.55 + 0.00022\cdot 70.55^2 = 2.36lbm$

→Natural frequency of the valve

$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{3822.66}{2.59\ lb_m 2.36}\cdot 32.174\cdot 12} = 78.21Hz$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2\cdot 78.21s^{-1}} = 0.0064\ s = 6.4\ ms$ (NOTE 1)

NOTE1: the calculation of the t_{open} with the equation of Cremer/Friedel/Pallacks gives 0.016s=16ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{6.4\ ms}{\sqrt{1-0.5^2}} = 7.39\ ms \qquad \text{(Eq.5.35)}$$

Step 3: Force Balance

→PRV Stability Part II

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

→Need tau (Ʈ)

$$t_{wave} = \frac{2L_p}{c_o} \qquad \text{(Eq.5.23)}$$

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) = min\left(\frac{\frac{2 \cdot L_p}{c}}{t_{open\ /\ close,d}}, 1\right) = min\left(\frac{\frac{2 \cdot 115.9ft}{637.4\ fts^{-1}}}{0.00739}, 1\right) = \min(49.2, 1) = 1$$

→dPwave (PRV Stability Pt II Eqn 21)

$$\Delta P_{wave} = \tau \frac{c_0 M_{close}}{A_p} + \tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \quad \text{NOTE 2} \qquad \text{(Eq.5.25)}$$

$$\tau \frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$$

$$\tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$$

→Assume Mclose = 80% of capacity

0.8·42274 Kg/h = 74558 lb/h

→c_0 = 596.8 ft/s

→ρ_0 = 37.2lb/ft3

→Dpipe = 60 mm = 2.3622 in

$$\Delta P_{wave,open} = 1 \cdot \frac{637.4fts^{-1} \cdot 93198lb_m h^{-1} \cdot \frac{h}{3600s}}{(2.3622in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(93198h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 37.2lb_m ft^{-3} \cdot ((2.3622in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 542195\ lb_m ft^{-1} s^{-2} + 9726\ lb_m ft^{-1} s^{-2} = 551921\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,open} = 551921\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 119.1 lb_f in^{-2}$$

$$\Delta P_{wave,close} = 1 \cdot \frac{637.4fts^{-1} \cdot 74558 \cdot \frac{h}{3600s}}{(2.3622in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(74558h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 37.2lb_m ft^{-3} \cdot ((2.3622n)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 433754\ lb_m ft^{-1} s^{-2} + 6224\ lb_m ft^{-1} s^{-2} = 439978\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,close} = 439978\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 94.96 lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 1^2 \cdot 0.567\ bar = 8.22\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2 \tau^2 \Delta P_{f,opening} = 0.8^2 1^2 0.567\ bar = 0.36288\ bar = 5.26\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$261.98 - 8.22 - 119.1 - 26.98 - 217.02 = -97.84$$

Closing:

$$261.98 - 5.26 - 94.96 - 26.98 - 217.02 = -72.98$$

→Force balance is negative → **chattering**

Step 4: Acoustic Analysis

→PRV Stability Part II

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

$$L \leq \frac{C}{4f_n}\sqrt{\frac{1.32x}{1.32x+x_{max}}}$$

→Equation constant is:

$$\frac{A_{pop}}{A_N}\frac{P_{full}}{P_{set}} = 1.2 \cdot 1.1 = 1.32$$

$$L_{crit} = \frac{C_0}{4f_n}\sqrt{\frac{1.32x}{1.32x+x_{max}}} = \frac{637.4fts^{-1}}{4\cdot 78.21s^{-1}}\sqrt{\frac{1.32\cdot 0.34\ in}{1.32\cdot 0.34+0.34}} = 1.54ft = 0.47m$$

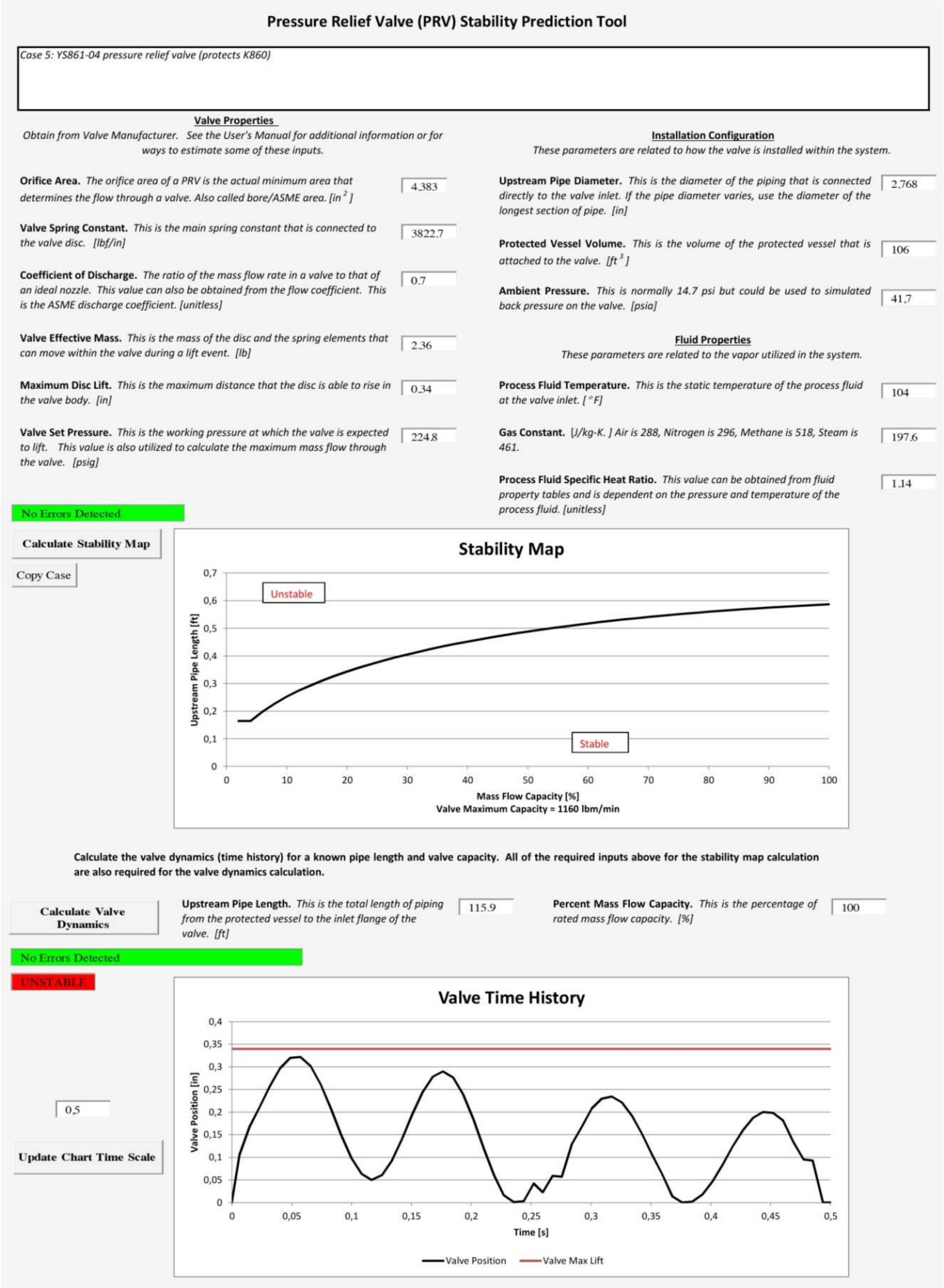
$$L_{crit} = 0.47m < L_p$$

$$L_{crit} = 0.47m < 35.32m$$

→PRV is likely to **low frequency cycling**

7.5.3 SWRI (2016)

The screenshot of the software results is:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 5: YS861-04 pressure relief valve (protects K860)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in^2]* 4.383

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 3822.7

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.7

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 2.36

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.34

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 224.8

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2.768

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft^3]* 106

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 41,7

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 104

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.14

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 115.9

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0,5

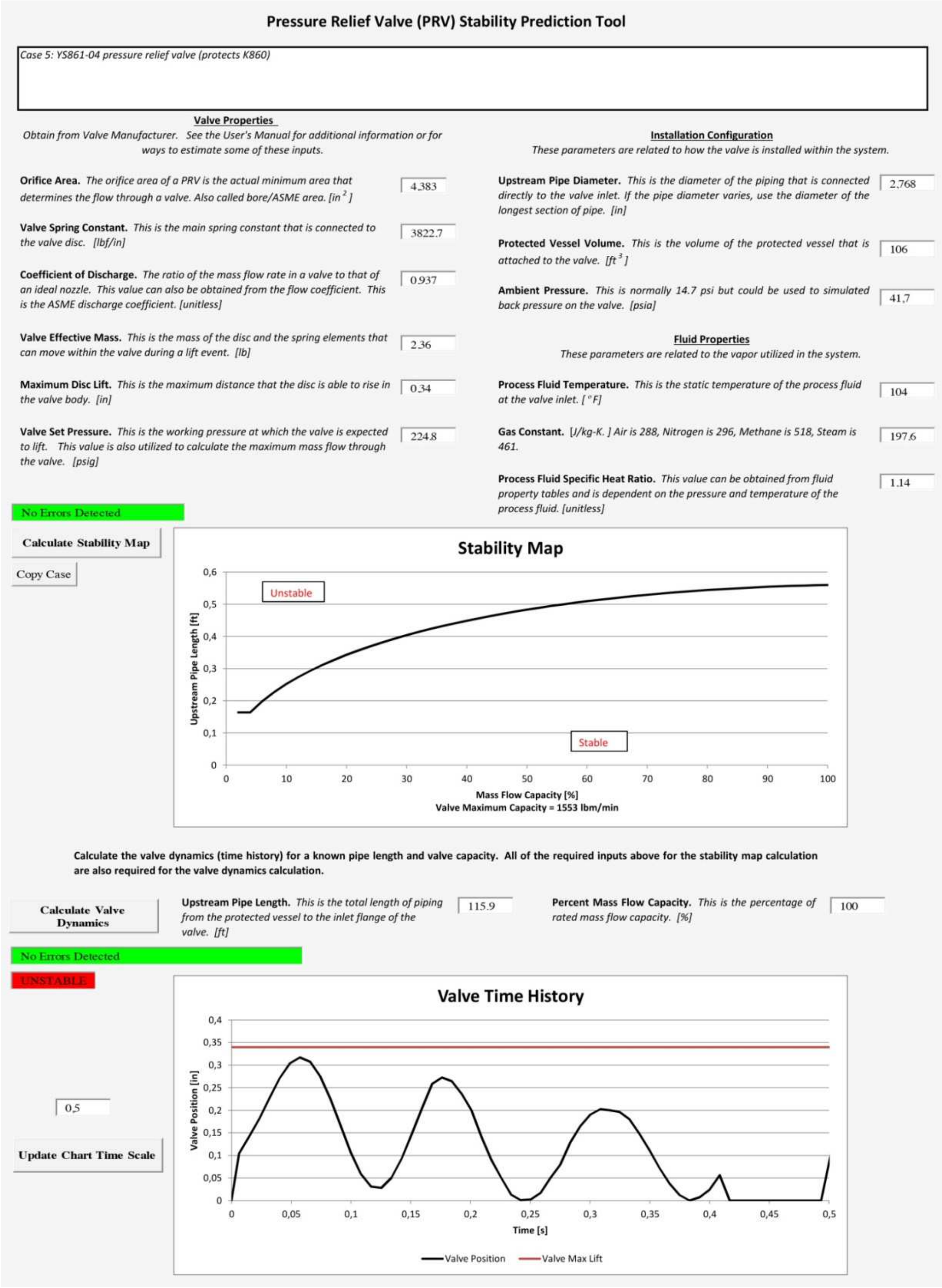
Figure 7.24: Stability results of SWRI software for YS861-04 (unreal flow).

However the software calculate a maximal flow of $1160\frac{lb}{min}$ but the real value is $1553\frac{lb}{min}$.

Thus, as with the case of valve Y700-01:

$$\frac{0.7}{1160\frac{lb}{min}}\cdot 1553\frac{lb}{min} = 0.937$$

Thus, the new result is:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 5: YS861-04 pressure relief valve (protects K860)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in^2]* 4.383

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 3822.7

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.937

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 2.36

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.34

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 224.8

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 2.768

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft^3]* 106

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 41,7

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 104

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 197.6

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.14

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 115.9

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0,5

Figure 7.25: Stability results of SWRI software for YS861-04 (real flow).

The stability map shows that the safety valve operates in the unstable region. The valve time history shows instability. It is observed that the disc operates at a low frequency of 8 Hz approximately. Therefore PRV suffers cycling.

7.5.4 Engineering analysis summary

According to the engineering analysis procedure described in section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? Yes

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

15.5-(13.95+0.31)>0.57

5) Does excessive built-up backpressure occur according to the specific PRV?

Yes, the built-up back backpressure is 1.86 barg, thus

(1.86/15.5)·100=12% <10%, NOT OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table 7.25:

Table 7.25: Stability analysis results for YS861-04

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	35.32	2.21	No	Yes
Inlet line length (Frommann and Friedel, 1998) ΔP 20%	35.32	1.03	No	Yes
Inlet line length (Frommann and Friedel, 1998) ΔP blowdown	35.32	0.51	No	Yes
Required flow > 25% rated flow (oversizing)			Yes	No
Compressible vapors criteria (oversizing)			No	Yes
Total backpressure for a conventional valve < 10% SP			No	Yes
Body bowl choking			No	Unknown
Acoustic pressure losses			No	Yes
API Simple Force Balance (Melhem, 2016)			No	Yes

8) Is the risk of relieving of the existing pressure relief valve quantified?
Yes, very low risk. It discharges to flare.

7.6 PRV YS-12(V15)

The sixth case study corresponds to the valve YS12 with an inlet pressure drop greater than 3% of the set pressure (not fulfill the 3% rule).A picture of the valve and the protected equipment is presented in figure 7.17.

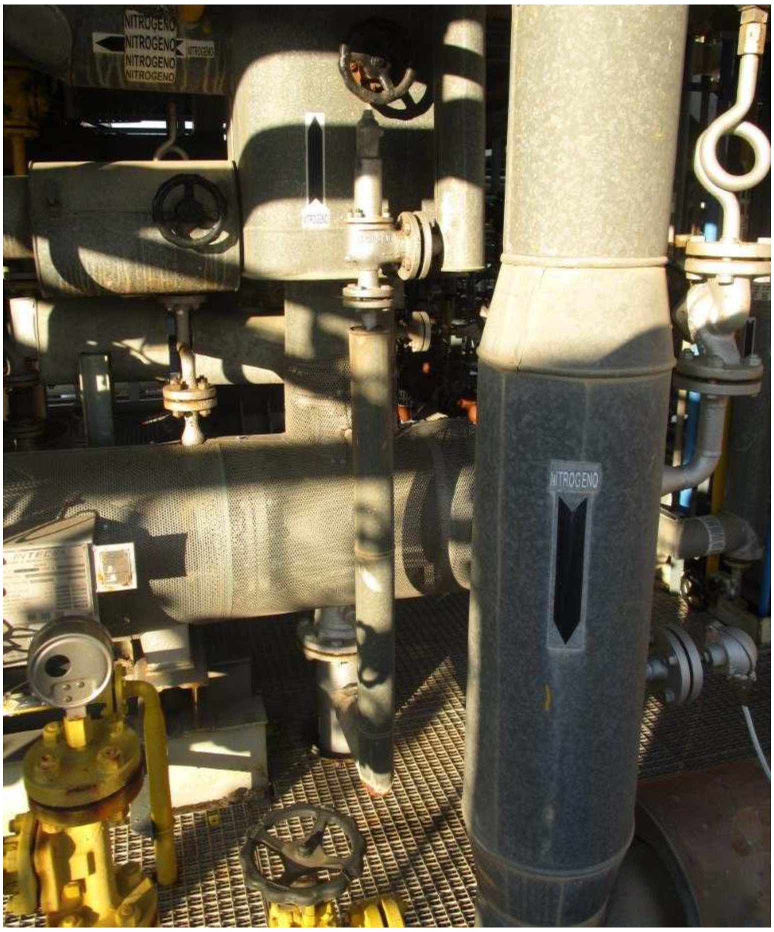


Figure 7.26: Picture of YS12 and protected equipment.

The relieving loads for fire scenario has been calculated.

The design conditions for the pressure relief valve according to the original specification sheet are in the following table:

Table 7.26: Design conditions for YS12.

Variable	Value	Units
SP	1	$barg$
T_R	305	$°C$
$Sempell\ valve$	$Model\ VSE2$	$-$
$Fluid$	$nitrogen\ gas$	$-$
W_R	109	$\frac{Kg}{h}$
W_{max}	183	$\frac{Kg}{h}$
$Area$	254	mm^2
$Valve\ weight$	9	Kg

d_0	18	mm
$DN\ inlet$	25	mm
$DN\ outlet$	40	mm
$PN\ inlet$	40	bar
$PN\ outlet$	16	bar
$\frac{h}{d_0}$	0.139	$-$
$\Delta P_{friction\ inlet}$	0.5	bar
P_B	0.3	$barg$

NOTE: Maximum capacity of valve is 183 kg/h, but the flow is limited by the maximal flow of the control valve, because of that, the maximal flow considered is 109 Kg/h

7.6.1 Smith / Burgess / Powers (2011)

Following the paper of D. Smith, J. Burgess, and C. Powers, Relief device inlet piping: beyond the 3% rule, HP, November 2011, pp59-66

A) Inlet line length (Cremer/Friedel/Pallaks, 2001, 2003)

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.6)}$$

$$d_{psvi} = 18mm = 0.7087in$$

$$t_0 > \frac{2L}{C} \qquad \text{(Eq.5.3)}$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}} \qquad \text{(Eq.5.5)}$$

$$t_0 = \left[0.015 + 0.02 \cdot \frac{\sqrt{2 \cdot d_{psvi}}}{\left(\frac{P_S}{P_{atm}}\right)^{\frac{2}{3}} \cdot (1 - \frac{P_{atm}}{P_S})^2}\right] \cdot (\frac{h}{h_{max}})^{0.7} \qquad \text{(Eq.5.4)}$$

$$\frac{h}{h_{max}} = 0.6$$

$$t_0 = \left[0,015 + 0,02 \cdot \frac{\sqrt{2 \cdot 0.7087}}{\left(\frac{29.01}{14.696}\right)^{\frac{2}{3}} \cdot (1 - \frac{14.696}{29.01})^2}\right] \cdot (0.6)^{0.7} = 0.054s$$

$$C = 223 \cdot \sqrt{\frac{KT}{MW}}$$

$$K = \frac{Cp}{Cp - 1.986} = \frac{17.5}{17.5 - 1.986} = 1.13 \qquad \text{(Eq.7.1)}$$

Cp from API Technical Data Book (1997),

Temperature considered 305ºC = 1041ºR

$$C = 223 \cdot \sqrt{\frac{1.13 \cdot 1041}{28}} = 1445 \frac{ft}{s} = 441 \frac{m}{s}$$

t wave (go and return)

$$t_{wave} = \frac{2L}{C} > \frac{2 \cdot 2.24}{441} = 0.01s$$

$$L < 111.5 \cdot t_0 \cdot \sqrt{\frac{KT}{MW}} = 111.5 \cdot 0.054 \cdot \sqrt{\frac{1.13 \cdot 1041}{28}} = 39.03ft = 11.9m$$

B) Inlet line length (Froman/Friedel, 1998) ΔP:20%

$$L_{100\%} < 9078 \cdot \frac{{d_i}^2}{W_{100\%}} \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

$$W_{100\%} = 109Kg/h = 240.304\ lb/h$$

$$P_s = 1barg \cdot 14.5038 = 14.5038psig$$

$$P_B = 0.3psig$$

$$L_{100\%} < 9078 \cdot \frac{0.7087^2}{240.304} \cdot (14.5038 - 0.3) \cdot 0.054 = 14.55ft = 4.43m$$

C) Inlet line length (Froman/Friedel, 1998) ΔP:blowdown

$$\mathrm{L} < 45390 \cdot \frac{{d_i}^2}{W_{\%}} \cdot \left(\frac{P_S - P_{RC}}{P_S}\right) \cdot (P_s - P_B) \cdot t_0 \qquad \text{(Eq.5.8)}$$

Blowdown=10% from LESER catalog

P_B from Aspen Flare analyzer (given by the petrochemical company)

$$\mathrm{L} < 45390 \cdot \frac{0.7087^2}{240.304} \cdot (0.1) \cdot (14.5038 - 0.3) \cdot 0.054 = 7.27ft = 2.22m$$

D) Required flow > 25% Maximal flow

$$\text{Req. flow} > 0.25 \cdot Maximal\ flow \qquad \text{(Eq.5.16)}$$

$$109 \frac{kg}{h} > 0.25 \cdot 183 = 45.8 \frac{kg}{h} \rightarrow OK$$

E) Acoustic pressure losses

$$\Delta P_{Acoustic} = \frac{L \cdot W_{PSV}}{12.6 \cdot {d_i}^2 \cdot t_0} + \frac{1}{10.5 \cdot \rho}\left(\frac{W_{PSV} \cdot L}{c \cdot d_i \cdot t_0}\right)^2 \qquad \text{(Eq.5.11)}$$

$$\rho = \frac{P_{SET} \cdot MW}{zRT} = \frac{14.5038 \cdot 28}{0.55 \cdot 10.731 \cdot 1041} = 0.07\frac{lb}{ft^3}$$

$$\Delta P_{Acoustic} = \frac{88.2 \cdot \frac{240.3}{3600}}{12.6 \cdot 0.7087^2 \cdot 0.054} + \frac{1}{10.5 \cdot 0.07}\left(\frac{\frac{240.3}{3600} \cdot 88.2}{1445 \cdot 0.7087 \cdot 0.054}\right)^2 = 17.23 + 0.015 = 17.25psi = 1.12bar$$

$\Delta P_{friction} = 0.5\ bar$

$\Delta P_{total} = 1.12bar + 0.5bar = 1.62\ bar$

$$(P_s - P_{RC}) = (P_s \cdot BD) > \Delta P_{TOTAL} = \Delta P_{Frictional} + \Delta P_{Acoustic} \qquad \text{(Eq.5.12)}$$

$(P_s \cdot BD) = 0.1 > 1.62 \rightarrow No\ check!$

F) Body bowl choking (D'Alessandro Method)

$$P_0 < \frac{P_C}{(1+F_0) \cdot \frac{A_n}{A_e}} \cdot \frac{1}{\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} - F_o} \qquad \text{(Eq.5.1)}$$

$A_n = 254mm^2$

$$A_e = \text{outlet area} = \frac{\pi \cdot 40^2}{4} = 1256.6mm^2$$

K=1.13(ideal gas)

$P_C = 0.30barg = 18.9psia = superimposed\ backpressure$

$$P_0 < \frac{18.9}{(1+0.1) \cdot \frac{254}{1256.6}} \cdot \frac{1}{\left(\frac{2}{1.13+1}\right)^{\frac{1.13}{1.13+1}} - 0.1} = 98.03psia$$

$P_0 = 2.113barg = 30.65psia$

$98.03psia < 30.65psia \rightarrow No\ check \rightarrow Possibility\ of\ body\ bowl\ chocking$

G) Compressible vapors criteria (Oversizing)

$$W_{PSV} > 0.2 \cdot V_{system} \cdot (\rho_{set} - \rho_{shut}) + W_{required} \qquad \text{(Eq.5.15)}$$

If this equation is fulfilled, the safety valve can chatter.

During the boiling process:

Pset at 1barg and 305°C = 2.701$\frac{lb}{ft^3}$

Pshut at 0.9barg and 305°C = 2.404$\frac{lb}{ft^3}$ (webbook nist)

Vsystem=0.86ft^3

Thus,

$$0.112\frac{lb}{s} > 0.2 \cdot 0.86 \cdot (2.701 - 2.404) + 0.364\frac{lb}{s}$$

$$0.112\frac{lb}{s} > 0.415 \rightarrow No\ fullfills!\ No\ chattering\ possibilities$$

7.6.2 Melhem (2016)

The equation to be used according to Melhem is:

1) Force balance

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

2) Acoustic analysis

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

Step 1: Speed of Sound

→PRV Stability Part II

$$c = c_0 = \sqrt{\frac{1}{ks\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{C_p}{C_v}\frac{1}{kT\rho}} = \sqrt{\frac{C_p}{C_v}\left[\frac{\partial P}{\partial \rho}\right]_T} \qquad \text{(Eq.5.30)}$$

→Evaluate at Inlet to Pipe and Inlet to PRV

Thus, using ASPEN HYSYS v8.6 TM with Peng Robinson as EOS

Table 7.27: Inlet to pipe/inlet to PRV properties for YS12.

	Temperature, ºC	Pressure, barg	Density lb/ft^3	Cp/Cv ideal
Inlet to pipe	305	1.1 (1)	2.996	1.37
Inlet to PRV	305	1.03 (6% SP)	2.789	1.37

(1) The relieving pressure is: 1.1 · Sp = 1.1 · 1 = 1.1 barg

So, the following table can be created

Table 7.28: Isothermal properties for YS12.

Temperature, ºC	P psig (barg)	Density lb/ft^3
305	14.94 (1.03)	0.03745
305	15.19 (1.0475)	0.03809
305	15.45 (1.065)	0.03872
305	15.7 (1.0825)	0.03936
305	15.95 (1.1)	0.04

Thus, the median

$$\left(\frac{\delta\rho}{\delta P}\right)_T = 0.036\frac{\frac{lb}{ft^3}}{psi}$$

Giving values

→Speed of sound at piping inlet

$$c = \sqrt{\frac{1.37}{0.036}\cdot 32.174\cdot 144} = 419.9\ ft/s$$

→Speed of sound at PRV inlet

$$c = \sqrt{\frac{1.37}{0.036}\cdot 32.174\cdot 144} = 419.9\ ft/s$$

Step 2: Opening Time

→PRV Stability Part II

$$t_{open} \approx \frac{1}{2\pi f_n}\sqrt{\frac{2}{\frac{A_{pop}}{A_{N^{-1}}}}} \approx \frac{1}{2f_n}\ (if\ \frac{A_{pop}}{A_N} = 1.2) \qquad \text{(Eq.5.34)}$$

$$t_{open,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}}$$

- Need mass in motion and spring constant. PRV Stability Part II

$$f = \frac{1}{\tau_n} = \frac{w_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K_s}{m_D}} \qquad \text{(Eq.5.33)}$$

→Spring Constant from Grolmes Correlation. PRV Stability Part II

$$K_s = C_1\left[\frac{P_{set}A_N}{x_{max}}\right] = C_2C_3\left[\frac{P_{set}A_N}{x_{max}}\right] = \left(\frac{P_{full\,flow}}{P_{set}}\right)\left(\frac{A_{pop}}{A_N}\right)\left[\frac{P_{set}A_N}{x_{max}}\right] \qquad \text{(Eq.5.31)}$$

$\frac{P_{full\,flow}}{P_{set}} = 1.1\ (10\%\ overpressure)$

$\frac{\mathrm{A_{pop}}}{\mathrm{A_N}} = 1.2\ (\text{assumed})$

Assuming initial lift is 60%

Thus,

$\frac{h}{h_{max}} = 0.6$

The parameters for a LESER safety valve, are:

$$A_N = \pi\frac{0.984^2}{4} = 0.76\ in2$$

$xmax$ = 1.5mm (0.139·18·60%)=0.06 in

$Pset$ = 1 barg = 14.5 psig = 29 psia

$$K_s = 1.1 \cdot 1.2 \cdot \frac{29 \cdot 0.76}{0.06\ \mathrm{in}} = 484.9\ \frac{lb_f}{in}$$

→Mass in Motion from Grolmes Correlation. PRV Stability Part II

$$m_D = \frac{M_{PRV}}{100}(1.8 + 0.022M_{PRV}) = 0.018M_{PRV} + 0.00022M^2{}_{PRV} \qquad \text{(Eq.5.32)}$$

$$m_D = 0.018 \cdot 19.8 + 0.00022 \cdot 19.8^2 = 0.44lbm$$

→Natural frequency of the valve

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_s}{m_D}} = \frac{1}{2\pi}\sqrt{\frac{484.9}{2.59\ lb_m 0.44} \cdot 32.174 \cdot 12} = 65.8Hz$$

→Valve opening time

$t_{open} \approx \frac{1}{2f_n} = \frac{1}{2 \cdot 65.8 s^{-1}} = 0.0076\ s = 7.6\ ms$ (NOTE 1)

NOTE1: the calculation of the t_{open} with the equation of Cremer/Friedel/Pallacks gives 0,054s=54ms. It seems that the values of m_D and k_s should be improved

→Damped valve opening time (coefficient 0.5)

$$t_{open,d} = t_{close,d} = \frac{t_{open}}{\sqrt{1-\varsigma^2}} = \frac{7.6\ ms}{\sqrt{1-0.5^2}} = 8.7\ ms \qquad \text{(Eq.5.35)}$$

Step 3: Force Balance

→PRV Stability Part II

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close} \qquad \text{(Eq.5.17)}$$

→Need tau (Ꚍ)

$$t_{wave} = \frac{2L_p}{c_o} \qquad \text{(Eq.5.23)}$$

$$\tau = min\left(\frac{t_{wave}}{t_{valve}}, 1\right) = min\left(\frac{\frac{2 \cdot L_p}{c}}{t_{open\ /\ close,d}}, 1\right) = min\left(\frac{\frac{2 \cdot 7{,}35 ft}{419.9 fts^{-1}}}{0.0076}, 1\right) = \min(4.6, 1) = 1$$

→dPwave (PRV Stability Pt II Eqn 21)

$$\Delta P_{wave} = \tau \frac{c_0 M_{close}}{A_p} + \tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \qquad \text{(Eq.5.25)}$$

$\tau \frac{c_0 M_{close}}{A_p} \rightarrow Fluid\ hammer\ term$

$\tau^2 \frac{M_{close}^2}{2\rho_0 A_p^2} \rightarrow Fluid\ inertia\ term$

→Assume Mclose = 80% of capacity

0.8·109 Kg/h = 192.2 lb/h

→c_0 = 371.1 ft/s

→ρ_0 = 0.03745 lb/ft3

→Dpipe = 28 mm = 1.1 in

$$\Delta P_{wave,open} = 1 \cdot \frac{419.9fts^{-1} \cdot 240.3lb_m h^{-1} \cdot \frac{h}{3600s}}{(1.1in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(240.3h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 0.03745lb_m ft^{-3} \cdot ((1.1in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,open} = 4247.02\ lb_m ft^{-1} s^{-2} + 1365\ lb_m ft^{-1} s^{-2}\ = 5612.02\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,open} = 5612.02\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 1.21 lb_f in^{-2}$$

$$\Delta P_{wave,close} = 1 \cdot \frac{419.9fts^{-1} \cdot 192.2 \cdot \frac{h}{3600s}}{(1.1in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2}} + 1^2 \cdot \frac{(192.2h^{-1} \cdot \frac{h}{3600s})^2}{2 \cdot 0.03745lb_m ft^{-3} \cdot ((1.1in)^2 \pi \cdot 0.25 \cdot \frac{ft^2}{144in^2})^2}$$

$$\Delta P_{wave,close} = 3396.9\ lb_m ft^{-1} s^{-2} + 873.76\ lb_m ft^{-1} s^{-2}\ = 4270.7\ lb_m ft^{-1} s^{-2}$$

$$\Delta P_{wave,close} = 4270.7\ lb_m ft^{-1} s^{-2} \cdot \frac{lb_f}{32.174 lb_m fts^{-2}} \cdot \frac{ft}{144\ in^2} = 0.92 lb_f in^{-2}$$

→Calculate ΔPf

→Use Tau

$$\Delta P_{f,wave,opening} = \tau^2 \Delta P_{f,opening} = 1^2 \cdot 0.5\ bar = 7.25\ psi \qquad \text{(Eq.5.28)}$$

→Assume 80% capacity during closing

$$\Delta P_{f,wave,closing} = 0.8^2 \tau^2 \Delta P_{f,opening} = 0.8^2 1^2 0.5\ bar = 0.32\ bar = 4.64\ psi$$

→Force balance equation

$$P_{source} - \Delta P_{f,wave} - \Delta P_{wave} - \Delta P_{back} > \Delta P_{close}$$

Opening:

$$15.95 - 1.21 - 7.25 - 4.35\ - 13.05 = -9.91$$

Closing:

$$15.95 - 0.92 - 4.64 - 4.35\ - 13.05 = -7.01$$

→Force balance is negative → **CHATTERING**

Step 4: Acoustic Analysis

→PRV Stability Part II

$$L \leq \frac{C}{4f_n}\sqrt{\frac{x}{x+x_0}} \qquad \text{(Eq.5.36)}$$

$$L \leq \frac{C}{4f_n}\sqrt{\frac{1.32x}{1.32x+x_{max}}}$$

→Equation constant is:

$$\frac{A_{pop}}{A_N}\frac{P_{full}}{P_{set}} = 1.2 \cdot 1.1 = 1.32$$

$$L_{crit} = \frac{C_0}{4f_n}\sqrt{\frac{1.32x}{1.32x + x_{max}}} = \frac{419.9fts^{-1}}{4 \cdot 65.8s^{-1}}\sqrt{\frac{1.32 \cdot 0.06\ in}{1.32 \cdot 0.06 + 0.06}} = 1.2ft = 0.37m$$

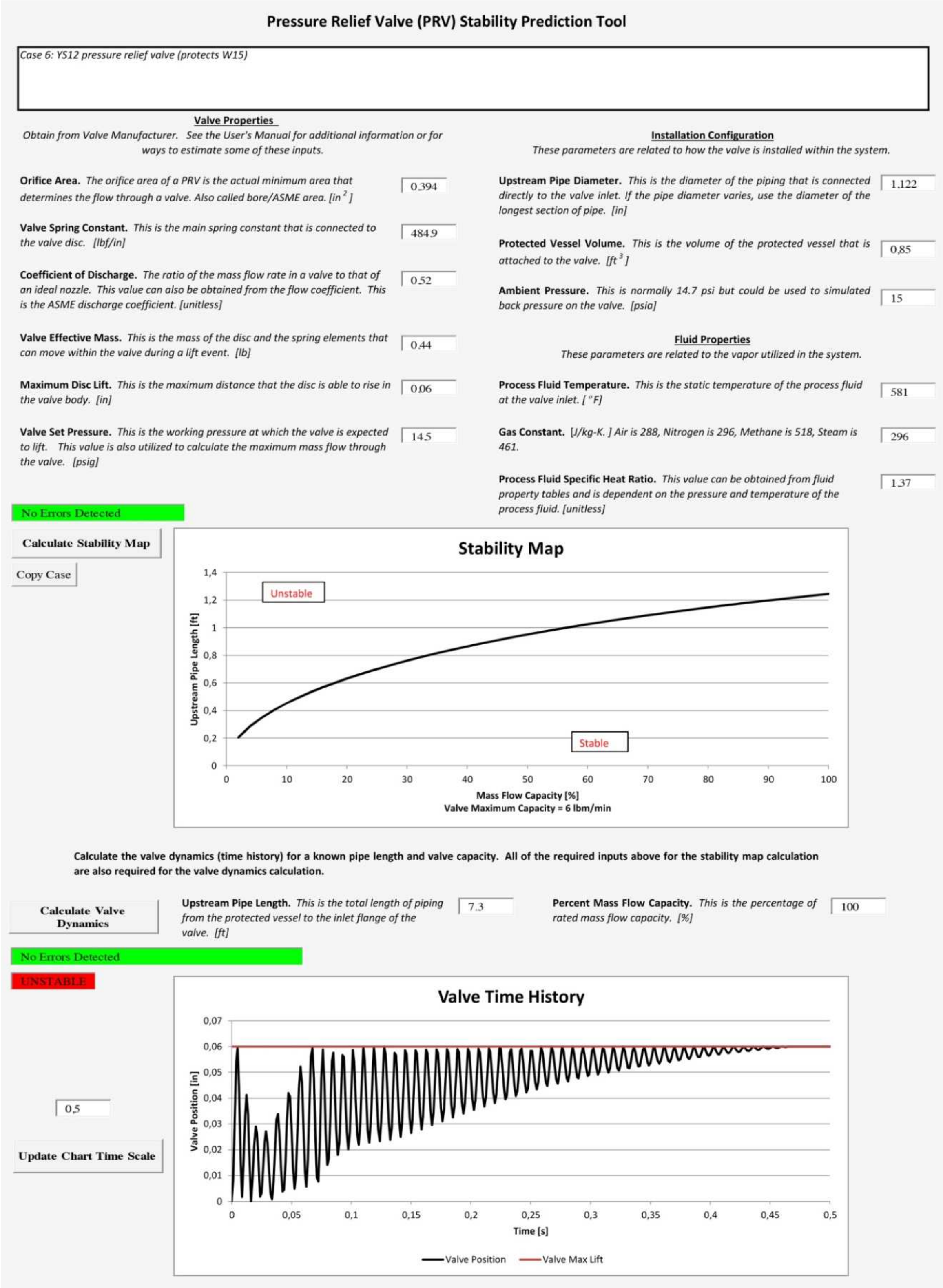
$$L_{crit} = 0.37m < L_p$$

$$L_{crit} = 0.37m < 2.24m$$

→PRV is likely to **high frequency cycling**

7.6.3 SWRI (2016)

The screenshot of the software results is presented here:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 6: YS12 pressure relief valve (protects W15)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in^2]* 0.394

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 484.9

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.52

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 0.44

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.06

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 14.5

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 1.122

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft^3]* 0,85

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 15

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 581

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 296

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.37

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 7.3

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 100

No Errors Detected

UNSTABLE

0,5

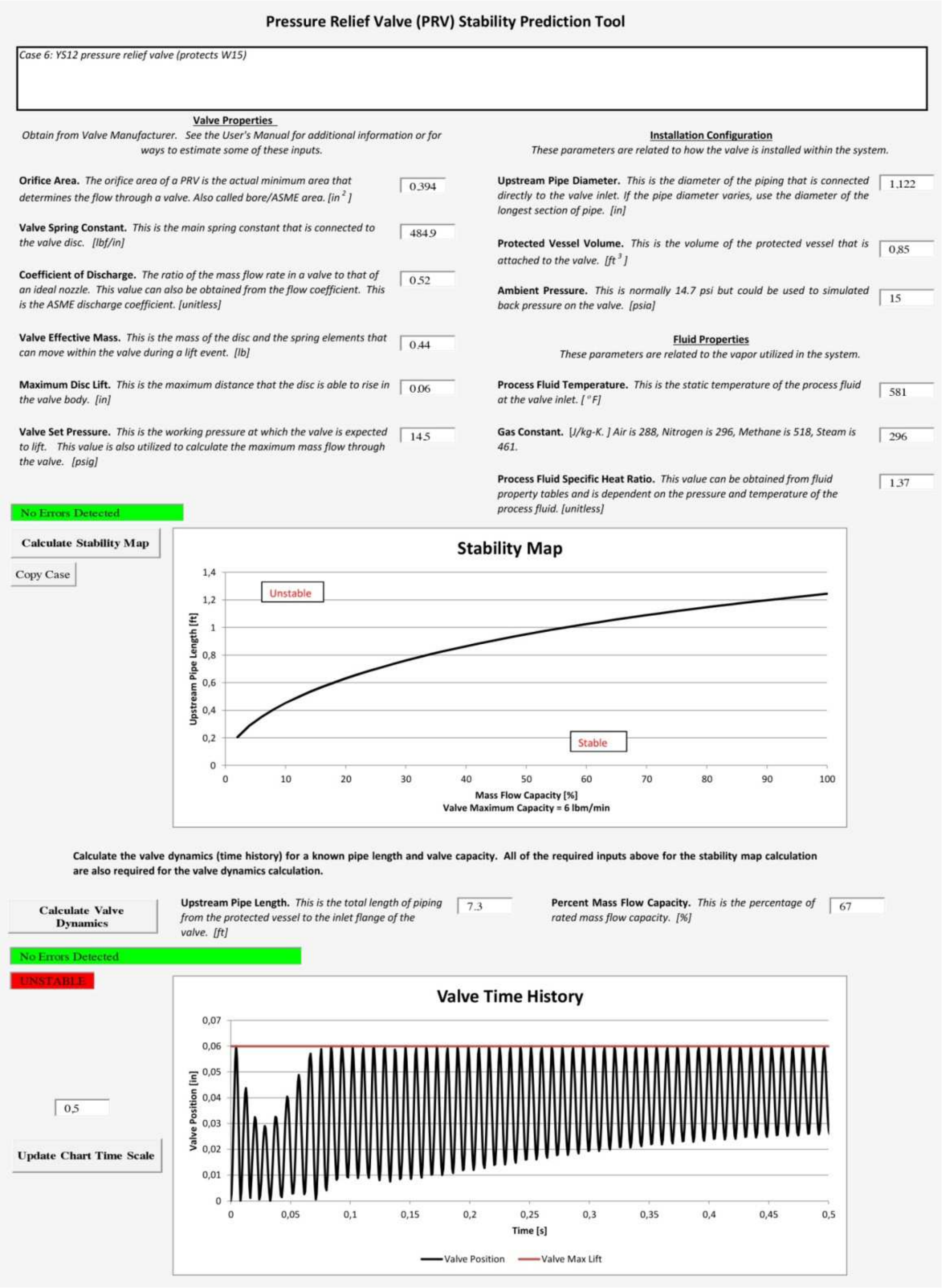
Figure 7.27: Stability results of SWRI software for YS12 (unreal flow).

However the software calculate a maximal flow of $6\,\frac{lb}{min}$ but due to the restriction orifice in the PRV inlet, the maximal flow to be relieved is $4\,\frac{lb}{min}$.

The stability map gives a maximal upstream pipe length to avoid instability at $\frac{4}{6} = 0.67 \rightarrow 67\%$ of rated flow, of $1.05\ ft$, also unstable.

A new run was made to check for instability in the valve time history at this flow $(4\,\frac{lb}{min})$.

The new result is:



Pressure Relief Valve (PRV) Stability Prediction Tool

Case 6: YS12 pressure relief valve (protects W15)

Valve Properties

Obtain from Valve Manufacturer. See the User's Manual for additional information or for ways to estimate some of these inputs.

Orifice Area. *The orifice area of a PRV is the actual minimum area that determines the flow through a valve. Also called bore/ASME area. [in ^{2}]* 0.394

Valve Spring Constant. *This is the main spring constant that is connected to the valve disc. [lbf/in]* 484.9

Coefficient of Discharge. *The ratio of the mass flow rate in a valve to that of an ideal nozzle. This value can also be obtained from the flow coefficient. This is the ASME discharge coefficient. [unitless]* 0.52

Valve Effective Mass. *This is the mass of the disc and the spring elements that can move within the valve during a lift event. [lb]* 0.44

Maximum Disc Lift. *This is the maximum distance that the disc is able to rise in the valve body. [in]* 0.06

Valve Set Pressure. *This is the working pressure at which the valve is expected to lift. This value is also utilized to calculate the maximum mass flow through the valve. [psig]* 14.5

Installation Configuration

These parameters are related to how the valve is installed within the system.

Upstream Pipe Diameter. *This is the diameter of the piping that is connected directly to the valve inlet. If the pipe diameter varies, use the diameter of the longest section of pipe. [in]* 1.122

Protected Vessel Volume. *This is the volume of the protected vessel that is attached to the valve. [ft ^{3}]* 0,85

Ambient Pressure. *This is normally 14.7 psi but could be used to simulated back pressure on the valve. [psia]* 15

Fluid Properties

These parameters are related to the vapor utilized in the system.

Process Fluid Temperature. *This is the static temperature of the process fluid at the valve inlet. [°F]* 581

Gas Constant. *[J/kg-K.] Air is 288, Nitrogen is 296, Methane is 518, Steam is 461.* 296

Process Fluid Specific Heat Ratio. *This value can be obtained from fluid property tables and is dependent on the pressure and temperature of the process fluid. [unitless]* 1.37

No Errors Detected

Calculate the valve dynamics (time history) for a known pipe length and valve capacity. All of the required inputs above for the stability map calculation are also required for the valve dynamics calculation.

Upstream Pipe Length. *This is the total length of piping from the protected vessel to the inlet flange of the valve. [ft]* 7.3

Percent Mass Flow Capacity. *This is the percentage of rated mass flow capacity. [%]* 67

No Errors Detected

UNSTABLE

0,5

Figure 7.28: Stability results of SWRI software for YS12 (real flow).

The stability map shows that the safety valve operates in the unstable region. The valve time history shows instability. During the first 0.1 seconds, seems chattering behavior, but from there the disc strikes at the top of its path at a frequency of 120 Hz approximately. Therefore PRV suffers fluttering.

7.6.4 Engineering analysis summary

According to the engineering analysis procedure described in section 5.3 (see table 5.2), the following questions will be treated:

1) According to the inspection records is there any evidence of past chattering?

No

2) Is the pressure relief valve well installed according to API 520, ISO 4126-9, etc.?

No, it does not follow the recommendation that the inlet pipe must be as short as possible and with a diameter larger than the inlet flange of the PRV.

3) Is the inlet piping and fittings at least as large as the PRV inlet?

Yes

4) Is there at least a 2% Set Pressure (SP) margin between PRV blowdown and the inlet pressure loss? No

$\mathrm{Sp} - (\mathrm{Blowdown} + 0.02 \cdot \mathrm{Sp}) > \Delta P_{friction\ inlet}$

1-(0.9+0.02)>0.5

5) Does excessive built-up backpressure occur according to the specific PRV?

Yes, the built-up back backpressure is 0.3 barg, thus

(0.3/1)·100=30%<10%, NOT OK for conventional valve

6) Is the time that the decompression wave goes back to the protected equipment and returns to the valve, less than the time required for the full opening of the valve?

See point 7.

7) Does the PRV fulfill API 520 II-2015 Simple Force Balance?

The results of the stability analysis are in the following table 7.29:

Table 7.29: Stability analysis results for YS12

Parameter evaluated	Inlet line length, m	Inlet line length to avoid chatter, m	Fulfills the condition?	Will chatter?
Inlet line leng (Cremers et al.,2001, 2003)	2.24	11.9	Yes	No
Inlet line length (Frommann and	2.24	4.43	Yes	No

Friedel, 1998) ΔP 20%				
Inlet line length (Frommann and Friedel, 1998) ΔP blowdown	2.24	2.22	Yes	No
Required flow > 25% rated flow (oversizing)			Yes	No
Compressible vapors criteria (oversizing)			No	No
Total backpressure for a conventional valve < 10% SP			No	Yes
Body bowl choking			No	Unknown
Acoustic pressure losses			No	Yes
API Simple Force Balance (Melhem, 2016)			No	Yes

8) Is the risk of relieving of the existing pressure relief valve quantified?

Yes, very low risk. It discharges to flare.

8 Results

8.1 Comparison of results of the different methods

It has been found that the velocity of sound in the fluid has great influence on the results. Hence the method of Melhem is more precise than that of Smith which takes the speed of sound for an ideal fluid.

Contradictions have been found in the comparison between static and dynamic methods. For example, case 1 is stable according to Melhem and unstable (chattering) according to SWRI and Smith.

Melhem is easier to use than Smith, and can be easily programmed as a spreadsheet.

SWRI is only applicable to gases and vapors, whereas Melhem and Smith is also applicable to liquids.

A summary of the results obtained is presented in the table below.

Table 7.30: Summary of stability analysis results

Case Studies / Method	**Smith / Burgess / Powers (2011)**	**Melhem (2016)**	**SWRI (2016)**
YS700-01	Chattering	NO Chattering	Chattering
YS702-01_Gas	NO chattering	NO chattering	Fluttering/ Cycling
YS702-01_Liquid	NO chattering	NO chattering	Not available
YS701-01/02	Chattering	Chattering	Chattering
YS860-01	Chattering	Chattering	Chattering
YS861-04	Chattering	Chattering	Fluttering/ Cycling
YS12	Chattering	Chattering	Fluttering/ Cycling

8.2 Weaknesses and strengths of the methods

The SWRI method gives stability indication for the entire flow range up to the rated flow. However the rated flow is calculated by the own configured equations and cannot correspond to the real rated flow as happened in all case studies.

In favor of Smith is that his methodology does not require K_s and m_D.

The value of K_s and m_D are obtained through the correlation of Grolmes, which is deduced from valves of American manufacturers. And this correlation is not validated for European valves.

With Melhem it becomes more difficult to find the root cause of the instability, since everything is reduced to the balance of forces. By the other hand, the method of Smith is broke down by different causes of origin of chattering.

Both Smith and Melhem assume accurate blowdown knowledge, and many manufacturers do not give it specifically for each valve model.

The Melhem method allows, in case the balance of forces is negative, to solve the type of instability that occurs in the valve.

Melhem needs a process simulator (e.g. ASPEN HYSYS) to obtain the variation of density as a function of pressure at the relief temperature.

SWRI software is not intended at the moment for use on valves following the AD-Merkblatt A2 norm (e.g. Leser, Sempell, ARI, etc.).

8.3 Recommendations for the engineering community

For the current practice of the engineering activity in safety valves, Melhem method (2016) is recommended, only if the exact value of the blowdown is available.

The use of dynamic methods such as SWRI is recommended only in cases where the Melhem equation is in the border of zero and the calculated rated flow matches the real rated flow.

Is very important to calculate with maximum precision the real value of the speed of sound in the relieved fluid.

9 Conclusions

As demonstrated in the statistical analysis, there has been an appreciable amount of accidents attributable to chattering. Therefore, it is necessary to have a simple and robust methodology to predict this phenomenon.

The study of static methods, based on recent publications by Melhem (2016) and Smith et al. (2011), has shown that there are inconsistencies between them. Fundamentally the differences are attributable to the consideration of real or ideal gas for the calculation of physical properties (e.g. the speed of sound in the fluid).

The Melhem method is recommended for the design of new installations. Always requesting the real value of the blowdown to the manufacturer.

In favor of Melhem is that his methodology can predict the type of instability (fluttering, cycling or chattering) and this allows to accept the design of existing installations without having to make modifications.

The dynamic SWRI method is excellent if mass in motion (m_D) and valve spring constant (K_s) are available. This software allows a visualization at real-time of the valve behavior. On the contrary, it is not suitable for liquids and is based on valves according to API 526 design. Thus, it is not suitable for valves designed in accordance with ISO 4126-1 or AD-Merkblatt A2, among other codes.

For the future it is recommended to continue the research by developing software that performs stability charts but with an internal database containing the parameters of all types of valves and different calculation methods. Thus, in case of contradictory results, the most restrictive one could be chosen.

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