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**Rigorous Determination of the Relieving Load for
Pressure Relief Valves. Dynamic vs Steady State
Calculations**

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Supervised by Dr. Josep Basco**

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Index

1. Introduction	11
1.1 Safety layers in the process industry.....	11
1.2 Introduction to pressure relief devices	12
1.2.1 Pressure Relief valve (PRV)	12
1.2.2 Safety valve (SV).....	16
1.2.3 Relief valve (RV).....	16
1.2.4 Safety relief valve (SRV)	16
1.2.5 Pilot-operated pressure relief valve (POPRV).....	16
1.2.6 Rupture disk	17
1.2.7 Pressure-vacuum valves.....	18
1.3 Introduction to static, semi-dynamic and dynamic approach	19
1.4 Objectives of the master thesis	19
2. Critical analysis of the accidents and latent failures of the pressure relief valves.....	19
2.1 Historical analysis of accidents	19
2.2 Deficiencies in installed pressure relief valves.....	21
2.2.1 Technical design faults.....	21
2.2.2 Technical maintenance faults.....	24
3. Relief load determination as a critical step in the engineering of relief systems.....	26
3.1 Steady state approach.....	29
3.2 Dynamic approach	30
3.3 Semi-dynamic approach	30
3.4 Advantages/disadvantages of each approach	31
4. Comparison for the fire scenario.....	31
4.1 Description for the case study.....	31
4.2 Literature survey of relief load calculation methods.....	34
4.3 Results of the dynamic simulation	35
4.3.1 Dynamic simulation. Results of Prophet, N., et al. (2019).....	35
4.3.2 Dynamic Simulation ASPEN HYSYS™ v10.....	38
4.3.3 Dynamic Simulation PSE™ software.....	39
4.4 Results of the simplified approach	42
4.4.1 Steady State Simulation. Results of Prophet, et al. (2019).....	43
4.4.2 Semi-Dynamic Simulation with ASPEN HYSYS™ v10.	44
4.5 Comments.....	59
5. Comparison for the scenario of Gas blow-by/Vapor breakthrough.....	60
5.1 Description for the case study.....	60
5.2 Literature survey of relief load calculation methods.....	63

5.3 Results of the dynamic simulation	65
5.4 Steady State Method with ASPEN HYSYS™ v10.....	68
5.5 Comments.....	72
6. Comparison for the scenario of heat exchanger tube rupture	75
6.1 Description for the case study.....	75
6.2 Literature survey of relief load calculation methods.....	77
6.3 Results of the dynamic simulation	78
6.4 Results of the simplified approach	82
6.5 Development of the spreadsheet Pis.....	84
6.6 Comments.....	84
7. Comparison for the scenario of thermal expansion in a blocked in vertical thermosiphon reboiler	85
7.1 Description for the case study.....	85
7.2 Literature survey of relief load calculation methods.....	87
7.3 Results of the dynamic simulation	88
7.4 Comments.....	91
8. Conclusions and future research.....	92
9. References	94
10. APPENDIX.....	96
10.1Appendix A. Case study 1: Comparison for the fire scenario.....	96
10.2Appendix B. Case study 2: Comparison for the scenario of Gas blow-by/Vapor breakthrough.....	96
10.3Appendix C. Case study 3: Comparison for the scenario of heat exchanger tube rupture	100
10.4Appendix D. Case study 4: thermal expansion in a blocked in vertical thermosiphon reboiler	101

Nomenclature

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BP	British Petroleum
BPCS	Basic Process Control System
DIERS	Design Institute for Emergency Relief Systems
EOS	Equation Of State
ESD	Emergency Shutdown
HAZOP	Hazard and Operability
ISO	International Organization for Standardization
LDPE	Low Density Polyethylene Plants
LOPA	Layer Of Protection Analysis
MAWP	Maximum Allowable Working Pressure
MHIDAS	Major Hazardous Incident Data Service
PED	Pressure Equipment Directive
PHA	Process Hazard Analysis
POPRV	Pilot-Operated Pressure Relief Valve
PRD	Pressure Relief Device
PRV	Pressure Relief Valve
RV	Relief Valve
SIS	Safety Instrumented System
SRV	Safety Relief Valve
SV	Safety Valve

List of figures

Figure 1.1 Safety layers in the process industry (Taken from Ronald J. Willey, Procedia Engineering 84 (2014) 12-22)	11
Figure 1.2 Pressure Relief Valve (PRV). (Taken from LESER catalogue).....	13
Figure 1.3 Conventional PRV with a single adjusting ring for blowdown control. (Taken from API 520, Part 1, 2020)	13
Figure 1.4 Balanced-bellows PRV. (Taken from API 520, Part 1, 2020).....	14
Figure 1.5 Balanced-bellows PRV with an Auxiliary Balanced Piston. (Taken from API 520, Part 1, 2020)	14
Figure 1.6 Conventional PRV with Threaded Connection. (Taken from API 520, Part 1, 2020).....	15
Figure 1.7 POPRV. (Taken from corona-serwis.com, assessed on January 2021).....	16
Figure 1.8. Pilot-operated Relief Valve with a no flowing modulating pilot valve. (Taken from API 520, Part 1, 2020)	16
Figure 1.9 Rupture disk. (Taken from API 520, Part 1, 2020)	17
Figure 1.10 Rupture disk installation (Taken from API 520, Part 1, 2020).....	17
Figure 1.11 Parts of a rupture disk (Taken from libertyair.net, assessed on January 2021) .	18
Figure 1.12 Pressure-vacuum valve (Taken from Braunsweiger-Flammenfilter catalogue, assessed on February 2021).....	18
Figure 2.1 Accidents related to failure of PRVs (Taken from Basco, (2015)).....	20
Figure 2.2 Percentage of well-installed devices according to the Short II (2006).....	21
Figure 2.3 Percentage of the condition of the relief devices installed according to Berwanger (2000)	22
Figure 2.4 Percentage of the condition of the relief devices installed according to Kumana and Aldeeb (2014)	22
Figure 2.5 Percentage of the condition of the relief devices installed according to Hellemans (2009).....	24
Figure 2.6 Percentage of the condition of the protected systems to Prophet et al. (2017)...	25
Figure 2.7 Percentage pressure relief scenario inadequate to Prophet et al.(2017).....	25
Figure 3.1 Procedure of valve sizing. (Taken from ISO 4126, Part 10, 2010)	26
Figure 3.2 Vapor pressure and heat of vaporization of pure, single-component paraffin hydrocarbon liquids (Taken from API Standard 521, 5 th Edition, 2007).....	30
Figure 4.1 Fire in factory (Taken from Google).....	32
Figure 4.2 Pressure vessel dimensions	33
Figure 4.3 Dynamic graph of vessel pressure versus time. (Taken from Prophet et al. (2019))	37
Figure 4.4 Dynamic graph of vessel contents temperature versus time. (Taken from Prophet et al. (2019)).....	37
Figure 4.5 Dynamic graph of liquid height versus time. (Taken from Prophet et al. (2019))	38
Figure 4.6 Flowsheet representation with ASPEN HYSYS™ v10	44
Figure 4.7 Flowsheet representation with ASPEN HYSYS™ v10 with expander.....	49
Figure 4.8 Semi-dynamic method to study in case of pool-fire.....	50
Figure 4.9 Representation PRD area without sensible heat, with density correction	52
Figure 4.10 Representation PRD area with sensible heat, with density correction	54
Figure 4.11 Representation PRD area without sensible heat, without density correction	56
Figure 4.12 Representation PRD area with sensible heat, without density correction	58
Figure 5.1 Example gas blow-by scenario due to control valve failing wide-open. (Taken from Melhem G.A. et al. (2016)).....	60
Figure 5.2 Liquid level in downstream vessel is below inlet nozzle. (Taken from Faulk, Aldeeb, 2015)	64
Figure 5.3 Liquid level in downstream vessel is above inlet nozzle. (Taken from Faulk, Aldeeb, 2015)	65

Figure 5.4 Downstream vessel overfills (Taken from Faulk, Aldeeb, 2015).....	65
Figure 5.5 Pressure histories for cases A and B in LPV. (Taken from Melhem G.A. et al. (2016))	66
Figure 5.6 Flow history from first PRV set at 150 psig. (Taken from Melhem G.A. et al. (2016))	67
Figure 5.7 Flow history from second PRV set at 157 psig. (Taken from Melhem G.A. et al. (2016))	67
Figure 5.8 Liquid level histories for cases A, B and C. (Taken from Melhem G.A. et al. (2016))	68
Figure 5.9 Flowsheet with ASPEN HYSYS™ v10.....	69
Figure 6.1 Heat exchanger data	75
Figure 6.2 Typical heat exchanger tube failures. (Taken from Melhem et al. (2019)).....	77
Figure 6.3 Schematic of the cooling water model for primary compression section (train 1) cooling water system in the LPDE unit. (Taken from a worldwide petrochemical company).	79
Figure 6.4 Pressure profile for 21-E-0109 (with 21RV1050). (Taken from a worldwide petrochemical company).....	81
Figure 7.1 Flowsheet reboiler	86
Figure 7.2 Thermodynamic mapping process inside tubes of the vertical thermosiphon reboiler	87
Figure 10.1 Backpressure correction factor, K_b , for balance spring-loaded PRV (vapors and gases). (Taken from API-520-I-2020)	96
Figure 10.2. CV characteristics. (Taken from ASPEN HYSYS™ v10).....	97
Figure 10.3. Valve operating characteristics. (Taken from ASPEN HYSYS™ v10)	97
Figure 10.4. CV characteristics. (Taken from ASPEN HYSYS™ v10).....	98
Figure 10.5. Valve operating characteristics. (Taken from ASPEN HYSYS™ v10).	99
Figure 10.6 Spreadsheet to calculate P_{is}	100

List of tables

Table 2.1 Summary of Berwanger and col. (2000).....	22
Table 2.2 Summary of Kumana and Aldeeb (2014).....	22
Table 2.3 Results of the investigations: survey of Westphal et al. 2016.....	23
Table 2.4 Results of the investigations: survey of Westphal et al. 2016.....	23
Table 2.5 Summary pressure relief scenario inadequate according to Prophet (2017).....	25
Table 3.1 Possible causes for overpressure in a system to be protected. (Taken from ISO 4126, Part 10, 2010)	27
Table 3.2 Summary advantages/disadvantages static, semi-dynamic and dynamic method.	31
Table 4.1 Liquid molar fraction in the pressure vessel.....	33
Table 4.2 Operation conditions.....	33
Table 4.3 Initial conditions at boiling point	34
Table 4.4 External fire dynamic simulation results. (Taken from Prophet et al. (2019)).....	36
Table 4.5 Summary flow rate and PRD area Prophet, et al. (2019)	36
Table 4.6 Summary Dynamic Simulation ASPEN HYSYS™ v10.	38
Table 4.7 Summary flow rate and PRD area ASPEN HYSYS™ v10	38
Table 4.8 Dynamic simulation with PSPPM™ software. Without sensible heat	39
Table 4.9 Summary flow rate and PRD area PSPPM™ without sensible heat	40
Table 4.10 Dynamic simulation with PSPPM™ software with sensible heat.....	41
Table 4.11 Summary flow rate and PRD area PSPPM™ with sensible heat.....	42
Table 4.12 External Fire Steady State Detailed Calculation Results. (Taken from Prophet et al. (2019)).....	43
Table 4.13 Summary flow rate and PRD area steady state method of Prophet, N.....	43
Table 4.14 Relation of % vaporized to latent heat.....	45
Table 4.15 Vapor properties vaporized 0,1013. (Taken from ASPEN HYSYS™ v10).	47
Table 4.16 Summary table to PRD area without sensible heat, with density correction	51
Table 4.17 Summary table to PRD area with sensible heat, with density correction	53
Table 4.18 Summary table to PRD area without sensible heat, without density correction...	55
Table 4.19 Summary table to PRD area with sensible heat, without density correction	57
Table 4.20 Summary all methods for calculate PSV area relief.....	59
Table 5.1 Liquid displacement scenarios data summaries. (Taken from Melhem G.A. et al. (2016))	61
Table 5.2 Different scenarios to study. (Taken from Melhem G.A. et al. (2016))	62
Table 5.3 Gas molecular fraction at two molecular weight. (Taken from Melhem G.A. et al. (2016))	63
Table 5.4 Summary of Dynamic solution Melhem, G. B. et al. (2016).....	68
Table 5.5 Summary components figure 5.9	69
Table 5.6 Summary case A.....	69
Table 5.7 Summary case B.....	69
Table 5.8 Summary Steady State Calculations.....	72
Table 5.9 Summary results of Dynamic Simulation and Simplified approach	72
Table 5.10 Summary Steady State Calculations, Cf valve 0,785.	74
Table 5.11 Summary results of Dynamic Simulation and Simplified approach recalculation .	74
Table 6.1 Heat exchanger design constants of 21-E-0109	75
Table 6.2 Shell data design	76
Table 6.3 Supercritical ethylene gas data	76
Table 6.4 Water data.....	76
Table 6.5 Control volumes sizes near the make-up 5th stage cooler W-5A (21-E-0109) and between 21-E-0109 to 21-RV-1050. (Taken from a worldwide petrochemical company)	80
Table 6.6 Dynamic model peak pressure results for tube rupture in 21E-0109 with 21RV-1050. (Taken from a worldwide petrochemical company).....	80
Table 6.7 Summary; rigorous and simplified method.	84

Table 7.1 Composition of the product in the column.....	85
Table 7.2 Normal operating conditions of the thermosiphon reboiler.....	86
Table 7.3 Reboiler data.....	86
Table 7.4 Results obtained con ASPEN HYSYS™ v10	90
Table 7.5 A summarise the valve type for the pressure of operation at 16 barg	91
Table 7.6 A summarise the valve type for the pressure of relief at 22 barg.....	91
Table 7.7 Valve type overview.....	92
Table 10.1 Flow 1 and 2 conditions. (Taken from ASPEN HYSYS™ v10)	97
Table 10.2 Flow 2 and 3 conditions. (Taken from ASPEN HYSYS™ v10).	98
Table 10.3 Flow 2 and 3 composition. (Taken from ASPEN HYSYS™ v10)	98
Table 10.4 Flow 1 and 2 conditions. (Taken from ASPEN HYSYS™ v10).	99
Table 10.5 Flow 1 and 2 composition. (Taken from ASPEN HYSYS™ v10).	99
Table 10.6 Flow 2 and 3 conditions. (Taken from ASPEN HYSYS™ v10).	100
Table 10.7 Flow 2 and 3 composition. (Taken from ASPEN HYSYS™ v10).	100
Table 10.8 Reboiler data. (Taken from a worldwide petrochemical company)	101
Table 10.9 Reboiler data. (Taken from a worldwide petrochemical company)	102
Table 10.10 Reboiler data to pressure operation 16 barg. (Print out from Aspen Exchanger Design and Rating™ v10)	103
Table 10.11 Reboiler data to pressure relief 22 barg. (Print out from Aspen Exchanger Design and Rating™ v10)	104
Table 10.12 Type of valve. (Taken from Sempell, Safety Relief Valves with DIN and ANSI Flanges, Catalogue KS27585).....	105

1. Introduction

Engineers often find it challenging to guarantee the safety of people around the world in multiple ways, for example, in house construction sector, in bridge buildings, in designing a car safety or in designing the safety of a factory. In these cases, and many more, engineering must be present.

The aim of this thesis is to compare different methods to calculate the relieving load of pressure relief valves in systems of chemical and pharmaceutical industry. The purpose is to find the best solution in order to avoid probable fatal accidents that would harm people, animals, rivers etc. In short, all the environment around.

1.1 Safety layers in the process industry

To talk about industry safety, it is important understand the multiple safety layers process that is defined by the LOPA (Layer of Protection Analysis). This means it is necessary to understand these terms.

The LOPA methodology is a semi-quantitative technique for assigning the SIL level required by a safety instrumented function. It consists of an analysis of the different layers of protection available in a certain process, evaluating its risk in the various scenarios and comparing the results with the admitted risk, previously defined based on the company's criteria of acceptance. This comparison allows us to define whether the existing protection layers are sufficient, or whether new protections need to be incorporated into the system.

Each safety layer, has the same importance as the previous one and the one after. In the process industry these are the existing safety layers, see figure 1.1:

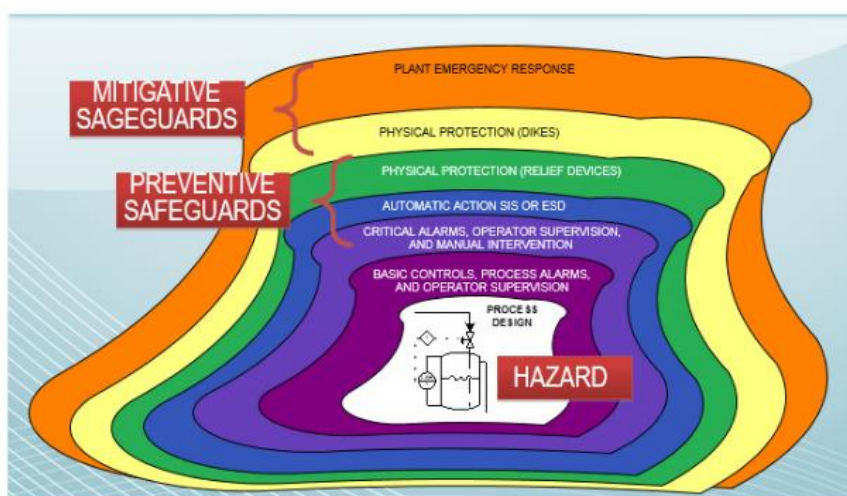


Figure 1.1 Safety layers in the process industry (Taken from Ronald J. Willey, Procedia Engineering 84 (2014) 12-22)

Figure 1.1 shows:

- Layer 1:** Process design.
- Layer 2:** Basic controls, process alarms and operator supervision.
- Layer 3:** Critical alarms, operator supervision and manual intervention; BPCS.
- Layer 4:** Automatic action; SIS or ESD.
- Layer 5:** Physical protection; relieve devices.
- Layer 6:** Physical protection; dikes.
- Layer 7:** Plant emergency response; and not shown.
- Layer 8:** Community emergency response

Throughout this thesis, the safety valves, rupture disks, pressure vacuum valves, i.e., the fifth layer will be studied and compared.

1.2 Introduction to pressure relief devices

Currently there are different processes and industries as refining, pharmaceutical or chemical industry which use different kind of high-pressure equipment.

Often this equipment is used to contain liquids which due to the high pressure makes liquid change its state, from liquid phase to gas phase.

In this equipment such as vessels, reactors, tanks, etc., there may be a possible occurrence of an abrupt increment of inlet pressure, for many different reasons, leaving the equipment at risk of fracture or rupture and causing an emergency.

To avoid overpressure scenarios in tanks, reactors, heat exchangers... pressure relief devices shall be installed in these devices, such as safety valves, relief valves or rupture discs.

These elements must be well calculated and installed for each piece of the equipment that are protecting from overpressure, for example, the design pressure of the equipment to be protected must be taken into account, to adjust the PRV set to an adequate value. It is important to know what type of fluid will pass through the PRV, if it is biphasic, only gas phase or liquid phase. This will cause the valve to require a different relieving area.

At next point these different relief pressure systems will be explained.

1.2.1 Pressure Relief valve (PRV)

A pressure relief valve or relief valve is a type of valve used to control or limit the accumulated pressure in a system.

If this type of device did not exist, the pressure of the system could increase until the design pressure, causing cracks or fractures, discharging stored gas or liquid into the atmosphere.

These devices are designed to automatically open, when the pressure in the system reaches the set point configured in the PRV. This set point pressure is always equal or lower than the design pressure of the system, to avoid system failures.

The flow through the PRV, when it is open, normally is directed to a collector flare or to atmosphere. If the PRV is properly calculated for the system, the pressure of the system will never exceed the design pressure of the vessel.

When the pressure in the system is lower than the set pressure of the PRV, the PRV will close.

The blowdown is usually stated as a percentage of set pressure and refers to how much the pressure needs to drop before the valve resets. The variation of the blowdown can be between 2–20%. Some valves have adjustable blowdowns.

Figures 1.2, 1.3, 1.4 1.5 and 1.6 show different models of pressure relief valves.



Figure 1.2 Pressure Relief Valve (PRV). (Taken from LESER catalogue)

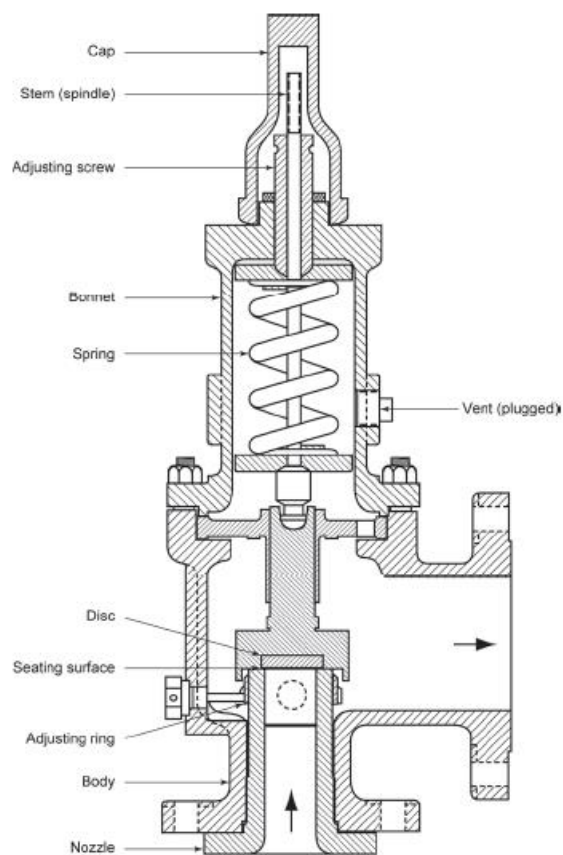


Figure 1.3 Conventional PRV with a single adjusting ring for blowdown control. (Taken from API 520, Part 1, 2020)

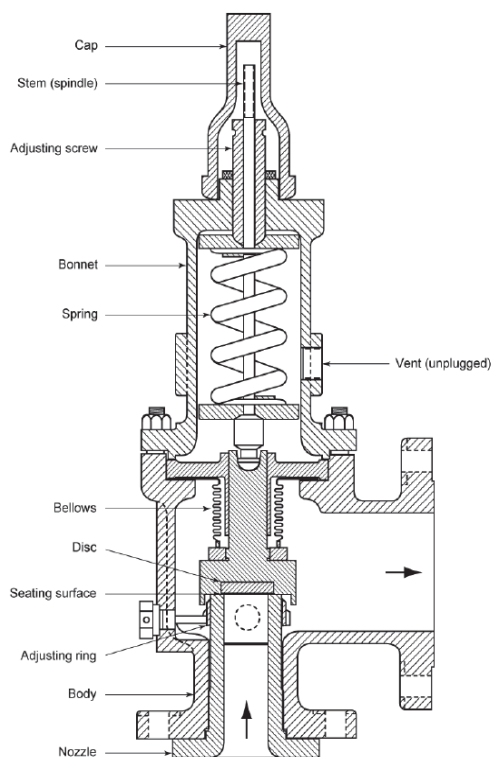


Figure 1.4 Balanced-bellows PRV. (Taken from API 520, Part 1, 2020)

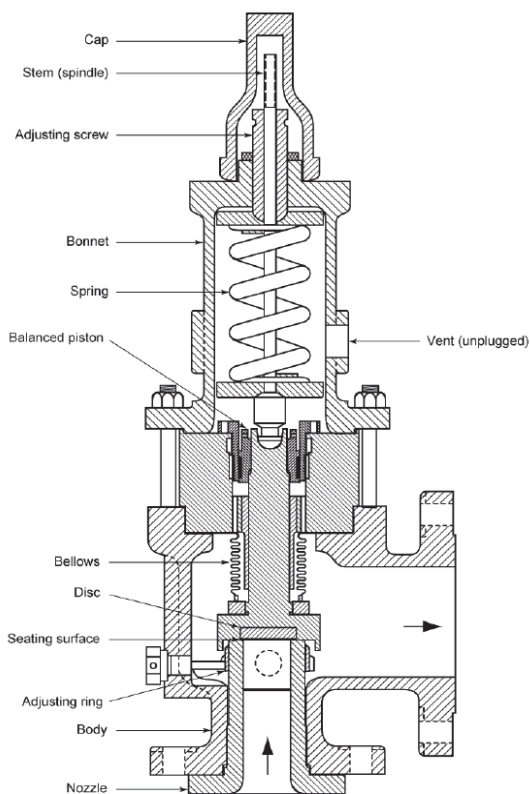


Figure 1.5 Balanced-bellows PRV with an Auxiliary Balanced Piston. (Taken from API 520, Part 1, 2020)

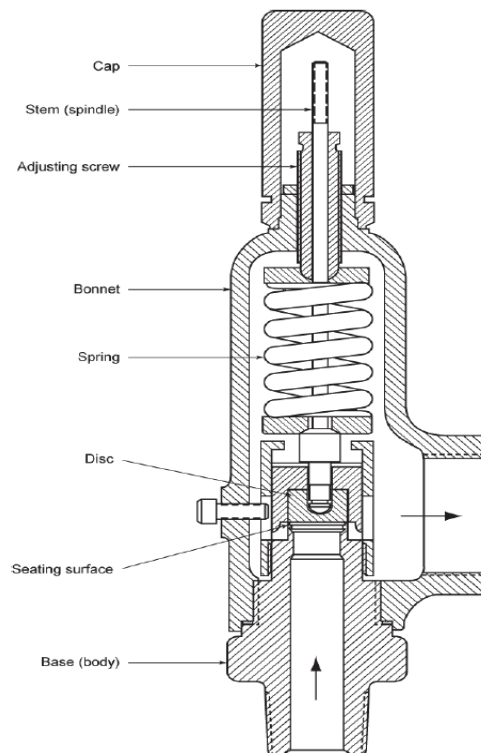


Figure 1.6 Conventional PRV with Threaded Connection. (Taken from API 520, Part 1, 2020)

As it is showed in the figures, the parts of the PRV are:

1. **Cap:** This protects the adjusting screw.
2. **Stem (spindle):** This accessory is provided for those applications where the mechanical lifting of the pilot is required for verification of valve operation. Lifting of the pilot spindle will permit the main valve to lift when the system pressure is at least equal to or greater than 75 % of the set pressure.
3. **Adjusting screw:** This is used to give more or less stress on the spring.
4. **Bonnet:** This part supports the pressure of the spring and provides protection at the same time.
5. **Spring:** when the spring is stretched, exerts pressure on bottom spring step to close the valve. When the pressure inlet of the protected system is over the set pressure of the spring, the spring is compressed to allow the valve to open.
6. **Vent (plugged):** This is used for the discharge of the backpressure.
7. **Balanced piston:** The balanced piston is used when there is a high pressure in the discharge of the PRV, and it is desired to counteract
8. **Bellows:** The bellows isolate the stem and is an internal part of the process.
9. **Disc:** Controls flow through the nozzle.
10. **Seating surface:** Surface with which the disc closes.
11. **Adjusting ring:** The adjusting ring is used to control the blowdown.
12. **Body:** Contains the pressure during the discharge and serves as support of the different fixed parts of the valve.
13. **Nozzle:** This part is connected to the system and contains pressure. There are three different types of connection, threaded, flanged or welded.

1.2.2 Safety valve (SV)

A spring-loaded pressure relief valve activated 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.

1.2.3 Relief valve (RV)

A spring-loaded pressure relief valve works by the static pressure upstream of the valve. The valve opens in proportion to the pressure increase over the opening pressure.

A relief valve is primarily used for incompressible fluids.

1.2.4 Safety relief valve (SRV)

A spring-loaded pressure relief valve may be used as either safety or a relief valve depending on the application. Today most valves are this type of valve.

1.2.5 Pilot-operated pressure relief valve (POPRV)

A pressure relief valve in which the major relieving device or main valve is controlled by and combined with a self-actuated auxiliary pressure relief valve. See figures 1.7 and 1.8



Figure 1.7 POPRV. (Taken from corona-serwis.com, assessed on January 2021)

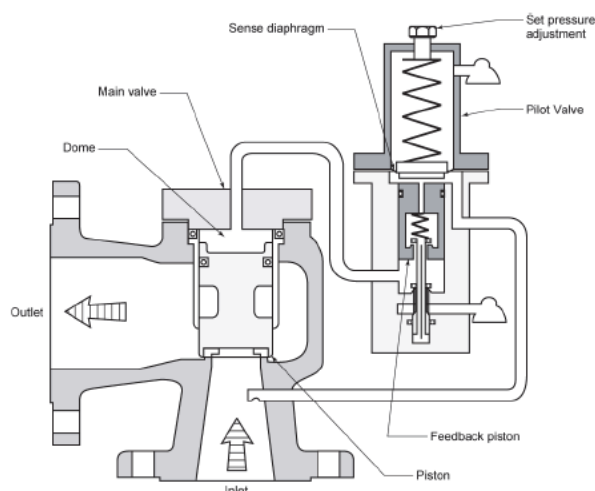


Figure 1.8. Pilot-operated Relief Valve with a no flowing modulating pilot valve. (Taken from API 520, Part 1, 2020)

1.2.6 Rupture disk

The rupture disk, is a non-reclosing pressure relief safety device. That means, when this device is ruptured it has to be replaced.

A rupture disk is a part that can be sacrificed because it has a one-time-use membrane that fails at a predetermined differential pressure, either positive or vacuum.

It can be used as single protection devices or as a secondary relief device for a conventional safety valve; as if the pressure increases and the safety valve fails or cannot relieve enough pressure fast enough, the rupture disk will broke meaning this pressure will be released. Rupture disks are often used in combination with safety relief valves, isolating the valves from the process, thereby saving on valve maintenance and creating a leak-tight pressure relief solution.

The speed of response the rupture disk is faster in comparison with safety valves. This is one reason why many times it is installed in industry process when the increased pressure in a system is very critical. Another characteristic is that these devices cannot be tested before selling to customer.

Figures 1.9, 1.10 and 1.11 shows different models of rupture disk.



Figure 1.9 Rupture disk. (Taken from API 520, Part 1, 2020)

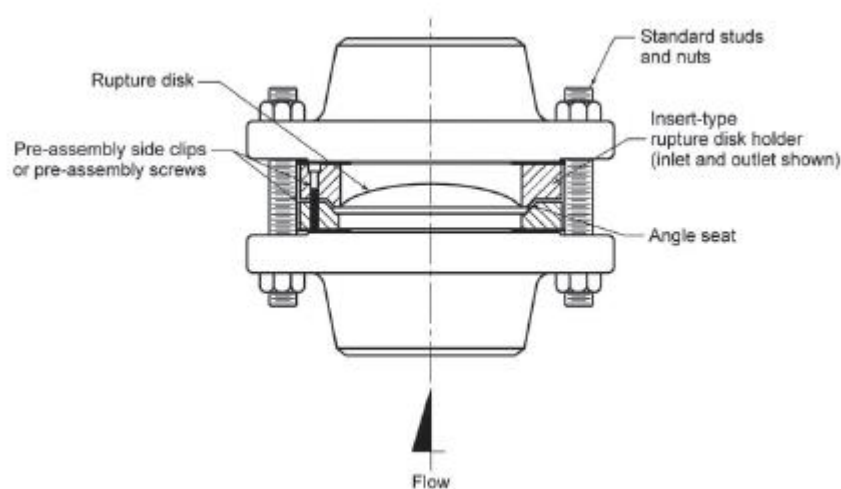


Figure 1.10 Rupture disk installation (Taken from API 520, Part 1, 2020)

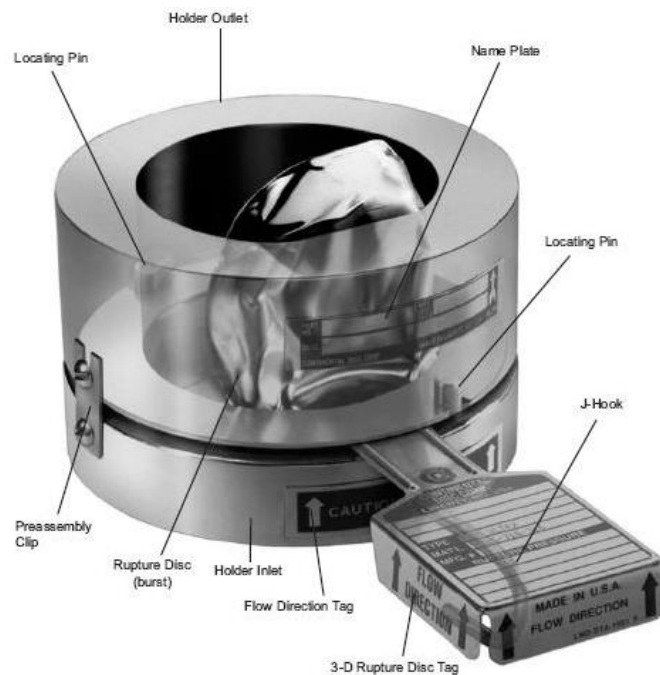


Figure 1.11 Parts of a rupture disk (Taken from libertyair.net, assessed on January 2021)

1.2.7 Pressure-vacuum valves

The pressure-vacuum valves are safety devices ready to work as an automatic regulator. These devices are in charge of opening the valve and equalizing the internal pressure with the external pressure in order to prevent vacuum inside the system.

These sorts of valves have some specific components like:

- A single action spring which activates the valve.
- A soft-seat, which is able to reach higher watertight levels than the required levels established by EN 12266-1, as long as the valves are exposed to a higher pressure than the atmospheric pressure in non-operating conditions.
- A huge load capacity.



Figure 1.12 Pressure-vacuum valve (Taken from Braunsweiger-Flammenfilter catalogue, assessed on February 2021)

1.3 Introduction to static, semi-dynamic and dynamic approach

In order to choose one of the relief pressure devices previously mentioned, that fulfils the needs of the pressure protection, the relief systems engineer must know the process properly. So, it is important be aware about properties like temperature, design pressures, kind of product (liquid, gas, mono-phase), if the product is foamy, etc.

Having said that the engineers have different methods to make a correct sizing of the PDR, as the static approach, the semi-dynamic approach or the dynamic approach.

Any of these studies are good to make a correct PRD sizing, however is essential to analyse properly each scenario, because depending on the scenario the PDR sizing could be wrong. Each method has some constraints explained during the thesis.

1.4 Objectives of the master thesis

Regarding in the previous points, the need to relieve overpressure in industrial process equipment is mandatory by standards and guidelines like ASME, PED, etc.

The serious consequences of not protecting equipment or not adequately protecting it from overpressures produced by both process conditions and possible external conditions, such as a fire have been verified.

Different relief devices have been mentioned that are available on the market and that are necessary to install for the safety of processes, people and the environment.

For these overpressure relief devices to function properly, it must be ensured that inside the equipment in which they are installed, they are correctly installed, and are well sized and adjusted, for the process they are protecting.

In order to correctly size these devices, it is necessary to know the correct process and to work with programs such as SuperChems™Expert. This program allows these devices to be sized correctly by applying dynamic methods. Often, these programs have a significant cost as they are benefiting the security of worker and device, most of the time. Therefore, this a cost that if it could be avoided could benefit the industry significantly.

The aim of this thesis is to demonstrate that it is not necessary to use the dynamic models available in dedicated software like SuperChems™Expert or Aspen dynamics etc. to obtain rigorous relieving loads. Thus, showing static methods effective results can be obtained as well.

2. Critical analysis of the accidents and latent failures of the pressure relief valves

2.1 Historical analysis of accidents

Historically several chemical accidents have happened resulting in relief device errors, some of the most relevant accidents in the last years are exposed below.

- BP Texas City (2005); March 2005, an explosion occurred when a gas hydrocarbon purge was running in a BP Oil refinery in Texas. One of the main factors of the explosion was a wrong design of the purge system, the accident left 15 dead and 180 injured.
- Sonat Exploration Company (1998); 4th March 1998, during the setting up of a plant, a vessel suffered an overpressure with no PRD. As a result of overpressure, the vessel rupture and produced a leak of inflammable gas with a resulting

explosion which effect included the death of 4 workers and several plant damages.

- First Chemical (2002); 13th October 2002, in a distillation tower an explosion caused a huge damage to a factory. A storage nitro toluene vessel ruptured and a fire started, a further study established the explosion occurred because of the wrong sizing for the PRD, and the overpressure tower could not relieve it.
- Goodyear (2008); 10th June 2008, during the replacement of a rupture disk in a heat exchanger, the equipment PRDs got blocked. The PRDs were not realigned and days later the exchanger started to run with the PDR's isolation valves blocked. During the start-up of the exchanger, an overpressure was produced causing an explosion and the death of an operator.
- Williams Olefins (2013); June 2013, Williams Olefins workers started up a reboiler that was out of service and had the PRDs blocked. At start-up vapor was put in to heat the reboiler, causing propane inside the reboiler heating up and increasing its pressure. With the PRD's blocked, they could not act, causing the explosion of the reboiler and the death of two workers.

Considering the importance of the pressure relief valves (PRV) to avoid accidents, A survey about chemical industry accidents and related with safety valves was made with the MHIDAS software (Basco, 2015).

The research was focused on accidents caused by an increased pressure of the system and a safety valve failure at the activation moment. From the 48 cases found (MHIDAS, 2007), 35 had a direct relation with mechanic failures of the safety valve, with the catastrophic consequences of 56 deaths, 292 injuries and 8.000 evacuated people.

% of mechanical failures in accidents due to PRV

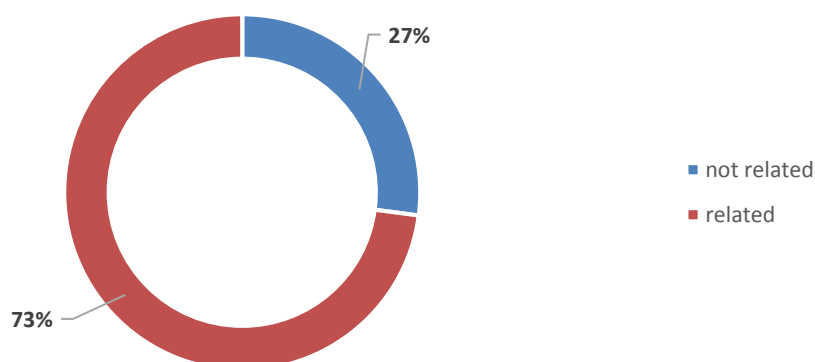


Figure 2.1 Accidents related to failure of PRVs (Taken from Basco, (2015))

It should be considered that the majority of failures generated in relief devices, which are currently installed in different systems around the world, do not have consequences as serious as those mentioned above because most of these devices will never have the need to activate. Although if it is expected of them, that they have to act, they will do it correctly.

In a study from DIERS Institute (CCPS, 1998), it was observed that among the 100 worst accidents from 1956 to 1986, 25 of them could result in failures in the activation of the pressure relief devices.

These failures might be caused by design mistakes or a poor maintenance of the valve.

2.2 Deficiencies in installed pressure relief valves

Some studies made about the existing differences found in the relief pressure devices are mentioned at this point.

The studies based in design mistakes in pressure relief devices are presented by:

- Short II (2006).
- Berwanger and col. (2000).
- Kumana and Aldeeb (2014).
- Westphal (2016).

And the differences related with a wrong maintenance of the PRV are mentioned by:

- Aird (1982).
- Smith (1995).
- Hellemans (2009).
- Chien et al. (2009).
- Prophet et al. (2017).

2.2.1 Technical design faults

Short II study takes a 120 pressure relief devices sampling, 67 of them were PRV's and 53 rupture disks. Multiple studies were applied to each relief device taking into account fire scenarios, interchange pipe failure, control valve failure, cooling failure, hydraulic expansion, blocked outlet and process alterations.

The study concluded just the 17,5 % of the installed devices were the correct size for the type of application they were made for.

Article Short II (2006)

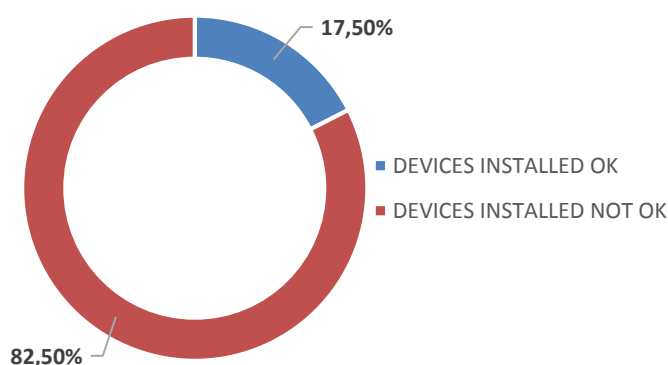


Figure 2.2 Percentage of well-installed devices according to the Short II (2006)

Berwanger and col. (2000) analysed the pressure relief devices of 272 plants from the US, they concluded that 14873 process systems must have relief pressure devices. The results are indicated below:

Table 2.1 Summary of Berwanger and col. (2000)

Systems analysed	PRV OK	Without PRV	Insufficient PRV	PRV Incorrect installation	PRV improperly installed
100%	60%	15%	7%	16%	2%
14873	8924	2231	1041	2380	297

Berwanger et al. results (2000)

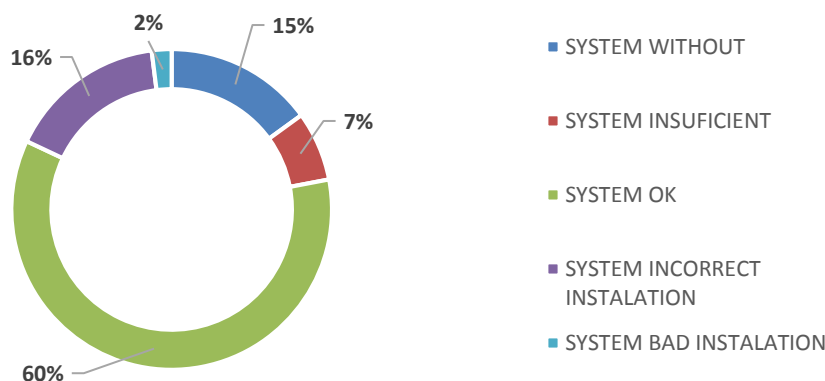


Figure 2.3 Percentage of the condition of the relief devices installed according to Berwanger (2000)

Kumana and Aldeeb (2014), study analysed the results of 1197 audits made from 2005 to 2014, finding problems and failures in 47% of cases. For instance, 13% of the audited equipment did not have a pressure relief device that they should have had.

Table 2.2 Summary of Kumana and Aldeeb (2014)

Systems analysed	Systems in good condition	Systems with deficiencies	Systems without PRV
100%	40%	47%	13%
80372	32149	37775	10448

Kumana and Aldeeb results (2014)

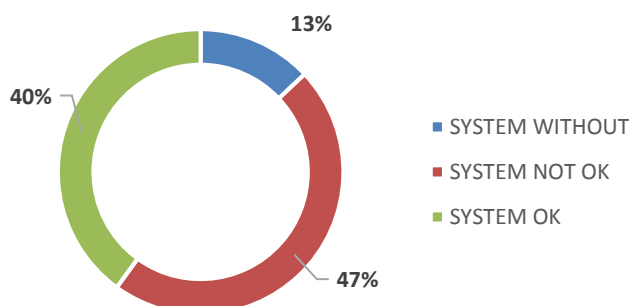


Figure 2.4 Percentage of the condition of the relief devices installed according to Kumana and Aldeeb (2014)

In 2016 Westphal conducted a study in which the results were compared with those obtained by Köper and Westphal (2001). In this study, the analysis of 1500 safety valves were carried out, obtaining the results of the following table 2.3. The values in parentheses correspond to the values obtained in 2001:

Table 2.3 Results of the investigations: survey of Westphal et al. 2016

Design Case	Ratio of SV for Design Case (%)	Ratio of SV With Design Failure (%)	Type of Deficiency		
			SV Size too Low	Inlet Pressure Loss	Back Pressure in Vent Line
Chemical Reaction	5% (3%)	1% (6%)	0,5% (2%)	0,1% (3%)	0,4% (1%)
Excessive Heating	18% (16%)	15% (36%)	3% (15%)	7% (12%)	5% (14%)
Gas Feed	25% (19%)	36% (46%)	5% (38%)	20% (7%)	11% (8%)
Liquid Feed	12% (19%)	10% (22%)	1% (15%)	2% (4%)	7% (4%)
Thermal Expansion	40% (43%)	3% (2%)	0% (1%)	1% (0%)	2% (1%)
Total	100%	14% (17%)	2% (10%)	6% (3%)	6% (4%)

The table 2.3 shows a total of 1500 valves installed, 14% had deficiencies in 2016 and in 2001 were 17%.

There is only a small room for improvement in the size of the PRV, it is surprising to see how the study was done 15 years ago and only 3% has been improved. Any improvement is good, however to this day still being insufficient.

The necessary measures to adopt to solve the problems found are shown below in table 2.4.

Table 2.4 Results of the investigations: survey of Westphal et al. 2016

Deficiency	Ratio	Required Measures	Ratio
Safety valve not sufficiently sized	14% (60%)	Larger Safety Valve	60% (53%)
		Restriction of Feed	40% (47%)
Pressure Loss in Inlet Line >3%	43% (18%)	Larger Diameter	57% (35%)
		Smaller Safety Valve Size	14% (2%)
		Restriction of Lift/Vibration Damper	29% (63%)
Back Pressure in Vent Line too High	43% (22%)	Larger Diameter	15% (22%)
		Smaller Safety Valve Size	23% (1%)
		Restriction of Lift/Vibration Damper	8% (38%)
		Bellow	54% (39%)

2.2.2 Technical maintenance faults

In the study made by Aird (1982), it is shown that 44% of safety valves opened out of range +/- 10% of its set pressure.

Smith (1995) analysed the behaviour of 13.000 safety valves, 18% of them just get opened at a pressure of 110% higher than the originally set adjustment. And 3% of the valves did not get opened at double the pressure of the set adjustments.

Hellemans (2009), analysed 750 complaints produced by the poor function of the PRV's, and determined that 10% of the PRV's did not have the correct size or were too big, 8% did not work properly cause of poor maintenance, 33% were installed wrong, 30% were damaged during transportation and handling, 12% had manufacturing defaults and the last 7% had some other deficiencies.

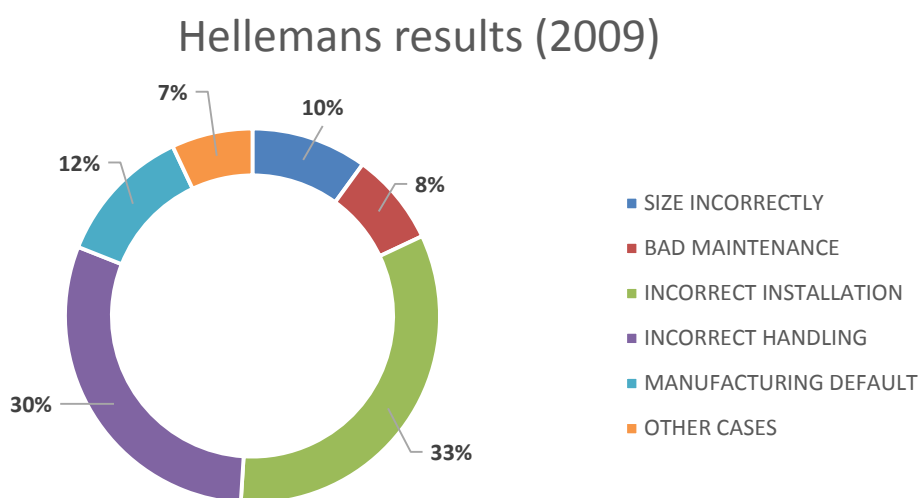


Figure 2.5 Percentage of the condition of the relief devices installed according to Hellemans (2009)

Chien et al. (2009), previously tested 292 PRV's which were going to be installed, and established that 4% of valves get opened on a pressure 119% higher than the setting adjustment pressure.

Prophet et al. (2017), made the study in an ethylene and propylene production facility. Of a total of 198 PRD's installed they analysed 124 systems in the study. They considered the PRD's adequate or inadequate based on the following points:

- Pressure relief requirement compared to relief capacity.
- Irreversible inlet line loss (3%).
- Backpressure (10% for conventional, manufacturer specific for others).
- Installation/Code violation issues.
- Temperature concerns.

The study concludes that of the 198 devices analysed, 135 were not adequate to protect the systems. So 63 devices were not protected against overpressure.

Prophet et al. results (2017)

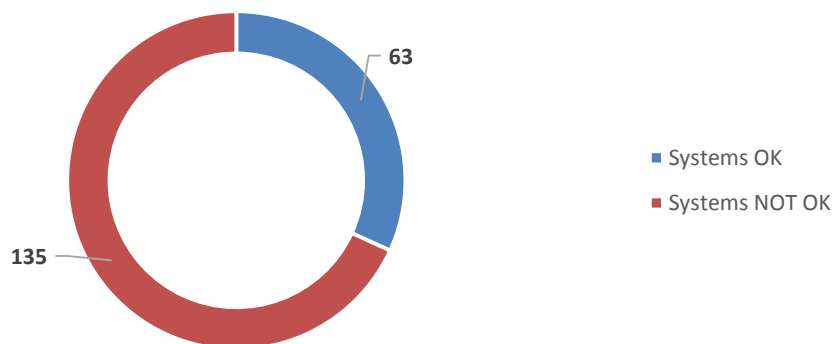


Figure 2.6 Percentage of the condition of the protected systems to Prophet et al. (2017)

The scenarios calculations related to pressure relief obtained the results below.

Table 2.5 Summary pressure relief scenario inadequate according to Prophet (2017)

	Relief Capacity	Irreversible Inlet Line Loss	Backpressure	Other
Cases	79	62	43	9
Percentage (%)	40,9	32,1	22,3	4,7

Prophet et al. results (2017)

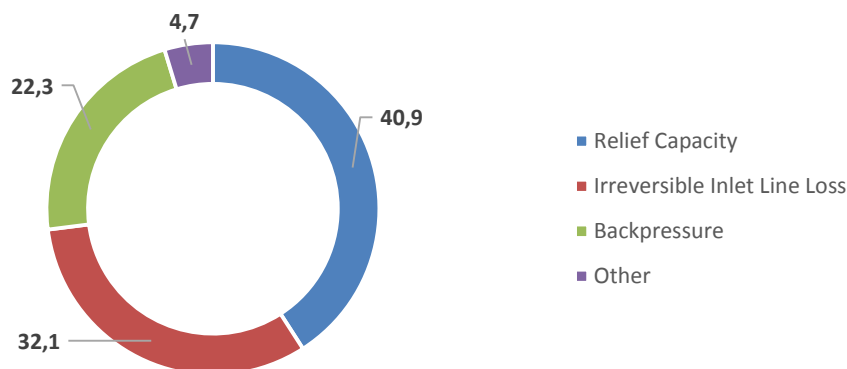


Figure 2.7 Percentage pressure relief scenario inadequate to Prophet et al. (2017)

All data and numbers mentioned show there are a large amount, around 40%-50%, of relief pressure devices that present deficiencies.

As mentioned before, a lot of these devices will never be detected, due to their activation never being needed.

3. Relief load determination as a critical step in the engineering of relief systems

In this chapter, will be analysed the steady state approach, the dynamic approach and the semi-dynamic approach. These methods are used to design and adapt the required areas of the PRD according to the variables existing in the process, such as the type of fluid (single-phase flow or two-phase flow), pressure, temperatures, etc.

Modelling overpressure scenarios dynamically allows a more accurate and less conservative analysis, requiring a more adapted relief device to the necessities of the system rather than the steady state approach.

It is important to understand the need to apply one type of method, having said this, different scenarios where the steady analysis can be as effective as the dynamic analysis, can be found.

The first point engineers must assure for a good relief device choice, is knowing if the fluid going through the connected system is one phase fluid or if it is a two-phase fluid.

In case of having a two-phase fluid, the required area of the relief device must be bigger than if it was only a one phase fluid, this must be taken into account, since in a pressure relief process of a biphasic fluid the liquid part obstructs the relief part of the vapor phase.

In order to correctly size the relief pressure devices, look at the diagram below:

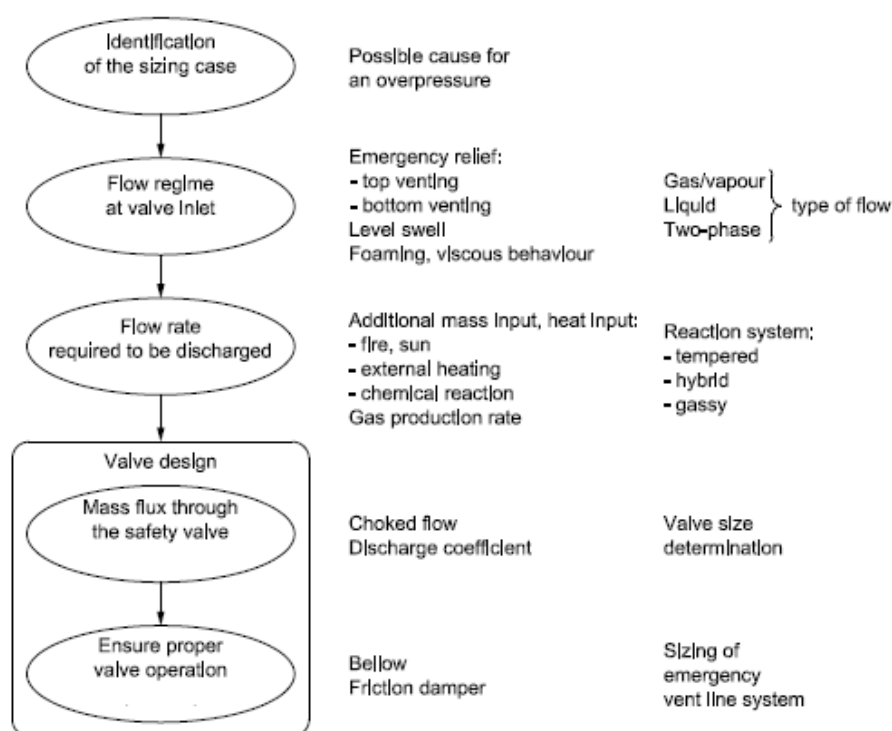


Figure 3.1 Procedure of valve sizing. (Taken from ISO 4126, Part 10, 2010)

The different steps of figure 3.1 are as explained:

Step 1: Identification of the sizing case

This first step is based on the identification of the possible deviations that a process may have in its normal operation, also evaluating the possible risk through a hazard evaluation

using procedures such as HAZOP, what if, etc, or also some quantitative methods such as fault-tree analysis or event-tree analysis.

These procedures analyse the reasons because the pressure increases. Table 3.1 shows the summary of the most frequent scenarios of pressure increase can be appreciated. These scenarios mustn't always be independent, it can be caused simultaneously or one after the other.

Table 3.1 Possible causes for overpressure in a system to be protected. (Taken from ISO 4126, Part 10, 2010)

Reasons for a pressure rise	Calculation of the mass flow rate required to be discharged
<p>Changed feed/exit mass flow rate:</p> <ul style="list-style-type: none"> — Inlet line: valve malfunction (e.g. sticking valve cone) — Pump/compressor operation failure — Heat exchanger: leakage/pipe crack — Unintentionally closed valve (power outage, wiring/operation failure) — Blockage of downstream pipelines or equipment — Overfilled tank 	<p>Fully opened process valve on an inlet line Take into account any constriction of the inlet, e.g. an orifice (pressure loss in process valve in inlet line is not taken into account). Maximum operating pressure or, in case of high hazard potential, maximum pressure possible on the high pressure side, for example relieving pressure of safety valve. (Pressure reducer is not acceptable as a safety system.) Maximum possible pumping pressure/flow rate Fully closed outlet valve</p> <p>Maximum possible pumping pressure/flow rate</p>
<p>Increased energy input:</p> <ul style="list-style-type: none"> — Solar radiation — Fire — Unusual/abnormal heating: Thermal expansion of enclosed liquids Shutdown of steam controller Cleaning: heating of solvents 	<p>Heat flux according to Table 2 and API RP 520-00 Maximum conductivity coefficient for clean heat exchange surfaces Temperature in the pressurized system equals the smaller of a) mixture boiling temperature at opening pressure; b) maximum heating temperature (e.g. steam temperature).</p>
<p>Decreased energy transfer:</p> <ul style="list-style-type: none"> — Cooler shutdown (cooling water/condenser) — Mixer shutdown (broken mixer shaft) — Poor mixing/separation — High viscosity 	<p>Decreased energy removal Total energy shutdown</p>
<p>Deterioration of the heat transfer (fouling)</p>	<p>Total or partial loss of energy removal</p>
<p>Changed reaction:</p> <ul style="list-style-type: none"> — Runaway reaction due to: Cooler shutdown (electrical circuit/pump failure) Charging failure (sequence, amount, substances) Dosing failure (sequence, substances, dosing rate) Impurities (starter inactive, catalysis) Side reactions (pH difference) Incorrect coupling/interruption of flows Back flow or flow from other systems Starting reaction or operating time Gas producing reaction (e.g. decomposition reaction) resulting from pollution (catalysis) 	<p>Characteristic quantities in safety engineering (e.g. temperature rise rate and also reaction enthalpy) Measurement of the temperature and pressure changes during a step reaction of the operation in an adiabatic reaction calorimeter Heat capacity of the steel of the pressurized system with the coolers included, if relevant. Pay attention to accumulation of reactive components (reaction stops due to a cooler breakdown or inactive catalyst; overdoses of an input). Gas production rate per initial mass inventory from laboratory tests [e.g. reaction calorimeter, see Equation (31), Table 2]</p>

Step 2: Flow regime at safety valve inlet

For the correct sizing of the relief device, one must know if will be a two-phase process at the valve inlet. To find out if a biphasic flow is going to happen there are several factors:

- Phenomenon of level swell.
- Influence of liquid viscosity and foaming behaviour on the flow regime.

- Prediction of the flow regime (gas/ two-phase flow).

Step 3: Calculation of the flow rate required to be discharged

In this step to avoid overpressure in the system it has to be known the flow rate required. There are several factors which cause the pressure rise inside the device, such as:

- The protection of excess flow into the equipment.
- Increased heat input due to fire exposure or external heating.
- Runaway reaction.

Step 4: Calculation of the dischargeable mass flux through a safety valve

The basis for sizing the safety valve is the equation for the energy for isentropic flow through a frictionless (ideal) nozzle. Thus, the mass flux, \dot{m}_{ideal} , through a theoretically perfect (adiabatic, frictionless) nozzle, expressed in kilograms per square metre - second, is as given in Equation:

$$\dot{m}_{ideal} = \frac{1}{v_{seat}} * \left(-2 \int_{P_0}^{P_{seat}} v dp \right)^{1/2} \quad (1)$$

Where:

- v_{seat} : Is the specific volume in the narrowest flow cross-section between the pressurized system and the valve seat, expressed in cubic metres per kilogram.
- P_{seat} : Is the pressure in the narrowest flow cross-section (usually the valve seat), expressed in Pascals.
- P_0 : Is the pressure at the sizing condition, expressed in Pascals.
- v : Is the specific volume in the nozzle between the inlet and the narrowest flow cross-section, expressed in cubic metres per kilogram.
- p : Is the pressure in the nozzle, expressed in Pascals.

In order to evaluate this integral, one must know the specific volume of the two-phase mixture, v , as a function of pressure along an isentropic path from the stagnation pressure, P_0 , to the pressure, P_{seat} , in the narrowest flow cross-section (usually in the valve seat).

Some coefficients used to measure the discharge flow through the relief device are mentioned below:

- Two-phase flow valve discharge coefficient, K_{dr} , 2ph.
- Flow coefficient, C .
- Compressibility coefficient, ω .
- Critical pressure ratio, η_{crit} .

Step 5: Check of the proper valve operation in vent line systems under plant conditions

All the pipes and elements that may be installed in the system to protect the relief device, might have a notable influence on the relief device operation. Depending on the design and installation, a relief device malfunction may be caused, therefore it is important to pay special attention at this point.

There are several methods for sizing relief devices, for example static analysis methods or dynamic analysis methods.

Dynamic analysis is used in pressure relief systems design and for calculating transitory pressure increases. It is also used to calculate the set points where the pressure relief devices are to be installed in the system.

Dynamic analysis can be carried out as long as conventional methods, such as static analysis, can be used before. Typically, these methods tend to be more restrictive than dynamic analysis. Usually, they give higher relief device sizing values than the analysis of the dynamic values.

The steady state approach, the dynamic approach and the semi-dynamic approach will be analysed below. All of them are used to design and adapt the areas of the PRD, according to the existing variables in the process, such as the type of fluid (single-phase or two-phase), pressure, temperatures, etc.

3.1 Steady state approach

The steady state approach has the goal of protecting the installed equipment, in the industrial process, of possible overpressure. In order to achieve this protection, the calculations are based on traditional sizing of the relief devices, and steady approach equations are used to establish the relief load required and the relief system capacity. These equations are included in the standards API-520 y 521.

To calculate a PRD with this method for the fire scenario for example, it is essential to use figure 3.2, of API-521, annex A, where the vapor pressure and latent heat of paraffin components of pure hydrocarbons are shown. The figure 3.2 can be applied directly to the mentioned components, but has the following limitations in hydrocarbon mixtures:

- In paraffin approximations of hydrocarbon mixtures composed by two components which molecular weight cannot vary more than propane to butane and butane to pentane can be applied.
- Isometric hydrocarbons, aromatics or cyclic compounds, paraffin hydrocarbon mixture slightly divergent of components that have slightly divergent molecular weights can be applied in the figure 3.2.
- Another example of a case in which it could be applied is in scenarios such as the rupture of a U blend in a heat exchanger, in which the gas escapes from the U blend and displaces the refrigerant fluid, producing an overpressure in the shell of the heat exchanger.

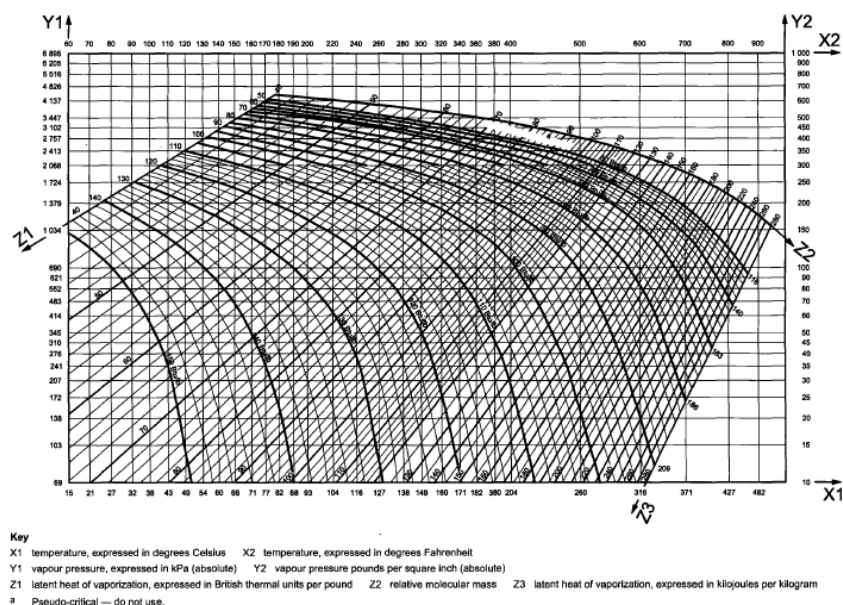


Figure 3.2 Vapor pressure and heat of vaporization of pure, single-component paraffin hydrocarbon liquids (Taken from API Standard 521, 5th Edition, 2007)

To estimate the latent heat of the mixture of various components, with a wide boiling range and different molecular weights, one must do the calculations and simulations with specific software.

The conditions analysed in it is chosen steady state approach are taken from a specific point in the process time, therefore, it is chosen for the most critical moment. So to ensure the PDR sizing fulfils all overpressure scenarios that might happen.

Usually, the obtained results in the steady approach are restrictive, and might cause oversizing in the relief devices.

3.2 Dynamic approach

The dynamic approach for the fire scenario for instance, is used to protect the equipment from overpressure, using a combination of the API 520/521 equations. It might also be used to better understand the stability in the industrial process, depending on possible controllable and uncontrollable eventualities based on time.

The unknowns which cause process changes could be caused by changes in the raw materials during the production process or heat transfer between the environment and the equipment.

In the case of incoherent results during the analysis of the software, one should apply the most restrictive values for the PRD.

It could be said that the dynamic approach is the best sizing system amongst the existing relief devices, but one must take into consideration that this approach needs previous information about the equipment.

3.3 Semi-dynamic approach

The semi-dynamic approach might be defined as a hybrid method between the steady state approach and the dynamic approach.

The semi-dynamic approach uses the basic equations of the API 520-521 to calculate the relief areas of the PRDs for the fire scenario for example. However, unlike the dynamic

approach, which modulates the areas in time, the semi-dynamic approach makes a time sample therefore making it less precise than the dynamic approach. Having said this, it is possible to monitor the needs during the process in time.

This dynamic cannot be made by the steady approach because usually it just analyses a certain point in the process, normally the most critical point.

3.4 Advantages/disadvantages of each approach

The advantages and disadvantages of the three analysis systems approaches are showed in table 3.2:

Table 3.2 Summary advantages/disadvantages static, semi-dynamic and dynamic method

Method	Advantage	Disadvantages
Steady	<ul style="list-style-type: none"> • Conservative method. • Economical method. • Calculation based on API-520/521. • In some implementations might obtain no conservative sizing results. 	<ul style="list-style-type: none"> • Might cause PRD's oversizing. • No reliable results in some implementations, so need the dynamic or the semi-dynamic analysis.
Dynamic	<ul style="list-style-type: none"> • Monitoring of the system in time. • Different simulations simultaneously. • If we obtain multiplied results, the most conservative are chosen. • Good adjustment of the PRDs 	<ul style="list-style-type: none"> • Expensive method. • Limited system simulation. • Large setting parameters must be introduced to correct sizing. • A system can only be analysed by dynamic approach if have been analysed by steady approach previously.
Semi-dynamic	<ul style="list-style-type: none"> • More economical than the dynamic approach. • Monitoring of the system in time. 	<ul style="list-style-type: none"> • Conservative trend.

4. Comparison for the fire scenario

This section develops a case study based on the fire scenario.

4.1 Description for the case study

The case of a pool-fire caused by an external agent, directly attacking the heads and wall of a pressure vessel will be described in the following chapter.



Figure 4.1 Fire in factory (Taken from Google)

When there is a fire emergency, the product inside the vessel must be known, as it is a vital aspect in the pressure equipment integrity.

Imagine that there is a half full vessel containing liquid, with a starting pool fire underneath in direct contact to the shell and heads of this vessel.

The vessel will start to warm up and because of the heat transfer, the contained liquid will also, until the boiling point is reached. This makes the liquid begin to evaporate increasing the pressure of the vessel until the set point of the safety valve is reached and begins to relief.

This process will continue over and over again while there is still liquid in the vessel, so that there is no risk of fracture by temperature in this case.

By the time the liquid in the vessel has almost completely vaporized, there will be no heat transfer between the fire and the liquid, and the walls of the vessel will begin to heat up dangerously.

Overheating of the walls can cause them to break and leak vapor into the atmosphere, which can cause an explosion when gas comes into contact with the fire.

In order to avoid and protect as much as possible that these highly inflammable and dangerous vessels, it is possible to provide the system with some elements such as:

- Thermal insulation.
- Deluge Systems.
- Pressure relief devices (PRD).

This shows that in chemical and pharmaceutical industry multiple emergency scenarios can occur, caused by many different problems.

There are different existing studies to determine an effective method to relieve overpressure in equipment and avoid emergency scenarios. The study and comparison of the steady state method and the dynamic method will be done.

Scenario 1, taken from Prophet, N., 2019, considering an emergency scenario caused by a pool fire which attacked a vessel, that contained propene, propane, 1-butene, 1, 3 butadiene, n-butane and 1-hexane.

The characteristics of the vessel are:

- Installed in vertical position.
- Design pressure: 17,23 barg.
- Operation pressure: 6,89 barg.
- Operation temperature: 309 K.
- Accumulation: 21 %.

Figure 4.2 shows the vessel dimensions:

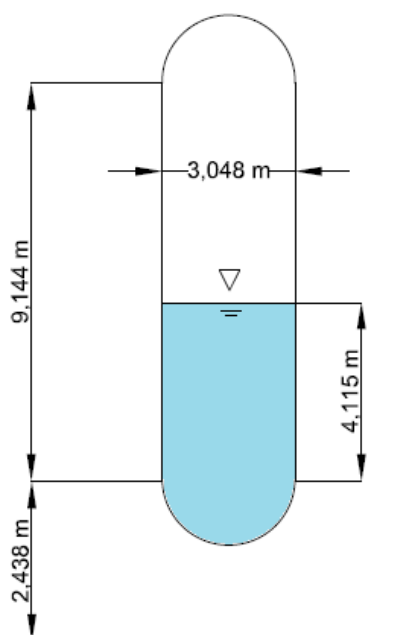


Figure 4.2 Pressure vessel dimensions

Previously, the composition of liquid in the vessel has been referenced. Table 4.1 shows the molar composition:

Table 4.1 Liquid molar fraction in the pressure vessel

COMPONENT	X_i (molar)	Molecular Weight (g/mol)
Propene	0,2358	42,08
Propane	0,2147	44,10
1 – butane	0,1768	56,11
1, 3 – butadiene	0,1902	54,09
n – butane	0,1236	58,12
1 – hexane	0,0589	84,16
TOTAL	1	

Table 4.2 shows the operating conditions of the process:

Table 4.2 Operation conditions

Condition of operation	Units
Operating pressure	6,89 barg
Operating temperature	309,1 K
Density at operating	549,1 kg/m ³

In the next point, the vessel condition and operation condition will be analysed, to simulate what happened the vessel when it was exposed to an external pool fire.

The determination when the operation condition is in a said 'normal condition', the vessel is exposed to by an external pool fire. This liquid inside the vessel will start to vaporize when it reaches 85,74 °C. (Calculated using Aspen Hysys™v10, with Peng-Robinson as EOS).

Table 4.3 shows the condition of the liquid in the vessel, at the normal operating conditions:

Table 4.3 Initial conditions at boiling point

Conditions at vaporized point	Units
Relieving pressure	17,24 x 1,21 = 20,86 barg
Relieving temperature	358,74 K
Density at relieving	467,1 kg/m ³

It is necessary to know the original volume of the liquid, at the normal operating condition.

Original volume of liquid at normal operating condition

$$Volume_{elliptical\ head\ 2:1} = \pi * \frac{D^3}{24} + \pi * h_{liq.cil.} * \frac{D^2}{4} \quad (2)$$

$$Volume_{elliptical\ head\ 2:1} = \pi * \frac{3,048^3}{24} + \pi * 4,115 * \frac{3,048^2}{4} = 33,73\ m^3 \quad (3)$$

$$549,1\ kg/m^3 * 33,73\ m^3 = 18521\ kg \quad (4)$$

Now, it is possible to study and compare different methods, to determine the nozzle to PRV, for the relief in overpressure in the vessel, when the liquid is vaporized.

4.2 Literature survey of relief load calculation methods

In this case, there is a doubt in the effectiveness of the effective heat, when there is a mixture of different vaporized components in a vessel.

The most accurate method is to perform successive dynamic vaporization and sizing analyses using detailed thermophysical properties. However, this system is very time consuming, it can lead to analysis errors and loss of precision.

An alternative to these dynamic analyses is to analyse each component of the mixture individually, determining its latent heat of vaporization under relief conditions and using the

most critical relief requirement. In theory this way of proceeding seems effective, but in practice it is quite difficult and complex, especially in mixtures with dissolved gases or small amounts of light components.

Knowing that the exposure of a vessel to a fire for a long time makes the PRDs unable to protect the vessel, as the vessel walls will weaken quicker. It is for this reason that many will use the initial latent heat, at the bubble point in the relief pressure, removing the light components first.

The steps of the most common and practical method are detailed below:

- Select a percentage of vaporized fluid.
- Determine the enthalpy change due to vaporization.
- Use that effective heat of vaporization to size the relief device.

Most engineers and companies select a vaporization percentage of 25%, recognizing that the initial vapor input, produced by the vaporization of the product, will pressurise the system and not overpressurise it.

Other companies and engineers will use different vaporization percentages, such as between 10-25% or between 5-10%.

The basis of the percentages can be mass, mol, volume or temperature, and since high precision values are not looked for, a mass percentage can be used wisely.

The increase in temperature of the system can produce sensible heat changes in the vapor and in the liquid. Sensible heat changes in the vapor can be omitted, as the vapor leaves through the relief device.

Removing sensible heat from the liquid, the system becomes more conservative, and the relief device will have a larger relief surface.

4.3 Results of the dynamic simulation

In this scenario, different dynamic simulations have been compared.

In scenarios like the one being studied at this point, there are several factors to take into account in order to correctly size the PRD.

Other than the information that was previously presented, it should be known that in any scenario where an external fire causes heat transfer and vaporization of liquids inside a vessel there will be energy produced.

This energy or heat produced by the increase in temperature will directly affect the design of the PRD, since it will have to go through it.

Therefore, at this point, four different studies will be carried out as shown in the figure 4.8. The studies will check what could happen when the sensible heat produced by the evaporation of the product is taken into account or not.

4.3.1 Dynamic simulation. Results of Prophet, N., et al. (2019)

The first dynamic simulation shown is the one accomplished in the article of Prophet, N., 2019. Table 4.4 shows the data from the dynamic simulation, the input data, the output data and the data when it is about to reach the PSV pressure set.

Table 4.4 External fire dynamic simulation results. (Taken from Prophet et al. (2019))

VESSELS CONTAINING TWO PHASES (DYNAMIC) (SUPPORT) INFORMATION	
Inputs	
Initial total mass	41474,24 lb
Volume full of liquid	45 %
Temperature	97,27 °F
Pressure	100 psig
User defined top flow type	Vapor
Top flow user specified backpressure	0 psig
Considerer external fire exposure	YES
Set pressure	250 psig
Discharge coefficient	0,975
Outputs	
Top: First Flow	
Time	0,608 h
Temperature	172,77 °F
Pressure	257,85 psig
Liquid flow rate	0 lb/h
Vapor flow rate	13502,89 lb/h
Total flow rate	13502,89 lb/h
Top: Flow at Maximum Pressure Data	
Time	1,874 h
Temperature	234,18 °F
Pressure	301,41 psig
Liquid flow rate	0 lb/h
Vapor flow rate	24007,01 lb/h
Total flow rate	24007,01 lb/h
Required relief device orifice area	0,785 in²

Table 4.5 shows the results obtained by the dynamic simulation when the pressure in the vessel is at its maximum.

Table 4.5 Summary flow rate and PRD area Prophet, et al. (2019)

Data	Results
Flow rate vapor (kg/h)	10899
Required relief device orifice area (cm²)	5,065

The attached graph that will help to better understand the process.

Figure 4.3 shows the pressure in the vessel as a function of time, and how it is constantly increasing until 0,6 h. At that time the pressure decreases since the PSV has been activated.

The slow increasing of the pressure can be seen although the PSV is activated, until the vessel is completely empty.

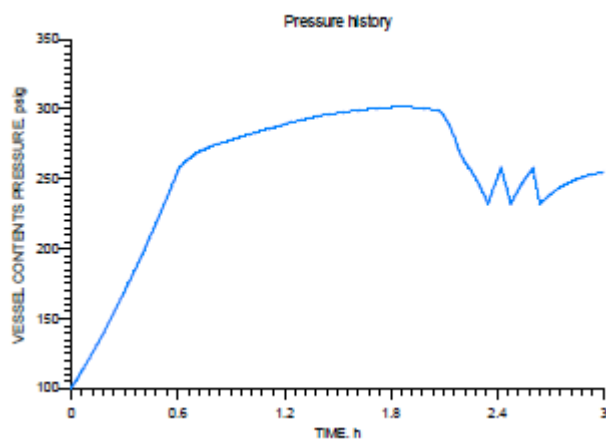


Figure 4.3 Dynamic graph of vessel pressure versus time. (Taken from Prophet et al. (2019))

Figure 4.4 shows vessel temperature. It is clearly seen how the temperature increases slowly, while the vessel still contains the product. When the vessel is completely emptied, the temperature ramp increases dangerously.

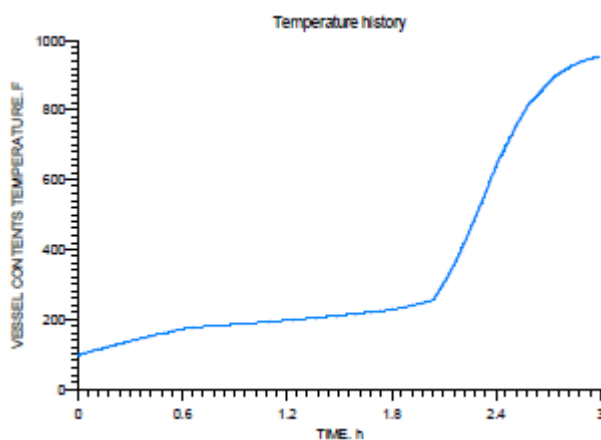


Figure 4.4 Dynamic graph of vessel contents temperature versus time. (Taken from Prophet et al. (2019))

In figure 4.5, the vessel liquid level is shown. The level of the liquid increases until 0,6 h, this is due to the thermal expansion that the product undergoes when it is heated by the action of external fire. Once the product begins to vaporize and the PSV opens, it is observed how the level goes down until it reaches zero.

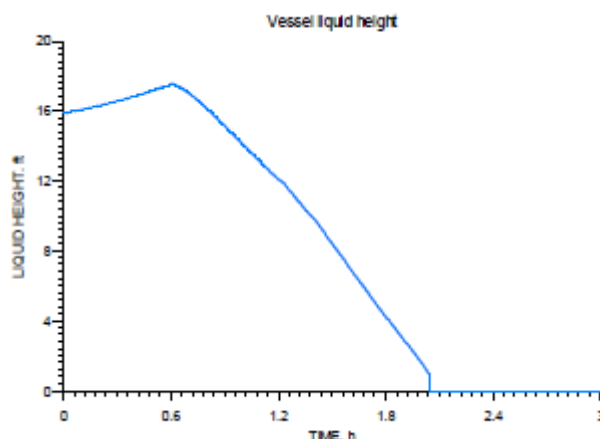


Figure 4.5 Dynamic graph of liquid height versus time. (Taken from Prophet et al. (2019))

4.3.2 Dynamic Simulation ASPEN HYSYS™ v10

At this point, the dynamic simulation has been carried out with the ASPEN HYSYS™ v10 software, obtaining the results showed in table 4.6:

Table 4.6 Summary Dynamic Simulation ASPEN HYSYS™ v10.

	Time [min]	% Vaporized	Temperature [°C]	Total Heat Flow [Kcal/h]	Wetted Area [m ²]	Heat Input [kJ/h]	Vapor Mass Flow [kg/h]	Vapor Volumetric Flow [m ³ /h]	Orifice Area [cm ²]
8,830	13,00	87,57	1,244E+004	58,63	4,381E+006	1,357E+004	267,0	5,825	
9,550	14,00	87,73	1,245E+004	58,00	4,342E+006	1,344E+004	264,4	5,770	
10,28	15,00	87,88	1,248E+004	57,47	4,310E+006	1,332E+004	262,0	5,717	
11,01	16,00	88,04	1,249E+004	56,95	4,277E+006	1,322E+004	259,9	5,673	
11,75	17,00	88,20	1,250E+004	56,32	4,238E+006	1,310E+004	257,4	5,620	
12,50	18,00	88,36	1,248E+004	55,79	4,206E+006	1,303E+004	256,0	5,589	
13,25	19,00	88,53	1,252E+004	55,26	4,173E+006	1,289E+004	253,3	5,531	
14,01	20,00	88,70	1,253E+004	54,63	4,134E+006	1,277E+004	250,8	5,478	
14,78	21,00	88,87	1,251E+004	54,10	4,101E+006	1,270E+004	249,3	5,446	
15,55	22,00	89,04	1,256E+004	53,47	4,062E+006	1,254E+004	246,2	5,379	
16,33	23,00	89,22	1,254E+004	52,94	4,029E+006	1,247E+004	244,7	5,348	
17,12	24,00	89,40	1,256E+004	52,42	3,996E+006	1,235E+004	242,3	5,296	
17,92	25,00	89,58	1,256E+004	51,79	3,957E+006	1,224E+004	240,1	5,248	
18,72	26,00	89,76	1,260E+004	51,26	3,924E+006	1,211E+004	237,4	5,191	
19,54	27,00	89,95	1,259E+004	50,63	3,884E+006	1,201E+004	235,4	5,148	
20,36	28,00	90,14	1,260E+004	50,10	3,851E+006	1,191E+004	233,3	5,102	
21,19	29,00	90,34	1,264E+004	49,57	3,818E+006	1,178E+004	230,7	5,047	
22,03	30,00	90,53	1,263E+004	48,94	3,778E+006	1,167E+004	228,6	5,002	
22,88	31,00	90,73	1,263E+004	48,42	3,744E+006	1,157E+004	226,5	4,958	
23,73	32,00	90,94	1,266E+004	47,78	3,704E+006	1,144E+004	223,8	4,899	
24,60	33,00	91,15	1,269E+004	47,26	3,671E+006	1,132E+004	221,4	4,847	
25,48	34,00	91,36	1,270E+004	46,73	3,637E+006	1,121E+004	219,2	4,802	
26,37	35,00	91,58	1,269E+004	46,10	3,597E+006	1,110E+004	217,0	4,754	
27,26	36,00	91,80	1,271E+004	45,57	3,563E+006	1,099E+004	214,8	4,706	

When a flow rate of 11670 kg/h of vaporization is obtained, which corresponds to 30% of vaporization, the required area that the software calculates for the PSV is 5,002 cm².

Table 4.7 shows the flow rate vapor and the required relief device orifice area with 30% vaporized.

Table 4.7 Summary flow rate and PRD area ASPEN HYSYS™ v10

Data	Results
Flow rate vapor (kg/h)	11670
Required relief device orifice area (cm ²)	5,002

4.3.3 Dynamic Simulation PSPPM™ software

At this point, several dynamic analyses have been performed with the PSPPM™ software. Two analysis have been made, one taking into account sensible heat and another analysis without sensible heat, with a vaporization range of 5% to 30%.

4.3.3.1 Dynamic Simulation without sensible heat

Table 4.8 shows scenario related equipment data, fluid properties, relief stream composition and a relief device summary. The simulation is with software PSPPM™ without sensible heat.

Table 4.8 Dynamic simulation with PSPPM™ software. Without sensible heat

V-100, V. Vessel
HYDROCARBON SEPARATOR

Expert Comments			
Scenario Related Equipment Data & Fluid Properties			
Surface Area		Relief Stream Properties	
Equipment Orientation	VERTICAL	Required Relief Rate	37768.691 lb/hr
HeadType	2 to 1 Ellipsoidal 2	Pressure	302.500 psig
Level Basis	13.500 ft	Temperature	194.206 F
Include Vertical Vessel Bottom?	Yes	Mass % Vapor	100.000%
Height	30 ft	Vapor MW	48.922
Diameter	10 ft	Vapor Z	0.696
Vessel Tangent Elevation	8 ft	Vapor K (Real)	1.375
Maximum Fire Height	25.000 ft	Vapor Viscosity	0.000 lb/ft-s
Heat flux Method	API 521	Vapor Pressure	
Wetted Surface Area	532.514 ft2	Liquid Gravity	
Additional Wetted Area	0.000 ft2	Liquid Viscosity	
Additional Area Factor	10.000%	Bulk Density	3.208 lb/ft3
Total Wetted Area	585.765 ft2	Stream MW	48.922
Fluid Properties		Environment Factor	
Stream Name	HYDROCARBON	Insulation Factor	1.000
Operating Temperature	97.000 F	Additional Factor	1.000
Operating Pressure	100.000 psig	Environment Factor	1.000
Operating Mass % Vapor	0.00%	Adequate drainage and fire-fighting equipment?	Yes
Operating Liquid Density	34.615 lb/ft3	Combustible Materials within 20 ft (6.1 m)?	No
Set Pressure	250.000 psig	Take Credit for Insulation?	No
Set Temperature	168.334 F	Relief Rate - Disengagement	
Relief Pressure	302.500 psig	Vessel Dynamics	Homogeneous
Bubble Temperature at Relief Pressure	186.224 F	Sigma (σ)	0.000 lbf/in
Liquid Density at Bubble Temperature	29.402 lb/ft3	Co	1.010
Vapor Density	3.208 lb/ft3	Co Correlation	0.000
Vapor MW	48.917	F	
Liquid Density	29.516 lb/ft3	Liquid Viscosity	0.000 lb/ft-s
Onset Method	Vapor only	Cp	0.738 Btu/lb/F
Fluid Properties - Heat Of Vaporization		Cp @ Relief	0.793 Btu/lb/F

Calculation Basis	Standard	Lamda (λ)	120.983 Btu/lb
Heat of Vaporization Basis	Mole	Relief Device Installed Below Vessel Top	No
Heat of Vaporization Range	5.00% to 30.00%	Vf	0.033 ft ³ /lb
Include Sensible Heat?	No	Vg	0.390 ft ³ /lb
Latent Heat of Vaporization	103.424 Btu/lb	Relief Phase	Vapor
Isentropic Expansion Coefficient	0.851	Relief Rate - Heat Input	
Vapor Rate Calculation Method	API 521 Simple Method	Area Exponent	0.820
Adjust for Liquid Swell for Vapor/Liquid Disengagement?	No	Heat Input Coefficient	21000.000
Adjust for Liquid Swell for Wetted Area?	No	Heat Input Rate	3906181.645 Btu/hr
Expanded Level		Relief Rate - Heat Input Time	
Expanded Volume Level Basis		Initial Liquid Volume	1191.187 ft ³
Total Expanded Wetted Area		Initial Liquid Mass	41232.624 lb
Scenario Information		Average Heat Capacity	0.702 Btu/lb/F
Rate Dependent Scenario?	No	Heat-up Environment Factor	1.000
Thermodynamic Engine Used?	Yes	Heat-Up Duty	3906.182 kBtu/hr
		Heat-Up Time	1902.187 sec
		Relief Rate	
		Vapor Relief Rate	37768.691 lb/hr
		Liquid Relief Rate	
		Total Relief Rate	37768.691 lb/hr
Relief Device Summary			
Relief Device Tag & Type	Required Relief Rate	Device Capacity	Required / Actual Area
PSV-100, PSV	37768.691 lb/hr	23417.800 lb/hr	1.266 in ² / 0.785 in ²
Relief Stream Composition			
Chemical Name	Chemical Formula	Mole Fraction	
ISOBUTENE	C4H8	0.151	
N-BUTANE	C4H10	0.097	
PROPANE	C3H8	0.268	
PROPYLENE	C3H6	0.309	
1,3-BUTADIENE	C4H6	0.158	
1-HEXENE	C6H12	0.017	

Table 4.9 shows flow rate vapor and the required relief device orifice area with 5% to 30% vaporization without sensible heat.

Table 4.9 Summary flow rate and PRD area PSPPM™ without sensible heat

Data	Results
Flow rate vapor (kg/h)	17147
Required relief device orifice area (cm²)	8,16

4.3.3.2 Dynamic Simulation with sensible heat

Table 4.10 shows scenario related equipment data, fluid properties, relief stream composition and a relief device summary. The simulation is with software PSPPM™ with sensible heat.

Table 4.10 Dynamic simulation with PSPPM™ software with sensible heat

V-100, V. Vessel
HYDROCARBON SEPARATOR

Expert Comments			
Scenario Related Equipment Data & Fluid Properties			
Surface Area		Relief Stream Properties	
Equipment Orientation	VERTICAL	Required Relief Rate	31508.171 lb/hr
HeadType	2 to 1 Ellipsoidal 2	Pressure	302.500 psig
Level Basis	13.500 ft	Temperature	194.206 F
Include Vertical Vessel Bottom?	Yes	Mass % Vapor	100.000%
Height	30 ft	Vapor MW	48.922
Diameter	10 ft	Vapor Z	0.696
Vessel Tangent Elevation	8 ft	Vapor K (Real)	1.375
Maximum Fire Height	25.000 ft	Vapor Viscosity	0.000 lb/ft-s
Heat flux Method	API 521	Vapor Pressure	
Wetted Surface Area	532.514 ft2	Liquid Gravity	
Additional Wetted Area	0.000 ft2	Liquid Viscosity	
Additional Area Factor	10.000%	Bulk Density	3.208 lb/ft3
Total Wetted Area	585.765 ft2	Stream MW	48.922
Fluid Properties		Environment Factor	
Stream Name	HYDROCARBON	Insulation Factor	1.000
Operating Temperature	97.000 F	Additional Factor	1.000
Operating Pressure	100.000 psig	Environment Factor	1.000
Operating Mass % Vapor	0.00%	Adequate drainage and fire-fighting equipment?	Yes
Operating Liquid Density	34.615 lb/ft3	Combustible Materials within 20 ft (6.1 m)?	No
Set Pressure	250.000 psig	Take Credit for Insulation?	No
Set Temperature	168.334 F	Relief Rate - Disengagement	
Relief Pressure	302.500 psig	Vessel Dynamics	Homogeneous
Bubble Temperature at Relief Pressure	186.224 F	Sigma (σ)	0.000 lbf/in
Liquid Density at Bubble Temperature	29.402 lb/ft3	Co	1.010
Vapor Density	3.194 lb/ft3	Co Correlation	0.000
Vapor MW	48.171	F	
Liquid Density	29.419 lb/ft3	Liquid Viscosity	0.000 lb/ft-s
Onset Method	Vapor only	Cp	0.738 Btu/lb/F
Fluid Properties - Heat Of Vaporization		Cp @ Relief	0.793 Btu/lb/F

Calculation Basis	Standard	Lamda (λ)	120.983 Btu/lb
Heat of Vaporization Basis	Mole	Relief Device Installed Below Vessel Top	No
Heat of Vaporization Range	5.00% to 30.00%	Vf	0.033 ft ³ /lb
Include Sensible Heat?	Yes	Vg	0.390 ft ³ /lb
Latent Heat of Vaporization	123.974 Btu/lb	Relief Phase	Vapor
Isentropic Expansion Coefficient	0.851	Relief Rate - Heat Input	
Vapor Rate Calculation Method	API 521 Simple Method	Area Exponent	0.820
Adjust for Liquid Swell for Vapor/Liquid Disengagement?	No	Heat Input Coefficient	21000.000
Adjust for Liquid Swell for Wetted Area?	No	Heat Input Rate	3906181.645 Btu/hr
Expanded Level		Relief Rate - Heat Input Time	
Expanded Volume Level Basis		Initial Liquid Volume	1191.187 ft ³
Total Expanded Wetted Area		Initial Liquid Mass	41232.624 lb
Scenario Information		Average Heat Capacity	0.702 Btu/lb/F
Rate Dependent Scenario?	No	Heat-up Environment Factor	1.000
Thermodynamic Engine Used?	Yes	Heat-Up Duty	3906.182 kBtu/hr
		Heat-Up Time	1902.187 sec
		Relief Rate	
		Vapor Relief Rate	31508.171 lb/hr
		Liquid Relief Rate	
		Total Relief Rate	31508.171 lb/hr
Relief Device Summary			
Relief Device Tag & Type	Required Relief Rate	Device Capacity	Required / Actual Area
PSV-100, PSV	31508.171 lb/hr	23475.525 lb/hr	1.054 in ² / 0.785 in ²
Relief Stream Composition			
Chemical Name	Chemical Formula	Mole Fraction	
ISOBUTENE	C ₄ H ₈	0.151	
N-BUTANE	C ₄ H ₁₀	0.097	
PROPANE	C ₃ H ₈	0.268	
PROPYLENE	C ₃ H ₆	0.309	
1,3-BUTADIENE	C ₄ H ₆	0.158	
1-HEXENE	C ₆ H ₁₂	0.017	

Table 4.11 shows flow rate vapor and the required relief device orifice area with 5% to 30% vaporization with sensible heat

Table 4.11 Summary flow rate and PRD area PSPPM™ with sensible heat

Data	Results
Flow rate vapor (kg/h)	14304
Required relief device orifice area (cm²)	6,79

4.4 Results of the simplified approach

For the simplified method, two studies will be compared, the first study is the Prophet, N., 2019, the second is a study carried out with the support of ASPEN HYSYS™ v10, obtaining results in different percentages of vaporization, which are increasing from 0,5% to 0,5% until reaching the value of 5% vaporization, and then the increase is 5% until reaching 99,99% vaporization.

4.4.1 Steady State Simulation. Results of Prophet, et al. (2019)

Table 4.12 show the results obtained by Prophet, et al. (2019).

Table 4.12 External Fire Steady State Detailed Calculation Results. (Taken from Prophet et al. (2019))

GAS/VAPOR RELIEF UNDER FIRE/USER HEATING USING CCPS/API 520 (SUPPORT) INFORMATION	
Inputs	
Vessel wetted surface area	75929,97 in ²
Additional wetted surface area	7592,80 in ²
Heating rate	3877954, 29 BTU/h
Set pressure	250 psig
Back pressure	0 psig
Percent overpressure	21 %
Discharge coefficient	0,975
Outputs	
Temperature at maximum pressure	187,37 °F
Compressibility factor	0,7
Density	3,16 lb/ft ³
Heat of vaporization	124,28 BTU/lb
Average molecular weight	48,14
Specific volume correction factor	0,88
Correction factor vapor density	3,16 lb/ft ³
Correction factor liquid density	27,20 lb/ft ³
Back pressure correction factor (Kb)	1,00
Flow is critical (choked)	Yes
Evaporation/relief rate	27582,44 lb/h
Volumetric flow rate	212817,51 SCFH
Required relief device orifice area	0,834 in²

Table 4.13 shows the PSV relief area results obtained in the simulation, when the relief flow is the maximum:

Table 4.13 Summary flow rate and PRD area steady state method of Prophet, N.

Data	Results
Flow rate vapor (kg/h)	12522
Required relief device orifice area (cm²)	5,38

4.4.2 Semi-Dynamic Simulation with ASPEN HYSYS™ v10.

To analyse this method, the figure 4.6 simulated with ASPEN HYSYS™ v10.

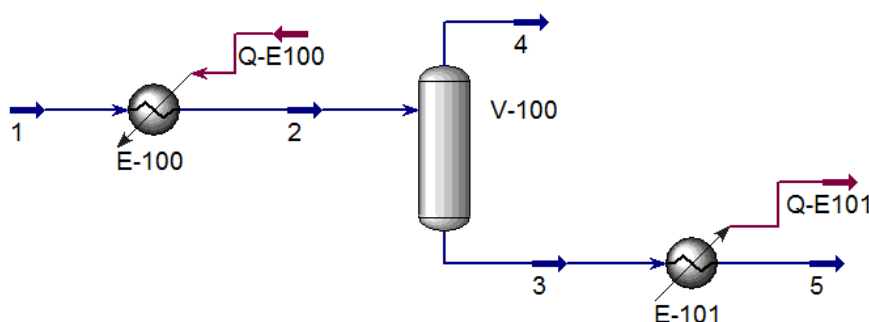


Figure 4.6 Flowsheet representation with ASPEN HYSYS™ v10

The flowsheet, contains E-100 heater to simulate a real fire. There is also a V-100 vessel to simulate the vessel exposed to fire.

There are a couple of streams at the exit point of the vessel. Flow 4 corresponds to the vapor generated. Flow 3 corresponds to liquid not vaporized. This last flow contains an E-101 cooler in order to balance the sensible heat.

The first step to apply the semi dynamic method, in the case that there isn't a sensible heat with density correction, is to calculate latent heat (λ) to the system. It is necessary to know the heat energy to vaporize the liquid and also to know the energy for the compensated sensible heat. These two values, got tested error in trial, with program ASPEN HYSYS™ v10, the values on the table 4.14. has been obtained.

The latent heat is calculated with this equation:

$$\lambda \text{ (Kcal/Kg)} = \frac{Q_{heater} - Q_{cooler}}{\%_{vaporized}} \quad (5)$$

For example, for value of vaporized to 0,1013%, the value of latent heat is:

$$\lambda \text{ (0,1013\%)} = \frac{10,3 - 5}{0,1013} = 52,32 \text{ kcal/kg} \quad (6)$$

Therefore, the table 4.14 shows the heat energy generated at Kcal/h, to vaporize every percentage point to study this case.

Table 4.14 Relation of % vaporized to latent heat

% vaporized	Temperature (°C)	Heater energy E-100(kcal/h)	Cooler energy E-101(kcal/h)	λ latent heat (kcal/kg)
0,1013	85,74	10,3	5	52,32
0,5	85,81	37,8	9	57,60
1	85,88	72,5	14	58,5
1,5	85,95	106,6	20	57,73
2	86,02	141,1	25	58,05
2,5	86,09	175,5	30,5	58,00
3	86,16	210	36	58,00
3,5	86,24	244,4	41	58,11
4	86,31	278,8	46	58,2
4,5	86,38	313,3	51	58,28
5	86,45	348	56	58,40
10	87,17	692	104	58,80
15	87,90	1036	146	59,33
20	88,65	1379,5	184	59,77
25	89,40	1723	216	60,28
30	90,18	2066,5	242,5	60,80
35	90,97	2410	264	61,31
40	91,78	2754	280	61,85
45	92,61	3098	290,5	62,38
50	93,47	3442	295,5	62,93
55	94,36	3786,5	295,5	63,47
60	95,28	4132	289	64,05
65	96,25	4479	277	64,64
70	97,26	4827	259	65,26
75	98,33	5177	235	65,89
80	99,47	5529,5	203,5	66,58
85	100,70	5884	165,3	67,28
90	102,00	6242	119	68,03
95	103,40	6603	64,3	68,82
100	104,90	6967	0,1	69,68

When there is a percentage of vaporized of 0,1013, ASPEN HYSYS™ v10 calculates the density is 29,16 lb/ft³, thus:

$$\frac{29,16 \text{ lb}}{\text{ft}^3} * \frac{0,454 \text{ kg}}{\text{lb}} * \frac{\text{ft}^3}{0,028 \text{ m}^3} = 472,8 \text{ kg/m}^3 \quad (7)$$

The mass in the vessel with 0,1013% of liquid vaporized is:

$$Mass_{0,1013\% \text{ vaporized}}: 18521,14 - \left(18521,14 * \frac{0,1013}{100}\right) = 18502,38 \text{ kg} \quad (8)$$

The volume at 0,1013% vaporized is:

$$Volume_{0,1013\% \text{ vaporized}}: 18502,38 \text{ kg} * \frac{\text{m}^3}{472,8 \text{ kg}} = 39,13 \text{ m}^3 \quad (9)$$

The next equation, calculates the height to any % of vaporization:

$$Volume_{\text{elliptical head } 2:1} = \pi * \frac{D^3}{24} + \pi * h * \frac{D^2}{4} \quad (10)$$

At the point where 0,1013 % is vaporized, the height of liquid in the vessel is:

$$39,13 = \pi * \frac{3,048^3}{24} + \pi * h * \frac{3,048^2}{4} \rightarrow h = 4,855 \text{ m} \quad (11)$$

Once the height of the product has been calculated, it begins to vaporize due to the increase in temperature, then the wet area must be calculated for a vertical vessel with a 2:1 elliptical head, according to the API RP 521 standard.

Equation 12, only applies to the bottom head of the vessel.

$$A_{\text{wetted}} = 1,089 * D^2 + \pi * D * h \quad (12)$$

$$A_{\text{wetted}} = 1,089 * 3,048^2 + \pi * 3,048 * 4,855 = 56,61 \text{ m}^2 \quad (13)$$

According to Wong, W. Y. (2000), the petroleum industry uses a conservative approach to account for piping and fittings, adding to 10% or 15% of the wetted surface areas of major and associated vessels to the total wetted-surfaces.

So, if the wet area increases 10%:

$$A_{ws} = 56,61 * 1,1 = 62,27 \text{ m}^2 \quad (14)$$

The volume of circulation at the valve calculated (Q)

$$Q = 43200 * F * A_w^{0,82} \quad (15)$$

$$Q = 43200 * 1 * 62,27^{0,82} = 1278769,94 \text{ W} \quad (16)$$

Table 4.14, the latent heat obtained with ASPEN HYSYS™ v10, when the percentage vaporized its 0,1013%, $\lambda=52,32 \text{ Kcal/Kg} = 218,70 \text{ kJ/Kg}$.

Then, to calculate mass rate flow:

$$W = \frac{Q}{\lambda} \quad (17)$$

Then:

$$W = \frac{1278,76994}{218,70} = 5,85 \text{ kg/s} \rightarrow 21060 \text{ kg/h} \quad (18)$$

The mass rate flow is corrected by volume variation factor:

$$W_{corr} = Q * \left(1 - \frac{\rho_v}{\rho_l}\right) \quad (19)$$

$$W_{corr} = 21060 * \left(1 - \frac{51,27}{472,81}\right) = 18776,32 \text{ kg/h} \quad (20)$$

In table 4.15, the vapor properties are showed. These values are from ASPEN HYSYS™ v10:

Table 4.15 Vapor properties vaporized 0,1013. (Taken from ASPEN HYSYS™ v10).

Vapor properties when 0,1013% vaporized	
Molecular Weight	48,06
Z (compressibility factor)	0,695
Temperature (K)	358,91

Because of the compressibility factor $z=0,695 < 0,8$, the isentropic expansion coefficient has to be used.

Applying the API 520-1-2020 equations

$$C = 520 * \sqrt{n * \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}} \quad (21)$$

C = is a function of the ratio of the ideal gas specific heats ($k= C_p/C_v$) of the gas or vapor at inlet relieving temperature.

n = is the ratio of specific heats (C_p/C_v) for an ideal gas at relieving temperature.

$$A = \frac{W_{corr}}{C * K_d * P_1 * K_b * K_c} * \sqrt{\frac{T * Z}{MW}} \quad (22)$$

A = is the required effective discharge area of the device, in² (mm²).

W_{corr} = is the required flow through the device, lb/h (kg/h).

K_d = is the effective coefficient of discharge; for preliminary sizing, use the following values;

- 0,975; when a PRV is installed with or without a rupture disk in combination.
- 0,62; when a PRV is not installed and sizing is for a rupture disk in accordance with 5.11.1.1.2 to API 520-1-2014.

P_1 = is the upstream relieving pressure, psia (KPa); this is the set pressure plus the allowable overpressure plus atmospheric pressure.

K_b = is the capacity correction factor due to backpressure; this can be obtained from the manufacturer's literature or estimated for preliminary sizing from the figure 10.1 in appendix A. The backpressure correction factor applies to balanced bellows valves only. For conventional and pilot-operated valves, use a value for K_b equal to 1,0. See 5.6.4 to API 520-I-2020 for conventional valve applications with backpressure of a magnitude that will cause subcritical flow.

K_c = is the combination correction factor for installations with a rupture disk upstream of the PRV;

- Equals 1,0 when the rupture disk is not installed.
- Equals 0,9 when a rupture disk is installed in combination with a PRV and the combination does not have a certified value.

T = is the relieving temperature of the inlet gas or vapor, °R (°F + 460) [K (°C + 273)].

Z = is the compressibility factor for the deviation of the actual gas from a perfect gas, evaluated at inlet relieving conditions.

MW = is the molecular weight of the gas or vapor at inlet relieving conditions.

$$n = \ln * \frac{P_1}{P_2} * \left[\ln * \frac{v_2}{v_1} \right]^{-1} = \ln * \frac{P_1}{P_2} * \left[\ln * \frac{\rho_2}{\rho_1} \right]^{-1} \quad (23)$$

The n factor is calculated in the first step, for this calculation, it is necessary to know the pressure and density of the gas before and after the PRV.

It is known, the pressure before the PRV is:

$$P_1 = \text{Design pressure} * 1,21 + 1,013 \quad (24)$$

$$P_1 = 17,23 * 1,21 + 1,013 = 21,87 \text{ barg} \quad (25)$$

To determine the value of pressure after the valve, it is known that the fluid to pass through the PRV is gas, so it is happening in an isentropic flash, and the ΔP of the valve it is a 60%, then:

$$P_2 = 21,87 * 0,6 = 13,12 \text{ barg} \quad (26)$$

With ASPEN HYSYS™ v10, the density is known before the PRV, to know the density after the PRV, an expander is needed to be added in flow 4.

Figure 4.7 shows the flowsheet representation with added expander.

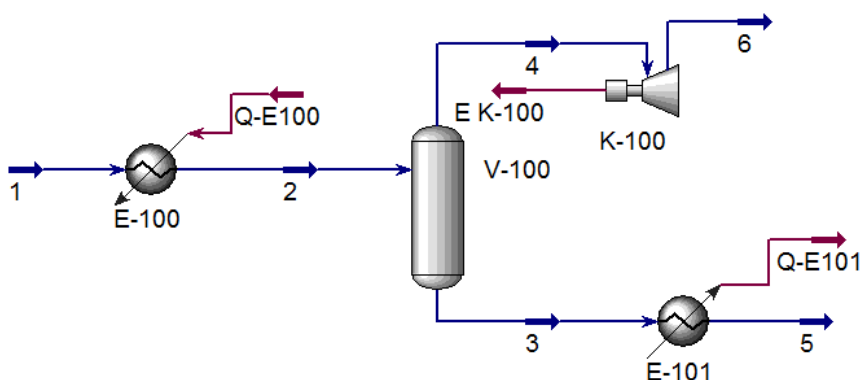


Figure 4.7 Flowsheet representation with ASPEN HYSYS™ v10 with expander.

$$n = \ln * \frac{21,87}{13,12} * \left[\ln * \frac{51,27}{29,14} \right]^{-1} = 0,904 \quad (27)$$

$$C = 520 * \sqrt{0,904 * \left(\frac{2}{0,904 + 1} \right)^{\frac{0,904+1}{0,904-1}}} = 303,59 \quad (28)$$

Area of PRV:

$$A_{orifice} = \frac{18776,32}{303,59 * 0,975 * 21,87 * 1 * 1} * \sqrt{\frac{646,04 * 0,695}{48,06}} = 8,86 \text{ cm}^2 \quad (29)$$

It is calculated that the area of the PRV when % of vaporization is 0,1013, with vapor corrected and without latent heat. For the rest of the points, there are tables where it is shown the percentage of vaporized liquid, and the area nozzle of the PRV, to relieve the pressure in the vessel, for the following cases:

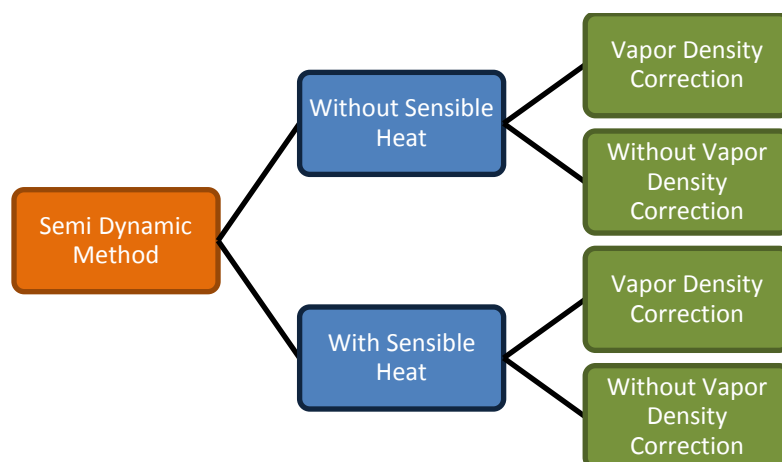


Figure 4.8 Semi-dynamic method to study in case of pool-fire

- Table 4.16, without sensible heat, with vapor density correction.
- Table 4.17, with sensible heat, with vapor density correction.
- Table 4.18, without sensible heat, without vapor density correction.
- Table 4.19, with sensible heat, without vapor density correction.

When the table of percentage of vaporization was created, the first point 0,1013 could be seen as a good place to start, it is not a precise point to calculate the nozzle area to the PRV. For this motive the area of PRV has been calculated from 0,1013% incremented every point 0,5%, until 5% vaporized. From this point, the percentage to vaporization has been calculated incremented every point 5%.

Table 4.16 Summary table to PRD area without sensible heat, with density correction

Vapor (%)	Heat (Kcal/h)	Heat comp (Kcal/h)	Mass (Kg)	VH (m ³)	h (m)	A weat (m ²)	Q (W) or (US)	λ (Kcal/Kg)	λ (KJ/Kg)	W corr (kg/h)	n factor	C	A orifice (cm ²)	Mol. Weight	ρV (kg/m ³)	ρL (kg/m ³)	Z	p out PRV (Kg/m ³)	T (°C)	T (°F)
0.1013	10.3	18502.38	39.13	4.855	62.27	1278755.10	52.32	218.70	18767.20	0.904	303.59	8.86	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
0.5	37.8	18428.54	38.98	4.834	62.04	1274957.26	57.60	240.77	16996.20	0.904	303.59	8.03	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
1	72.5	18335.93	38.78	4.807	61.76	1270190.97	58.50	244.53	16672.16	0.904	303.59	7.87	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
1.5	106.6	18243.33	38.59	4.780	61.48	1265420.75	57.73	241.33	16830.11	0.904	303.59	7.95	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
2	141.1	18150.72	38.39	4.753	61.20	1260646.58	58.05	242.65	16675.15	0.904	303.59	7.88	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
2.5	175.5	18058.11	38.19	4.726	60.91	1255868.44	58.00	242.44	16626.27	0.904	303.59	7.85	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
3	210	17965.51	38.00	4.700	60.63	1251086.30	58.00	242.44	16626.27	0.904	303.59	7.82	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
3.5	244.4	17872.90	37.80	4.673	60.35	1246300.14	58.11	242.92	16467.15	0.904	303.59	7.78	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
4	278.8	17780.30	37.61	4.646	60.06	1241509.95	58.20	243.28	16379.70	0.904	303.59	7.74	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
4.5	313.3	17687.69	37.41	4.619	59.78	1236715.70	58.29	243.65	16291.56	0.904	303.59	7.69	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
5	348	17595.09	37.19	4.589	59.46	1231292.19	58.40	244.11	16188.74	0.904	303.51	7.64	48.20	51.32	473.13	0.696	29.15	86.45	647.28	
10	692	16669.03	35.21	4.317	56.60	1182510.07	58.80	245.78	15441.11	0.902	303.31	7.29	48.35	51.37	473.46	0.696	29.15	87.17	648.58	
15	1036	15742.97	33.24	4.048	53.76	1133633.63	59.33	248.01	14668.74	0.901	303.23	6.93	48.50	51.42	473.62	0.696	29.17	87.90	649.89	
20	1397.5	14816.91	31.26	3.777	50.91	1084054.26	60.68	253.62	13716.60	0.901	303.15	6.48	48.65	51.46	473.94	0.696	29.19	88.65	651.24	
25	1723	13890.86	29.29	3.506	48.06	1034040.70	60.28	251.97	13169.09	0.900	303.07	6.22	48.80	51.51	474.27	0.696	29.20	89.40	652.59	
30	2066.5	12964.80	27.32	3.236	45.21	985559.61	60.80	254.14	12418.66	0.900	302.99	5.86	48.96	51.56	474.59	0.696	29.22	90.18	653.99	
35	2410	12038.74	25.35	2.966	42.37	935753.09	61.31	256.29	11675.76	0.899	302.91	5.51	49.11	51.61	474.92	0.696	29.23	90.97	655.42	
40	2754	11112.69	23.38	2.696	39.52	880827.27	61.85	258.53	10932.91	0.899	302.90	5.16	49.28	51.64	475.40	0.696	29.25	91.78	656.87	
45	3098	10186.63	21.41	2.427	36.69	828707.87	62.39	260.79	10196.83	0.897	302.71	4.81	49.44	51.69	475.73	0.696	29.25	92.61	658.37	
50	3442	9260.57	19.45	2.158	33.86	775930.72	62.93	263.05	9465.40	0.897	302.69	4.46	49.61	51.72	476.05	0.697	29.27	93.47	659.92	
55	3786.5	8334.51	17.49	1.889	31.03	722262.25	63.47	265.32	8735.80	0.897	302.68	4.12	49.78	51.76	476.54	0.697	29.28	94.36	661.52	
60	4132	7408.46	15.53	1.620	28.20	667814.97	64.05	267.73	8004.84	0.896	302.55	3.77	49.96	51.79	477.02	0.697	29.28	95.28	663.17	
65	4479	6482.40	13.58	1.353	25.38	612487.98	64.65	270.22	7274.30	0.895	302.42	3.43	50.15	51.82	477.51	0.698	29.28	96.25	664.92	
70	4827	5556.34	11.62	1.085	22.55	556040.68	65.26	272.77	6542.65	0.895	302.41	3.08	50.34	51.85	478.16	0.698	29.30	97.26	666.74	
75	5177	4630.29	9.67	0.818	19.74	498559.95	65.89	275.43	5810.16	0.895	302.34	2.74	50.54	51.87	478.65	0.698	29.30	98.33	668.66	
80	5529.5	3704.23	7.73	0.551	16.93	439623.05	66.58	278.28	5071.50	0.894	302.28	2.34	50.75	51.89	479.29	0.699	29.30	99.47	670.72	
85	5884	2778.17	5.79	0.285	14.13	379058.28	67.28	281.23	4327.79	0.893	302.17	2.04	50.97	51.89	479.94	0.700	29.28	100.70	672.93	
90	6242	1852.11	3.85	0.020	11.34	316408.33	68.03	284.38	3573.03	0.893	302.10	1.69	51.21	51.90	480.75	0.700	29.28	102.00	675.27	
95	6603	926.06	1.92	0.000	11.13	311582.57	68.83	287.70	3478.46	0.893	302.10	1.64	51.47	51.90	481.40	0.701	29.28	103.40	677.79	
99.99	6967	0.1	1.85	0.00	0.000	311582.57	69.68	291.25	3436.85	0.892	301.99	1.62	51.74	51.90	482.21	0.702	29.27	104.90	680.49	

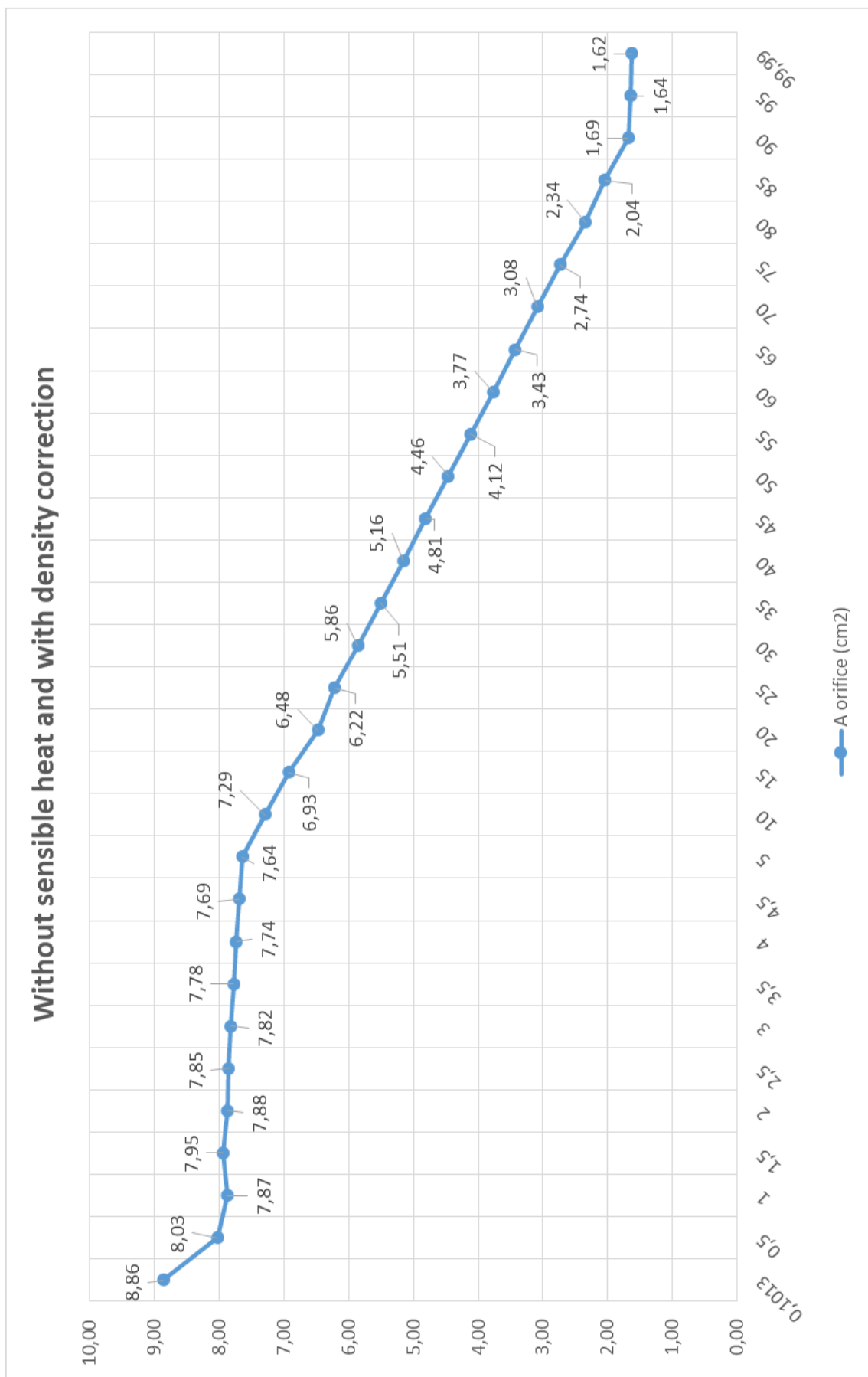


Figure 4.9 Representation PRD area without sensible heat, with density correction

Table 4.17 Summary table to PRD area with sensible heat, with density correction

Vapor (%)	Heat (Kcal/h)	Heat comp (Kcal/h)	Mass (kg)	VH (m3)	h (m)	A weat (m2)	Q (W) or (l/s)	λ (Kcal/kg)	λ (KJ/kg)	W (kg/h)	W corr (kg/h)	n factor	C	A orifice (cm2)	Mol. Weight	pV (kg/m3)	pL (kg/m3)	Z	p out PRV (kg/m3)	T (°C)	T (°F)
0.1013	10.3	18502.38	39.13	4.86	62.27	1278755.10	101.68	425.01	10831.43	9656.91	0.904	303.59	4.56	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
0.5	37.8	18428.54	38.98	4.83	62.04	1274957.26	75.60	316.01	14524.46	12949.48	0.904	303.59	6.12	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
1	72.5	18335.93	38.78	4.81	61.76	1270190.97	72.50	303.05	15088.89	13452.71	0.904	303.59	6.35	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
1.5	106.6	18243.33	38.59	4.78	61.48	1265420.75	71.07	297.06	15335.40	13672.49	0.904	303.59	6.46	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
2	141.1	18150.72	38.39	4.75	61.20	1260046.58	70.55	294.90	15389.43	13720.66	0.904	303.59	6.48	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
2.5	175.5	18058.11	38.19	4.73	60.91	1255068.44	70.20	293.44	15407.54	13736.80	0.904	303.59	6.49	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
3	210	17965.51	38.00	4.70	60.63	1251086.30	70.00	292.60	15392.72	13730.66	0.904	303.59	6.48	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
3.5	244.4	17872.90	37.80	4.67	60.35	1246900.14	69.83	291.88	15371.48	13704.66	0.904	303.59	6.47	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
4	278.8	17780.30	37.61	4.65	60.06	1241909.95	69.70	291.35	15340.65	13677.16	0.904	303.59	6.46	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
4.5	313.3	17687.69	37.41	4.62	59.78	1236715.70	69.62	291.02	15298.48	13639.57	0.904	303.59	6.44	48.06	51.27	472.81	0.695	29.14	85.76	646.04	
5	348	17595.09	37.19	4.59	59.46	1231792.19	69.60	290.93	15236.25	13583.66	0.904	303.51	6.41	48.20	51.32	473.13	0.696	29.15	86.45	647.28	
10	692	16669.03	35.21	4.32	56.60	1182510.07	69.20	289.26	14717.19	13120.48	0.902	303.31	6.20	48.35	51.37	473.46	0.696	29.15	87.17	648.58	
15	1036	15742.97	33.24	4.05	53.76	1133633.63	69.07	288.70	14136.13	12601.53	0.901	303.23	5.95	48.50	51.42	473.62	0.696	29.17	87.90	649.89	
20	1397.5	14816.91	31.26	3.78	50.91	1084054.26	69.88	292.08	13361.51	11910.62	0.901	303.15	5.62	48.65	51.46	473.94	0.696	29.19	88.65	651.24	
25	1723	13890.86	29.29	3.51	48.06	1034040.70	68.92	288.09	12921.67	11518.18	0.900	303.07	5.44	48.80	51.51	474.27	0.696	29.20	89.40	652.59	
30	2066.5	12964.80	27.32	3.24	45.21	983559.61	68.88	287.93	12297.38	10961.35	0.900	302.99	5.17	48.96	51.56	474.59	0.696	29.22	90.18	653.99	
35	2410	12038.74	25.35	2.97	42.37	932573.09	68.86	287.82	11664.34	10396.75	0.899	302.91	4.91	49.11	51.61	474.92	0.696	29.23	90.97	655.42	
40	2754	11112.69	23.38	2.70	39.52	880827.27	68.85	287.79	11018.26	9821.36	0.899	302.90	4.63	49.28	51.64	475.40	0.696	29.25	91.78	656.87	
45	3098	10186.63	21.41	2.43	36.69	828707.87	68.84	287.77	10367.14	9240.67	0.897	302.71	4.36	49.44	51.69	475.73	0.696	29.25	92.61	658.37	
50	3442	9260.57	19.45	2.16	33.86	775930.72	68.84	287.75	9707.32	8652.79	0.897	302.69	4.08	49.61	51.72	476.05	0.697	29.27	93.47	659.92	
55	3786.5	8334.51	17.49	1.89	31.03	722622.25	68.85	287.77	9035.37	8054.05	0.897	302.68	3.80	49.78	51.76	476.54	0.697	29.28	94.36	661.52	
60	4132	7408.46	15.53	1.62	28.20	667814.97	68.87	287.86	8351.67	7444.97	0.896	302.55	3.51	49.96	51.79	477.02	0.697	29.28	95.28	663.17	
65	4479	6482.40	13.58	1.35	25.38	612487.98	68.91	288.03	7655.19	6824.43	0.895	302.42	3.22	50.15	51.82	477.51	0.698	29.28	96.25	664.92	
70	4827	5556.34	11.62	1.08	22.55	556040.68	68.96	288.24	6944.70	6191.59	0.895	302.41	2.92	50.34	51.85	478.16	0.698	29.30	97.26	666.74	
75	5177	4630.29	9.67	0.82	19.74	498559.95	69.03	288.53	6220.52	5546.42	0.895	302.34	2.62	50.54	51.87	478.65	0.698	29.30	98.33	668.66	
80	5529.5	3704.23	7.73	0.55	16.93	439623.05	69.12	288.92	5477.86	4884.86	0.894	302.28	2.25	50.75	51.89	479.29	0.699	29.30	99.47	670.72	
85	5884	2778.17	5.79	0.29	14.13	379058.28	69.22	289.35	4716.05	4206.21	0.893	302.17	1.98	50.97	51.89	479.94	0.700	29.28	100.70	672.93	
90	6242	1852.11	3.85	0.02	11.34	316408.33	69.36	289.91	3929.10	3504.91	0.893	302.10	1.65	51.21	51.90	480.75	0.700	29.28	102.00	675.27	
95	6603	926.06	1.92	0.00	11.13	31582.57	69.51	290.53	3860.84	3444.59	0.893	302.10	1.62	51.47	51.90	481.40	0.701	29.28	103.40	677.79	
99.99	6967	0.1	1.85	0.00	11.13	311582.57	69.68	291.25	3851.32	3436.80	0.892	301.99	1.62	51.74	51.90	482.21	0.702	29.27	104.90	680.49	

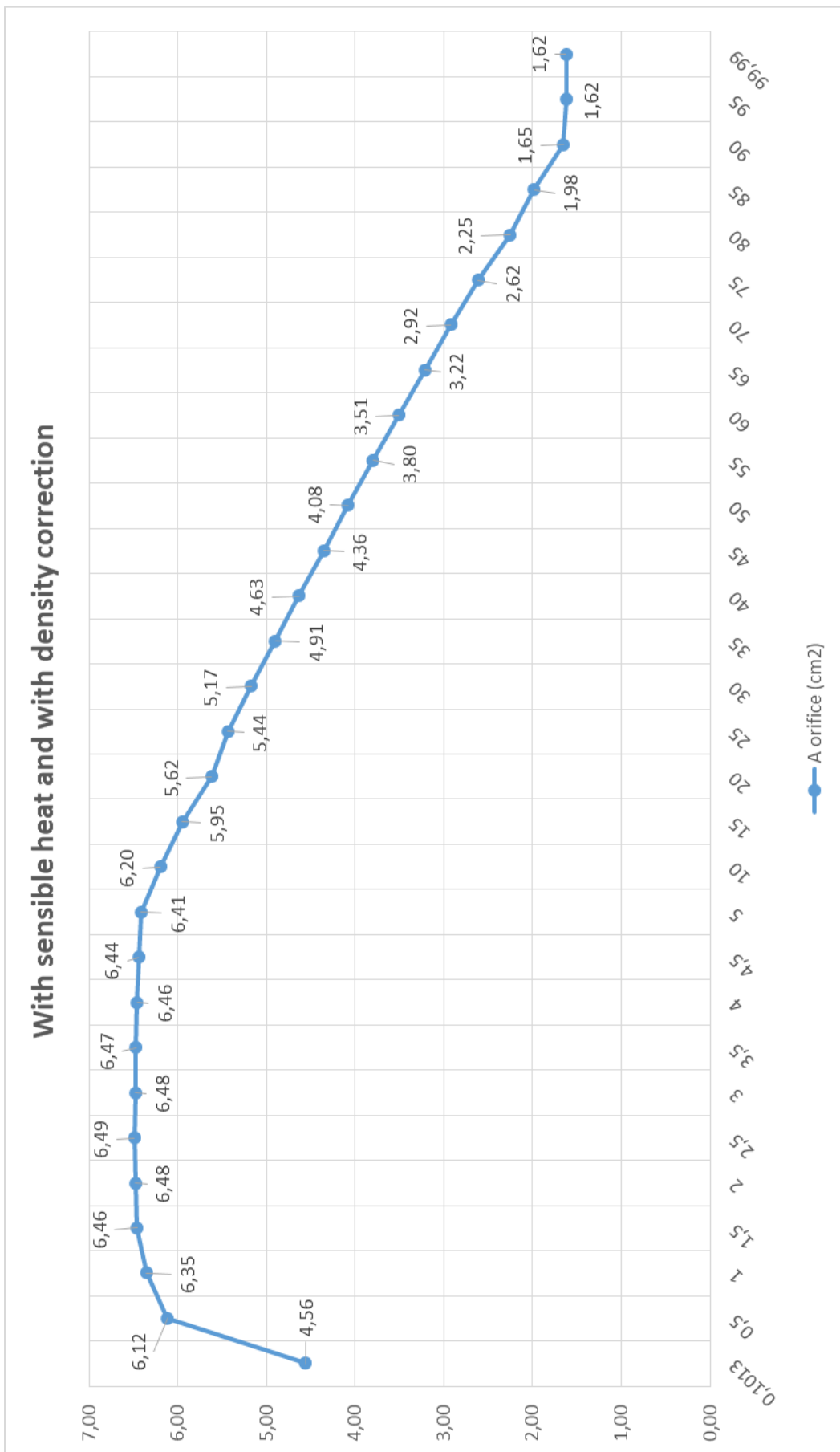


Figure 4.10 Representation PRD area with sensible heat, with density correction

Table 4.18 Summary table to PRD area without sensible heat, without density correction

Vapor (%)	Heat (Kcal/h)	Heat comp (Kcal/h)	Mass (kg)	VH (m ³)	h (ft)	A weat (m ²)	Q (W) or (J/s)	λ (Kcal/kg)	λ (KJ/kg)	W (kg/h)	C	A orifice (cm ²)	Mol.	Weight pV (kg/m ³)	pL (kg/m ³)	Z	p out PRV (kg/m ³)	T (°C)	T (°F)
0.1013	10.3	18502.38	39.13	4.86	62.27	1278755.10	52.32	218.70	210.49	76	303.59	9.94	48.060	51.27	472.81	0.695	29.14	85.76	646.04
0.5	37.8	18428.54	38.98	4.83	62.04	1274957.26	57.60	240.77	19063.36	303.59	9.00	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
1	72.5	18335.93	38.78	4.81	61.76	1270190.97	58.50	244.53	18699.90	303.59	8.83	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
1.5	106.6	18243.33	38.59	4.78	61.48	1265420.75	57.73	241.33	18877.07	303.59	8.92	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
2	141.1	18150.72	38.39	4.75	61.20	1260646.58	58.05	242.65	18703.26	303.59	8.83	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
2.5	175.5	18058.11	38.19	4.73	60.91	1255868.44	58.00	242.44	18648.43	303.59	8.81	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
3	210	17965.51	38.00	4.70	60.63	1251086.30	58.00	242.44	18577.42	303.59	8.77	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
3.5	244.4	17872.90	37.80	4.67	60.35	1246300.14	58.11	242.92	18469.96	303.59	8.72	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
4	278.8	17780.30	37.61	4.65	60.06	1241509.95	58.20	243.28	18371.87	303.59	8.68	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
4.5	313.3	17687.69	37.41	4.62	59.78	1236715.70	58.29	243.65	18273.02	303.59	8.63	48.060	51.27	472.81	0.695	29.14	85.76	646.04	
5	348	17595.09	37.19	4.59	59.46	1231292.19	58.40	244.11	18158.27	303.51	8.57	48.200	51.32	473.13	0.696	29.15	86.45	647.28	
10	692	16669.03	35.21	4.32	56.60	1182510.07	58.80	245.78	17320.23	303.31	8.18	48.350	51.37	473.46	0.696	29.15	87.17	648.58	
15	1036	15742.97	33.24	4.05	53.76	1133633.63	59.33	248.01	16455.09	303.23	7.77	48.500	51.42	473.62	0.696	29.17	87.90	649.89	
20	1397.5	14816.91	31.26	3.78	50.91	1084054.26	60.68	253.62	15387.48	303.15	7.26	48.650	51.46	473.94	0.696	29.19	88.65	651.24	
25	1723	13890.86	29.29	3.51	48.06	1034040.70	60.28	251.97	14773.75	303.07	6.97	48.800	51.51	474.27	0.696	29.20	89.40	652.59	
30	2066.5	12964.80	27.32	3.24	45.21	983559.61	60.80	254.14	13932.32	302.99	6.57	48.960	51.56	474.59	0.696	29.22	90.18	653.99	
35	2410	12038.74	25.35	2.97	42.37	932573.09	61.31	256.29	13099.28	302.91	6.18	49.110	51.61	474.92	0.696	29.23	90.97	655.42	
40	2754	11112.69	23.38	2.70	39.52	880827.27	61.85	258.53	12265.27	302.90	5.78	49.280	51.64	475.40	0.696	29.25	91.78	656.87	
45	3098	10186.63	21.41	2.43	36.69	828707.87	62.39	260.79	11439.85	302.71	5.40	49.440	51.69	475.73	0.696	29.25	92.61	658.37	
50	3442	9260.57	19.45	2.16	33.86	775930.72	62.93	263.05	10619.19	302.69	5.01	49.610	51.72	476.05	0.697	29.27	93.47	659.92	
55	3786.5	8334.51	17.49	1.89	31.03	722262.25	63.47	265.32	9800.18	302.68	4.62	49.780	51.76	476.54	0.697	29.28	94.36	661.52	
60	4132	7408.46	15.53	1.62	28.20	667814.97	64.05	267.73	8979.73	302.55	4.23	49.960	51.79	477.02	0.697	29.28	95.28	663.17	
65	4479	6482.40	13.58	1.35	25.38	612487.98	64.65	270.22	8159.83	302.42	3.85	50.150	51.82	477.51	0.698	29.28	96.25	664.92	
70	4827	5556.34	11.62	1.08	22.55	556040.68	65.26	272.77	7338.46	302.41	3.46	50.340	51.85	478.16	0.698	29.30	97.26	666.74	
75	5177	4630.29	9.67	0.82	19.74	498559.95	65.89	275.43	6516.32	302.34	3.07	50.540	51.87	478.65	0.698	29.30	98.33	668.66	
80	5529.5	3704.23	7.73	0.55	16.93	439623.05	66.58	278.28	5687.16	302.28	2.62	50.750	51.89	479.29	0.699	29.30	99.47	670.72	
85	5884	2778.17	5.79	0.29	14.13	379058.28	67.28	281.23	4852.37	302.17	2.29	50.970	51.89	479.94	0.700	29.28	100.70	672.93	
90	6242	1852.11	3.85	0.02	11.34	316408.33	68.03	284.38	4005.46	302.10	1.89	51.210	51.90	480.75	0.700	29.28	102.00	675.27	
95	6603	64.3	926.06	1.92	0.00	11.13	311582.57	68.83	287.70	3898.81	302.10	1.84	51.470	51.90	481.40	0.701	29.28	103.40	677.79
99.99	6967	0.1	1.85	0.00	0.00	11.13	311582.57	69.68	291.25	3851.38	301.99	1.82	51.740	51.90	482.21	0.702	29.27	104.90	680.49

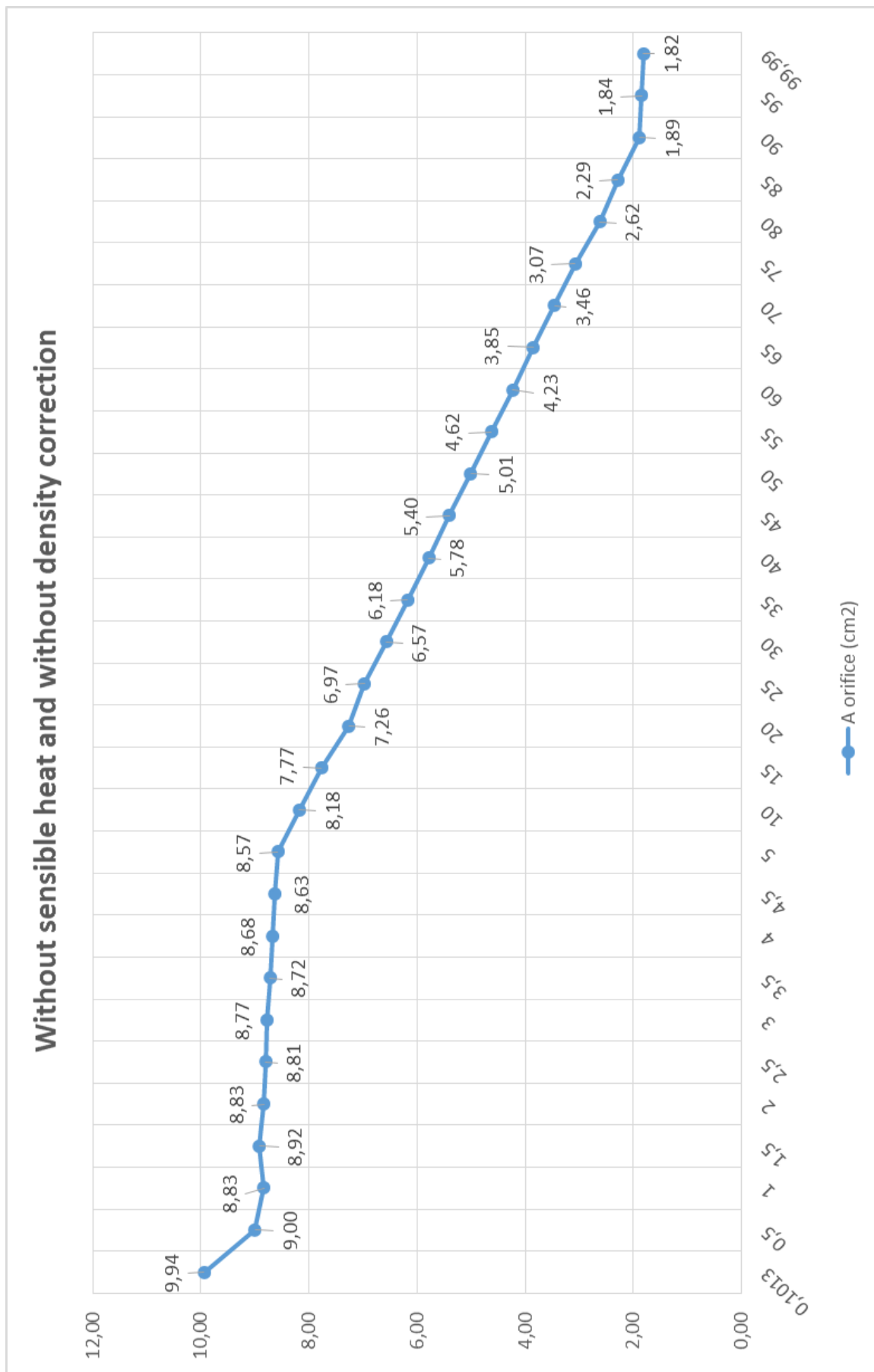


Figure 4.11 Representation PRD area without sensible heat, without density correction

Table 4.19 Summary table to PRD area with sensible heat, without density correction

Vapor (%)	Heat (Kcal/h)	Heat comp (Kcal/h)	Mass (Kg)	VH (m ³)	h (m)	A weat (m ²)	Q (W) or U (s)	λ (Kcal/Kg)	λ (KJ/Kg)	W (Kg/h)	C	A orifice (cm ²)	Mol. Weight (cm ³)	p _v (Kg/m ³)	p _t (Kg/m ³)	Z	p out PRV	T (°C)	T (°F)
0.1013	10.3	5	18502.38	39.13	4.86	62.27	1278755.10	101.68	425.01	10831.43	303.59	5.12	48.060	51.27	472.81	0.695	1.797	85.76	646.04
0.5	37.8	9	18428.54	38.98	4.83	62.04	1274957.26	75.60	316.01	14524.46	303.59	6.86	48.060	51.27	472.81	0.695	1.797	85.76	646.04
1	72.5	14	18335.93	38.78	4.81	61.76	1270190.97	72.50	303.05	15088.89	303.59	7.13	48.060	51.27	472.81	0.695	1.797	85.76	646.04
1.5	106.6	20	18243.33	38.59	4.78	61.48	1265420.75	71.07	297.06	15335.40	303.59	7.24	48.060	51.27	472.81	0.695	1.797	85.76	646.04
2	141.1	25	18150.72	38.39	4.75	61.20	1260646.58	70.55	294.90	15389.43	303.59	7.27	48.060	51.27	472.81	0.695	1.797	85.76	646.04
2.5	175.5	30.5	18058.11	38.19	4.73	60.91	1255868.44	70.20	293.44	15407.54	303.59	7.28	48.060	51.27	472.81	0.695	1.797	85.76	646.04
3	210	36	17965.51	38.00	4.70	60.63	1251086.30	70.00	292.60	15392.72	303.59	7.27	48.060	51.27	472.81	0.695	1.797	85.76	646.04
3.5	244.4	41	17872.90	37.80	4.67	60.35	1246300.14	69.83	291.88	15371.48	303.59	7.26	48.060	51.27	472.81	0.695	1.797	85.76	646.04
4	278.8	46	17780.30	37.61	4.65	60.06	1241509.95	69.70	291.35	15340.65	303.59	7.25	48.060	51.27	472.81	0.695	1.797	85.76	646.04
4.5	313.3	51	17687.69	37.41	4.62	59.78	1236715.70	69.62	291.02	15298.48	303.59	7.23	48.060	51.27	472.81	0.695	1.797	85.76	646.04
5	348	56	17595.09	37.19	4.59	59.46	1231292.19	69.60	290.93	15236.25	303.51	7.19	48.200	51.32	473.13	0.696	1.798	86.45	647.28
10	692	104	16669.03	35.21	4.32	56.60	1182510.07	69.20	289.26	14717.19	303.31	6.95	48.350	51.37	473.46	0.696	1.798	87.17	648.58
15	1036	146	15742.97	33.24	4.05	53.76	1133633.63	69.07	288.70	14136.13	303.23	6.67	48.500	51.42	473.62	0.696	1.799	87.90	649.89
20	1397.5	184	14816.91	31.26	3.78	50.91	1084054.26	68.88	292.08	13361.51	303.15	6.31	48.650	51.46	473.94	0.696	1.800	88.65	651.24
25	1723	216	13890.86	29.29	3.51	48.06	1034040.70	68.92	288.09	12921.67	303.07	6.10	48.800	51.51	474.27	0.696	1.801	89.40	652.59
30	2066.5	242.5	12964.80	27.32	3.24	45.21	983559.61	68.88	287.93	12297.38	302.99	5.80	48.960	51.56	474.59	0.696	1.802	90.18	653.99
35	2410	264	12038.74	25.35	2.97	42.37	932573.09	68.86	287.82	11664.34	302.91	5.50	49.110	51.61	474.92	0.696	1.803	90.97	655.42
40	2754	280	11112.69	23.38	2.70	39.52	880827.27	68.85	287.79	11018.26	302.90	5.20	49.280	51.64	475.40	0.696	1.804	91.78	656.87
45	3098	290.5	10186.63	21.41	2.43	36.69	828707.87	68.84	287.77	10367.14	302.71	4.89	49.440	51.69	475.73	0.696	1.804	92.61	658.37
50	3442	295.5	9260.57	19.45	2.16	33.86	775930.72	68.84	287.75	9707.52	302.69	4.58	49.610	51.72	476.05	0.697	1.805	93.47	659.92
55	3786.5	295.5	8334.51	17.49	1.89	31.03	722262.25	68.85	287.77	9035.37	302.68	4.26	49.780	51.76	476.54	0.697	1.806	94.36	661.52
60	4132	289	7408.46	15.53	1.62	28.20	667814.97	68.87	287.86	8351.67	302.55	3.94	49.960	51.79	477.02	0.697	1.806	95.28	663.17
65	4479	277	6482.40	13.58	1.35	25.38	612487.98	68.91	288.03	7655.19	302.42	3.61	50.150	51.82	477.51	0.698	1.806	96.25	664.92
70	4827	259	5556.34	11.62	1.08	22.55	556040.68	68.96	288.24	6944.70	302.41	3.27	50.340	51.85	478.16	0.698	1.807	97.26	666.74
75	5177	235	4630.29	9.67	0.82	19.74	498559.95	69.03	288.53	6220.52	302.34	2.93	50.540	51.87	478.65	0.698	1.807	98.33	668.66
80	5529.5	203.5	3704.23	7.73	0.55	16.93	439623.05	69.12	288.92	5477.86	302.28	2.53	50.750	51.89	479.29	0.669	1.807	99.47	670.72
85	5884	165.3	2778.17	5.79	0.29	14.13	379058.28	69.22	289.35	4716.05	302.17	2.22	50.970	51.89	479.94	0.700	1.806	100.70	672.93
90	6242	119	1852.11	3.85	0.02	11.34	316408.33	69.36	289.91	3929.10	302.10	1.85	51.210	51.90	480.75	0.700	1.806	102.00	675.27
95	6603	64.3	926.06	1.92	0.00	11.13	311582.57	69.51	290.53	3860.84	302.10	1.82	51.470	51.90	481.40	0.701	1.806	103.40	677.79
99.99	6967	0.1	1.85	0.00	0.00	11.13	311582.57	69.68	291.25	3851.32	301.99	1.82	51.740	51.90	482.21	0.702	1.805	104.90	680.49

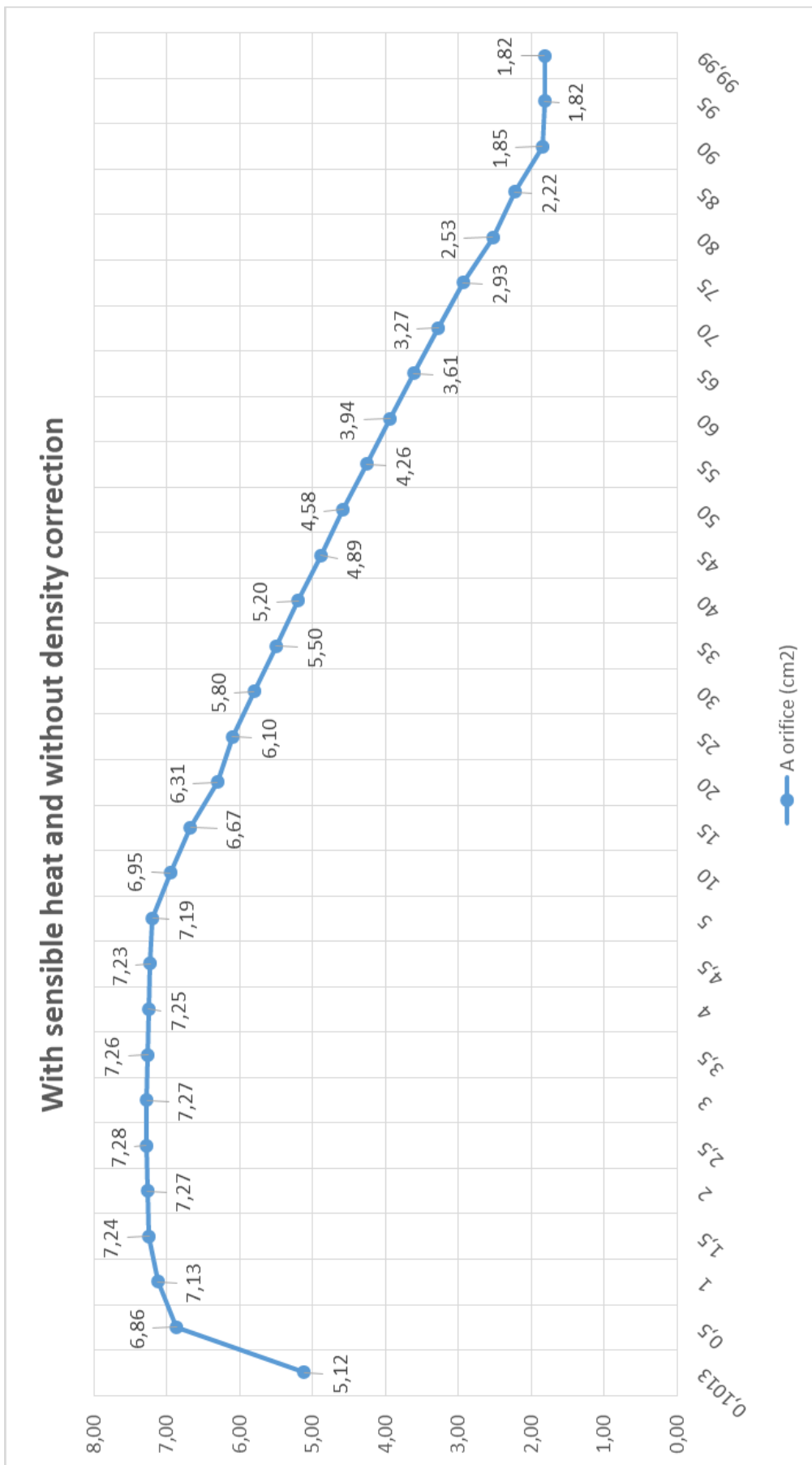


Figure 4.12 Representation PRD area with sensible heat, without density correction

4.5 Comments

Table 4.20 shows the summary of all the cases previously analysed.

Table 4.20 Summary all methods for calculate PSV area relief

Method	Simulation	Sensible heat	Vapor density correction	% vaporization	Flow (kg/h)	PSV Area Required (cm ²)
Dynamic	Prophet, N., (2019)	With	With	-	10899	5,06
	ASPEN HYSYS™ v10	With	With	30%	11670	5,00
	PSPPM™	Without	Without	5 to 30%	17147	8,16
	PSPPM™	With	Without	5 to 30%	14305	6,79
Steady-State	Prophet, N., (2019)	With	Without	5 to 30%	12522	5,38
Semi-Dynamic	ASPEN HYSYS™ v10	Without	With	30%	12419	5,86
	ASPEN HYSYS™ v10	With	With	30%	10961	5,17
	ASPEN HYSYS™ v10	Without	Without	30%	13932	6,57
	ASPEN HYSYS™ v10	With	Without	30%	12297	5,80

As can be seen in the table 4.20, different percentage vaporization points have been found with their different flow rates.

In the case **without sensible heat with vapor density correction**, the data cannot be contrasted, since it has only been calculated for the semi-dynamic case.

In the case **with sensible heat with vapor density correction**, two studies have been carried out for the dynamic method, a study carried out by Prophet, N.

The second made with ASPEN HYSYS™ v10. The area values for PRV resulting from both studies are 5,06 cm² and 5,00 cm², respectively.

In the semi-dynamic study performed, a relief area for PRV of 5,17 cm² was obtained.

Table 4.10 shows the case **with sensible heat without vapor density correction**, at this point there is only simulation data with the PSPPM™ software. According to the report available the vaporization range contemplated by the software is between 5% and 30% and does not define the exact point at which the values obtained are measured. The flow rate can be taken as a reference, which does give a fixed value of 14305 Kg/h and a relief area for the PRV of 6,79 cm².

It is also observed as in the results obtained in the Steady State of Prophet, N. et al. (2019), it is not known the percent of vaporization, but having the flow rate, which is 12522 Kg/h with a relief area for PRV of 5,38 cm².

Regarding the method in the table 4.20, previous results can be contrasted.

For the PSPPM™ method, which does not know exactly the percent of vaporization, but rather the range, it can show the flow rate that is the closest in the study is at the point of 15% vaporization, with a flow rate of 14136 Kg/h, and an area of 6,67 cm².

To contrast the result of the method of Prophet, N., by also ignoring the percent of vaporization it focuses on the flow rate, it is seen that the flow rate that is the closest in the study is a flow rate of 12297 kg/h, which corresponds to a 30% vaporization, resulting in an area for the PRV of 5,80 cm².

In the case of **without sensible heat without vapor density correction**, the study was carried out with the dynamic method with the PSPPM™ software, obtaining a vaporization range of 5 to 30%, a flow rate of 17147 kg/h and a relief area for the 8,16 cm² PRV.

Looking at the results obtained in the semi-dynamic method for a relief flow similar to that of the PSPPM™ method, it can be seen that at a vaporization percentage of 10%, we have a flow rate of 17320 kg/h, obtaining a relief area for the PRV of 8,18 cm².

5. Comparison for the scenario of Gas blow-by/Vapor breakthrough

This section develops a case study based on the gas blow-by/vapor breakthrough scenario.

5.1 Description for the case study

In this case it will be described a vessel overpressure scenario, produced by high pressured gas input in a vessel designed for low pressure.

The studied installation is showed in the figure 5.1.

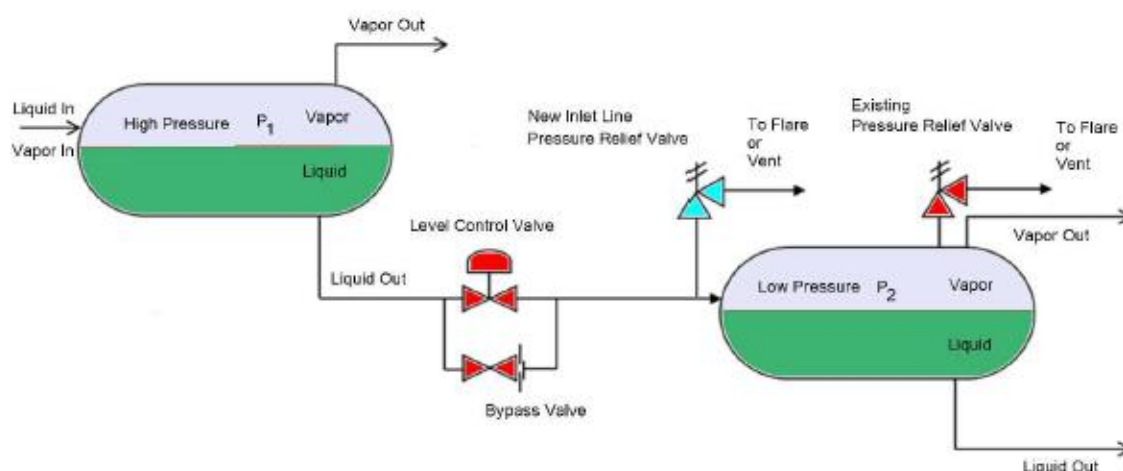


Figure 5.1 Example gas blow-by scenario due to control valve failing wide-open. (Taken from Melhem G.A. et al. (2016))

In this case, it can be considered the following hypothesis:

- The first vessel above works with a higher pressure than the second.
- No liquid inputs are considered in any vessel, however vapor inputs might be considered.
- The valve installed in the pipe connected to both vessels, has a fail-open configuration.
- There are no pumps in the pipe connecting both vessels.

Table 5.1 shows a summary of the characteristics of the installation.

Table 5.1 Liquid displacement scenarios data summaries. (Taken from Melhem G.A. et al. (2016))

HPV Upstream vessel	LPV Downstream vessel	Flow limiting element	Relief system
Horizontal cylindrical vessel with hemispherical heads	Horizontal cylindrical vessel with 2:1 elliptical heads	Control valve with a port size= 7,303 cm	Piping liquid inventory= 0,83 m ³
Liquid volume = 47,82 m ³ or 47,6 %	Liquid volume = 39,36 m ³ or 64,8 %	CV: 23	Two 6Q8 PRVs in service
Total volume = 100,46 m ³	Total volume = 60,709 m ³	Effective control valve ideal flow area = 3,90 cm ²	Set points of 10,34 and 10,82 barg
P = 131 barg	P = 5,17 barg		API flow area: 70,97 cm ²
T = 324,82 K	T = 329,26 K	Liquid Cd = 1(*)	
	MAWP = 10,34 barg		Gas / two phase Cd= 0,975
Initial contents in vapor space, hydrogen and some light hydrocarbons (MW ranging from 2 to 3,9)	Initial contents in vapor space, hydrogen and some light hydrocarbons (MW ranging from 2 to 3,9)		Total existing relief flow area= 142 cm ²
Initial contents in liquid space, sour water	Initial contents in liquid space, sour water		
	Normal outflow rate for sour water= 136,27 m ³ /h		

(*) The authors of the paper confirmed Cd:1 and not Cd: 0,71.

In this study some scenarios are considered, assuming that in all of them the valve which links both vessels has suffered a failure and gets to the open point thus all the liquid volume

stored in the vessel above (High Pressure Vessel HPV) will refill the vessel below (Low Pressure Vessel LPV), letting the HPV empty and raising the liquid level in the LPV significantly.

Considering the nature of the liquid transferred from HPV to LPV is uniform, an increase of the liquid volume in the LPV will be caused. If the vessel is not able to remove this liquid volume, the pressure will grow, forcing the existing relief valve to open and relieving the overpressure suffered by the LPV.

Taking into account the volume of product that the two vessels contain and its volume, it is possible that LPV floods, in that case the flow that the PRVs will alleviate can be biphasic or liquid phase one.

If the area of the PRVs is not big enough to relieve the pressure which was originally designed, it could arrive to a point where the LPV pressure match the HPV pressure causing the loss of the mechanical integrity in LPV.

It has to be remarked that LPV has a continuous liquid purge by the low part with a constant flow. The HPV has no liquid input, so there will be a moment that LPV will not receive liquid and will receive vapor only.

Considering the liquid level in LPV is high enough to get the vapor phase in it, producing bubbles that could cause as getting two phases in the relief process.

In the following table 5.2 it is showed the different cases for this scenario:

Table 5.2 Different scenarios to study. (Taken from Melhem G.A. et al. (2016))

Case A	Case B	Case C	Case D
Start-up	Start-up	Start-up	Normal operation
Gas MW= 2	Gas MW= 3,7	Gas MW= 2 and 3,7	Gas MW= 3,7
Control valve wide open	Control valve wide open	Control valve wide open	Control valve wide open
Only gas flow into HPV	Only gas flow into HPV	Only gas flow into HPV	Gas and liquid flow into HPV
600 GPM ⁽¹⁾ liquid outflow from LPV	600 GPM liquid outflow from LPV	Outflow from LPV is blocked	Normal inflow and outflows from HPV and LPV
HPV P= 131 barg	HPV P= 131 barg	HPV P= 131 barg	HPV P= 126,52 barg
Case A	Case B	Case C	Case D
Start-up	Start-up	Start-up	Normal operation
Gas MW=2	Gas MW=3,7	Gas MW= 2 and 3,7	

(1) GPM: Gallons (US) per minute.

Next table 5.3 the vapor composition is shown at MW=2 or at MW=3,7.

Table 5.3 Gas molecular fraction at two molecular weight. (Taken from Melhem G.A. et al. (2016))

COMPONENT	MOLE FRACTION (MW=2 kg/kmol)	MOLE FRACTION (MW=3,7 kg/kmol)
Hydrogen	0,92481	0,99800
Methane	0,04052	0,00108
Ethane	0,00954	0,00025
Hydrogen sulphide	0,01824	0,00049
Propane	0,00377	0,00010
n-butane	0,00312	0,00008

5.2 Literature survey of relief load calculation methods

This study is intended to describe the gas blow-by (also known as vapor breakthrough) overpressure scenario. This complex variation of inlet control valve failure may occur in cases of a pressure vessel operating at a high pressure, whose liquid bottoms are on level control, discharging into a lower-pressure system.

The inlet control valve failure scenario is an applicable overpressure contingency when the upstream normal operating pressure exceeds the downstream systems maximum allowable working pressure (MAWP). In addition, gas blow-by must be considered. Blow-by can occur when this type of inlet control valve fails open, emptying the upstream vessel liquid inventory into the downstream vessel of interest, with subsequent vapor or two-phase flow into the downstream vessel.

When this occurs, the relief devices on the low-pressure system should be designed to handle the vapor flow through the liquid control valve. It is quite possible that the downstream vessel is not designed to withstand volumes and pressures like the upstream vessel.

In the situation where the upstream vessel is being emptied into the downstream vessel, these situations in the downstream vessel can be created:

- That the downstream vessel has enough volume to store the product from the upstream vessel without completely flooding.
- That the downstream vessel does not have enough volume to store the product from the upstream vessel, in this case it would be completely flooded.

Once the liquid has been emptied from the upstream vessel, the product will continue to be transferred, but in this case it will be in the gas phase. This means that the operating conditions of the downstream vessel will equal those of the upstream vessel.

Dynamic modelling allows you to analyse:

- Increase in temperature and pressure of the contents of the container with the passage of time.
- Phase, fluid level, and volume changes over time.
- Time and duration of pressure valve relief.

To model this scenario dynamically, some characteristics of the installation components must be known (Faulk, Aldeeb, 2015).

The following characteristics of the upstream vessel must be known:

- Vessel orientation - vertical, horizontal or spherical. Vessel dimensions.

- Type of head - elliptical, conical, round, or flat.
- Liquid level; if unknown, a conservative estimate may be made based on vessel orientation, heads, and dimensions.
- Elevation of outlet nozzle connected to piping which flows to the control valve - measured relative to the bottom tangent line if a vertical vessel, and relative to the bottom of the vessel if horizontal.
- Additional liquid volume; only used if this liquid volume (in boot or piping) is relevant to the volume draining into the downstream vessel.

It is also necessary to know the following characteristics of the downstream vessel:

- Vessel orientation - vertical, horizontal or spherical.
- Vessel dimensions.
- Type of head - elliptical, conical, round, or flat.
- Liquid level; if unknown, a conservative estimate may be made based on vessel orientation, heads, and dimensions.
- Elevation of inlet nozzle connected to piping which flows from the control valve - measured relative to the bottom tangent line of a vertical vessel, and relative to the bottom of the vessel if horizontal.
- Pressure relief device set pressure.
- Indication of whether a high level alarm is present, independent of the potential failure mechanisms. If there is intent to take credit for operator intervention in the event of overfilling, the time for operator intervention is also needed.

The following characteristics of the control valve will also be required:

- Control valve size.
- Manufacturer.
- Model specifications are required in order to obtain the appropriate valve coefficients.

Knowing the liquid volumes of the upstream vessel and the downstream vessel when the failure valve opening scenario occurs, may be that the relief device installed in the downstream vessel not only relieves gas but it can also relieve fluid.

Figure 5.2 shows a scenario in which the upstream vessel has been emptied below the product outlet mouth, and the downstream vessel has been filled below the product inlet mouth. Therefore, no more liquid will be transferred and the only thing that will be transferred is gas. In this case the PRD will only relieve gas.

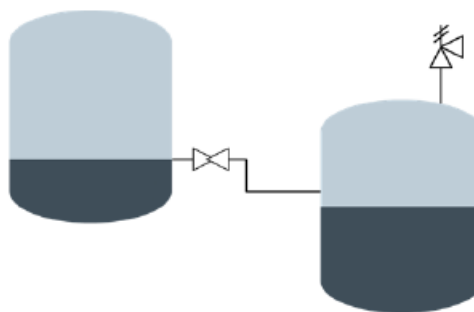


Figure 5.2 Liquid level in downstream vessel is below inlet nozzle. (Taken from Faulk, Aldeeb, 2015)

Figure 5.3 shows the scenario in which the upstream vessel has emptied below the product outlet nozzle, and the downstream vessel has been filled above the product inlet mouth, but the water vessel downstairs has not been fully filled.

This situation causes that at the time the gas enters, a bubbling occurs in the liquid in the downstream vessel and this causes the volume of the liquid to increase.

It is possible that in this scenario, the PRD alleviates two phases.

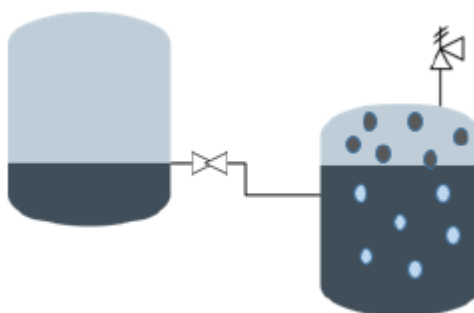


Figure 5.3 Liquid level in downstream vessel is above inlet nozzle. (Taken from Faulk, Aldeeb, 2015)

Figure 5.4 shows the scenario in which the upstream vessel has been emptied below the product outlet mouth, and the downstream vessel has been filled above the product inlet mouth and the downstream vessel it has been completely filled.

In this situation there are two relief situations for the PRD. Initially, as the downstream vessel fills, the PRD depressurizes gas. When the downstream vessel is full, the PRD relieves liquid or gas / liquid. This will be the case until the PRD has been able to evacuate the volume of liquid equal to the volume of gas that is entering it.

When the fluid level has dropped low enough, the PRD will only relieve gas again. This scenario is very important, since the relief surface of the PRD changes a lot if it has to relieve only gas, or has to relieve a two-phase flow. A two-phase or liquid flow will make the surface of the PRD nozzle need to be larger.

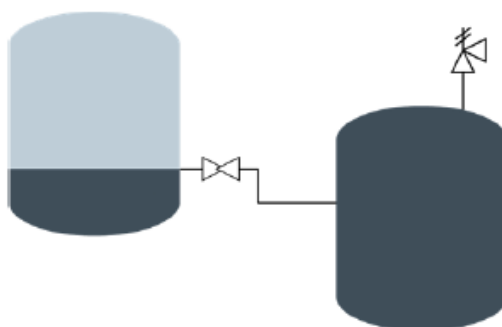


Figure 5.4 Downstream vessel overfills (Taken from Faulk, Aldeeb, 2015)

5.3 Results of the dynamic simulation

To run the dynamic study, it is known that at the beginning of the product transfer between HPV and LPV, when the fluid has a MW 2,063 goes through the control valve, producing a flash which makes a pressure drop to 926 psig and a temperature drop at 267,43 K (21,7 °F). When all the fluid almost gets transferred completely between HPV and LPV, the fluid will have a MW 3,77 and a pressure drop and temperature of 63,60 barg (922,5 psig) and 274,26 K (34 °F) respectively.

As it is pointed out previously the LPV has two valves with a set pressure of 10,34 and 10,82 barg (150 and 157 psig), however according to API 520-2020 rule the pressure is about

$10,34 \cdot 1,16 = 11,99$ barg and $10,82 \cdot 1,16 = 12,55$ barg ($150 \cdot 1,16 = 174$ psig and $157 \cdot 1,16 = 182,12$ psig). Therefore when LPV's pressure reaches 11,99 barg (174 psig), one of the two valves will get opened in order to relief the pressure.

According to the details of the previous table 5.1, the HPV and the pipe have a total liquid volume of $48,65 \text{ m}^3$ while the free space of vapor in the LPV is just $21,53 \text{ m}^3$.

The flow from HPV to LPV is $218,15 \text{ m}^3/\text{h}$. LPV have a blowdown capable of evacuating a flow of $600 \text{ US GPM} = 136,27 \text{ m}^3/\text{h}$.

The time required to get the HPV:

$$\frac{48,65 \text{ m}^3}{218,15 \text{ m}^3/\text{h}} = 0,223 \text{ h} = 13,38 \text{ min} \quad (30)$$

During this time of flow transferring, the LPV will evacuate:

$$0,223 \text{ h} \cdot 136,27 \text{ m}^3/\text{h} = 30,38 \text{ m}^3 \quad (31)$$

Therefore, is possible to know the highest volume the LPV will have in these conditions:

$$V_{HPV} + V_{LPV} - V_{blowdown_{LPV}} = 48,65 + 39,36 - 30,38 = 57,63 \text{ m}^3 \quad (32)$$

That means the highest level of the LPV will be:

$$\frac{V_{\text{max water LPV}}}{V_{LPV}} = \frac{57,63}{60,71} = 0,95 = 95\% \quad (33)$$

The fact that the LPV's level reaches 95% might cause the fluid which flows through the PRVs get two phases. In the dynamic simulation using SuperChems™ Expert, according to the Melhem et al. (2016), it is proved both PRVs are ready to work with two phase fluids.

Figure 5.5 shows this scenario.

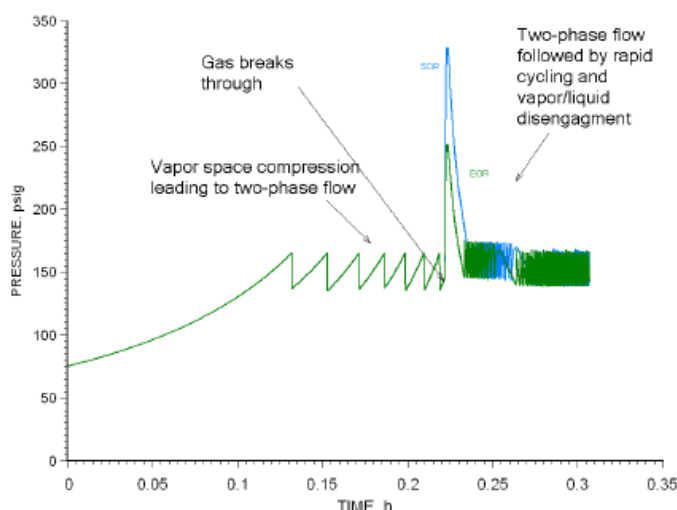


Figure 5.5 Pressure histories for cases A and B in LPV. (Taken from Melhem G.A. et al. (2016))

Figure 5.6 shows the flow rate of vapor and biphasic that passes through the relief valve, set to a pressure set of 150 psig, when it opens due to the pressure in the vessel reaching the pressure set of the valve.

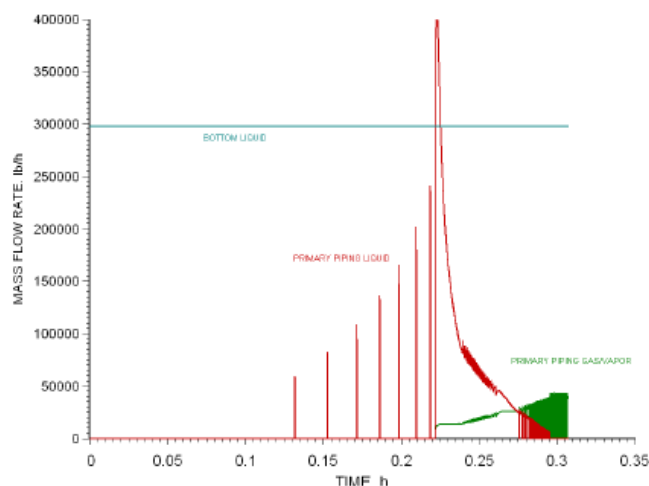


Figure 5.6 Flow history from first PRV set at 150 psig. (Taken from Melhem G.A. et al. (2016))

Figure 5.7 shows the flow rate of vapor and biphasic that passes through the relief valve, set to a pressure set of 157 psig, when it opens due to the pressure in the vessel reaching the pressure set of the valve.

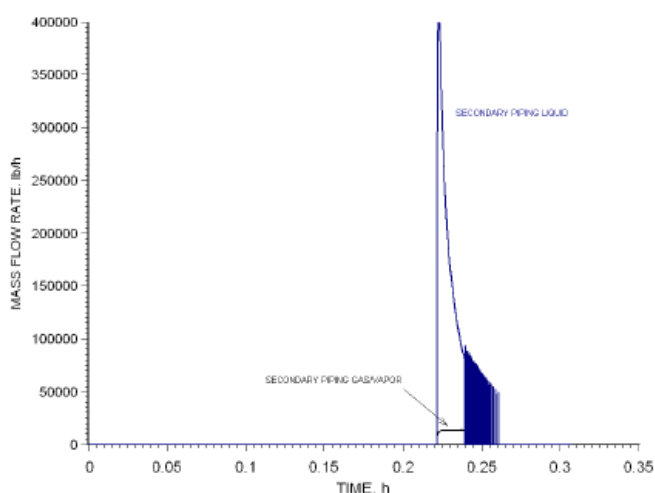


Figure 5.7 Flow history from second PRV set at 157 psig. (Taken from Melhem G.A. et al. (2016))

Previous figures 5.5, 5.6 and 5.7, it can be seen that as the liquid level raises the vapor get compressed and the pressure increases. Having two PRVs with a set pressure of 11,99 barg (174 psig) y 12,55 barg (182 psig) respectively, the first one will open before the other.

That happens until the time reaches 0,223 h where the level raises to 95%. In this moment the pressure rapidly increases exceeding both valves set, making both valves get opened. Also, in this moment the fluid flowing through the PRVs has two phase flow.

In this study it can be clarified that the two valves are not well dimensioned for a two phases flow, because both valves completely opened are not able to relieve the LPV overpressure. It is known that after this moment, the transfer from HPV to LPV has finished, therefore the LPV level starts to drop because its purge valve it is open. Figure 5.8 shows:

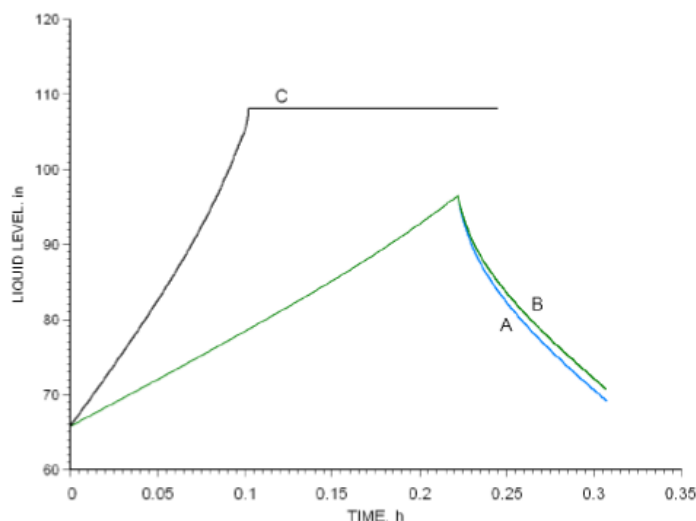


Figure 5.8 Liquid level histories for cases A, B and C. (Taken from Melhem G.A. et al. (2016))

Previous figure 5.8 the levels progression of the cases A, B and C are shown, but in the last one the LPV purge valve it is closed so the LPV level increase quicker than the cases A, B and D.

Therefore, the LPV will be flooded when 21,35 m³ had been transferred. The time required will be:

$$\frac{21,35 \text{ m}^3}{218,15 \text{ m}^3/\text{h}} = 0,0978 \text{ h} = 5,87 \text{ min} \quad (34)$$

Once the LPV gets flooded it will have reached 131 barg pressure and a liquid phase fluid will flow through the PRVs.

With the dynamic analysis and using SuperChems™ Expert, the flow of the PRV when the pressure reaches 11,99 barg have been calculated at same the time they have been established for MW: 2,063 a 266,81 K expansion temperature and a 9,177 m³/h flow.

Table 5.4 shows the calculation of the PRV area is performed with the dynamic method, obtaining the following results in the PRV area;

Table 5.4 Summary of Dynamic solution Melhem, G. B. et al. (2016)

Molecular Weight	Flow Rate (m ³ /h)	Relief Area PRV (cm ²)
2,063	9177	539
3,77	6760	397

5.4 Steady State Method with ASPEN HYSYS™ v10

In order to carry out the simplified study, the pressure drop produced by the valve during the transfer of product from HPV to LPV had to be simulated with ASPEN HYSYS™ v10, and the output of product through the PRV has also been simulated. In this way, temperatures produced by pressure changes in the system have been simulated.

The ASPEN HYSYS™ v10 circuit diagram used is shown below:

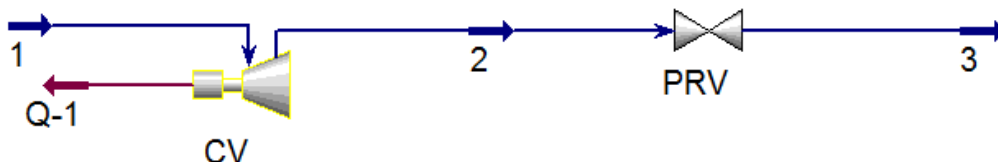


Figure 5.9 Flowsheet with ASPEN HYSYS™ v10

Table 5.5 shows a description of the components used in the flowsheet diagram above:

Table 5.5 Summary components figure 5.9

COMPONENT	DESCRIPTION
Flow 1	Fluid conditions HPV
CV	Valve between HPV-LPV
Flow 2	Fluid condition after CV
PRV 150 psig	PRV adjusted 174 psig
Flow 3	Fluid condition after PRV

Tables 5.6 and 5.7 shows details by ASPEN HYSYS™ v10.

Case A

Table 5.6 Summary case A

Molecular weight	2,063 kg/kmol
Backpressure valve	67,1 barg
Backpressure valve temperature	266,8 K
Temperature expansion PRV	266,4 K

Case B

Table 5.7 Summary case B

Molecular weight	3,77 kg/kmol
Backpressure valve	67,4 barg
Backpressure valve temperature	268,7 K
Temperature expansion PRV	267,3 K

To calculate the areas of the PRVs, it is necessary to find the flow that will circulate through them. For this, the Masoneilan manual, (Ref VSH) has been used, to be able to understand the procedure and the characteristics of a valve with a c_v : 23 [gpm][psi].

The formulas used for this calculation are:

Critical pressure

$$\Delta P_c = P_1 - P_2 \quad (35)$$

- ΔP_c : Pressure difference between inlet pressure P_1 and outlet pressure P_2 .
- P_1 : Inlet pressure in absolute bar (bara).
- P_2 : Outlet pressure in absolute bar (bara).

$$\Delta P_c = 0,5 * C_f^2 * P_1 \quad (36)$$

- C_f : Valve critical flow factor.

Flow calculation

$$C_v = \frac{Q * \sqrt{G * T_{HPV}}}{257 * C_f * P_1} \quad (37)$$

- C_v : Flow coefficient (U.S. gallons/min).
- Q : Flow rate (m³/h).
- T_{HPV} : Temperature (K).
- G : Gas density (air = 1).

$$G = \frac{MW}{MW_{air}} \quad (38)$$

Relief area

$$A = \frac{11,78 * Q}{K_d * K_w * K_c * K_v} * \sqrt{\frac{G_1}{P_1 - P_2}} \quad (39)$$

- A : Area (mm²).
- Q : Flow rate (L/min).
- K_d : 0,71 (Melhem et al. (2016)).
- K_w : 1, Atmospheric pressure.
- K_c : 1.
- K_v : 1.
- G_1 : Specific gravity of the liquid.
- P_1 : Relieving pressure, KPag.
- P_2 : Backpressure, kPag.

Case A (MW 2,063)

Critical pressure

$$\Delta P_c = 131 - 67,15 = 63,85 \text{ barg} \quad (40)$$

$$63,85 = 0,5 * C_f^2 * 132 \rightarrow C_f = 0,983 \quad (41)$$

Flow

$$23 = \frac{Q * \sqrt{\frac{2,063}{28,97} * 324,82}}{257 * 0,983 * 132} \rightarrow Q = 159475 \text{ m}^3/\text{h} \quad (42)$$

Pressure and temperature compensation

$$Q = 159475 \text{ m}^3/\text{h}@15^\circ\text{C a } 1,013\text{bara} * \frac{1,013}{13,01} * \frac{266,45}{273 + 15} = 11488 \text{ m}^3/\text{h} \quad (43)$$

$$11488 \text{ m}^3/\text{h} \rightarrow 191466 \text{ L}/\text{min} \quad (44)$$

Area required

$$A = \frac{11,78 * 191466}{1 * 1 * 1 * 1} * \sqrt{\frac{1}{1200 - 0}} = 65110 \text{ mm}^2 \rightarrow 651 \text{ cm}^2 \quad (45)$$

Case B (MW: 3,77)

Critical pressure

$$\Delta P_c = 131 - 67,40 = 63,60 \text{ barg} \quad (46)$$

$$63,60 = 0,5 * C_f^2 * 132 \rightarrow C_f = 0,982 \quad (47)$$

Flow

$$23 = \frac{Q * \sqrt{\frac{3,77}{28,97} * 324,82}}{257 * 0,982 * 132} \rightarrow Q = 117850 \text{ m}^3/\text{h} \quad (48)$$

Pressure and temperature compensation

$$Q = 117850 \text{ m}^3/\text{h}@15^\circ\text{C a } 1,013\text{bara} * \frac{1,013}{13,01} * \frac{267,31}{273 + 15} = 8517 \text{ m}^3/\text{h} \quad (49)$$

$$8517 \text{ m}^3/\text{h} \rightarrow 141950 \text{ L}/\text{min} \quad (50)$$

Area required

$$A = \frac{11,78 * 141950}{1 * 1 * 1 * 1} * \sqrt{\frac{1}{1200 - 0}} = 48271 \text{ mm}^2 \rightarrow 483 \text{ cm}^2 \quad (51)$$

Table 5.8, the simulation values with ASPEN HYSYS™ v10 are shown.

Table 5.8 Summary Steady State Calculations

Molecular Weight	Flow Rate (m³/h)	Relief Area PRV (cm²)
2,063	11488	651
3,77	8517	483

5.5 Comments

Once the two analyses have been carried out, it can be seen how in the dynamic study as the LPV product level increases, one of the PRVs has a set point of 10,34 barg, and is capable of dislodging the overpressure that is generated in the LPV, without the need for the PRV set to relieving a set point of 10,82 barg to act.

The problem with these PRVs is that when the LPV vessel has been flooded, and through the PRVs there is only liquid phase product, the relief devices are not capable of relieving the overpressure in the LPV. Therefore, it can be said that PRVs do not adequately protect the LPV, and in figure 5.5 it can be seen clearly since the LPV pressure increases near 22,75 barg (330 psig) in time approximately 0,223 h, when initially it should not have exceeded the pressure of 10,82 barg (157 psig).

In the dynamic study, Melhem, G.A., the calculation of the area of the PRVs has been carried out, for a MW: 2,063 and MW: 3,77 obtaining a relief area of the PRVs of 539 cm² and 397 cm² respectively.

Therefore, the relief area to which the PRVs had been initially designed is insufficient.

Table 5.9, a summary of the values and the calculated values can be seen.

Table 5.9 Summary results of Dynamic Simulation and Simplified approach

Method	Author	Molecular Weight	Flow Rate (m³/h)	Relief Area PRV (cm²)
Dynamic	Melhem, G. A.	2,063	-	142(*)
Dynamic	Melhem, G. A.	3,77	-	142(*)
Dynamic	Melhem, G. A.	2,063	9177	539
Dynamic	Melhem, G. A.	3,77	6760	397
Steady state	Estorach, J.	2,063	11488	651
Steady state	Estorach, J.	3,77	8517	483

(*) Area initially existing in dynamic simulation. See table 5.1.

In the table 5.9, the values obtained in my steady state study and that of Melhem, G. A., do not match 100%. My calculation is much more conservative than that of Melhem, G. A., indicating that it is possible that some of the values used by Melhem, G. A., do not correspond to mine.

One of the factors that can influence the discrepancy of the areas obtained may be the Cf of the valve contemplated in the Melhem, G.A. et al. (2016), so knowing the values obtained in their study, the calculations have been made to find the Cf of the valve assumed by Melhem, GA, obtaining the following results.

CASE A, MW: 2,063

Calculating flow without temperature and pressure compensation;

$$Q * \frac{1,013}{13,01} * \frac{266,82}{273,15 + 15} = 9177 \text{ m}^3/\text{h} \rightarrow Q = 127282 \text{ m}^3/\text{h} \quad (52)$$

Calculating the C_f of the valve;

$$23 = \frac{127282 * \sqrt{\frac{2,063}{28,97} * (273,15 + 51,67)}}{257 * C_f * 132} \rightarrow C_f = 0,785 \quad (53)$$

CASE B, MW: 3,77

For case B, the flow rate is calculated without compensating for temperature and pressure;

$$Q * \frac{1,013}{13,01} * \frac{265,54}{273,15 + 15} = 6760 \text{ m}^3/\text{h} \rightarrow Q = 94211 \text{ m}^3/\text{h} \quad (54)$$

Calculating the C_f of the valve;

$$23 = \frac{94211 * \sqrt{\frac{3,77}{28,97} * (273,15 + 51,67)}}{257 * C_f * 132} \rightarrow C_f = 0,785 \quad (55)$$

Carrying out calculations with a $C_f = 0,785$, the following flows and areas are obtained;

CASE A; MW: 2,063

Flow

$$23 = \frac{Q * \sqrt{\frac{2,063}{28,97} * 324,82}}{257 * 0,785 * 132} \rightarrow Q = 127353 \text{ m}^3/\text{h} \quad (56)$$

Pressure and temperature compensation

$$Q = 127353 \text{ m}^3/\text{h} @ 15^\circ\text{C} \text{ a } 1,013 \text{ bara} * \frac{1,013}{13,01} * \frac{266,45}{273,15 + 15} = 9169 \text{ m}^3/\text{h} \quad (57)$$

$$9169 \text{ m}^3/\text{h} \rightarrow 152817 \text{ L}/\text{min} \quad (58)$$

Area required

$$A = \frac{11,78 * 152817}{1 * 1 * 1 * 1} * \sqrt{\frac{1}{1200 - 0}} = 51967 \text{ mm}^2 \rightarrow 520 \text{ cm}^2 \quad (59)$$

Case B (MW: 3,77)

Flow

$$23 = \frac{Q * \sqrt{\frac{3,77}{28,97} * 324,82}}{257 * 0,785 * 132} \rightarrow Q = 94208 \text{ m}^3/\text{h} \quad (60)$$

Pressure and temperature compensation

$$Q = 94208 \text{ m}^3/\text{h}@15^\circ\text{C a } 1,013\text{bara} * \frac{1,013}{13,01} * \frac{267,31}{273,15 + 15} = 6805 \text{ m}^3/\text{h} \quad (61)$$

$$6805 \text{ m}^3/\text{h} \rightarrow 113417 \text{ L}/\text{min} \quad (62)$$

Area required

$$A = \frac{11,78 * 113417}{1 * 1 * 1 * 1} * \sqrt{\frac{1}{1200 - 0}} = 38568 \text{ mm}^2 \rightarrow 386 \text{ cm}^2 \quad (63)$$

Table 5.10 shows the summary steady state calculations when Cf value is 0,785.

Table 5.10 Summary Steady State Calculations, Cf valve 0,785.

Molecular Weight	Flow Rate (m³/h)	Relief Area PRV (cm²)
2,063	9169	520
3,77	6805	386

The following table 5.11 shows the comparison with the results of Melhem, G. A., with the new results obtained;

Table 5.11 Summary results of Dynamic Simulation and Simplified approach recalculation

Method	Author	Molecular Weight	Flow Rate (m³/h)	Relief Area PRV (cm²)
Dynamic	Melhem, G. A.	2,063	-	142 (*)
Dynamic	Melhem, G. A.	3,77	-	142 (*)
Dynamic	Melhem, G. A.	2,063	9177	539
Dynamic	Melhem, G. A.	3,77	6760	397
Steady state	Estorach, J.	2,063	9169	520
Steady state	Estorach, J.	3,77	6805	386

(*) Area initially existing in dynamic simulation. See table 5.1.

It looks like the resulting areas are practically identical.

6. Comparison for the scenario of heat exchanger tube rupture

This section develops a case study based on the heat exchanger tube rupture scenario.

6.1 Description for the case study

The Low Density Polyethylene Plants (LDPE) work at pressures of around 1000 or 1500 barg.

For polyethylene production it is necessary to have well controlled process temperatures and for this, heat exchangers are used. Below are some of the current exchanger types in the industry:

- Double tube.
- Compact.
- Casing tube.
- Plates.

A shell exchanger from a worldwide petrochemical company (21-E-0109) is used in the high-pressure polyethylene production process to maintain the required ethylene temperature.

Figure 6.1 shows the figure to heat exchanger design constants and heat exchanger data.

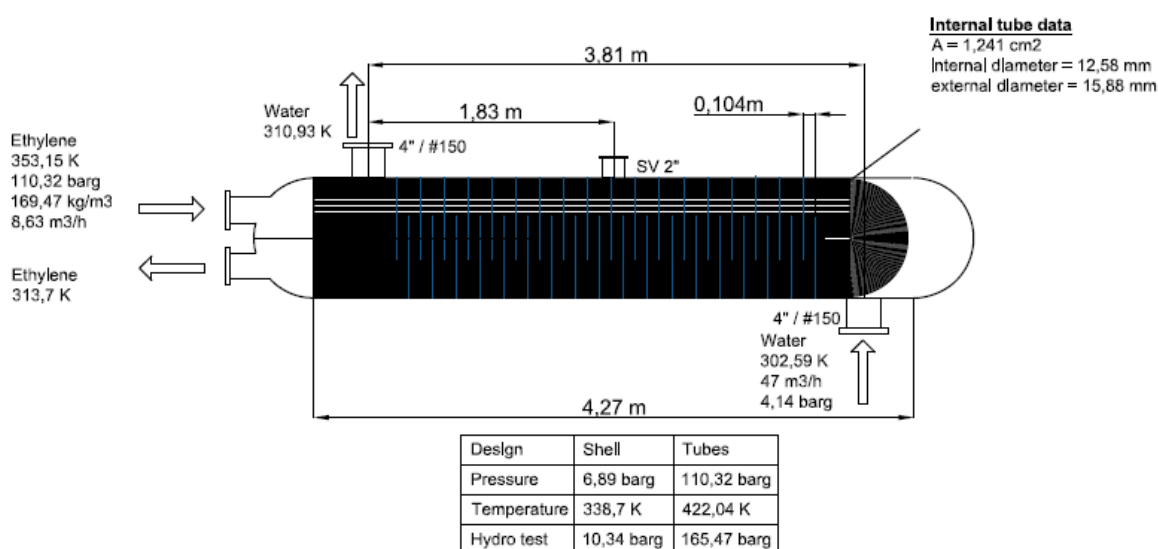


Figure 6.1 Heat exchanger data

Table 6.1 shows heat exchanger design constants.

Table 6.1 Heat exchanger design constants of 21-E-0109

Heat exchanger design constants		
Design	Shell	Tubes
Pressure	6,89 barg (100 psig)	110,32 barg (1600 psig)
Temperature	338,71 K (150 °F)	422,04 K (300 °F)
Hydro test	10,34 barg (150 psig)	165,47 barg (2400 psig)

The following table 6.2 shows the heat exchanger data:

Table 6.2 Shell data design

Shell data design	
Heat exchanger length	4,27 m (14,02 ft)
Heat exchanger outer diameter	32,38 cm (12,75 in)
Heat exchanger wall width	8,38 mm (0,33 in)
Number of U bends	70
U bend diameter	15,88 mm (5/8 in)
U bend wall width	3,30 mm (0,13 in)
U bend inner diameter	12,58 mm (0,50 in)
U bends length	3,99m (13ft 1 in)
Number of baffles	36
Distance between baffles	10,48 cm (4,125 in)

The table 6.3 shows the process conditions for ethylene:

Table 6.3 Supercritical ethylene gas data

Supercritical Ethylene Gas Data	
Initial temperature	353,1 K (176 °F)
Final temperature	313,7 K (105 °F)
Δ Temperature	39,4 K (71°F)
Pressure; P_0	111,3 bara (1614,4 psia)
Molecular Weight	28,05 (kg/kmol)
Gas ratio; γ (C_p/C_v)	1,096

The table 6.4 shows the water data:

Table 6.4 Water data

Water data	
Initial temperature	302,5 K (85 °F)
Final temperature	310,9 K (100 °F)
Density	1006,8 kg/m ³ (62,096 lb/ft ³)

According to API-521-2020, when the pressure difference between the fluid to be cooled and the refrigerant fluid is greater than 70 barg, it is mandatory to carry out a rupture study of one of the exchanger tubes, to analyse the response of the shell to the overpressure produced by the rupture.

In this case, the study takes into account that the tube rupture occurs at a point on the tube curve, this causes the flow of ethylene gas to escape from the pipe with an overpressure wave causing the displacement of the cooling water of the exchanger.

This will in fact cause an immediate pressure rise in the exchanger that will have to be controlled by the PRV to prevent the exchanger from cracking and breaking.

Another problem that occurs in a scenario of this type is that ethylene will escape in the gas phase through the PRV, which may produce an explosive atmosphere outside the vessel.

6.2 Literature survey of relief load calculation methods

One of the risk scenarios in the industry is the rupture of an internal tube of a heat exchanger. This sudden rupture produces the release of the fluid contained in the exchanger tubes and a sudden rise in pressure in the exchanger shell, if the pressure inside the exchanger tubes is higher than the pressure of the shell.

Exchanger tube failures or breaks can occur for various reasons such as:

- Metal erosion.
- Vibration fatigue.
- Thinning from overheating.
- Thermal fatigue.

Figure 6.2, the mentioned scenarios are shown;

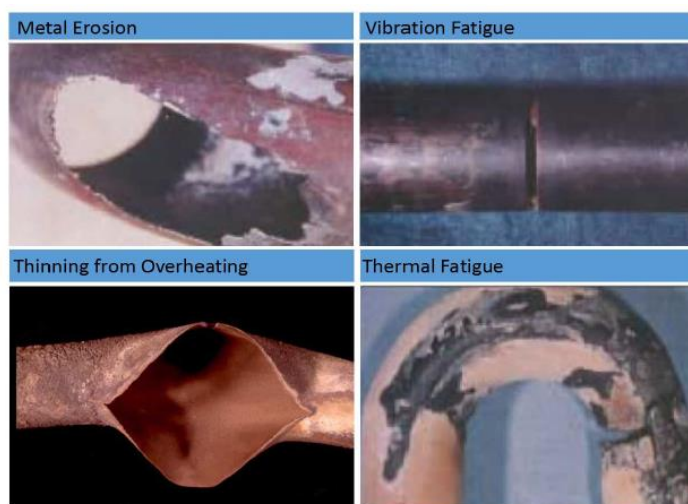


Figure 6.2 Typical heat exchanger tube failures. (Taken from Melhem et al. (2019)).

There are several factors that can cause the breakdown of these elements:

- Reverberation caused by the circulation of the fluid inside the tubes.
- Geometry of heat exchanger.
- Poor selection of building materials.
- Deficiencies in the construction of the heat exchanger.

Defects in the exchanger such as bad welds, corrosion or erosion of the pipes can cause vortices. These vortices can cause the tube to reverberate, vibrate or oscillate.

These effects can make long tubes or poorly supported tubes begin to move, causing the tubes to collide with each other or with the exchanger shell. As a result of these impacts,

it is possible that the tube is damaged in such a way that the area of passage of the fluid has decreased by crushing.

The typical points where the tubes have a higher percentage of breakage are:

- In U bends, the external lines have a lower natural frequency making them more susceptible to faults.
- Tube inlet and outlet nozzles.
- Areas where tubes are poorly supported or completely unsupported.
- Tubes located in deflector windows.

In the past, heat exchangers have been protected with rupture discs for an overpressure scenario caused by the rupture of an internal tube, this was because it was believed that rupture discs acted faster than PRVs.

This belief is no longer supported by The Energy Institute (2015) and The Institute of Petroleum (2000) studies, which confirms that a heat exchanger can be effectively protected with PRVs. The study concludes that the PRVs can open and release the overpressure in a time of 5 ms, on the other hand, the installation of non-fast acting rupture discs, can make it act with a time of 100 ms.

When a break appears in one of the heat exchangers tubes, with a time between 0,2 and 0,7 ms, the high-pressure gas causes an impact on the liquid creating an expansive wave, the duration of which will depend on factors such as the speed of sound, the type of liquid refrigerant or length of the heat exchanger. This shock wave will cause the liquid to move in the exchanger, causing it to exit through the PRVs.

The PRV relief process will make an initial cabal only in the liquid phase go from a two-phase flow, therefore, the PRV must be well dimensioned to be able to relief the overpressure fast enough so that the exchanger does not fracture.

6.3 Results of the dynamic simulation

The dynamic simulation of the rupture of the exchanger tube 21-E-0109, has been carried out in the dynamic analysis "Dynamic tube rupture evaluation 21-E-0109 & 21-E-0110".

To carry out this dynamic simulation, the volume of the exchanger has been divided into three parts, as shown in the following figure 6.3.

The model used was that of Sumaria et al. (1976).

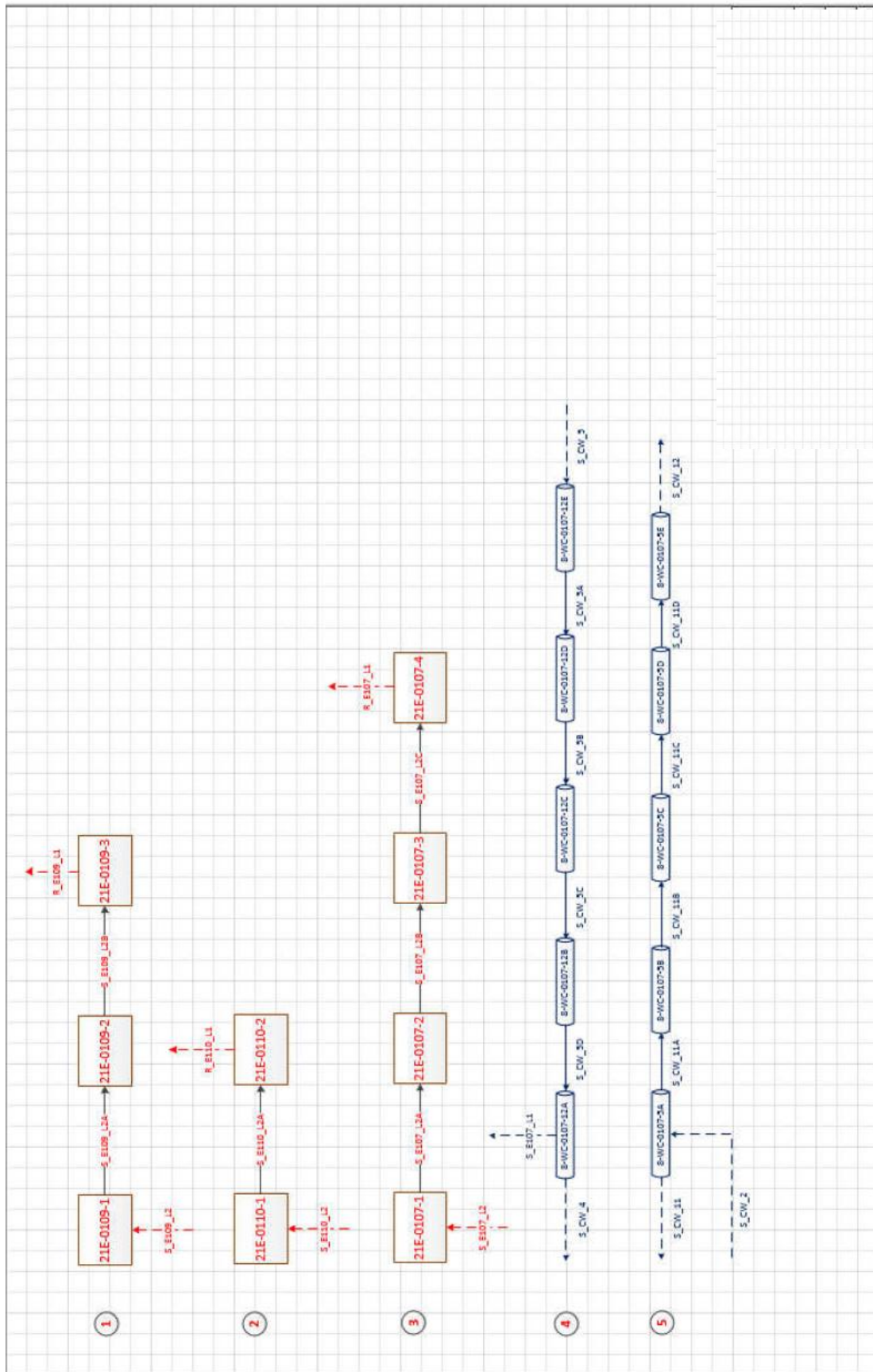


Figure 6.3 Schematic of the cooling water model for primary compression section (train 1) cooling water system in the LPDE unit. (Taken from a worldwide petrochemical company)

The following table 6.5 shows the volume control values obtained in each of the sections of the heat exchanger 21-E-0109.

Table 6.5 Control volumes sizes near the make-up 5th stage cooler W-5A (21-E-0109) and between 21-E-0109 to 21-RV-1050. (Taken from a worldwide petrochemical company)

Model CV Name	P&ID Tag/Line Number	Control Volume Size (ft³)	Comments
21E-0109-1	21E-0109-1 Shell	2,42	Tube rupture occurs here
21E-0109-2	21E-0109-2 Shell	2,42	
21E-0109-3	21E-0109-3 Shell	2,42	Tube rupture occurs here

The table 6.6 shows the maximum pressure reached by the tube break, in the heat exchanger segment, where the relief valve 21-RV-1050 is installed.

Table 6.6 Dynamic model peak pressure results for tube rupture in 21E-0109 with 21RV-1050. (Taken from a worldwide petrochemical company)

Tag	Exchanger Description	P&ID	MAWP (psig)	P_{Peak} (psig)	Accumulation (% Over MAWP)
21E-0109 (SS)	Make-Up 5 th Stage Cooler W-5A	4041-100-KE-01SHT3A-1 Rev. 44	100 ³	635	535%

The table 6.6 shows the maximum pressure value reached is 43,78 barg (635 psig). The value indicated in the table 6.6 can be compared with the following figure 6.4.

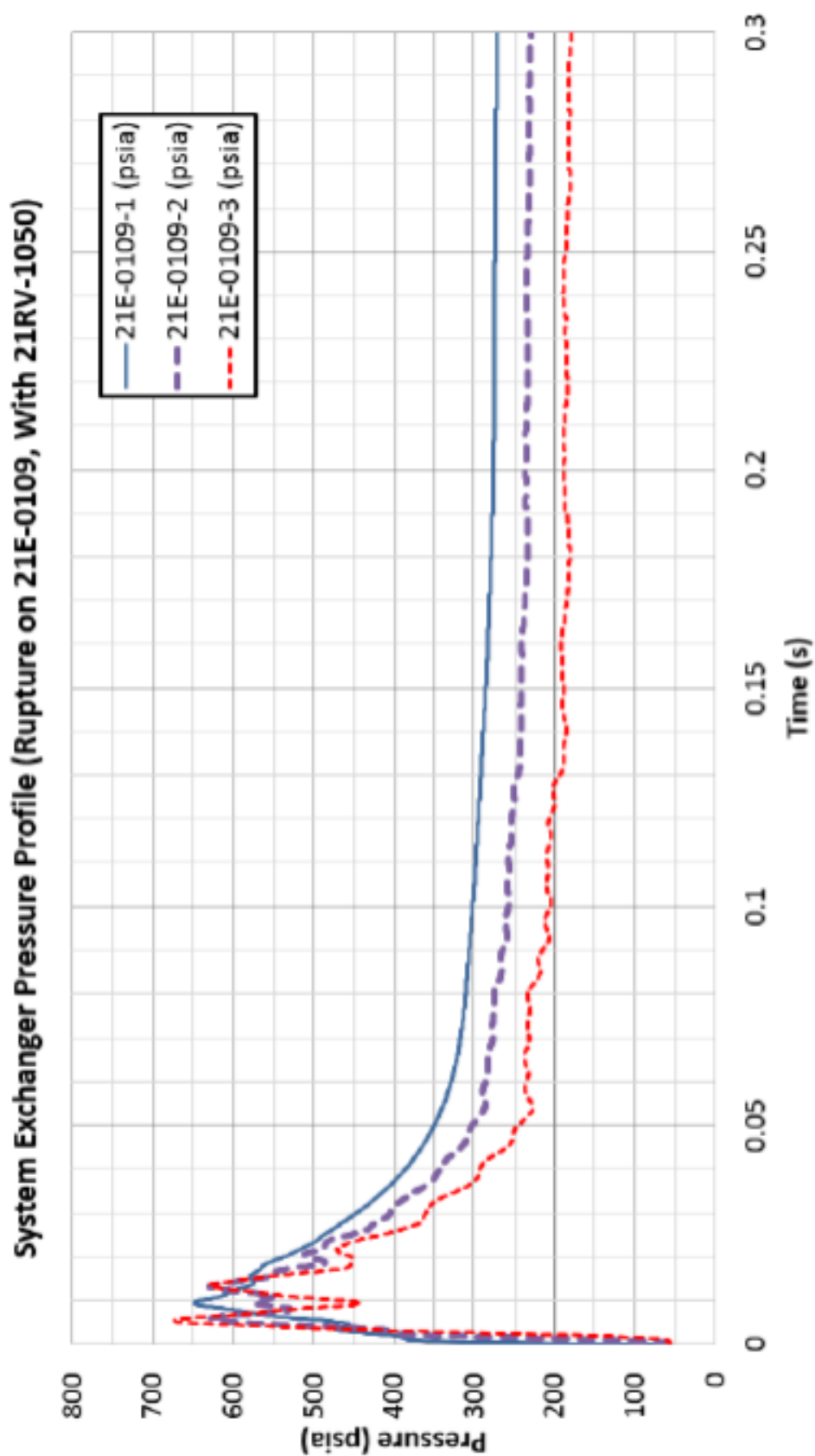


Figure 6.4 Pressure profile for 21-E-0109 (with 21RV1050). (Taken from a worldwide petrochemical company)

The previous figure 6.4 shows the reaction to pressure in the first milliseconds, from the rupture of the exchanger tube. Three lines are shown, each line corresponds to each of the segments in which the volume of the heat exchanger has been divided.

The first segment, 21-E-0109-1, in the first 10 milliseconds the pressure rises suddenly from a working pressure of approximately 3,44 bar (50 psia) to a pressure of approximately 44,82 bar (650 psia). The pressure reached in this segment is higher than that indicated in table 6.6 since in this segment there is no relief valve 21-RV-1050.

At the point of rupture, a wave is generated that raises the pressure in the segment to 44,82 bar. This wave will travel through the rest of the heat exchanger preventing the pressure from increasing further in this segment.

Looking at the second segment, 21-E-0109-2, the graph shows how, due to the wave, the pressure reaches 43,78 bar (635 psig), this is the value indicated in table 6.6 where one can locate the relief valve 21-RV-1050.

The wave will continue traveling through the exchanger until it passes the entire surface, and will not rise further in this segment due to the activation of the relief valve and the exchanger depressurizing.

In segment 21-E-0109-3, pressure reaches approximately 46,88 bar (680 psig). This is due to the fact that when the overpressure wave reaches the third segment, it no longer has any further to travel and thus is dampened. The wave rebounds at the end of the exchanger and returns, generating a greater overpressure than in any of the other two segments.

This sector shows how in the next 10 milliseconds, the pressure drops and rises again, this is due to the fact that the gas from the broken tube continues to be expelled and produce more overpressure waves, therefore the pressure in this segment continues to rebound until it finally stabilizes in approximately 50 milliseconds.

250 milliseconds after the tube rupture, the relief valve is fully open and the exchanger pressure has stabilized.

Segment 1, being the closest to the tube rupture, is the one that sustains the highest pressure, 18,96 bar (275 psia), segment 2, which contains RV, remains constant at a pressure of 16,89 bar (245 psia), and the third segment, is maintained at a lower pressure of 13,10 bar (190 psia).

Although the different pressures have stabilized 250 ms after the tube rupture, they are all above the design pressure of 6,89 bar (100 psia), and this can cause the exchanger to rupture.

6.4 Results of the simplified approach

The simplified approach is based on the publication of the Institute of Energy, London, 2015.

To calculate the volume of water inside the exchanger, the internal volume of the exchanger is calculated first;

$$\varnothing_{int\ shell} = 323,8 - (8,38 \times 2) = 307\ mm \quad (64)$$

Total number of tubes in the exchanger;

$$number\ of\ U\ bends = 70 \times 2 = 140 \quad (65)$$

Inside diameter of U bends;

$$\varnothing_{int\ U\ bends} = 15,88 - 3,30 = 12,58\ mm \quad (66)$$

Area through which ethylene escapes in gas phase;

$$A = \pi * \frac{D^2}{4} = \pi * \frac{12,58^2}{4} = 124,29\text{mm}^2 \quad (67)$$

U-bend length;

$$L_{U\ bend} = 3,99\text{m} \quad (68)$$

Volume of the shell;

$$\text{Volume of the shell} = V_{cylinder} + V_{head\ ellip\ 2:1} \quad (69)$$

$$\text{Volume of the shell} = \pi * L * \frac{D_{int\ shell}^2}{4} + \pi * \frac{D_{int\ shell}^3}{24} \quad (70)$$

$$\text{Volume of the shell} = \pi * 4,27 * \frac{0,307^2}{4} + \pi * \frac{0,307^3}{24} = 0,32\text{m}^3 \quad (71)$$

Volume of the U bends;

$$\text{Volume of the U bends} = n^{\circ}\ U\ bends * \pi * L * \frac{D_{ext\ U\ bends}^2}{4} \quad (72)$$

$$\text{Volume of the tubes} = (70 * 2) * \pi * 3,99 * \frac{(0,016)^2}{4} = 0,11\text{m}^3 \quad (73)$$

Volume of liquid in shell;

$$\text{Volume}_{liquid\ in\ shell} = \text{Volume}_{shell} - \text{Volume}_{tubes} = 0,32 - 0,11 = 0,21\text{m}^3 \quad (74)$$

The distance between baffles is known to be 10,48 cm.

Tube break at the top of the exchanger;

$$L_e = ((n^{\circ}\ baffles + 1) * D_{internal_shell}) + L_{shell} \quad (75)$$

$$L_e = ((36 + 1) * 307) + 4270 = 15629\ \text{mm} = 15,63\ \text{m} \quad (76)$$

Shell area

$$A_s = \frac{\text{Volume}_{liquid\ in\ shell}}{L_e} = \frac{0,21}{15,63} = 0,0134\text{m}^2 \quad (77)$$

Now the sonic velocity of the gas in the middle of the water has to be calculated. To do this, it is necessary to calculate the average temperature of the gas;

$$\frac{353,15 + 313,71}{2} = 333,43\ \text{K} \quad (78)$$

The sonic velocity of the gas is calculated;

$$a = \sqrt{\frac{\gamma * R * T}{MW}} = \sqrt{\frac{1,096 * 8314 * 333,43}{28,05}} = 329 \text{ m/s} \quad (79)$$

- a : Gas Sonic velocity (m/s).
- R : Gas constant (J/kmol*K).
- γ : Ratio of specific heats of the HP gas.

In order to calculate the maximum pressure point, which is in the first ms when the tube breaks, the following formula is used;

$$P_{is}(P_{is} - P_r)^\gamma = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} * P_0 * \left(\frac{C_D * a * \rho_l * c * A_t}{A_s}\right) \quad (80)$$

- P_{is} : Is the incident initial step pressure (Pa).
- P_r : Initial Shell pressure (Pa).
- C_D : Is the coefficient for discharge is the tube.
- A_t : Is twice the total cross-sectional area of the tube (m²).
- A_s : Is the characteristic shell area (m²).
- P_0 : Is the source pressure of the HP gas (Pa).
- ρ_l : Is the density of the liquid (kg/m³).
- c : Is the wave speed in the liquid (m/s).

$$P_{is}(P_{is} - 514985)^{1,096} = \left(\frac{2}{1,096 + 1}\right)^{\frac{1,096}{1,096 - 1}} * 11130896 * \left(\frac{0,62 * 329 * 995 * 1517,75 * 0,000124156}{0,0134}\right)^{1,096} \quad (81)$$

$$P_{is} = 4511783 \text{ Pa abs} = 45,12 \text{ bara} = 44,54 \text{ barg} = 645,97 \text{ psig} \quad (82)$$

6.5 Development of the spreadsheet Pis

For this case, a spreadsheet has been created, in which all the formulas used in the previous point are summarized.

In the spreadsheet, it is only necessary to enter the technical characteristics of the heat exchanger and gas data for the obtained value of Pis. In appendix C. figure 10.6 shows the spreadsheet.

6.6 Comments

The table 6.7 shows the results with the dynamic method and the simplified method;

Table 6.7 Summary; rigorous and simplified method.

Method	Pressure (psig)
Dynamic	635
Simplified	646

The resulting values from both analyses are practically the same, concluding that for this type of application, it will not be necessary to perform the dynamic method to find the maximum pressure that the exchanger shell can reach.

Once the maximum pressure point that the heat exchanger must withstand has been checked and verified, solutions must be found to avoid fracture;

- Replace or resize the PSV with a device that is capable of relieving the overpressure produced in the exchanger.
- Replace the relief device with a device that is capable of acting as quickly as possible to avoid overpressure.
- Find an exchanger that is able to withstand the sudden increase in pressure.

Appendix C shows a spreadsheet of calculations created to resolve this type of dimensions in the relief device, in a simple way.

7. Comparison for the scenario of thermal expansion in a blocked in vertical thermosiphon reboiler

This section develops a case study based on the thermal expansion in a blocked in vertical thermosiphon scenario.

7.1 Description for the case study

In the case in study there is a distillation column shown in figure 7.1. In which, at the bottom of a propene-propane splitter there is a mixture of propane and propylene in the liquid phase. This mixture leaves the column at the bottom and goes to a vertical thermosiphon, where the mixture is heated with vapor. Heating the mixture causes the product to vaporize.

Table 7.1 shows the composition of the liquid mixture at the bottom of the column.

Table 7.1 Composition of the product in the column

Components	Weight fraction
Propane	0,8424
Propylene	0,1576

The reboiler that's installed vertically has the inlet for the product to be vaporized at the bottom, and horizontally it has the inlet for the low vapor flow. In the upper part of the reboiler, there is a PRV, adjusted to a pressure of 20 barg, and it protects the reboiler in case of overpressure.

According to API 520-Part I, 2020, it must be taken into account that the relief pressure to which the PRD has to be adjusted is the set pressure that is desired in the system multiplied by 10% overpressure. Therefore in this case, the relief pressure is:

$$20 \text{ barg} * 1,1 = 22 \text{ barg} \quad (83)$$

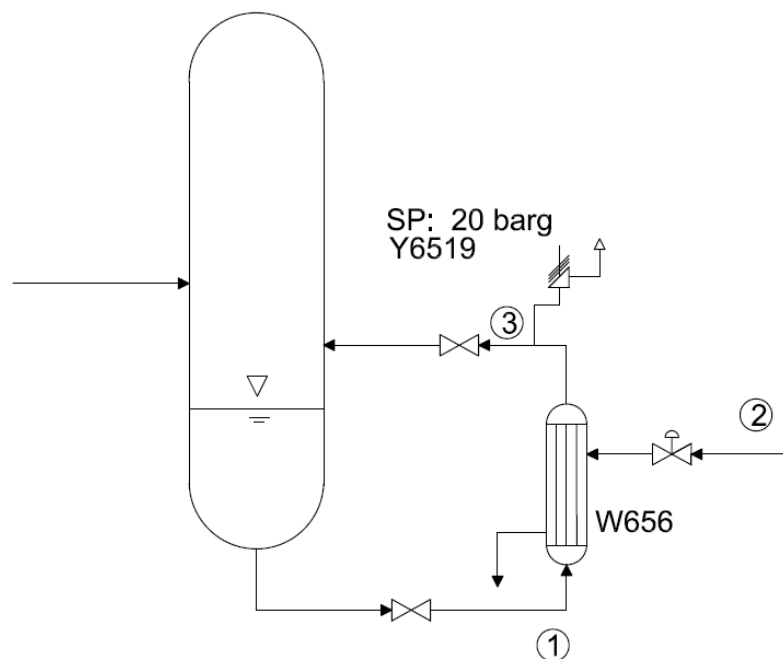


Figure 7.1 Flowsheet reboiler

The flowsheet shows the set point of the relief device and the three numbered reboiler streams.

Table 7.2 shows the normal operating conditions of the reboiler.

Table 7.2 Normal operating conditions of the thermosiphon reboiler

Current	Flow (kg/h)	Molar fraction liquid	Molar fraction vapor	Flow liquid (kg/h)	Flow vapor (kg/h)	Pressure (barg)	Temperature (°C)
1	157093	1	0	157093	0	16	68,2
2	3500	0	1	0	3500	1,8	133
3	157093	0,8385	0,1614	131736	25357	16	68,4

Table 7.3 shows the characteristics of the reboiler.

Table 7.3 Reboiler data

Reboiler data	
Length of tubes	2500 mm
OD tubes	25,4 mm
ID tubes	21,4 mm
Pitch	32 mm Δ
Number of tubes	400
Number of baffles	6

In this study, the scenario that due to an operating incident in the normal functioning of the column and reboiler (W656) is shown, the inlet and outlet valve of the reboiler were blocked. This effect will cause the reboiler product to heat up and begin to vaporize due to the effect of the vapor. The vaporization of the product causes an increase in pressure in the reboiler. The pressure in the reboiler will increase until the pressure reaches 20 barg, which is the set pressure of Y6519.

Figure 7.2 shows the curve, from the thermodynamic mapping (Mollier diagram), pressure-enthalpy of the propane-propylene mixture. The curve shows the different points of ΔT under relief conditions.

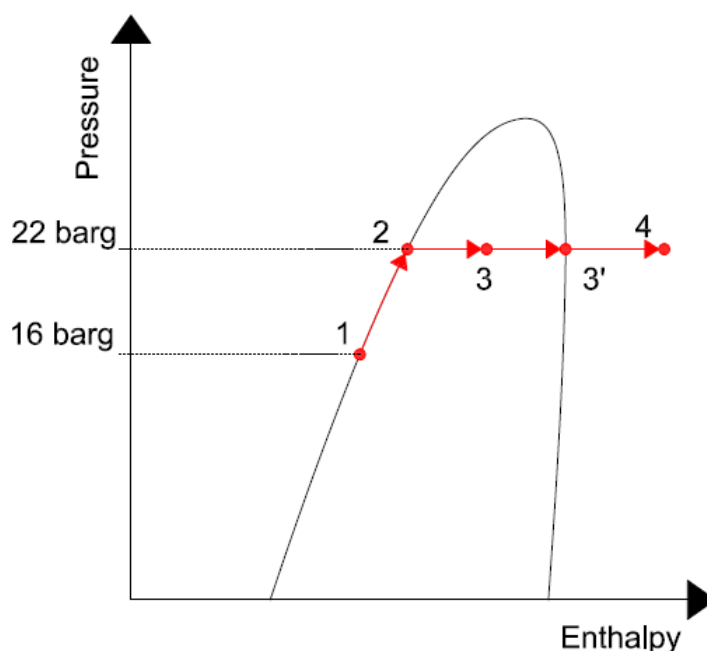


Figure 7.2 Thermodynamic mapping process inside tubes of the vertical thermosiphon reboiler

The points that appear in the diagram mean:

1. The decrease in ΔT under relief conditions is not considered.
2. The decrease in ΔT under relief conditions it is considered.
3. There is vaporization of the propane-propylene mixture.
- 3'. The entire propane-propylene mixture has vaporized.
4. The vapor heats to 157 °C.

7.2 Literature survey of relief load calculation methods

Most practicing engineers would simply assume complete vapor-liquid disengagement (provided the relief device is on the reboiler return line or on the tower), use the clean duty for the reboiler, and the heat of vaporization for the reboiler contents to generate a maximum vaporization rate. Perhaps some would go a step further and use the clean overall heat transfer coefficient (U) and surface area (A) and consider the actual temperature differential

at point 2 to calculate the 'reduced' duty. This should be a conservative estimate of the relief requirement in the two-phase region, provided the vapor-liquid disengagement assumption is valid (or valid for peak relieving conditions, see Simpson, L.L. (2005)).

If one wants to evaluate the system with no disengagement (homogeneous vessel venting), one could extend the analysis of Ouderkerk; it is more complicated because one has an additional set of data to track, but can perform the same analysis. Leung has an alternative methodology that looks at a case of constant heat input for volumetric heating in an attempt to determine the peak relieving rate (Leung, J.C. (1986)).

7.3 Results of the dynamic simulation

For this study, the simulation of values with ASPEN HYSYS™ v10 and Aspen Exchanger Design and Rating™ v10 has been used. The simulation has been carried out at a pressure of 16 barg, which is the normal operating pressure, and at a pressure of 22 barg, which is the first pressure point at which the relief valve must open due to the increase in pressure.

Appendix D shows the results obtained with the Aspen Exchanger Design and Rating™ v10 software, when the operating pressure of 16 barg and a PRD activation pressure of 22 barg.

According to the results obtained in the simulation, this is the procedure used to calculate the transmitted heat, with normal operating conditions.

$$Q = A * U * \Delta T \quad (84)$$

Each of the components of the equation, significant:

- Q : Heat transmitted (W).
- A : Area of the surface of heat transmission (m²).
- U : Transference of heat.
- ΔT : Difference in mean heat.

The mean temperature difference is calculated:

$$\Delta T = \left(\frac{(T_{in\ shell\ side} - T_{out\ tube\ side}) - (T_{out\ shell\ side} - T_{in\ tube\ side})}{\ln \left(\frac{T_{in\ shell\ side} - T_{out\ tube\ side}}{T_{out\ shell\ side} - T_{in\ tube\ side}} \right)} \right) \quad (85)$$

The mean temperature difference is calculated. The calculation of the transmitted heat when the operating pressure is 16 barg:

$$Q = 77,1 * 323,8 * \left(\frac{(130,79 - 48,18) - (129,49 - 48,07)}{\ln \left(\frac{130,79 - 48,18}{129,49 - 48,07} \right)} \right) = 2047467\ W \quad (86)$$

$$Q = 2047467\ W \approx 2047\ kW \quad (87)$$

Knowing the heat transmitted, the vaporized flow rate can be shown.

$$Q = F * \lambda \quad (88)$$

- Q : Heat transmitted (W).
- F : Vaporized flow (kg/h).
- λ : Latent heat (kJ/kg).

It's known that:

$$2047kW = 7369200 \text{ kJ/h} \quad (89)$$

The average latent heat made is obtained in the simulation:

$$\lambda = \frac{289,7 + 289,2}{2} = 289,45 \text{ kJ/kg} \quad (90)$$

Therefore, the vaporized flow:

$$7369200 = F * 289,45 \quad (91)$$

$$F = 25459 \text{ kg/h} \quad (92)$$

The calculation of the heat transmitted when the pressure has risen to 22 barg, and the relief valve begins to open.

$$Q = 77,1 * 324 * \left(\frac{(130,78 - 62,56) - (129,49 - 62,49)}{\ln \left(\frac{130,78 - 62,56}{129,49 - 62,49} \right)} \right) = 1688879 \text{ W} \quad (93)$$

$$Q = 1688879 \text{ W} \approx 1688 \text{ kW} \quad (94)$$

It is known that:

$$1688 \text{ kW} = 6076800 \text{ kJ/h} \quad (95)$$

The average latent heat made is obtained in the simulation:

$$\lambda = \frac{251,7 + 251,4}{2} = 251,55 \text{ kJ/kg} \quad (96)$$

The vaporized flow for a pressure of 22 barg is.

$$6076800 = F * 251,55 \quad (97)$$

$$F = 24157 \text{ Kg/h} \quad (98)$$

Once the vaporization flow rates have been calculated, the result of how much the area of the relief device has to be, will be obtained.

To calculate the orifices of relief devices for gases or vapours, using the following formula (taken from SEMPELL Catalogue).

$$A_0 = 0,1791 * \frac{q_m}{\Psi * \alpha_d * P} * \sqrt{\frac{T * Z}{MW}} \quad (99)$$

- A_0 : Smallest flow section (mm²).
- q_m : Capacity (kg/h).
- Ψ : Flow function.
- α_d : Flow coefficient allotted for liquids.
- P : Set pressure absolute (bar).
- T : Absolute temperature of the medium upstream of the valve with set pressure (K).
- Z : Real gas factor of medium in pressure chamber.
- MW : Molar mass (kmol/kg).

Simulating with ASPEN HYSYS™ v10, the following values necessary to perform the relief calculation have been obtained.

Table 7.4 Results obtained con ASPEN HYSYS™ v10

Molar fraction propylene	0,16
Molar fraction propane	0,84
Vapor fraction	1,00
Relief temperature (°C)	56,87
Relief pressure (bara)	21,01
Isentropic exponent (C_p/C_v or K)	1,085
Molar mass (kmol/kg)	43,76
Compressibility factor (Z)	0,6792

With the value of isentropic exponent (K) obtained with the simulation with ASPEN HYSYS™ v10, the value of flow function (Ψ).

$$\Psi = 0,431 * K^{0,346} \quad (100)$$

$$\Psi = 0,431 * 1,085^{0,346} = 0,443 \quad (101)$$

The value of flow coefficient allotted for liquids (α_d), got from the table 10.12in appendix D. The calculation of the relief area (A_0) of the PRD, for an operating pressure of 16barg.

$$A_0 = 0,1791 * \frac{25459}{0,443 * 0,82 * 21,01} * \sqrt{\frac{(273,15 + 57,68) * 0,6792}{43,76}} = 1353mm^2 \quad (102)$$

Knowing the area obtained, and checking the table 10.12 in appendix D, for an A_0 : 1353 mm², the result of the type of valve is indicated in table 7.5.

Table 7.5 A summarise the valve type for the pressure of operation at 16 barg

Valve type (SEMPELL Catalogue)	J
Diameter (mm²)	44
Inlet diameter nominal (mm)	80
Outlet diameter nominal (mm)	150

The calculation of the relief area (A_0) of the PRD, for a relief pressure of 22 barg.

$$A_0 = 0,1791 * \frac{24157}{0,443 * 0,82 * 21,01} * \sqrt{\frac{(273,15 + 57,68) * 0,6792}{43,76}} = 1285mm^2 \quad (103)$$

Knowing the area obtained, and checking the table 10.12 in appendix D, for an A_0 : 1285 mm² the result of the type of valve is indicated in table 7.6.

Table 7.6 A summarise the valve type for the pressure of relief at 22 barg

Valve type (SEMPELL Catalogue)	J
Diameter (mm²)	44
Inlet diameter nominal (mm)	80
Outlet diameter nominal (mm)	150

7.4 Comments

In the study when there is a higher heat transfer, more vaporization is obtained from the product. According to the results obtained, for a working pressure of 16 barg, greater heat transfer and greater vaporization of the product are obtained.

In the situation presented at the beginning of the case, in which there is a blockage at the boiler inlet and outlet due to an incident, the pressure and the temperature increases and the heat exchange decreases, since the product in the liquid phase inside the exchanger heats up and hotter and this causes it to vaporize less.

Therefore, since there is less vapor at a pressure of 22 barg, this makes the relief area of the relief device smaller.

According to table 10.12, SEMPELL catalogue, For the obtained areas, the type of valve to be installed is the same.

Therefore, the study shows that at an operating pressure of 16 barg and a relief pressure of 22 barg, the valve installed and calculated is the same, although initially it might be thought that the valve could be smaller, impacting on economic savings.

Table 7.7 shows a summary of this study.

Table 7.7 Valve type overview

Pressure (barg)	Flow vaporized (kg/h)	Relief area calculated (mm²)	Type valve (SEPELL Catalogue)	Diameter (mm²)
16	25459	1353	J	44
22	24157	1285	J	44

8. Conclusions and future research

In this thesis, the analysis and comparison of different methods have been carried out to calculate the required area of pressure relief valves. The objective was to compare studies already done in a dynamic approach, using programs such as SuperChems™ Expert, etc, with other one done by paper and pencil steady state calculations.

The comparison between the results of this study and the results obtained by the programs, intended to demonstrate that in some specific scenarios, it is not necessary to have access to this dynamic simulators in order to correctly size relief devices.

It has been found that if not dynamic software is used, it is very difficult to obtain all the simulation points provided by the programs. In turn, these points are not entirely necessary, since the main thing is the point at which the PRD will relieve the greatest relieving load. The rest of the points may be interesting to know, but they should not be decisive for the safety of people and the facilities.

Each of the studied scenarios: fire, gas blow-by/vapor breakthrough, heat exchanger tube rupture and thermal expansion in a blocked in vertical thermosiphon, present different conclusions to take into account.

Fire case scenario;

- It is important, to take into account the sensible heat and density correction.
- When sensible heat or density correction are considered, the calculations are more conservative, therefore the required area obtained is higher.
- The reference percentage of vaporization to size the relief device has been taken in this study us 30%.
- Including or not the sensible heat has an important paramount in the required area. According to table 4.20 results it is recommended to take in to account the sensible heat in the calculation.

Gas blow-by/vapor breakthrough scenario;

- It has been necessary to suppose some variables to compare this study with the study of Melhem, G. A..
- It is necessary to know exactly all the instruments and characteristics of the process instruments.
- We have modified some parameters of the control valves calculation in order to much the reports of Melhem, G. A.. Thus, we could compare the required area of the safety valve of the LPV.

Heat exchanger tube rupture scenario;

- The result obtained concludes that it is not necessary to perform a dynamic simulation, since the area of the relief device calculated by a simplified method is practically the same as that of the dynamic simulation, table 6.7.

About the thermal expansion in a blocked in vertical thermosiphon scenario, it has not been contrasted with other results obtained. The thermal expansion of a thermosiphon has been studied when the inlet and the outlet valve have been blocked.

This blockage causes an increase in pressure inside the reboiler. Analysing the case, it has been found that:

- When the inlet and outlet of the reboiler thermosiphon is blocked, the pressure rises dangerously inside the thermosiphon.
- When the pressure increases to 22 barg (relieving pressure of the safety valve), there is less heat transfer, therefore the product vaporizes less. This makes the PRV relief required area smaller.
- For this case, only the first moment in which the pressure starts to relieve has been calculated.
- The conclusions obtained from this case studied demonstrate there is not a difference in calculating the required area at working pressure or at relieving pressure. But it has to be checked case by case.

With all the cases analysed, the final conclusions are:

Fire scenario

- In the fire scenario, it would not be necessary to perform a dynamic analysis, since with the semi-dynamic analysis applied for this scenario, it would be for the correct dimensioning of the PRV enough rigorous.
- Semi-dynamic analysis is more conservative than dynamic analysis when sensible heat is taken into account.
- In this case, when applying semi-dynamic analysis, to obtain the best results of PRV sizing, sensible heat has to be included.

Blow-by/vapor breakthrough scenario

- In the gas blow-by/vapor breakthrough scenario, a dynamic simulation is not required. The steady state for this scenario would be correct. It can be seen in table 5.11 as the result obtained in the dynamic study by Melhem, G.A. it is almost the same that has been calculated in this thesis.
- For the gas blow-by/vapor breakthrough scenario, it is only necessary to find the maximum flow to relieved by the safety valves, in order to size correctly the valves. For this reason, it is not necessary to apply the dynamic study.

Heat exchanger tube rupture scenario

- For the heat exchanger tube rupture scenario, the simplified system has been used to obtain the maximum pressure that the heat exchanger will reach and the values obtained have been compared with dynamic simulation, in table 6.7. The results were almost the same.
- To correctly size the PRV, the most critical pressure wave has been found, and with this value, the area of the PSV to be installed can be correctly calculated.
- It is not necessary to find the different pressure changes suffered by the heat exchanger over time, since this pressure will not exceed that found with the

simplified method. Therefore, it can be said that it is not necessary to use the dynamic method.

Thermal expansion in a blocked in vertical thermosiphon reboiler scenario

- For the thermal expansion in a blocked in vertical thermosiphon reboiler scenario, the area required by the PSV of the first two points of the thermodynamic mapping (Mollier diagram) has been calculated, which can be seen in figure 7.2.
- In the study carried out, it can be seen how the vaporized product varies not too much being at point one (16 barg) and at point 2 (22 barg).
- It is not necessary using a dynamic method for this scenario. The vaporisation will decrease a little more over time, and the required area of the PSV will vary little.

In this thesis, it has been found that it is not always necessary to make large economic investment in process simulators to have a correct dimensioning of the PRDs of facilities that work with liquids or gases pressurized. In the scenarios presented, none of the cases requires a dynamic study to be carried out to obtain a rigorous required area of the PRDs.

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10. APPENDIX

10.1 Appendix A. Case study 1: Comparison for the fire scenario

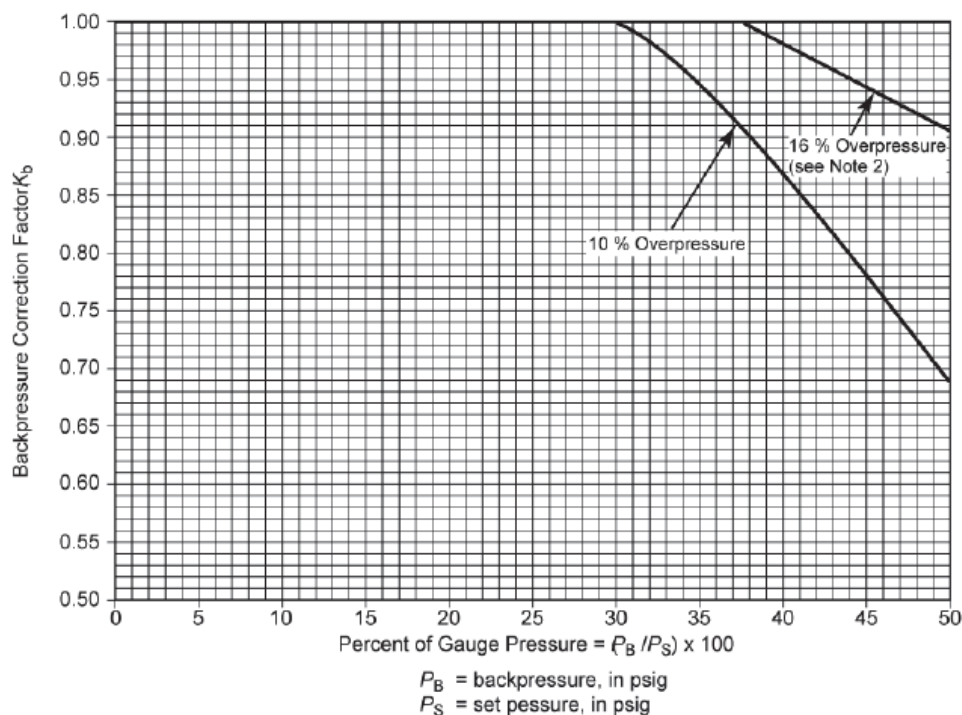


Figure 10.1 Backpressure correction factor, K_b , for balance spring-loaded PRV (vapors and gases). (Taken from API-520-I-2020)

10.2 Appendix B. Case study 2: Comparison for the scenario of Gas blow-by/Vapor breakthrough

MW: 2,063; ASPEN HYSYS SIMULATION

Figure 10.2 shows isentropic efficiency and Delta P of the valve with software ASPEN HYSYS™ v10.

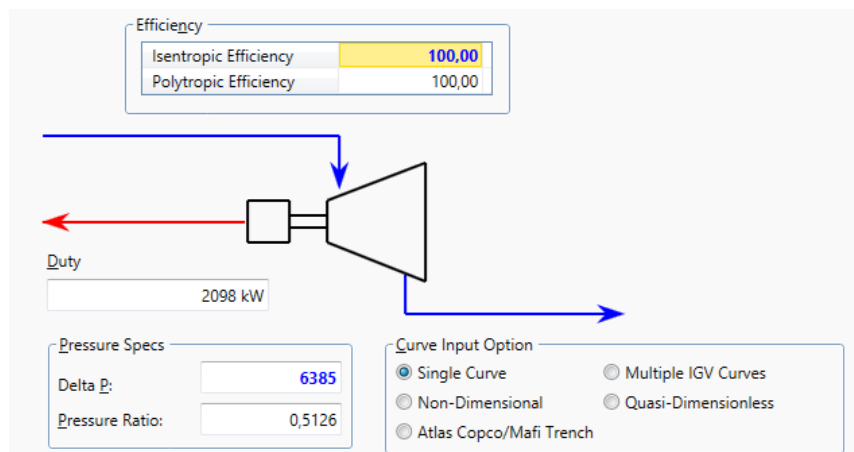


Figure 10.2. CV characteristics. (Taken from ASPEN HYSYS™ v10)

Table 10.1 shows flow 1 and 2 conditions, simulated with software ASPEN HYSYS™ v10.

Table 10.1 Flow 1 and 2 conditions. (Taken from ASPEN HYSYS™ v10)

Name	1	2
Vapour	1,0000	1,0000
Temperature [C]	51,67	-6,334
Pressure [kPa]	1,310e+004	6715
Molar Flow [kgmole/h]	4447	4447
Mass Flow [kg/h]	9172	9172
Std Ideal Liq Vol Flow [m3/h]	128,6	128,6
Molar Enthalpy [kJ/kgmole]	660,7	-1037
Molar Entropy [kJ/kgmole-C]	84,99	84,99
Heat Flow [kJ/h]	2,938e+006	-4,613e+006

Figure 10.3 shows PRV operating characteristics simulated with software ASPEN HYSYS™ v10.

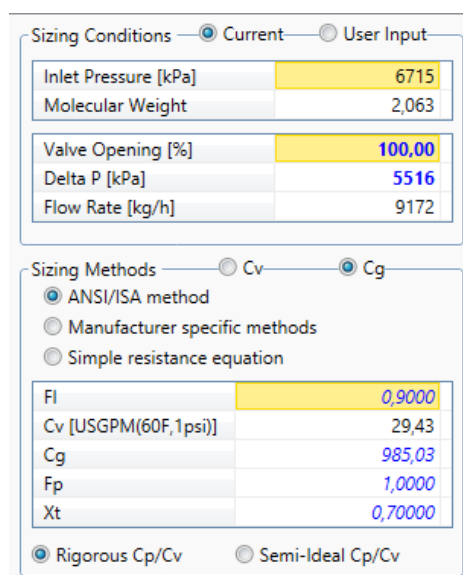


Figure 10.3. Valve operating characteristics. (Taken from ASPEN HYSYS™ v10)

Table 10.2 shows flow 2 and 3 conditions, simulated with software ASPEN HYSYS™ v10.

Table 10.2 Flow 2 and 3 conditions. (Taken from ASPEN HYSYS™ v10).

Name	2	3
Vapour	1,0000	1,0000
Temperature [C]	-6,334	-6,700
Pressure [kPa]	6715	1200
Molar Flow [kgmole/h]	4447	4447
Mass Flow [kg/h]	9172	9172
Std Ideal Liq Vol Flow [m3/h]	128,6	128,6
Molar Enthalpy [kJ/kgmole]	-1037	-1037
Molar Entropy [kJ/kgmole-C]	84,99	99,48
Heat Flow [kJ/h]	-4,613e+006	-4,613e+006

Table 10.3 shows flow 2 and 3 compositions, simulated with software ASPEN HYSYS™ v10.

Table 10.3 Flow 2 and 3 composition. (Taken from ASPEN HYSYS™ v10)

	2	3
Hydrogen	0,9980	0,9980
Methane	0,0011	0,0011
Ethane	0,0003	0,0003
H2S	0,0005	0,0005
Propane	0,0001	0,0001
n-Butane	0,0001	0,0001

MW: 3,77; ASPEN HYSYS SIMULATION

Figure 10.4 shows isentropic efficiency and Delta P of the valve with software ASPEN HYSYS™ v10.

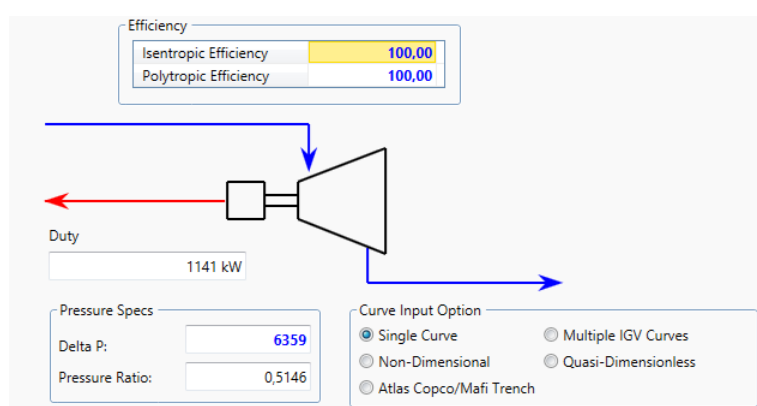


Figure 10.4. CV characteristics. (Taken from ASPEN HYSYS™ v10)

Table 10.4 shows flow 1 and 2 conditions, simulated with software ASPEN HYSYS™ v10.

Table 10.4 Flow 1 and 2 conditions. (Taken from ASPEN HYSYS™ v10).

Name	1	2
Vapour	1,0000	1,0000
Temperature [C]	51,67	-4,428
Pressure [kPa]	1,310e+004	6741
Molar Flow [kgmole/h]	2433	2433
Mass Flow [kg/h]	9172	9172
Std Ideal Liq Vol Flow [m3/h]	75,64	75,64
Molar Enthalpy [kJ/kgmole]	-4225	-5914
Molar Entropy [kJ/kgmole-C]	92,17	92,17
Heat Flow [kJ/h]	-1,028e+007	-1,439e+007

Table 10.5 shows flow 1 and 2 compositions, simulated with software ASPEN HYSYS™ v10.

Table 10.5 Flow 1 and 2 composition. (Taken from ASPEN HYSYS™ v10).

	1	2
Hydrogen	0,9248	0,9248
Methane	0,0405	0,0405
Ethane	0,0095	0,0095
H2S	0,0182	0,0182
Propane	0,0038	0,0038
n-Butane	0,0031	0,0031

Figure 10.5 shows PRV operating characteristics simulated with software ASPEN HYSYS™ v10.

Sizing Conditions — Current — User Input

Inlet Pressure [kPa]	6741
Molecular Weight	3,771
Valve Opening [%]	100,00
Delta P [kPa]	5159
Flow Rate [kg/h]	9172

Sizing Methods — Cv — Cg

- ANSI/ISA method
- Manufacturer specific methods
- Simple resistance equation

FI	0,9000
Cv [USGPM(60F, 1psi)]	21,79
Cg	729,37
Fp	1,0000
Xt	0,70000

Rigorous Cp/Cv — Semi-Ideal Cp/Cv

Figure 10.5. Valve operating characteristics. (Taken from ASPEN HYSYS™ v10).

Table 10.6 shows flow 2 and 3 conditions, simulated with software ASPEN HYSYS™ v10.

Table 10.6 Flow 2 and 3 conditions. (Taken from ASPEN HYSYS™ v10).

Name	2	3
Vapour	1,0000	1,0000
Temperature [C]	-4,428	-5,698
Pressure [kPa]	6741	1582
Molar Flow [kgmole/h]	2433	2433
Mass Flow [kg/h]	9172	9172
Std Ideal Liq Vol Flow [m3/h]	75,64	75,64
Molar Enthalpy [kJ/kgmole]	-5914	-5914
Molar Entropy [kJ/kgmole-C]	92,17	104,3
Heat Flow [kJ/h]	-1,439e+007	-1,439e+007

Table 10.7 shows flow 2 and 3 compositions, simulated with software ASPEN HYSYS™ v10.

Table 10.7 Flow 2 and 3 composition. (Taken from ASPEN HYSYS™ v10).

	2	3
Hydrogen	0,9248	0,9248
Methane	0,0405	0,0405
Ethane	0,0095	0,0095
H2S	0,0182	0,0182
Propane	0,0038	0,0038
n-Butane	0,0031	0,0031

10.3 Appendix C. Case study 3: Comparison for the scenario of heat exchanger tube rupture

Calculate Pis

Shell data design		U bends design		Gas data									
Heat exchanger length (m)	4,27	U bends length (m)	3,99	γ: ratio specific heats	1,096								
Heat exchanger outer diameter (mm)	323,8	U bend diameter(mm)	15,88	R: constant gases (J/Kmol·°K)	8314								
Heat exchanger wall width (mm)	8,38	U bend wall width (mm)	3,3	Molecular weight of the gas	28,05								
Heat exchanger inlet diameter (mm)	307,04	Inner diameter of the tubes (mm)	12,58	Initial gas temperature (°K)	353,15								
Number of baffles	36	Area through which ethyl gas escapes (mm2)	124,29	Final gas temperature (°K)	313,71								
Distance between baffles (mm)	104,8	Number of U bends	70	Average gas temperature (°K)	333,49								
Le: Break the tube at the top of the exchanger (mm)	15630,48	At: twice the total cross-sectional area of the tube (m2)	0,000124156	Supersonic gas velocity (m/s)	329,11								
Volume of the heat exchanger (m3)	0,32	Pr->Initial shell pressure (Pa)	514985	Pis*(Pis-Pr)^γ	7,75783E+13								
Heat exchanger area (m2)	0,0134	Cd: coefficient discharge of the tube	0,62	Pis: is the incident initial step pressure (Pa)	-4,703125								
Volume U bends (m3)	0,11	ρl: liquid density (kg/m3)	995	Calculate Pis									
Volume of the liquid	0,21	c: the wavespeed in the liquid (m/s)	1517,75										
		Po: is the source pressure of the HP gas (Pa)	11130896	<table border="1" style="display: inline-table; border-collapse: collapse;"> <tr> <td>4511390,028</td> <td>Pa abs</td> </tr> <tr> <td>45,11390028</td> <td>bara</td> </tr> <tr> <td>44,53494598</td> <td> barg</td> </tr> <tr> <td>645,8903215</td> <td>psig</td> </tr> </table>		4511390,028	Pa abs	45,11390028	bara	44,53494598	barg	645,8903215	psig
4511390,028	Pa abs												
45,11390028	bara												
44,53494598	barg												
645,8903215	psig												

Figure 10.6 Spreadsheet to calculate Pis

10.4 Appendix D. Case study 4: thermal expansion in a blocked in vertical thermosiphon reboiler

Table 10.8 Reboiler data. (Taken from a worldwide petrochemical company)

Process Engineering Data Sheet Heat Exchanger		Job No. [REDACTED]
		Item No. [REDACTED]
		Sheet 1 of 2
		Site/Bldg. No.
1 Project	[REDACTED]	
2 Brief designation	SPLITTER REBOILER (STEAM HEATED) 80m ² , p _e =20/20 bar	
3 Use	<input checked="" type="checkbox"/> Evaporator <input type="checkbox"/> Condenser <input type="checkbox"/> Heat exchanger without phase transition	
4 Problem		
5		
6 Ref. process flow sheet		
7 Construction	<input checked="" type="checkbox"/> Tubular with <input checked="" type="checkbox"/> fixed head <input type="checkbox"/> floating head <input type="checkbox"/> U-tubes	
8	<input type="checkbox"/> Plate heat exchanger <input type="checkbox"/> Spiral-plate heat exchanger	
9 Arrangement	<input checked="" type="checkbox"/> vertical <input type="checkbox"/> horizontal <input type="checkbox"/> inclined at _____° to horizontal	
10 Qty.	<input type="checkbox"/> in series <input type="checkbox"/> parallel Heat exchanger surface total 80 m ² /per unit 80	
Process Data and Physical Properties		
11		
12 Composition	Substance	GLS M
13	PROPANE + C ₄ -HYDROCARBONS	X
14	"	X
15		
16		
17 G - Gaseous		
18 L - Liquid		
19 S - Solid	LOW PRESSURE STEAM ST1	X
20 M - Mol. mass kg/keol	CONDENSATE	X
21	Liquid	kg/h
22	Vapor	kg/h
23 Mass flow, normal	Inert gas	kg/h
24	total	kg/h
25	Requ. load range	kg/h
26	Liquid	m ³ /h
27	Vapor + inert gas	m ³ /h
28	Gas, sensible heat	kW
29	Liquid, sensible heat	kW
30	Condensation or evaporation	kW
31	total	kW
32	normal	°C
33	max./min.	°C
34	normal	bar
35	max./min.	bar
36	Boiling/condensation temperature	°C
37	Solidification temperature	°C
38	Density	kg/m ³
39	Gaseous	kg/m ³
40	Liquid	kg/m ³
41	Viscosity	mPa s
42	Gaseous	mPa s
43	Liquid	mPa s
44	Heat conduc-	W/m K
45	tivity	W/m K
46	Specific heat	kJ/kg K
47	capacity	kJ/kg K
48	Heat of vaporization	kJ/kg
49		kJ/kg
50		

	Tube side	Shell side
	in	out
157 093	137 736	
25 357		
		3500
		3500
157 093		3500
2106		2106
68.2	68.4	133
1	1	1
77		2.8
1		1
68.4		130
474		935
38.6		1.52
0.099		0.27
0.077		0.073
0.138		0.665
0.025		0.027
2.49		4.245
1.80		2.796
265		2773
285		

Marked where applicable 1) DESIGN DATA: -50 -50
20/20 BAR (G); 120/200 °C

0	20.02.90	Ull
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Table 10.9 Reboiler data. (Taken from a worldwide petrochemical company)

Process Engineering Data Sheet					Jet No.	
Heat Exchanger					Item No.	
Project					Sheet	2 of 2
					Site/Bldg. No.	
Calculation and Design per Unit						
1	No. of passes, tubeside	1	Tube Outside dia. d_o	25.4	mm	
2	No. of tubes per unit calc.	400 effective	Tube wall thickness s	2	mm	
3	No. of baffles per unit	ABT. 6	Tube Length l	2500	mm	
4	Cut away baffle segment	25 % 200	Baffle dia.		mm	
5	Shell inside dia.	ABT. 800	Baffle borehole		mm	
6	Patch	<input checked="" type="checkbox"/> Triangular Δ <input type="checkbox"/> Square <input type="checkbox"/> Square \diamond		32	mm	
7	Material	Shell (TSTE 355) L.T.C.S.	Tube sheets (TSTE 355) L.T.C.S.			
8		Tubes (TST 355N) L.T.C.S.	Gaskets Shell side			
9		Channels (TSTE 355) L.T.C.S.	Gaskets Tube side			
10	Insulation	<input type="checkbox"/> yes <input type="checkbox"/> no				
11	Designation		Tube side		Shell side	
12	Type of coating	-				
13	Thickness of coating					
14	Heat conductivity of coating					
15	Fouling factor		3.4×10^{-4}		3.4×10^{-4}	
16	Heat conductivity of tube material					
17	Mean velocity		0.68		-	
18	Pressure drop allowable/calculated		1 0.16		1-	
19	Mean heat transfer coefficient α		1148		7367	
20	Safety factor as addition to α					
21	Mean tube wall temperature					
22	Mean shell wall temperature					
23	Mean logarithmic temperature difference, corrected		62.9			
24	Heat exchanger surface (related to d_o and l) calculated/effective		74.9		80	
25	Mean overall heat transfer coefficient (related to d_o) calc./eff.		447		1	
26	Heat duty, normal				2106	
27	Remarks					
28		* LIQUID STATIC HEAD				
29						
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50	Marked where applicable <input checked="" type="checkbox"/>					
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Table 10.10 Reboiler data to pressure operation 16 barg. (Print out from Aspen Exchanger Design and Rating™ v10)

Heat Exchanger Specification Sheet															
1	Company:														
2	Location:														
3	Service of Unit:			Our Reference:											
4	Item No.:			Your Reference:											
5	Date:	Rev No.:	Job No.:												
6	Size:	787 - 2500	mm	Type:	BEM Vertical	Connected in: 1 parallel 1 series									
7	Surf/unit(eff.)	77,1	m ²	Shells/unit	1	Surf/shell(eff.) 77,1 m ²									
8	PERFORMANCE OF ONE UNIT														
9	Fluid allocation			Shell Side			Tube Side								
10	Fluid name														
11	Fluid quantity, Total			3364			157093								
12	Vapor (In/Out)			kg/h	3364	0	0	24999							
13	Liquid			kg/h	0	3364	157093	132094							
14	Noncondensable			kg/s	0	0	0	0							
15															
16	Temperature (In/Out)			°C	130,79	129,49	48,07	48,18							
17	Bubble / Dew point			°C	129,71 / 129,71	129,49 / 129,49	48,41 / 48,63	48,15 / 48,37							
18	Density Vapor/Liquid			kg/m ³	1,44 /	/ 934,82	/ 453,99	27,88 / 453,66							
19	Viscosity			mPa-s	0,0133 /	/ 0,2255	/ 0,0711	0,009 / 0,0712							
20	Molecular wt, Vap				18,01			43,72							
21	Molecular wt, NC														
22	Specific heat			kJ/(kg-K)	2,223 /	/ 4,218	/ 4,083	1,743 / 4,084							
23	Thermal conductivity			W/(m-K)	0,0272 /	/ 0,6889	/ 0,0838	0,0205 / 0,0836							
24	Latent heat			kJ/kg	2166,9	2167,5	289,7	289,2							
25	Pressure (abs)			bar	2,68946	2,672	17,12731	17,02715							
26	Velocity (Mean/Max)			m/s	3,06 / 6,58		1,03 / 2,29								
27	Pressure drop, allow./calc.			bar	0,25855	0,01746	0,17647	0,10015							
28	Fouling resistance (min)			m ² -KW	0,00034		0,00034	0,0004	Ao based						
29	Heat exchanged			2028,1	kW		MTD (corrected) 81,28		°C						
30	Transfer rate, Service			323,8	Dirty 1018,7		Clean 4199,8		W/(m ² -K)						
31	CONSTRUCTION OF ONE SHELL						Sketch								
32				Shell Side		Tube Side									
33	Design/Vacuum/test pressure			bar	20 / /	20 / /									
34	Design temperature			°C	200	120									
35	Number passes per shell				1	1									
36	Corrosion allowance			mm	3,18	3,18									
37	Connections			In mm	1 190 / -	1 240 / -									
38	Size/Rating			Out	1 40 / -	1 290 / -									
39	ID			Intermediate	/ -	/ -									
40	Tube #:	400	OD:	25,4	Tks. Average	2	mm	Length:	2500	mm	Pitch:	32	mm	Tube pattern:	30
41	Tube type: Plain			Insert:None			Fin#:		#/m		Material:Carbon Steel				
42	Shell Carbon Steel			ID	790	OD	800	mm	Shell cover -						
43	Channel or bonnet Carbon Steel			Channel cover -											
44	Tubesheet-stationary Carbon Steel			Tubesheet-floating -											
45	Floating head cover -			Impingement protection None											
46	Baffle-cross Carbon Steel			Type	Single segmental	Cut(%d)	25,44	VertiSpacing:	c/c	350	mm				
47	Baffle-long -			Seal Type			Inlet 620,03				mm				
48	Supports-tube			U-bend	0		Type								
49	Bypass seal			Tube-tubesheet joint			Expanded only (2 grooves)(App.A 't')								
50	Expansion joint -			Type			None								
51	RhoV2-Inlet nozzle			754	Bundle entrance		79	Bundle exit		207	kg/(m-s ²)				
52	Gaskets - Shell side			Tube side			Flat Metal Jacket Fibe								
53	Floating head														
54	Code requirements			ASME Code Sec VIII Div 1			TEMA class R - refinery service								
55	Weight/Shell			2961,5	Filled with water		4651,2	Bundle		1560,5	kg				
56	Remarks														
57															
58															

Table 10.11 Reboiler data to pressure relief 22 barg. (Print out from Aspen Exchanger Design and Rating™ v10)

TEMA Sheet

Heat Exchanger Specification Sheet

1	Company:									
2	Location:									
3	Service of Unit:					Our Reference:				
4	Item No.:					Your Reference:				
5	Date:		Rev No.:			Job No.:				
6	Size: 787 - 2500		mm		Type: BEM Vertical		Connected in: 1 parallel 1 series			
7	Surf/unit(eff.)		77.1 m ²		Shells/unit 1		Surf/shell(eff.) 77.1 m ²			
8	PERFORMANCE OF ONE UNIT									
9	Fluid allocation				Shell Side			Tube Side		
10	Fluid name									
11	Fluid quantity, Total				2772			157093		
12	Vapor (In/Out)		kg/h		2772		0		0 23679	
13	Liquid		kg/h		0		2772		157093 133414	
14	Noncondensable		kg/s		0		0		0 0	
15										
16	Temperature (In/Out)		°C		130.78		129.49		62.49 62.56	
17	Bubble / Dew point		°C		129.67 / 129.67		129.49 / 129.49		62.73 / 62.95 62.53 / 62.75	
18	Density Vapor/Liquid		kg/m ³		1.44 /		/ 934.82		/ 423.36 36.08 / 423.14	
19	Viscosity		mPa-s		0.0133 /		/ 0.2255		/ 0.0589 0.0093 / 0.059	
20	Molecular wt, Vap				18.01				43.72	
21	Molecular wt, NC									
22	Specific heat		kJ/(kg-K)		2.223 /		/ 4.218		/ 4.771 1.804 / 4.773	
23	Thermal conductivity		W/(m-K)		0.0272 /		/ 0.6889		/ 0.0768 0.0222 / 0.0767	
24	Latent heat		kJ/kg		2167		2167.5		251.7 251.4	
25	Pressure (abs)		bar		2.68578		2.672		23.12259 23.02532	
26	Velocity (Mean/Max)		m/s		2.52 / 5.41				1.04 / 1.88	
27	Pressure drop, allow./calc.		bar		0.25855		0.01378		0.16458 0.09727	
28	Fouling resistance (min)		m ² -K/W		0				0 0 Ao based	
29	Heat exchanged		1670.9 kW				MTD (corrected) 66.91 °C			
30	Transfer rate, Service		324 Dirty 277.5				Clean 277.5		W/(m ² -K)	
31	CONSTRUCTION OF ONE SHELL									
32					Shell Side			Tube Side		
33	Design/Vacuum/test pressure		bar		20 / /		20 / /			
34	Design temperature		°C		200		120			
35	Number passes per shell				1		1			
36	Corrosion allowance		mm		3.18		3.18			
37	Connections		In mm		1 190 / -		1 240 / -			
38	Size/Rating		Out		1 40 / -		1 290 / -			
39	ID		Intermediate		/ -		/ -			
40	Tube #: 400		OD: 25.4		Tks. Average 2		mm		Length: 2500 mm Pitch: 32 mm Tube pattern:30	
41	Tube type: Plain		Insert:None		Fin#:		#/m		Material:Carbon Steel	
42	Shell Carbon Steel		ID 790		OD 800		mm		Shell cover -	
43	Channel or bonnet Carbon Steel								Channel cover -	
44	Tubesheet-stationary Carbon Steel								Tubesheet-floating -	
45	Floating head cover -								Impingement protection None	
46	Baffle-cross Carbon Steel		Type Single segmental		Cut(%d) 25.44		Verti Spacing: c/c 350		mm	
47	Baffle-long -		Seal Type				Inlet 620.03		mm	
48	Supports-tube U-bend		0				Type			
49	Bypass seal				Tube-tubesheet joint		Expanded only (2 grooves)(App.A 'i')			
50	Expansion joint -				Type None					
51	RhoV2-Inlet nozzle 512		Bundle entrance 54		Bundle exit 140		kg/(m-s ²)			
52	Gaskets - Shell side -		Tube side		Flat Metal Jacket Fibre					
53	Floating head -									
54	Code requirements		ASME Code Sec VIII Div 1		TEMA class R - refinery service					
55	Weight/Shell		2961.5 Filled with water 4651.2		Bundle 1560.5		kg			
56	Remarks									
57										
58										



Table 10.12 Type of valve. (Taken from Sempell, Safety Relief Valves with DIN and ANSI Flanges, Catalogue KS27585)

Orifice letter	d_o [mm]	A_o [mm ²]	K_d^* Gases & Vapors	K_d Liquids	P_{max} [bar]
VSE 0	7,5	44,2	0,75	0,55	320
VSE 0	9,0	63,6	0,75	0,55	320
A I - III	18	254	0,52	0,43	200
A IV	13	133	0,82	0,55	500
B	18	254	0,70	0,50	450
C	18	254	0,82	0,55	450
D	24,5	471	0,62	0,36	315
E	24,5	471	↑	↑	315
F	28	616	↑	↑	280
G	33	855	↑	↑	224
H	38	1134	↑	↑	200
J	44	1521	↑	↑	180
K	51	2043	0,82	0,55	160
L	59	2734	↓	↓	140
M	69	3739	↓	↓	100
N	80	5027	↓	↓	71
P	93	6793	↓	↓	56
Q	107	8992	0,77	↓	40
R	126	12469	0,77	↓	31,5
S	147	16971	↑	↑	22,4
T	175	24052	↑	↑	16,0
U	202	32047	0,74	(0,50) ⁽¹⁾	12,5
V	230	41547	↓	↓	9,0
W	270	57255	↓	↓	7,1
X	323	81939	↑	↑	4,5
Y	376	111036	(0,70) ⁽¹⁾	(0,45) ⁽¹⁾	3,15
Z	438	150674	↓	↓	2,0