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**Pressure-Vacuum relief valve design for storage tanks.
Comparison between API2000, API2000 Annex A,
EN14015, ISO28300 and TRGS509.**

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1 Introduction/Background

In the storage and processing industry, low-pressure or atmospheric tanks play a pivotal role in the safe containment and handling of a wide range of substances. These tanks, which operate at pressures close to atmospheric, are used in various applications such as storing chemicals, oil, food products, and other critical liquids. An essential aspect of ensuring safety in these facilities is the proper management of controlled release of gases and vapors accumulated within the tanks, a process known as venting.

Atmospheric tanks are the equipment that are involved in more accidents, probably because low-pressure storage tanks are fragile and easily damaged by slight overpressure or vacuum. [18]

This overpressure or vacuum can be caused by different factors, primarily due to tank filling and emptying, also known as outbreathing and inbreathing, respectively. Additionally, thermal effects resulting from weather changes can impact the vapor stored inside the tank. For instance, during a heatwave or a summer rainstorm, temperature changes can affect the pressure tank. Conversely, when the tank is exposed to fire or high temperatures, the liquid inside begins to evaporate and expand, leading to an increase in internal pressure. To relieve this pressure, gas is vented from the tank either into the atmosphere or a confined space. The combination of these effects, whether from liquid movement or thermal changes, determines the total normal inbreathing or outbreathing flow rate of the tank.

The correct selection and application of venting calculation standards are crucial to ensure the integrity of tanks, prevent potential risks to health and the environment, and comply with prevailing industrial and safety regulations.

In this context, the present research focuses on conducting a comprehensive comparison of different standards used in venting calculations for low-pressure or atmospheric tanks. The study aims to analyze and contrast the methodologies established by key international standards and highlight the practical implications of applying these methodologies in real-world scenarios.

1.1 Definition and function of pressure-vacuum relief valves

Protecting a tank with pressure-vacuum relief valves is essential to ensure the safety of workers, maintain the tank's integrity, ensure process performance, prevent contamination and comply with regulations. These valves play a crucial role in the safe and efficient operation liquid and gas storage and processing systems in a variety of industries.

The vented product vapors can be poisonous, odorous, flammable, or simply represent the loss of product. Therefore, these emissions could contaminate the atmosphere. For several years, many tanks were protected with open vents or goosenecks.

For these reasons, it is necessary to implement valves that are capable of protecting the tank.

Pressure-vacuum relief valves, also known as pressure and vacuum relief valves, are safety devices designed to regulate the pressure within a closed system, such as a storage tank or vessel, keeping it within safe limits. These valves are capable of automatically opening in response to changes in the internal pressure of the system, either to release excess pressure or to allow air in to prevent excessive vacuum formation. The ventilation devices, which are in the form of pressure and vacuum relief valves, should not be shut off.

These valves need to be simple and robust valves that do not require external control, are trouble-free, and reliably fulfill the expected tanks: maintaining and compensating pressure and vacuum.

In summary, pressure-vacuum relief valves are essential components used in industrial and commercial applications to protect equipment and systems by controlling pressure variations, thereby preventing hazardous situations such as overpressurization or implosions.

1.2 Types of pressure-vacuum relief valves

In recent decades, there have been significant advancements in the design and efficiency of pressure-vacuum relief valves. These improvements have focused on enhancing safety, reliability, and the valves' ability to protect tanks and systems in various industrial applications. Innovations have addressed challenges such as controlled pressure and vacuum release, the minimization of pollutant emissions, and adaptability to specific environments. This evolution has resulted in more effective and efficient systems that help prevent accidents and reduce environmental impacts.

In this section, the main types of pressure-vacuum relief valves are introduced.

1.2.1 Direct-acting vent valves

Two basic types of pressure or vacuum vents, direct-acting vent valves and pilot-operated vent valves, are available to provide overpressure or vacuum protection for low-pressure storage tanks. Direct-acting vent valves can be weight-loaded or spring-loaded. These venting devices not only provide overpressure protection but also conserve product.

Direct-acting valves are available to provide pressure relief, vacuum relief, or a combination of pressure and vacuum relief. Larger, direct-acting vent valves are available to provide emergency relief and can provide access to a tank's interior for inspection.

The direct-acting pressure and vacuum relief valves have weight-loaded or spring-loaded valve pallets. When there is an excess pressure in the tank, the pressure valve pallet guided in the housing lifts and releases the flow into the atmosphere until the pressure falls below the set pressure. The valve then re-seats. The vacuum side of the valve is tightly sealed by the additional overpressure load. When there is a vacuum in the tank, the overpressure of the atmosphere lifts the vacuum disc, and the tank is vented.

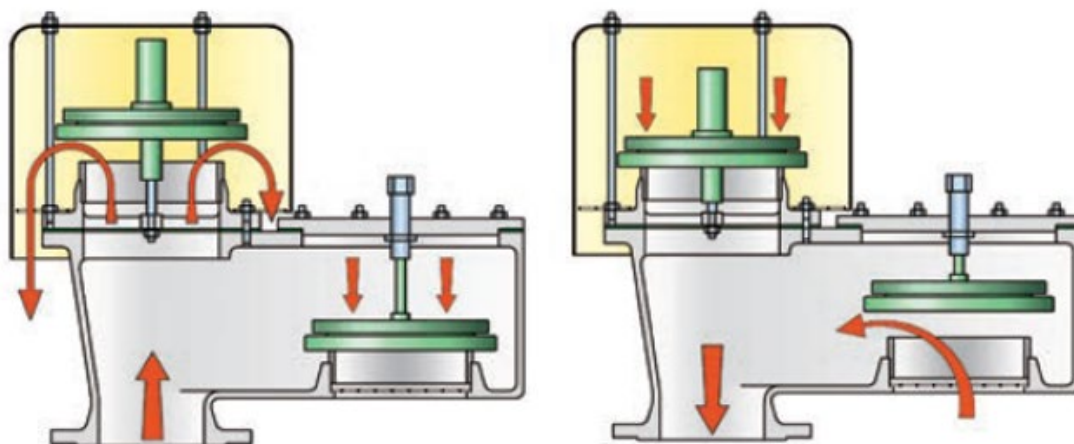


Figure 1: Functionality diagram of pressure-vacuum relief valves. [25]

A soft, nonstick material is typically used on the sealing surface of the pallet. This material can prevent the pallet for sticking to the nozzle. Seat leakage typically starts at 75% to 90% of set pressure and varies strongly for different technologies. Another parameter to consider is the blowdown.

Blowdown is the difference between opening and closing (reseating) pressure of a relief device. This pressure difference is expressed as a pressure percentage of the set pressure.

Spring-loaded vent valves should be used for pressure or vacuum settings that exceed the typical set values of weight-loaded, because the supporting structure and space for the added weights is not available. [2]

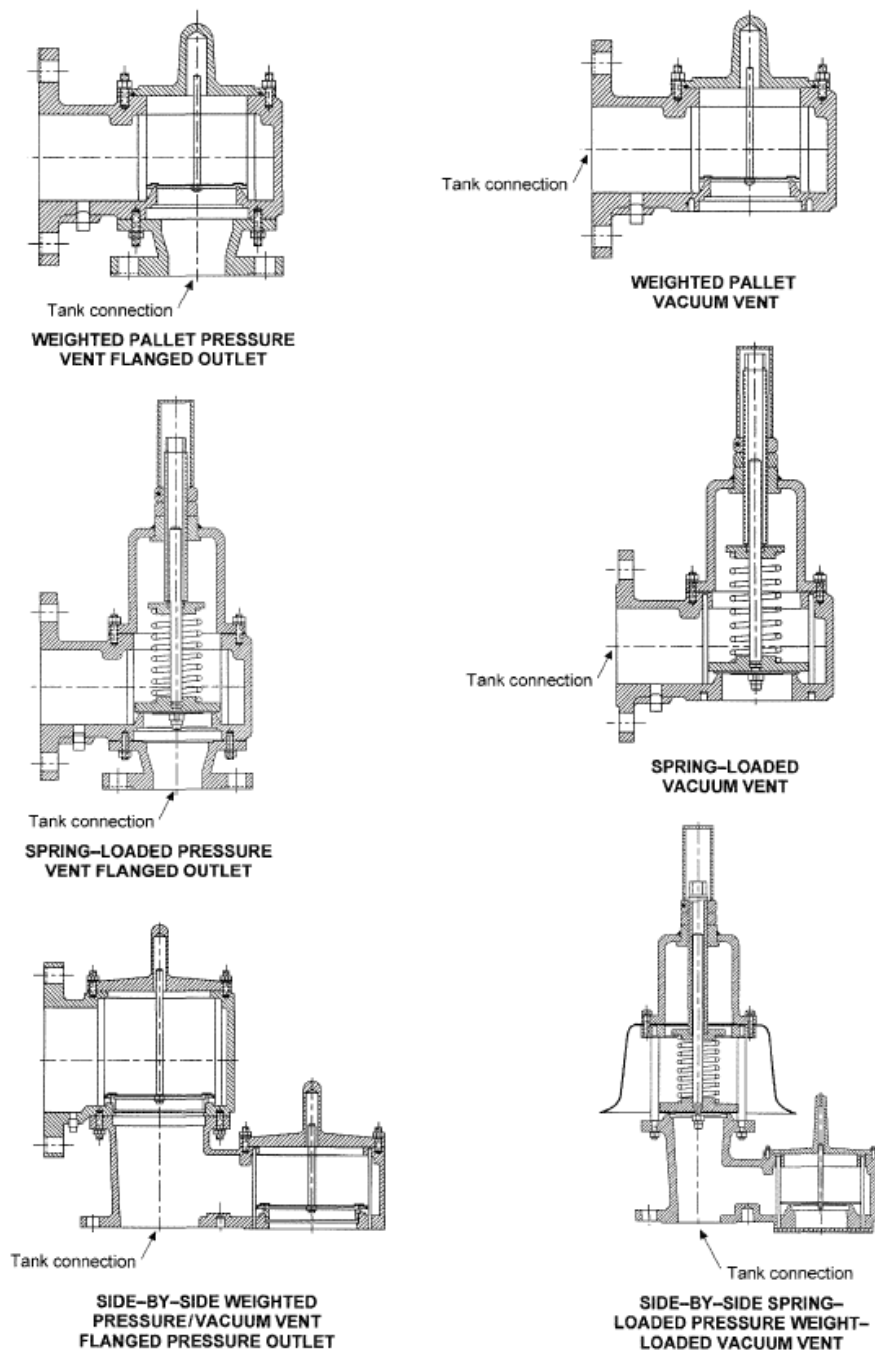


Figure 2: Different types of direct-acting vents. [1]

1.2.2 Pilot-operated vent valves

Pilot-operated vent valves are available to provide pressure relief, vacuum relief, or a combination of pressure and vacuum relief. Some vent valves can be equipped with flanged outlet if it is necessary to pipe pressure-relief vapors away.

A pilot-operated vent valve for pressure relief uses tank pressure, not weights or a spring to keep the vent valve seat closed. The main seat is held by tank pressure acting on a large-area diaphragm. This tank pressure covers an area greater than the seat sealing area, so the net pressure force is always in the direction to keep the seat closed. The volume above the diaphragm is called the dome. If the diaphragm fails, the dome pressure decreases, and the vent valve opens.

The pilot is a small control valve that continuously senses tank pressure. When the tank pressure increases to set pressure, the pilot actuates to reduce the pressure in the dome volume, the force holding the seat closed is reduced and the seat lifts to permit tank pressure to discharge through the vent valve. When the tank pressure decreases, the pilot closes, the dome volume repressurizes, and the main seat closes.

A pilot-operated vent valve for vacuum relief uses atmospheric pressure to keep the seat closed. The force holding the seat closed is equal to the seat sealing area times the pressure differential across the seat. This pressure differential is equal to atmospheric pressure plus the tank vacuum. When the tank vacuum equals the pilot set, the pilot opens to apply tank vacuum to the large dome volume above the diaphragm.

Atmospheric pressure acting on the downstream side of the diaphragm forces the diaphragm and seat up. Little or no increase in tank vacuum beyond the vent valve setting is required to obtain full lift of the seat. When the tank vacuum decreases, the pilot closes, and atmospheric pressure enters the dome to close the main seat. [2]

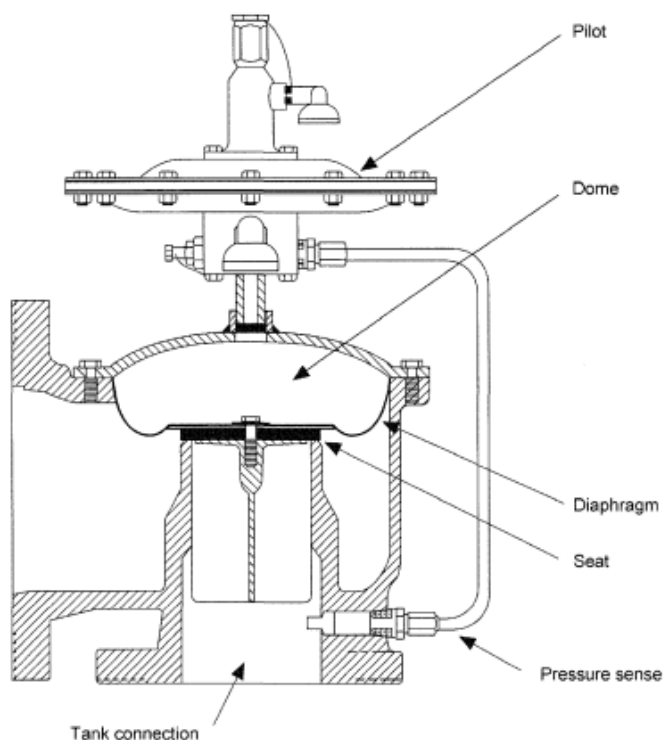


Figure 3: Pilot-operated pressure vent (single diaphragm). [1]

1.3 Pressure-vacuum relief valves as an independent layer of protection

Pressure-vacuum relief valves are fundamental elements in ensuring tank protection and process safety. These devices act as a protective layer against unforeseen changes that could pose a danger to the correct operation of the system.

In this section, pressure-vacuum relief valves are introduced as an independent protective layer. The levels or layers of protection can be determined through Layer of Protection Analysis (LOPA). This method involves an analysis of the different protective layers available in a specific process, evaluating the risk associated with various scenarios and comparing the results to the accepted risk criteria previously defined by the company.

The innermost layer represents the industrial process, the second protective layer consists of process control. Following that, the third layer is based on prevention, and subsequently, the mitigation layer. Finally, on the outermost layer, there are the layers formed by the self-protection plan and the external emergency plan, respectively.

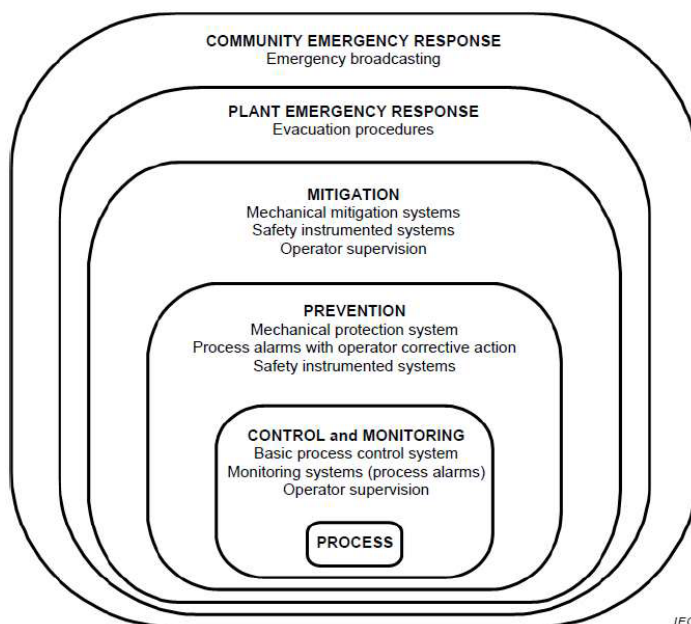


Figure 4: Layers of protection. [16]

In the previous figure, the diagram of the different protection layers is shown. The next is to provide a brief description of what each of them consists of.

- **Process:**
The innermost layer represents the industrial process itself. It includes the core equipment, operations, and procedures that make up the production process.
- **Control and monitoring:**
Basic safety processes that allow for modifications to continually adapt the process to desired needs.
- **Prevention:**
In this layer are included the mechanical components, safety alarms to initiate corrective actions, and finally, this layer also includes safety instruments such as pressure-vacuum relief valves.
- **Mitigation:**

All the corrective actions that have not been addressed by the prevention layer and are attempted to be mitigated to avoid reaching emergency scenarios and situations.

- **Plant Emergency Response:**
This layer is reached when safety measures capable of stopping the incident's progression have not been implemented. In this case, damage reduction and minimizing the impact are carried out.
- **Community Emergency Response:**
When the plant's emergency response is not sufficient to reduce the damage, the last layer of protection is activated, which involves implementing the emergency plan that affects the surrounding area and not just the plant's area.

IEC 61511 considers pressure-vacuum relief valves to be part of the prevention layer since they prevent high-risk scenarios from occurring. A well-designed device of this type can relieve pressure or vacuum peaks, avoiding the activation of an upper layer.

2 Objectives and scope

This thesis aims to provide a comparison of the main standards for the design of venting systems for atmospheric or low-pressure storage tanks.

A comprehensive examination of existing standards for pressure-vacuum venting system design is required to establish the guidelines governing the sizing and operation of pressure-vacuum relief valves. The standards analyzed throughout the study are API 2000 7th Edition Main Body and Annex A, DIN EN 14015, ISO 28300 and TRGS 509.

By critically analyzing these regulations, this study will recommend a standard for the sizing of pressure-vacuum relief valves, providing a review of each of the standards identifying lacks, inconsistencies, or areas that may require improvement. It should be noted that this study is focused on uninsulated fixed-roof storage tanks.

In this thesis, a literature review of the tank breathing main studies is performed, in which models are provided for the calculation of venting rates, and in some, considering the effect of condensation not considered in any of the current standards.

Finally, which is the selected standard and taking into account the possible effect of condensation, the thesis includes the sizing of pressure-vacuum relief valves installed in a tank farm located in Tarragona.

3 Analysis of accidents/incidents due to poor design of pressure-vacuum relief valves

Safety in industrial environments is a constant concern, and a critical aspect of this issue is the prevention of accidents and incidents related to equipment and processing systems. Among the numerous components that play a crucial role in protecting facilities and personnel are pressure-vacuum relief valves. These valves, often overlooked but of fundamental importance, are specifically designed to regulate pressure and vacuum in closed systems. However, when their design is deficient or inadequate, the consequences can be catastrophic.

In this context, this analysis focuses on evaluating accidents and incidents attributable to the poor conception and design of pressure-vacuum relief valves. These events not only pose a potential danger to facility integrity and personnel safety but can also have a significant impact on operational continuity and repair costs. Examining these incidents and learning from them is essential to improve the standards of design, implementation, and maintenance of pressure-vacuum relief valves, which, in turn, contributes to a safer and more efficient industrial environment.

Throughout this exploration, it will be addressed concrete examples of accidents and incidents related to deficient valve design; highlighting the importance of a precise focus in their engineering, and other events that can lead to accidents. By understanding the implications of inadequate design and the lessons learned from past situations, the industry can progress towards more robust and resilient systems that safeguard the integrity of facilities and the safety of those working in them.

Pressure-vacuum relief valves are typically responsible for protecting atmospheric or low-pressure systems. It should be noted that the storage tanks are the equipment that is involved in more accidents, probably because storage tanks are fragile and easily damaged by slight overpressure or vacuum. These kinds of tanks normally their vacuum tolerance is very low, typically not greater than -14 mbarg, unless mechanically reinforced with vacuum support rings. [18]

For this reason, process tanks and vessels can withstand internal pressures much larger than the vacuums needed to collapse them. Tanks and vessels often collapse when they are emptied without proper venting, or when their vents are obstructed. It is also possible to collapse a vented tank, if it is filled with steam and cooled rapidly.



Figure 5: Some examples of tank implosions due to vacuum. [10]

Here is an accident that could have been avoided if a good design and a thorough analysis of potential scenarios applicable to tank's normal operation had been conducted. In this case, the tank was cleaned with steam, so it was empty before starting the cleaning operation. Subsequently, an attempt was made to cool the tank with cold water to expedite

the process. The tank's venting system was neither designed nor sized for the vacuum resulting from this rapid cooling, leading to its failure due to extremely low internal pressure.



Figure 6: Low-pressure storage tank after its implosion. [10]

Following this incident, venting devices with greater relief capacity were installed. It is important to consider all scenarios that can result in pressures below atmospheric and ensure that venting devices will be suitable for those scenarios, including abnormal operations (such as the condensation of tank vapors due to heavy cold rain after prolonged exposure to sunlight).

Another crucial aspect to ensure the safety and integrity of the tank is to guarantee that venting and overpressure-vacuum relief devices are always kept in operation. In this instance, the tank's venting port was covered with plastic during the product discharge, resulting in a severe tank implosion.



Figure 7: Implosion caused by the obstruction of the outlet orifice. [10]

Simultaneously, do not forget about accidents caused by undesired overpressures. In the case of these types of accidents, according to Chang et.al [5], approximately 85% are attributed to fires and explosions. Within this percentage, about 33% are caused by lightning, and roughly 30% result from human errors, including improper operational practices and

maintenance. Other causes include equipment failures, sabotage, cracks and ruptures, leaks and line ruptures, static electricity, open flames, and so on. Nevertheless, most of these accidents could have been prevented if proper engineering criteria had been applied, including the correct sizing and design of pressure-vacuum and emergency relief valves.

4 Critical review of current regulations for the design of pressure-vacuum relief valves

This section explores the existing regulatory frameworks governing the design and operation of pressure-vacuum systems. Pressure-vacuum systems are crucial components in various industries, including petrochemical, pharmaceutical, and manufacturing. These systems are responsible for maintaining safe pressure levels within containers and preventing potentially catastrophic incidents such as overpressure or implosions.

This critical review aims to delve into the significance of regulations in ensuring the safety, reliability, and environmental responsibility of pressure-vacuum systems. It examines how different regulatory bodies, both national and international, address these systems' design, installation, and maintenance. The goal is to assess whether current regulations adequately address evolving industry needs, technological advancements, and emerging safety concerns.

By scrutinizing these regulations, this review aims to shed light on potential gaps, inconsistencies, or areas where improvements may be needed. Ultimately, it seeks to contribute valuable insights to enhance the effectiveness and relevance of regulations governing pressure-vacuum systems, fostering safer industrial practices, and reducing the risk of accidents.

4.1 API 2000 (2014)

API 2000 (American Petroleum Institute) deals with atmospheric venting and low-pressure storage tanks. This standard covers the requirements for normal venting capacity (due to liquid movement and thermal effects) and emergency venting capacity due to external fire. API 2000 is applicable for both above-ground and underground refrigerated tanks, except for floating roof tanks. The operating pressure range of these tanks is from vacuum to 15 psig.

It should be noted that API 2000 is based on liquid products from petroleum, so a good engineering analysis and judgment will be necessary whenever implementing this standard for other types of products.

4.1.1 Assumptions and approximations

Due to the large number of variables associated with the calculation of required venting, API makes a series of assumptions that apply to different latitudes and conditions. These assumptions and approximations are shown in Annex E of the standard. [2]

It is considered that the tank is completely filled with vapor and therefore there is no liquid in the tank. Since these are low-pressure tanks, there could be a vapor phase and a liquid phase, but assuming that there is only vapor in the tank places us in the most conservative part. This more conservative aspect is due to the fact that the heat absorbed by the tank walls will stay in the same walls due to the poor heat transfer between the vapor phase and the tank walls. Then, the tank shell will lose strength and will be more prone to failure.

Another assumption made by API 2000 is that the heat flux (cooling) through the tank bottom is considered negligible. If the heat transfer coefficient at the tank bottom is compared with the walls and the top of the tank, it can be determined that this coefficient is significantly lower. Therefore, there will be a much smaller heat flux at the bottom than in the rest of the tank.

Finally, regarding the tank walls, it is considered that the minimum thickness in all parts is 4 mm according to DIN 4119 and for the minimum inclination of the roof, a conservative value of 15° is taken. It should be noted that no additional heat capacity other than the tank wall itself is taken into account. The value of the emissivity ratio of radiation by the walls is conservatively taken from painted bronze aluminum, this value is $\epsilon=0.6$.

- *Tank Heating Assumptions:*

For the heating of the tank, a series of additional assumptions are taken into account, in addition to those mentioned above. Below is a list of these:

- The tank is filled only with air.
- No liquid residue that can evaporate during heating is considered.
- Initially, the walls and the contents of the tank are considered to be in thermal equilibrium at a temperature of 15 °C.
- Thermal convection occurs in the interior and exterior areas of the tank. The heat transfer coefficient is 2 W/(m²·K).
- Solar radiation starts at an expected maximum value and remains constant.
- The ambient temperature is constant until the maximum volumetric flow rate is reached.

- *Tank Cooling Assumptions:*

For the cooling of the tank, a series of additional assumptions are taken into account, in addition to those mentioned above. Below is a list of these:

- The tank is filled only with air.
- Initially, the atmosphere and the walls of the tank are considered to be in thermal equilibrium at a temperature of 55 °C, regardless of the construction and volume of the tank.
- Cooling due to rainfall starts immediately and during its continuity its characteristics are constant. To determine the inbreathing venting flow rate, it is assumed that the rain density is 225 kg/m²·h with an angle of 30° from the horizontal and a temperature of 15 °C. The heat transfer coefficient of rain to the environment has a value of 15 W/(m²·K).
- Thermal convection occurs in the internal area of the tank [heat transfer coefficient (wall to interior) is equal to 5 W/(m²·K)] and the cooling of the film occurs on the outside of the tank with a heat transfer coefficient of 5000 W/(m²·K).
- A possible deviation of the average temperature of the tank atmosphere due to mixing with cold ambient air is considered negligible.

4.1.2 Calculation of required venting rates

For the calculation of the required venting rates, API 2000 describes the main causes of the possible overpressure or vacuum that may occur during tank operation. It should be noted that this study only takes into account the venting from liquid transfer effects (pump in / pump out) and thermal effects. As for emergency venting rates, it only applies to the case of external fire. The standard also mentions a number of normal operating scenarios that will not be taken into account in this study, such as utility failure, chemical reactions or control valve failure, among others.

In the case of applying multiple abnormal scenarios, only the one with the highest flow rate is considered, and it is treated as the design scenario, so double jeopardy is not

considered. Additionally, API 2000 does not specify which device is responsible for protecting the tank from these scenarios.

4.1.2.1 Calculation of required flow capacity for normal outbreathing and inbreathing

In the calculations shown below, all the assumptions, considerations, and approximations explained above have already been taken into account.

- *Required venting flow rate due to liquid movement:*

1. Regarding outbreathing:

A distinction is made based on the volatility of the stored product. The product is considered non-volatile if it has a vapor pressure equal to or less than 5 kPa and volatile if it is greater than 5 kPa.

- In the case of non-volatile products, the required venting flow rate will be:

$$\dot{V}_{op} = \dot{V}_{pf} \quad (1)$$

Where:

\dot{V}_{op} : outbreathing volumetric flow rate due to liquid movement [Nm³/h]

\dot{V}_{pf} : maximum volumetric filling rate [m³/h]

- In the case of volatile products, the required venting flow rate will be:

$$\dot{V}_{op} = 2 \cdot \dot{V}_{pf} \quad (2)$$

Volatile products will have a higher outbreathing flow rate due to changes in the liquid-vapor equilibrium.

On the other hand, flashing liquids present a much higher required venting flow rate. The flash phenomenon occurs when the vapor pressure of the product entering the tank is greater than the tank's operating pressure. In this case, other calculations would have to be carried out to determine how this venting requirement should be increased.

2. Regarding inbreathing:

The required inbreathing venting flow rate due to liquid movement should be the maximum liquid discharge capacity of the tank.

$$\dot{V}_{ip} = \dot{V}_{pe} \quad (3)$$

Where:

\dot{V}_{ip} : inbreathing venting requirement due to liquid movement [Nm³/h]

\dot{V}_{pe} : maximum rate of liquid discharging [m³/h]

The calculated inbreathing assumes ambient air flow through the tank vent. It is typical to assume the ambient air is at normal or standard conditions. If a medium other than air is used for vacuum relief, then it may be necessary to convert the rate to an air equivalent flow.

- *Required venting flow rate due to thermal effects:*

The thermal effects (inbreathing/outbreathing) are due to the atmospheric heating or cooling of the outer surface of the tank. The calculation of these thermal effects is a function of the vapor volume of the tank. In the case of vertical tanks, using a tank volume based on the height of the shell is considered acceptable. These effects are more pronounced when the tank is not insulated.

3. Regarding outbreathing:

The thermal outbreathing is defined as the movement of stored gas towards the outside of the tank due to an expansion and/or vaporization of the liquid content after an increase in the external temperature of the tank. This expansion or vaporization can cause a pressure buildup inside the tank if the venting capacity is smaller than the expansion/vaporization capacity.

Therefore, the required flow rate of outbreathing due to thermal effects is calculated using the following expressions:

$$\dot{V}_{OT} = Y \cdot R_i \cdot V_{tk}^{0.9} \quad (4)$$

Where:

\dot{V}_{OT} : outbreathing volumetric flow rate due to thermal effects [Nm³/h]

V_{tk} : tank volume [m³]

R_i : reduction factor for insulation ($R_i=1$ if no insulation is used; $R_i=R_{inp}$ for partially insulated tanks [see equation (6)]; $R_i=R_{in}$ for fully insulated tanks [see equation (5)])

Y : latitude factor [dimensionless]

Table 4.1.1. Y factor for various latitudes.

Latitude	Y factor
Below 42°	0.32
Between 42° and 58°	0.25
Above 58°	0.2

The reduction factor for insulation is calculated using the following equations:

- Fully insulated:

$$R_{in} = \frac{1}{1 + \frac{h \cdot l_{in}}{\lambda_{in}}} \quad (5)$$

Where:

h: the inside heat-transfer coefficient [W/(m² K)]
 λ_{in} : the thermal conductivity of insulation [W/(m·K)]
 l_{in} : the wall thickness of the insulation [m]

- Partially insulated:

$$R_{inp} = \frac{A_{inp}}{A_{TTS}} \cdot R_{in} + \left(1 - \frac{A_{inp}}{A_{TTS}}\right) \quad (6)$$

Where:

A_{inp} : the insulated surface area of the tank [m²]
 A_{TTS} : the total tank surface area (shell and roof) [m²]

4. Regarding inbreathing:

Thermal inbreathing is considered when air or inert gas enters the interior of the tank, which occurs when the external temperature of the tank decreases significantly. This results in condensation of the vapor in the tank's headspace, causing a decrease in pressure inside the tank. Therefore, it is this pressure difference that causes the inflow of inbreathing current into the tank to compensate for and stabilize the tank pressure.

Therefore, the required flow rate of inbreathing due to thermal effects is calculated using the following expressions:

$$\dot{V}_{IT} = C \cdot R_i \cdot V_{tk}^{0.7} \quad (7)$$

Where:

\dot{V}_{IT} : inbreathing volumetric flow rate due to thermal effects [Nm³/h]

V_{tk} : tank volume [m³]

R_i : reduction factor for insulation [-] ($R_i=1$ if no insulation is used; $R_i=R_{inp}$ for partially insulated tanks [see equation (6)]; $R_i=R_{in}$ for fully insulated tanks [see equation (5)])

C: factor that depends on vapor pressure, average storage temperature and latitude [-]

Table 4.1.2. C factor values.

Latitude	C factor			
	Vapor pressure similar to Hexane		Vapor pressure higher than hexane, or unknown	
	Average storage temperature °C			
	<25	≥25	<25	≥25
Below 42°	4	6.5	6.5	6.5
Between 42° and 58°	3	5	5	5
Above 58°	2.5	4	4	4

4.1.2.2 Calculation of required flow capacity for external fire (emergency venting)

When the tank is exposed to an external fire, the required venting flow rate may exceed the normal outbreathing flow rate. In this situation, it is necessary to determine the flow rate that should be released outside the tank in order to protect the tank structure and everything surrounding it.

The required venting flow rate due to an external fire case is calculated using the following expressions:

$$q = 906.6 \cdot \frac{Q \cdot F}{L} \left(\frac{T}{M} \right)^{0.5} \quad (8)$$

Where:

Q: the heat input from fire exposure [W]

L: the latent of vaporization of the stored liquid at the relieving pressure and temperature [J/kg]

T: the absolute temperature of the relieving vapor [K]

M: the molecular mass of the vapor

q: the required flow capacity for tanks subject to fire exposure [Nm³/h]

F: the environmental factor

A_{TWS} = total wetted area of the tank [m²]

Table 4.1.3. Heat input, Q.

Wetted Surface Area, A _{TTS} [m ²]	Design Pressure [kPag]	Heat Input, Q [W]
<18.6	≤103.4	63150A _{TWS}
≥18.6 and <93	≤103.4	224200(A _{TWS} ^{0.566})
≥93 and <260	≤103.4	630400(A _{TWS} ^{0.338})
≥260	>7 and ≤103.4	43200(A _{TWS} ^{0.82})
≥260	≤7	4129700

To determine the required wetted area of the tank, the following premises are followed:

- For spherical tanks, the wetted area is considered to be 55% of the total surface area of the tank up to a maximum height of 9.14 m above the ground.
- For horizontal tanks, the wetted area is equal to 75% of the total surface area of the tank up to a maximum height of 9.14 m above the ground.
- For vertical tanks, the wetted area is equal to the total surface area of the vertical shell up to a maximum height of 9.14 m above the ground. In cases where the tank bottom is not on the ground, an additional portion of area should be considered.

Finally, to determine the value of the remaining parameter in order to calculate the required venting flow rate due to the external fire case, the following table is followed:

Table 4.1.4. Environmental factors for nonrefrigerated aboveground tanks.

Tank Design/Configuration	Insulation Conductance [W/(m ² ·K)]	Insulation Thickness [cm]	F factor
Bare metal tank	-	-	1.0
Insulated tank	22.7	2.5	0.3
	11.4	5.1	0.15
	5.7	10.2	0.075
	3.8	15.2	0.05
	2.3	25.4	0.03
	1.9	30.5	0.025
Concrete tank or fireproofing	-	-	*
Water-application facilities	-	-	1.0
Depressuring and emptying facilities	-	-	1.0
Underground storage	-	-	1.0
Earth-covered storage above grade	-	-	1.0
Impoundment away from tank	-	-	1.0

*Use the F-factor for an equivalent conductance value of insulation.

The values of the environmental F-factor are only valid in the case where the tank is not refrigerated and is located above the ground.

It is important to note that there is a type of tank that has a design that anticipates this emergency scenario during its construction. This design is based on a weak fixation of the roof to the tank structure. Therefore, in the event of a considerable overpressure, the roof undergoes a rupture that is capable of releasing this overpressure. In this type of tank, an emergency venting system would not be required, but its installation is recommended.

4.2 API 2000 Annex A (2014)

This calculation methodology has been used in the storage tanks of the petrochemical sector in the United States since the 1940s. Generally, the required venting capacities indicated

by this method are lower than the general calculation method of API 2000 in terms of vacuum venting requirements. It is important to note that this method only allows for determining the requirements for normal inbreathing and outbreathing due to liquid movement and thermal effects; therefore, it cannot be applied in the case of an external fire. Highlight that API 2000 Annex A was the primary calculation methodology up to the fifth edition (1998). [1]

The following are the conditions that must be met to apply this calculation method:

- The tank volume must be less than 30,000 m³.
- The maximum operating temperature of the vapor space in the tank is approximately 49 °C.
- The tank should not have insulation.
- The temperature of the contents and feed of the tank must be lower than the boiling temperature when operating at the maximum tank pressure.

4.2.1 Calculation of required venting rates

It should be noted that the assumptions and considerations made in this standard are explained throughout this section.

Below, the corresponding tables are shown to determine the different required flow rates:

Table 4.2.1. API 2000 Annex A normal venting requirements due to liquid movement.

Flash Point/Boiling Point [°C]	Inbreathing	Outbreathing
	Liquid movement out	Liquid movement in
Flash point ≥ 38	0.94	1.01
Boiling Point ≥ 150	0.94	1.01
Flash point < 38	0.94	2.02
Boiling point < 150	0.94	2.02

From the previous table, it should be noted that the values shown correspond to 1 Nm³/h of air for every m³/h of liquid flow rate.

To identify which row to use, both the flash point and boiling point data of the product can be considered, although in cases where both values are available, the flash point should always be taken into consideration.

As for the required venting flow rates due to thermal effects:

Table 4.2.2. API 2000 Annex A normal venting requirements due to thermal effects.

Tank Capacity [m ³]	Inbreathing [Nm ³ /h of air]	Outbreathing	
		Flash Point ≥ 37.8 or Normal Boiling Point ≥ 149 [Nm ³ /h of air]	Flash Point < 37.8 or Normal Boiling Point < 149 [Nm ³ /h of air]
10	1.69	1.01	1.69
20	3.38	2.02	3.38
100	16.9	10.1	16.9
200	33.8	20.3	33.8
300	50.4	30.4	50.4
500	84.5	50.7	84.5
700	118	71.0	118
1000	169	101	169
1500	254	152	254
2000	338	203	338
3000	507	304	507
3180	537	322	537
4000	647	388	647
5000	787	472	787
6000	896	538	896
7000	1003	602	1003
8000	1077	646	1077
9000	1136	682	1136
10000	1210	726	1210
12000	1345	807	1345

14000	1480	888	1480
16000	1615	969	1615
18000	1750	1047	1750
20000	1877	1126	1877
25000	2179	1307	2179
30000	2495	1497	2495

Interpolation of intermediate values in the table is allowed.

For heat transfer from ambient conditions resulting in an increase of temperature in the vapor space, the volumetric expansion rate is expected to be much slower than the contraction rate as the heating of ambient air does not occur as rapidly. In these cases, the increase in temperature of the vapor space caused by the liquid temperature can have a greater impact; however, this necessarily means a partially filled tank. In addition, the increase in liquid temperature can result in some vaporization of the residual liquid if that liquid is volatile.

The volumetric expansion rate may be estimated as 60 % of the volumetric contraction rate caused by ambient heat transfer for nonvolatile liquids, and may be estimated at 100 % of the volumetric contraction rate for volatile liquids, according to API 2000 Annex A. [2]

In establishing the basis above, it is recognized that the requirements for outbreathing are somewhat conservative; however, some conservatism is believed to be desirable to take into account both unusual climatic conditions and products that can generate more vapor than gasoline generates. Also, the cost involved for a larger venting device is very small, considering the overall cost of a tank. This conservatism also provides some margin of safety if the liquid entry rates slightly exceed the design rates.

It should be noted that the cooling of the vapor space in the tank is based solely on a maximum heat transfer rate or a maximum rate of temperature change. Therefore, the boundary conditions for inbreathing calculation will be:

- A maximum heat transfer coefficient of 63 W/m².
- A temperature change rate with a maximum value of 56 K/h.

As a result, for small tanks with a volume less than 3180 m³, the required inbreathing flow rate due to thermal effects is limited by the maximum temperature change rate of 56 K/h in the tank headspace. Assuming an initial temperature of 48.9 °C, the approximate required venting flow rate corresponds to 0.169 Nm³/h of air per cubic meter of the tank.

$$\dot{V}_{IT} = 0.169 \cdot V_{tk} \quad (9)$$

On the other hand, for tanks with a volume between 3180 and 30,000 m³, the required inbreathing flow rate due to thermal effects is limited by the heat transfer coefficient of 63 W/m². This calculation approximates 0.577 Nm³/h of air per square meter of exposed tank surface.

$$\dot{V}_{IT} = 0.577 \cdot A_{exp} \quad (10)$$

Where:

A_{exp} : exposed surface area of the tank [m²]

It should be noted that for tanks with a large volume, such as 30,000 m³, the venting requirements assume a total surface area of 4324 m², a heat transfer coefficient of 63 W/m², an initial temperature of 48.9 °C, and the properties of the fluid in the tank headspace are those of air. Therefore, for a 30,000 m³ tank, the calculated venting requirement is 0.577 Nm³/h of air per square meter of exposed tank surface, and the maximum rate of temperature change is 28 K/h.

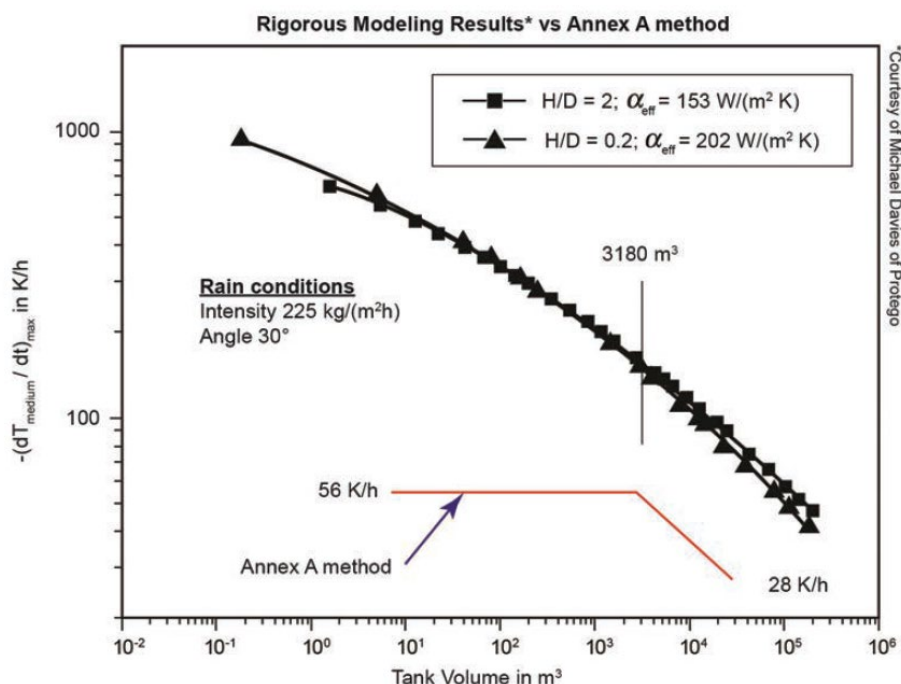


Figure 8: Maximum rate of temperature change; API 2000 Annex A vs Main Body. [2]

One aspect to consider is the lack of condensation of the tank vapor during cooling. This is an essential assumption in the application of this annex.

Previously, API 2000 Annex A referred to the required emergency flow rate due to the external fire case, but now it is only referenced in the API 2000 main body. Moreover, API 2000 7th Edition includes the Annex G for the explanation of differences in thermal inbreathing using the general method and Annex A method.

4.3 ISO 28300 (2008)

ISO 28300 (International Organization for Standardization) is the sixth edition of API 2000, thus having the same title as the seventh edition of API 2000. This standard is intended for the same type of industry and tanks described earlier in section API 2000.

For determining the required venting flow rates in different scenarios (inbreathing and outbreathing due to liquid movement/thermal effects and external fire case), the same assumptions and approximations as explained in API 2000 are followed. [17]

4.3.1 Calculation of required venting rates

In this section, the different calculations for the required venting flow rates are introduced. Since ISO 28300 is practically the same standard as API 2000, not all calculations will be detailed as they have been previously introduced in the API 2000 section.

For this reason, only the differences with API 2000 regarding the calculation methodology will be mentioned.

One notable difference is that ISO 28300 does not specify the factor to be applied to volatile products. Instead, the increase in outbreathing due to liquid movement must be taken into account based on the evaporation ratio. Many times, determining the value of the evaporation ratio is challenging because many product safety data sheets do not include this information, or they reference that it can be approximated by the Henry's constant.

The rest of the calculation methodology, both for normal inbreathing/outbreathing and for the external fire case, is identical to the one developed previously in the API 2000 section.

4.4 EN 14015 (2005)

This document specifies the requirements for the materials, design, fabrication, erection, testing and inspection of site built, vertical flat bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperatures and above, and the technical agreements that need to be reached.

This European standard reflects the current practice within oil, petrochemical, chemical, food and general bulk liquids, both European and world-wide. The practice is based on the theory of design stresses or allowable stresses.

This document applies to storage tanks with the following characteristics:

- Design pressure less than 500 mbarg and design internal negative pressure not lower than 20 mbarg
- Design metal temperature not lower than -40 °C and not higher than 300 °C.
- Maximum design liquid level not higher than the top of the cylindrical shell.

It's worth noting that this regulation is very extensive as it provides a detailed description of the design and manufacturing of the tank, among many other sections. For this reason, this section will primarily focus on Annex L of the standard.

The annex L gives requirements for the normal pressure, normal vacuum and emergency venting of fixed-roof tanks with or without internal floating roofs constructed to conform to this document. [11]

4.4.1 Calculation of the required venting rates

Next, in this section, the calculations proposed by EN14015 to determine the maximum flow rates required for normal breathing and emergency scenarios are presented below.

4.4.1.1 Calculation of required flow capacity for normal outbreathing and inbreathing

This standard considers that outbreathing y inbreathing of vents and valves shall be a combination of pump capacity and thermal effects.

- *Pump capacities:*

1. Outbreathing

The outbreathing shall be the maximum specified pump filling capacity for the tank for products stored below 40 °C or with a vapor pressure less than 50 mbarg.

$$U_{op} = U_{pf} \quad (11)$$

Where:

U_{op} = the outbreathing venting requirement [Nm³/h]

U_{pf} = the maximum filling rate [m³/h]

For spiked products (e.g., with methane) the maximum venting capacity shall be increased by a multiplication factor of 1.7 to correct the pumping rate to take into account the gas evolved from spiked products during the filling process. Besides, for products stored above 40 °C or with a vapor pressure greater than 50 mbarg, the outbreathing shall be increased by the evaporation rate.

2. Inbreathing

The inbreathing shall be the maximum specified pump discharging capacity for the tank.

$$U_{ip} = U_{pe} \quad (12)$$

Where:

U_{ip} = the inbreathing venting requirement [Nm³/h]

U_{pe} = the maximum rate of pump discharging [m³/h]

- *Thermal effects:*

Thermal outbreathing and inbreathing due to atmospheric heating or cooling of the external surfaces of the tank, comprising the area of the shell and the projected area of the roof, shall be considered.

3. Outbreathing

The maximum possible flow rate caused by heating shall be calculated in accordance with the following formula:

$$U_{OT} = Y \cdot R_o \cdot V_T^{0.9} \quad (13)$$

$$R_o = \left(1 - \frac{\Delta P_{ap}}{140}\right)^{1.6} \quad (14)$$

Where:

ΔP_{ap} = the accumulation pressure [mbarg] (if ΔP_{ap} is < 5 mbarg or unknown, use $R_o=1$)

R_o = the reduction factor for thermal outbreathing [-]

Y = latitude factor [dimensionless] (see Table 4.1.1.)

V_T = tank volume [m³]

The reduction factor for complete and partially insulation is determined by the equations (5) and (6) respectively.

4. Inbreathing

The maximum possible flow rate caused by cooling down shall be calculated in accordance with following formula:

$$U_{IT} = C \cdot R_i \cdot V_T^{0.7} \quad (15)$$

$$R_i = \left(1 - \frac{\Delta P_{av}}{140 + P_{vp}}\right)^{1.6} \quad (16)$$

Where:

R_i = the reduction factor for thermal inbreathing [-]

C = factor that depends on vapor. pressure, average storage temperature and latitude [-] (see Table 4.1.2.)

P_{vp} = the vapor pressure of the liquid at highest temperature [mbar] (if P_{vp} is unknown use $R_i = 1$)

ΔP_{av} = the accumulation vacuum [mbarg]

V_T = tank volume [m³]

Once the equations corresponding to the required venting flow rates due to tank filling and emptying, as well as thermal effects, have been presented, it should be noted that the total flow rates for outbreathing and inbreathing will be the sum of both effects. The following equations show the total flow rates for outbreathing and inbreathing, respectively:

$$U_{OUT} = U_{OT} + U_{op} \quad (17)$$

$$U_{IN} = U_{IT} + U_{ip} \quad (18)$$

4.4.1.2 Calculation of maximum flow rates for emergency venting

In the case of external fire, very high outbreathing capacities may be needed. If the existing pressure relief valves for normal operating conditions are not capable of handling such high capacities, emergency outbreathing systems shall be provided.

It's worth noting that there are different emergency scenarios, but in this case, external fire is considered the design scenario. The tank can be heated up by a nearby fire leading to a sudden large expansion of the gas volume in a few minutes, and after hours to a full evaporation of the product.

$$U_{FB} = 4 \cdot 10^4 A_w^{0.82} \frac{R_{inf}}{H_v} \sqrt{\frac{T}{M}} \quad (19)$$

Where:

U_{FB} = the flow rate by evaporation due to external fire case [Nm^3/h]

A_w = the surface area of the tank shell heated by fire [m^2]

R_{inf} = the reduction factor for insulation [-]

H_v = the heat of vaporization [kJ/kg]

T = the boiling temperature [K]

M = the molar weight of the product [kg/kmol]

4.5 TRGS 509 (2014)

TRGS 509 (*Technische Regeln für Gefahrstoffe 509*) is a German technical guideline that addresses the safe handling of hazardous substances in confined spaces. It is designed to provide guidelines and recommendations to prevent risks associated with exposure to hazardous substances in enclosed environments. One of the key aspects of TRGS 509 is the ventilation and venting systems. [33]

Storage of hazardous substances up to flash point below 55 °C; for higher flash points, additional protective measures may be necessary. TRGS 509 does not apply to the following cases: for ammonium nitrate and its mixtures, see TRGS 511; for explosives, see 2nd Explosives Ordinance, for organic peroxides, see GefStoffV, for the storage of gases, see TRBS 3146, for bulk goods in bulk in warehouses, for filling stations and filling plants, see TRBS 3151.

TRGS 509 does not allow for tank insulation or containment tanks. For insulated tanks or tanks within containment tank should consider venting instead according to standards like ISO 28300 or API 2000. Furthermore, only normal venting flow rates are taken into account, but it does not specify how to determine the emergency flow rate.

Below are the equations provided to calculate normal venting flow rates due to thermal effects according to TRGS 509.

$$\dot{V}_E = 0.17 \cdot \left(\frac{H}{D}\right)^{-0.52} \cdot V_{tk}^{0.89} \quad (20)$$

$$\dot{V}_A = 4.8 \cdot V_{tk}^{0.71} \quad (21)$$

Where:

\dot{V}_E : outbreathing flow rate due to thermal effects [Nm³/h]

\dot{V}_A : inbreathing flow rate due to thermal effects [Nm³/h]

H: tank height [m]

D: tank diameter [m]

V_{tk} : tank volume [m³]

To determine the total outbreathing and inbreathing flow rates, the pump-in and pump-out flow rates must be taken into account. In this case, TRGS 509 does not apply any factor depending on whether the product is volatile or not.

Therefore, the first equation corresponds to the total outbreathing flow rate, and the second one corresponds to the inbreathing flow rate.

$$\dot{V}_{out} = \dot{V}_E + \dot{V}_{pump-in} \quad (22)$$

$$\dot{V}_{in} = \dot{V}_A + \dot{V}_{pump-out} \quad (23)$$

4.6 MIE APQ 0-10 and ITC (RD 656-2017)

One of the objectives of this thesis is to compare the different current regulations and standards that govern and are applied to the design of low-pressure tanks. Additionally, the intention is to analyze the case of designing a low-pressure tank located in Tarragona. For this reason, it is necessary to understand the current legislation regarding this type of tank in the country.

In Spain, the storage of chemical products is regulated by the Regulation on the Storage of Chemical Products and its Complementary Technical Instructions MIE APQ 0 to 10. The APQ Regulation (Real Decreto 656/2017) aims to establish safety conditions for the storage, loading, unloading, and transfer of hazardous chemical products. It serves as a benchmark in industrial safety and is mandatory for any installation storing products classified as hazardous, whether in solid, liquid, or gaseous state.

This regulation contains general rules, as well as complementary technical instructions (ITCs) that must be applied in new construction, expansions, and modifications of existing facilities, establishing requirements for the safety of individuals and property.

The scope of this regulation is very broad; for this reason, the complementary technical instruction MIE APQ-1 "Storage of Flammable and Combustible Liquids in Fixed Containers" is introduced briefly. The Article 10 of this ITC details normal and emergency vents, as well as venting systems and the requirements corresponding to this type of venting.

The RD 656/2017 indicates that all venting systems, except those of floating roof tanks, will be marked and certified by the manufacturer according to procedures determined in the UNE-EN ISO 28300 standard. Furthermore, normal and emergency vents for atmospheric low-pressure storage will be sized according to the ISO 28300 standard.

Therefore, in Spain, the standard that regulates the design of pressure/vacuum valves for atmospheric or low-pressure tanks corresponds to ISO 28300. This regulation has been detailed earlier in the thesis. [26]

4.7 Comparison of regulations for inbreathing, outbreathing and fire cases

Having analyzed the different standards and regulations that regulate vent flows for normal operation and for the case of an external fire emergency, is proceed to compare the different equations and the assumptions that each of the standard take into account. The following table shows all the equations that are attributed to the calculation of the required venting flow rates.

The units of the different variables appearing in the equations are shown in the respective standards.

Table 4.7.1. Comparison of equations according to the different standards.

Standard	Required venting flow rates [Nm ³ /h]				Fire case
	Outbreathing pump in	Outbreathing thermal effect	Inbreathing pump out	Inbreathing thermal effect	
API 2000	Non volatile: $\dot{V}_{op} = \dot{V}_{pf}$ Volatile: $\dot{V}_{op} = 2 \cdot \dot{V}_{pf}$	$\dot{V}_{OT} = Y \cdot R_i \cdot V_{tk}^{0.9}$	$\dot{V}_{ip} = \dot{V}_{pe}$	$\dot{V}_{IT} = C \cdot R_i \cdot V_{tk}^{0.7}$	$q = 906.6 \cdot \frac{Q \cdot F}{L} \left(\frac{T}{M} \right)^{0.5}$
API 2000 Annex A	Flash point ≥ 38 °C: $\dot{V}_{op} = 1.01 \cdot \dot{V}_{pf}$ Flash point < 38 °C: $\dot{V}_{op} = 2.02 \cdot \dot{V}_{pf}$	See Table 4.2.2.	$\dot{V}_{ip} = 0.94 \cdot \dot{V}_{pe}$	See Table 4.2.2.	See API 2000
ISO 28300	Non volatile: $\dot{V}_{op} = \dot{V}_{pf}$ Volatile: $\dot{V}_{op} = \text{Evap. rate} \cdot \dot{V}_{pf}$	$\dot{V}_{OT} = Y \cdot R_i \cdot V_{tk}^{0.9}$	$\dot{V}_{ip} = \dot{V}_{pe}$	$\dot{V}_{IT} = C \cdot R_i \cdot V_{tk}^{0.7}$	$q = 906.6 \cdot \frac{Q \cdot F}{L} \left(\frac{T}{M} \right)^{0.5}$
EN 14015	Non volatile: $\dot{V}_{op} = \dot{V}_{pf}$ Volatile: $\dot{V}_{op} = \text{Evap. rate} \cdot \dot{V}_{pf}$	$\dot{V}_{OT} = Y \cdot R_i \cdot V_{tk}^{0.9}$	$\dot{V}_{ip} = \dot{V}_{pe}$	$\dot{V}_{IT} = C \cdot R_i \cdot V_{tk}^{0.7}$	$U_{FB} = 4 \cdot 10^4 A_w^{0.82} \frac{R_{inf}}{H_v} \sqrt{\frac{T}{M}}$
TRGS 509	$\dot{V}_{op} = \dot{V}_{pf}$	$\dot{V}_E = 0.17 \cdot \left(\frac{H}{D} \right)^{-0.52} \cdot V_{tk}^{0.89}$	$\dot{V}_{ip} = \dot{V}_{pe}$	$\dot{V}_A = 4.8 \cdot V_{tk}^{0.71}$	-

5 Design methods in the case of non-condensable vapors

Proper management of non-condensable vapors in low-pressure tanks is a fundamental aspect of the liquid storage industry. These vapors, including gases such as air, nitrogen, and other non-condensable components, can significantly impact the internal pressure of tanks. As the temperature of the liquid contained within the tank varies due to environmental conditions and loading/unloading operations, a phenomenon known as "thermal breathing" occurs.

Thermal breathing refers to the process by which non-condensable vapors are released or absorbed by the tank to equalize internal pressure as the liquid temperature changes. Excessive pressure buildup can have adverse consequences, such as tank deformation or uncontrolled vapor release into the environment, which can be not only hazardous but also costly in terms of efficiency and regulatory compliance.

To address these challenges, various studies have been conducted and methods for designing and controlling thermal breathing devices for low-pressure tanks have been developed. These studies focus on understanding the characteristics of non-condensable vapors, their physical properties, and how they interact with stored liquids. Through theoretical analysis, computational simulations, and practical experiments, researchers aim to identify factors influencing thermal breathing and develop strategies for its effective management.

For this reason, in this section the main studies conducted on cases in which the tank vapors are non-condensable are presented.

5.1 Förster (1984)

Förster et al. [13] analyze the required flow rates due to thermal effects in order to prevent deformation of the tank, which is assumed to have been exposed to prolonged and uninterrupted solar exposure followed by severe cold rain.

The authors assume that there is temperature homogeneity within the tank's contents and, therefore, it is only affected by the passage of time. Furthermore, the method proposed by Förster, also known as PTB, does not consider any heat transfer between the tank walls due to the thermal gradient between the hot surface and the cold surface. Therefore, a uniform temperature is assumed that depends solely on time.

It is worth noting that both surface liquid evaporation and tank vapor condensation are not taken into account. The only effect considered to result from temperature variation is the expansion or compression of the vapor space.

The maximum breathing Flow rate is shown below:

$$\max(\dot{V}) = \frac{V_B}{T_B} \cdot \frac{dT_B}{dt} \quad (24)$$

Where:

V_B = volume of tank [m³]

T_B = temperature of tank products [K]

5.1.1 Simplified approach in function of the tank geometry

In Förster's work, an analytical model is developed to calculate the required venting flow rates due to thermal effects. This method can be simplified for cylindrical tanks with conical roofs constructed according to DIN 4119.

In this approximation, the authors consider a minimum tank wall thickness of 4 mm, assuming a lower thermal capacity and a more conservative maximum temperature gradient, dT_B/dt . Additionally, the tank only contains dry air at an initial temperature of 15°C. To maximize the heat from solar radiation to the stored products in the tank, an emissivity and absorption coefficient of 0.6 is considered, which corresponds to an aluminum coating. This value is mentioned in Annex E of the API 2000 7th Edition (2014) standard.

The convective heat transfer coefficients to the walls, α_U (external) and α_B (internal), have been set equal to 2 W/(m² K). For the external heat transfer coefficient, α_U , this consideration is conservative for a range of tank volumes from 10 to 10,000 m³ and a ratio H/D from 0.2 to 2.

Therefore, for the specified values of emissivity and absorption coefficients, heat transfer coefficients, and a ratio H/D equal to or greater than 0.2 for tanks with a volume between 10 to 10,000 m³, the maximum required outbreathing flow rate corresponds to the following equation.

$$\max(\dot{V}_{out}) = 0.171 \cdot (H/D)^{-0.52} \cdot V_B^{0.89} \quad (25)$$

This equation has been integrally adopted within TRGS 509. Furthermore, it exhibits a strong similarity to the equation (4) proposed by the API 2000 standard, as if a ratio H/D of 0.5 is considered and the tank is located in central Europe, the same expression is obtained.

For the inbreathing requirements, the authors approach neglects the cooling effect brought by the breathing of colder ambient air inside the tank. This effect has been analyzed in recent publications, as discussed in this thesis, such as the one by Moncalvo and Davies in 2016 [21].

In this case, the simplified approach in function of tank geometry takes into account an initial temperature of 55°C for both the tank walls T_{EO} and the product stored inside the tank T_{B0} (air), while the ambient temperature is 15°C. It is important to note that for these values, the internal heat transfer coefficient α_B is 5 W/(m² K), while the coefficient between the tank walls and the rain film is 5000 W/(m² K). Furthermore, the heat transfer coefficient between the environment and the rain film, α_U , is 15 W/(m² K), assuming a wind speed of 10 m/s.

In the PTB method, extreme rainfall conditions are assumed to provide a more conservative scenario. These conditions take into account a mass flow rate of rain of 225 kg/(m² h). It is worth noting that this value is also referenced in the API 2000 7th Edition, Annex E.

5.1.2 Validation and simplified approach in function of the tank geometry

The authors of the PTB model validated their method against measurements performed by Sigel et. al [32] with a cylindrical tank of diameter and height of 10.6 and 8.5 meter. For an experimental set with θ_0 ($T_{B0} - T_{wa}$) \leq 20 K and a rain intensity of 60 kg/(m² h), an increment of the external heat transfer coefficient α_U from zero to 5 W/(m² K), which is the

value specified in API 2000 Annex E, caused an increment about 20% of the maximum inbreathing rate. With increasing rain intensity, the convective wind cooling, which is proportional to the external heat transfer α_U , could become negligible as rain rinse cooling dominates.

The authors concluded that, under the assumptions of a worst case scenario with a very large rain intensity 225 kg/(m² h) and neglecting the tank wall thickness, the correlation in the next equation can be developed, which matches with the formula for thermal inbreathing in API 2000 7th Edition (equation (7)) for C=5. According to PTB, the H/D ratio plays a marginal role.

$$\max(\dot{V}_{in}) = 0.12 \cdot (T_{B0} - T_{wa}) \cdot V_B^{0.71} \quad (26)$$

Where:

T_{B0} = initial temperature of tank products (in this case 55 °C) [K]

T_{wa} = temperature of rain drops (in this case 15°C) [K]

It should be noted that the equation (26) has been integrally adopted within TRGS 509, taking into account that the considered temperature difference is 40°C. Therefore, the PTB model still has a significant influence on the venting flow rate calculations today.

5.2 Salatino (1999)

The model proposed by Salatino et al. [27] considers the temperature non-uniformity inside the tank. In this study, a simplified method is presented to estimate the maximum inbreathing for a tank with non-condensing products. Furthermore, Salatino compares this model to the older version of API 2000 (1992), current Annex A.

Salatino presents a design procedure for thermal venting devices for atmospheric liquid storage tanks which takes into account temperature non-uniformity by the recourse to a multiple-zone description of the tank enclosures, shell and roof.

Initially, the paper introduces a reference scenario in which a first and a second phase are identified. In the first phase, the environment is warm and sunny, and therefore, the tank is exposed to intense solar radiation. Meanwhile, in the second phase, the environmental conditions change, a rainstorm occurs, and the ambient temperature decreases. Consequently, the temperature of the vapor inside the tank also decreases, leading to a reduction in pressure, in other words, creating a vacuum.

5.2.1 Assumption and approximations

The authors assess the variables before and after the change in climatic conditions. The following equation represents the energy balance of the tank, and it should be noted that the conduction through the metal walls is not considered as it is deemed to have a negligible impact.

$$\rho_e c_e s \frac{dT}{dt} = ks\nabla^2 T + q\varepsilon + h_A(T_A - T) + h_G(T_G - T) \quad (27)$$

Where:

ρ_e = density of the metal element [kg/m³]

c_e = heat capacity of the metal element [kJ/(kg K)]

s = metal element thickness [mm]

$\nabla^2 T$ = Laplacian temperature of the element [K]

t = time [s]

k = thermal conductivity of metal [W/(m K)]

q = incident radiative flux [W/m²]

ε = Surface emissivity of metal [-]

h_A = heat transfer coefficient of metal and ambient [W/(m² K)]

T_A = temperature of the ambient [K]

h_G = heat transfer coefficient of metal and stored gas [W/(m² K)]

T_G = temperature of the stored gas [K]

From the previous equation, the first term can be neglected if a pseudo-steady process is considered. Additionally, the second term is generally much smaller than the rest; therefore, it could also be disregarded due to its lesser impact. Finally, the last three terms refer to radiation heat, convection heat from the surroundings of the tank, and convection heat from the stored gases, respectively.

In this way, it can be obtained the energy balance of the gas inside the tank, allowing us to determine the gas temperature value before the change in climatic conditions.

$$T_G = \frac{\sum A_i h_{iG} T_i}{\sum A_i h_{iG}} \quad (28)$$

Where:

A_i = surface "i" area [m²]

h_{iG} = heat transfer coefficient between "i" and the gas [W/(m² K)]

T_i = temperature of "i" [K]

Subscript "i" = corresponds to R for roof, S for Shell and L for liquid

Once the rainstorm begins ($t=0$ s), the temperature of the tank shell, roof, and the gas stored inside the tank decreases significantly. In the study, the theoretical maximum attainable vacuum in the tank is defined, assuming no condensation takes place, as follows:

$$|p_2 - p_1| = p_1 \left(1 - \frac{T_{G,2}}{T_{G,1}} \right) \quad (29)$$

Where:

p_2 = vapor pressure of the gas after rainstorm occurs [mm w.g.]

p_1 = vapor pressure of the gas before rainstorm occurs [mm w.g.]

$T_{G,2}$ = temperature of the gas after rainstorm occurs [K]

$T_{G,1}$ = temperature of the gas before rainstorm occurs [K]

The maximum inbreathing flow rate is a function of the heat transfer coefficients between the gas and either the liquid or each individual tank surface in contact with it.

$$\dot{V}_{\max, \text{in}} = \sum \frac{A_i h_{iG}}{c} \cdot \frac{R}{p(T_{G,1} - T_{G,2})} \quad (30)$$

In this equation c is the molar specific heat at constant pressure, R the universal gas constant and p the pressure inside the tank, while $T_{G,1}$ and $T_{G,2}$ are the asymptotical gas temperatures before and after the rainstorm. The units of the variables in the equation (30) are shown in the original study [27].

5.2.2 Results

The determination of the heat transfer coefficients is crucial to the estimation temperature inside the tank. For this reason, application of the above procedure is exemplified in the following.

A cone-roof tank characterized by the following geometrical parameters is considered; diameter 70 m and height 15 m; liquid storage capacity: 56000 m³; roof tangent: 0.167 and total volume tank: 63000 m³. Initial ambient and shell temperature was 309 K, calculated roof temperature was 337 K, and liquid temperature was 298 K. The final temperatures of the Shell, roof, and surroundings end up reaching 293 K. Using the following heat transfer coefficients, could be obtained the initial and final gas temperatures, with $T_{G,1}$ and $T_{G,2}$ being 315 K and 294 K, respectively.

Table 5.2.1. Heat transfer coefficients between gas and either liquid or tank roof or tank shell.

Heat transfer coefficient h_{iG} [W/(m ² K)]	Gas & Liquid (h_{LG})	Gas & Roof (h_{RG})	Gas & Shell (h_{SG})
Initial	3	3	3
Final	3	5	5

Salatino et. al [27], with the aim of simplifying the model, consider an approximate value for the heat transfer coefficients (h_{LG} , h_{RG} y h_{SG}) of 4 W/(m² K) and a gas temperature drop of 25 °C. These approximations lead to a more conservative model and approximation of the inbreathing rate.

Therefore, equation (30) can be replaced by the following expression:

$$\dot{V}_{\max, \text{in}} = KV_{\text{tank}}^{2/3} \left(\frac{1 + 2H/D}{\sqrt[3]{H/D}} \right) \quad (31)$$

Where:

K = constant of 2.6 [m/h]

H= height of tank [m]

D= tank diameter [m]

The following table summarizes the inbreathing requirements obtained from Salatino's model versus other practical methodologies.

Table 5.2.2. Comparison among several calculation method as done by Salatino [27].

Calculation method	Formula	Max. thermal inbreathing [m ³]
API 2000 Annex A	Table A.3 (see Table 4.2.2.) $\dot{V}_{\max,\text{in}} \propto V_{\text{tank}}^{0.7}$	4100
Naumann Formula	$\dot{V}_{\max,\text{in}} \propto D^2(1 + 4H/D)$	12800
PTB – TRbF Formula	$\dot{V}_{\max,\text{in}} \propto V_{\text{tank}}^{0.71}$	11300
pr EN 265001	N/A	6300-10500
Salatino – Dynamic simulation	N/A	9600
Salatino equation (30).	$\dot{V}_{\max,\text{in}} = \sum \frac{A_i h_{iG}}{c} \cdot \frac{R}{p(T_{G,1} - T_{G,2})}$	10000
Salatino equation (31)	$\dot{V}_{\max,\text{in}} = KV_{\text{tank}}^{2/3} \left(\frac{1 + 2H/D}{\sqrt[3]{H/D}} \right)$	9900

5.2.3 Conclusions

The authors compare the inbreathing flow rates obtained with those calculated using API 2000 Annex A, Naumann, and PTB methods.

It can be observed that the maximum inbreathing flow rate determined by API 2000 Annex A is notably lower than the inbreathing flow rates obtained by the other methods. On the other hand, the flow rates determined by Salatino range between 9600 and 10000 m³/h; therefore, the simplified model is considered an acceptable and slightly conservative tool for designing inbreathing devices, which are easier to use than the direct numerical method. However, the flow rates proposed by the Naumann and PTB formulas are slightly higher. The previous table clearly shows that all three models developed by the authors approach the upper range of the pr EN 265001, and therefore, ISO 28300 and API 2000 7th Main Body.

Regarding the impact of condensation, the study mentions the importance of considering the increase in inbreathing flow rate due to this phenomenon but does not provide any simulations to study the effects of condensation.

In conclusion, the simplified method by Salatino is deemed acceptable as it calculates a conservative maximum inbreathing flow rate. However, the authors believe that the application

of API 2000 Annex A does not appear to be sufficiently conservative and consistent for sizing safety devices designed to handle these thermal breathing scenarios. Therefore, for the design of such devices, the application of a safer and more conservative method than that proposed by API should be considered.

6 Design methods in the case of condensable vapors

In the standards and regulations analyzed earlier, there is no provision or specific methodology to account for the potential condensation of vapors inside atmospheric and low-pressure tanks. These vapors within these tanks can condense due to thermal effects caused by intense rainfall, leading to tank deformation and/or collapse.

Therefore, there is a lack of information in current standards on how to calculate the required inbreathing venting flow rates due to vapor condensation in the tank headspace.

As a result of this situation, various studies have been conducted in recent decades to develop methods aimed at considering the maximum possible inbreathing flow rates due to condensation caused by thermal effects.

For this reason, in this section the main studies conducted on cases in which the tank vapors are condensable are presented.

6.1 Fullarton (1987)

In the late 1980s, Fullarton et. al [14] developed a model that considered the effect of heavy rainfall outside the tank after prolonged and uninterrupted exposure to sunlight. This effect can lead to the condensation of the stored product inside the tank.

The general equations of this model are based on several conservative and simple approximations to facilitate the calculation of the maximum flow rate with sufficient rigor.

First, the general equation for calculating the total inbreathing flow rate due to gas contraction by condensation is presented:

$$\dot{V} = \frac{V_G}{T_G} \left| \frac{dT_G}{dt} \right| + \frac{\dot{M}_G}{\rho_G} \quad (32)$$

Where:

\dot{V} = total thermal inbreathing volumetric flow [m^3/s]

V_G = volume of the tank occupied by the gas phase [m^3]

T_G = temperature of the gas phase [K]

\dot{M}_G = gas condensation ratio [kg/s]

ρ_G = gas density [kg/m^3]

The gas temperature profile is obtained as a function of time, and thus the previous equation can be used to calculate the maximum thermal inbreathing flow rate when the gas temperature profile is at its maximum.

Next, a diagram of the mass and energy balance of the tank is presented. In this diagram, the prefixes G, W, and A correspond to the gas inside the tank, the tank wall, and the atmosphere outside the tank, respectively.

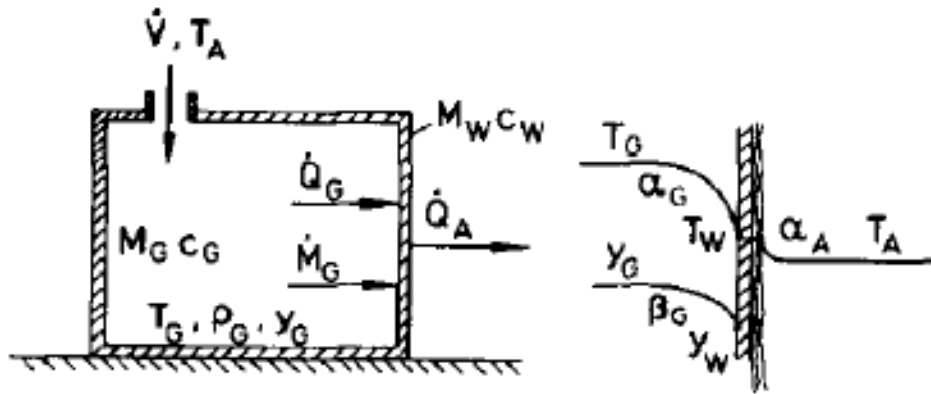


Figure 9: Diagram of the mass and energy balance of the tank. [14]

The equations for the energy balance of the gas and the tank wall in this diagram are:

$$M_G c_G \frac{dT_G}{dt} = -\dot{Q}_G \quad (33)$$

$$\dot{Q}_G = \alpha_G A (T_G - T_W) \quad (34)$$

$$M_W c_W \frac{dT_W}{dt} = \dot{Q}_G + \dot{M}_G \Delta h_v - \dot{Q}_A \quad (35)$$

$$\dot{Q}_A = \alpha_A A (T_W - T_A) \quad (36)$$

$$\dot{M}_G = \rho_G \beta_G A * (y_G - y_w) \quad (37)$$

Where:

M_G = mass of gas inside the tank [kg]

c_G = specific heat capacity of the gas [kJ/(kg K)]

\dot{Q}_G = convective heat flux from the gas to the tank walls [W]

\dot{Q}_A = convective heat flux from the tank walls to the exterior [W]

α_G = heat transfer coefficient [kg/m³]

c_W = specific heat capacity of the wall [kJ/(kg K)]

A = area of the tank [m²]

y_G = mass fraction of gas assuming it is saturated at T_G [dimensionless]

y_w = mass fraction of vapor at the tank wall [dimensionless]

Δh_v = latent heat of vaporization [J/kg]

β_G = mass transfer coefficient [m/s]

T_W = wall tank temperature [K]

T_A = atmosphere temperature [K]

6.1.1 Assumptions and approximations

For obtaining the previous equations, a series of approximations and conservative assumptions have been followed regarding temperatures and heat transfer coefficients used in the calculation method.

- *Regarding the temperature:*

Following the same reasoning as Förster [13], the initial temperature of the gas inside the tank is $T_{G0} = 55 \text{ }^\circ\text{C}$, as a result of prolonged exposure to intense solar radiation. On the other hand, the ambient temperature at which rain occurs is $T_A = 15 \text{ }^\circ\text{C}$. This temperature is considered constant over time and equal to the rain temperature since the heat transfer coefficient from the tank wall to the water film of the rain significantly exceeds that of the rainwater to the surroundings. Therefore, the rainwater film quickly reaches the temperature of the wall.

- *Regarding the transfer of mass and heat inside the tank:*

The heat transfer inside the tank is governed by free convection. The driving force is the density difference due to the temperature and concentration difference between the gas and the tank wall. The heat transfer coefficient between the gas and the tank wall α_G is considered to be constant and has a value of $5 \text{ W/m}^2 \text{ K}$. Consequently, the mass transfer coefficient β_G can be obtained from the relationship:

$$\beta_G = \alpha_G / \rho_G c_G Le^{0.66} \quad (38)$$

Where the Lewis number corresponds to:

$$Le = \frac{\kappa_G}{\delta_G} = \lambda_G / \rho_G c_G \delta_G \quad (39)$$

λ_G = gas thermal conductivity [W/(m K)]

δ_G = gas diffusion coefficient [m^2/s]

κ_G = gas thermal diffusivity [m^2/s]

Le = Lewis number [dimensionless]

6.1.2 Approximate method

In the study, Fullarton develops an approximate calculation method in which differential equations are not applied, and simplified equations are provided.

In addition, the study defines dimensionless parameters corresponding to temperature and time, which transform the previous energy balances into ordinary differential equations. Another dimensionless parameter introduced is the capacity ratio C , which relates the density and heat capacity in the tank wall and gas, taking into account the dimensions of the tank.

- Adimensional temperature:

$$\theta = \frac{T - T_A}{T_0 - T_A} \quad (40)$$

- Adimensional time:

$$\tau = \frac{\alpha_G A}{\rho_G c_G V_G} t \quad (41)$$

Where:

V_G = gas volume [m³]

t = time [s]

- Capacity ratio:

$$C = \frac{\rho_w c_w s_w}{\rho_G c_G} \cdot \frac{1 + 4H/D}{H} \quad (42)$$

Where:

s_w = wall thickness [m]

H = tank height [m]

D = tank diameter [m]

c_w = specific heat capacity of the wall [J/(kg K)]

ρ_w = wall density [kg/m³]

Fullarton distinguishes three steps to solve the equations and obtain the thermal inbreathing ratio:

- *Step 1: Without condensation:*

In this first case, the vapor in the tank's headspace is assumed to be non-condensable. Therefore, it is assumed that the tank wall is automatically cooled as if the entire tank at temperature T_0 were submerged in a water bath at temperature T_A .

$$\dot{V}_N = \frac{\alpha_G A}{\rho_G c_G} \frac{T_0 - T_A}{T_0} \quad (43)$$

Where:

\dot{V}_N = inbreathing flow rate [m³/s]

By inserting the numerical values considered earlier in the study, the equation can be simplified, and the maximum inbreathing flow rate can be obtained from the diameter and height of the tank.

$$\dot{V}_N = 1.5D(D + 4H) \quad (44)$$

- *Step 2: Cooling of the gas and tank wall, without condensation:*

At the beginning of the rain, the tank wall's temperature rapidly decreases, and the interior vapor temperature of the tank also cools down, but at a slower rate. The volumetric

inbreathing flow rate due to the thermal effect first increases and reaches a maximum value \dot{V}_{\max} , then decreases.

Fullarton defines a reduction factor that relates \dot{V}_{\max} to \dot{V}_N from the Naumann equation approximation.

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + \alpha_G/\alpha_A(C + 1)} \theta_{\max} \quad (45)$$

Where:

η = the reduction factor [dimensionless]

θ_{\max} = the maximum adimensional temperature coefficient [dimensionless]

The maximum adimensional temperature coefficient refers to the peak value of the adimensional temperature profile obtained in the calculations. It represents the highest rate of change of temperature with respect to time during the cooling process of the gas and tank wall due to the rain exposure. This coefficient is crucial in determining the maximum inbreathing flow rate (\dot{V}_{\max}) as mentioned in Step 2 of Fullarton's method.

In the case of θ_{\max} , the author uses a value of 0.85 for simplicity, without providing any further clarification or explanation regarding this specific choice. It is important to note that this value may have been selected based on assumptions or previous research in the field, but the exact reasoning for choosing 0.85 is not explicitly mentioned in the study.

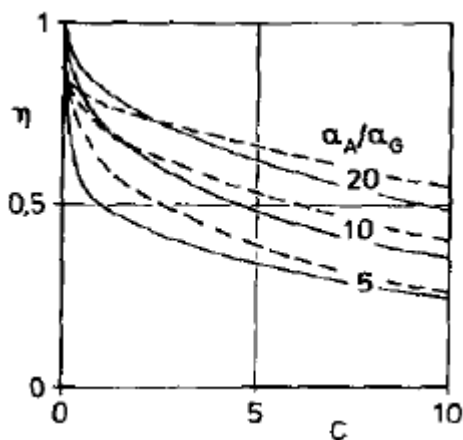


Figure 10: Reduction factor η vs the capacity factor C for different values of α_A/α_G [14]

In the previous figure, two trend lines can be observed. The solid line corresponds to the capacity factor obtained from the numerical solution, while the dashed line corresponds to the capacity factor obtained from the approximate solution.

Increasing the capacity factor has a direct effect on reducing the reduction factor. This suggests that the tank's geometry significantly influences the reduction factor. Additionally, it can be determined that increasing the heat transfer coefficient on the exterior, α_A , leads to an increase in the reduction factor. Therefore, it can be concluded that a higher reduction factor results in obtaining a higher inbreathing flow rate.

- *Step 3: Influence of condensation:*

It is assumed that the air is saturated with vapor at $T_0 = 55 \text{ }^\circ\text{C}$. Following equation (32) of mass transfer with the linearization of the vapor pressure and Lewis's equation, it can be reformulated as follows:

$$\dot{V} = \frac{V_G}{T_G} \left| \frac{dT_G}{dt} \right| \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_G \right) \quad (46)$$

*= equilibrium value of saturation

The author defines a condensation factor (χ) as the ratio between the maximum inbreathing with condensation and without condensation.

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_0 \right) \left(\frac{p_{\text{air}} c_{\text{air}}}{p_G c_G} \right) \left[\frac{1 + \alpha_G / \alpha_A (C + 1)}{1 + \alpha_G / \alpha_A (C + K)} \right] \quad (47)$$

$$K = 1 + \alpha_{G,\text{wet}} / \alpha_G \quad (48)$$

The effect of condensation on the maximum inbreathing flow rate (eq. (47)) can be differentiated into three factors. The first factor takes into account the increase in volumetric flow rate due to the condensation flux. The second factor considers that the heat capacity of vapor is generally higher than that of air. Lastly, the third factor refers to the decrease in the tank wall temperature due to the condensation energy.

It should be noted that the factor "K" appearing in the previous equation (48) is not defined at any point throughout the study, and therefore, its origin is unknown.

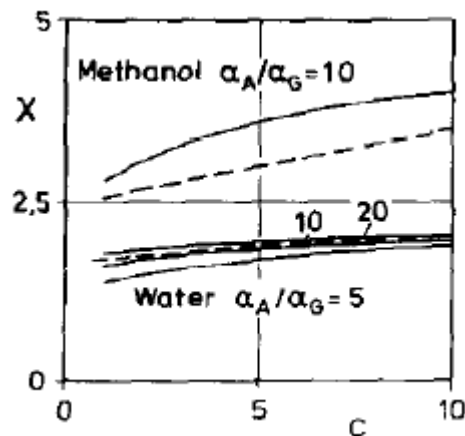


Figure 11: Condensation factor χ vs the capacity factor C for different values of α_A / α_G [14]

The previous figure describes how the factor of condensation (χ) varies with the capacity factor (C) and the external heat transfer coefficient (α_A / α_G) for two different types of vapors (saturated water vapor and saturated methanol vapor).

In the case of saturated water vapor, changes in the capacity factor and the external heat transfer coefficient do not significantly affect the factor of condensation.

However, for saturated methanol vapor, as the capacity factor increases (i.e., for smaller storage tanks), the value of the condensation factor (χ) increases considerably, leading to an increase in the inbreathing flow rate.

Therefore, the factor of condensation (χ) depends on the type of condensable vapor stored, and for this reason, Fullarton assigns a range of χ values based on the type of condensable gas.

Table 6.1.1. Range of values of the condensation factor χ according to the different products.

Product	Condensation factor (χ)
Air saturated with water, hexane or heptane	1.5-2
Air saturated with ethanol	2-2.5
Air saturated with methanol	3-4

Finally, the complex case of the change in gas and tank wall temperature with vapor condensation from the product can be calculated using the Naumann equation together with the reduction factor (η) and condensation factor (χ).

$$\dot{V}_{K,max} = \dot{V}_N \cdot \eta \cdot \chi \quad (49)$$

The volumetric flow rate \dot{V}_N depends only on the height and diameter of the tank. In cases where the initial assumption of $(T_0 - T_A)$ is not equal to 40 °C, the new temperature difference should be considered, and equation (44) cannot be used when considering only the tank dimensions. Instead, equation (43) should be applied.

6.1.3 Results

Fullarton in order to apply this approximate method and analyze the effects that would occur, shows the example of a tank.

In the following figures shown below, the change in the temperature of the tank and the gas over time, as well the variation of the inbreathing flow rate over time, is displayed. It is assumed that the tank has a volume of 4000 m³ and extreme rainfall is occurring.

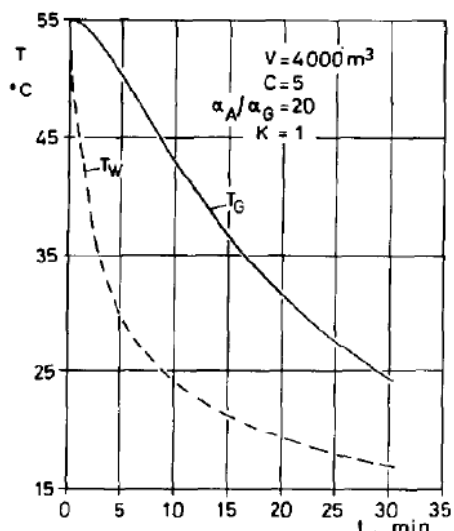


Figure 12: Temperature of the gas and the tank wall over time. [14]

The heat transfer coefficient to the exterior is considerably higher than that of the gas, causing the tank wall temperature to decrease rapidly. The maximum cooling rate is reached at approximately 6 minutes when the maximum temperature difference between T_G and T_W occurs.

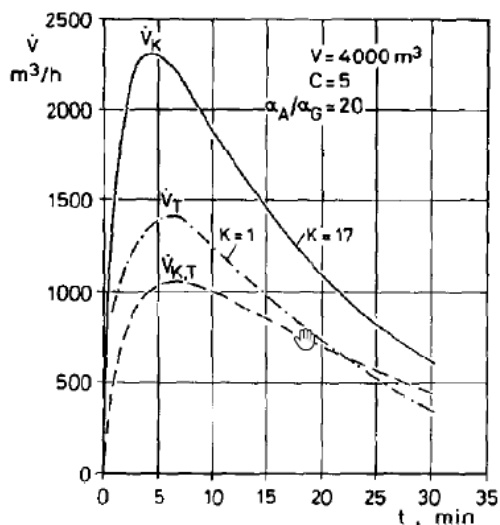


Figure 13: Inbreathing flow rate in function of time. [14]

In Figure 13, the different inbreathing rates are shown over time. The dashed line with dots represents the case of the tank filled with dry air, which does not involve any condensation. The peak of the volumetric inbreathing rate in this case, \dot{V}_T , is approximately 1400 m³/h.

On the other hand, the solid line represents the case where the tank is filled with air saturated with water vapor, considering condensation inside the tank. The volumetric inbreathing rate in this case, \dot{V}_K , peaks at approximately 2250 m³/h.

Finally, the dotted line represents the fraction of the volumetric inbreathing rate that occurs due to thermal contraction. The volumetric inbreathing rate in this case, $\dot{V}_{K,T}$, peaks at approximately 1050 m³/h. Due to the heat of condensation released, this rate is smaller than the rate \dot{V}_T without condensation.

To reinforce these results, Fullarton conducted an experiment to analyze the effect of condensation on the inbreathing rate due to thermal effects. In this experiment, a preheated glass flask with a volume of 6 liters is cooled from the outside with water at 15 °C to simulate heavy rainfall.

The experiment consists of three different study cases, distinguished by the product filling the container: dry air, air saturated with water vapor, and air saturated with methanol vapor. By applying equation (44) with an area of 0.16 m², a \dot{V}_N of 300 l/h is obtained. The reduction factor η for the dry air case is calculated using equation (45). As for the condensation factor χ , it is determined using equation (47).

Table 6.1.2. Maximum inbreathing rates obtained in the Fullarton experiment.

Product	\dot{V}_{max} (l/h)	Adimensional factor
Air	75-90	$\eta = 0.25$
Air saturated with water	150-180	$\chi = 2$
Air saturated with methanol	300-330	$\chi = 4$

The table 6.1.2. shows the results of Fullarton's experiment, from which it can be deduced that the condensation of both methanol vapor and water vapor significantly increases the inbreathing flow rate compared to the flow rate in the case of dry air without condensation.

6.1.4 Conclusions

The Fullarton study does not provide specific values for the condensation factor (χ) depending on the condensable vapor. However, it mentions that it assigns a range of χ values according to the type of condensable gas.

The range of χ values can vary depending on the nature of the condensable vapor stored in the tank. This range can be determined experimentally or through numerical analysis for different types of condensable vapors. The condensation factor (χ) will be a function of various parameters, such as vapor characteristics and tank conditions, so its specific value should be determined for each particular case.

Therefore, specific studies are required to determine the range of χ values depending on the type of condensable vapor stored in the tank.

On the other hand, the Fullarton study provides a calculation methodology to address the complex case where the change in gas and tank wall temperature is considered, along with the condensation of the product vapor. This calculation is performed using the Naumann equation together with the reduction factor (η) and the condensation factor (χ).

With this methodology, the maximum inbreathing flow rate that considers the effect of product vapor condensation on the tank walls and interior gas can be obtained. This allows for

a more accurate approximation of the volumetric inbreathing flow rate in real situations where condensation occurs.

It should be noted that this calculation is more complex and may require the use of numerical methods to solve the differential equations involved in the process. Therefore, this methodology may be more challenging to apply compared to the simplified approximations presented earlier. However, it provides more accurate results when considering product vapor condensation in the analysis of inbreathing flow rate.

6.2 Holtkötter (1995)

In the study by Holtkötter et al [15], the concept of spontaneous condensation was highlighted, which forms as an aerosol inside the tank. This aerosol-like condensation does not occur in the same way as the condensation that forms on the tank walls, as indicated in other studies.

The authors conducted an experimental study using a 1.18 m³ tank with the goal of determining the inbreathing flow rates generated and comparing them with their theoretical method. Additionally, they analyzed products with different characteristics and volatilities to understand the impact of condensation on the tank's venting flow rate when storing isopropanol, methanol, and water.

For the experimental analysis, the authors used a cylindrical atmospheric tank with a height of 1.5 m and a diameter of 1 m, with a tank wall thickness of 1.2 mm. The initial gas temperature inside the tank was 55 °C, and the tank wall temperature was 31 °C. Subsequently, the tank was cooled by spraying it with water at 15 °C to simulate a rainfall rate of 10 kg/h. This mass flow rate of water covered up to 5.5 m² of the tank's external surface.

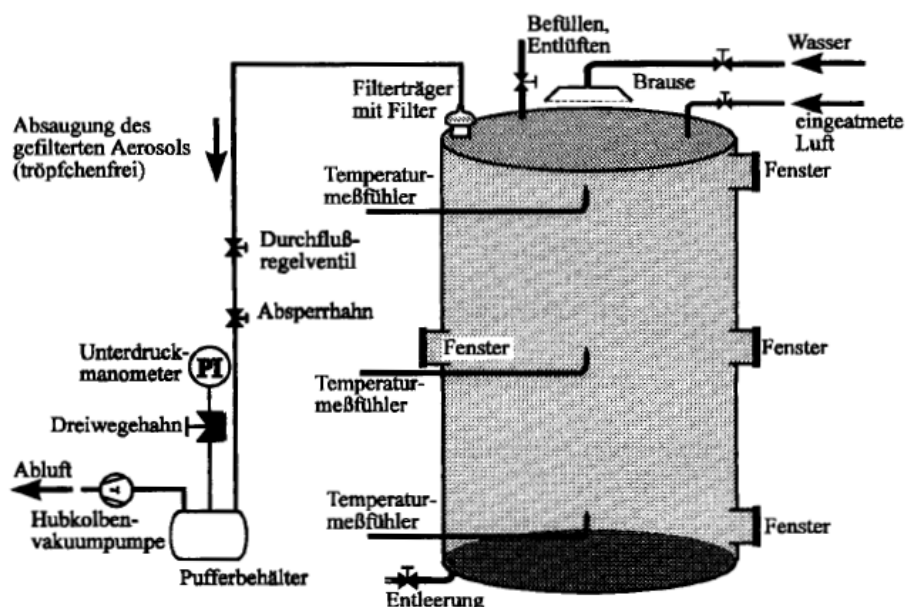


Figure 14: Scheme of Holtkötter experimental tank. [15]

In the previous diagram, you can see the different components that make up the tank system. The tank has three temperature sensors (Temperaturmeßfühler), several windows for visual analysis of the interior of the tank (Fenster), the water spray system (Brause), and the

inlets and outlets from the tank's interior. Additionally, there is a filter on the tank's roof to measure the fraction of condensate formed by spontaneous condensation.

6.2.1 Results

The measurements of inbreathing flow rates in Holtkötter et al. [15] experiment is recorded when a temperature difference of 40 °C between the gas inside the tank and the water from the spray outlet is detected. This maximum temperature difference is also considered in API 2000, where the initial tank temperature is 55 °C, and the temperature of the rain film is 15 °C.

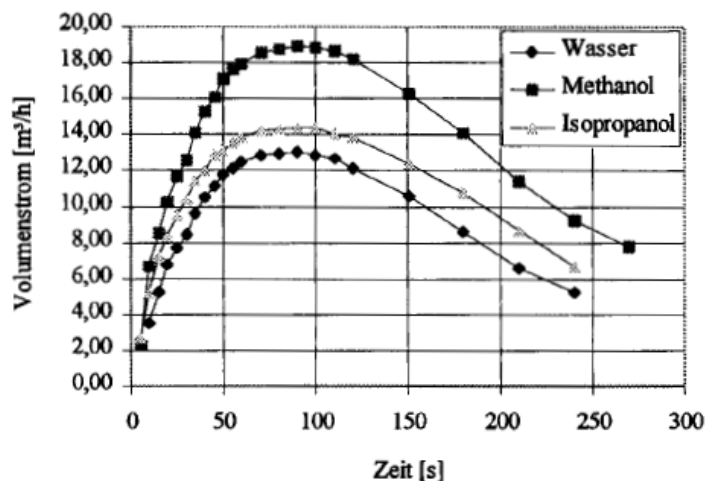


Figure 15: Thermal inbreathing profiles for the different products. [15]

The flow rate profiles for thermal inbreathing in the previous figure indicate that the maximum flow rate occurs in all three cases at approximately 95 seconds after starting the experiment and spraying the tank with water at 15 °C.

It can be determined that the maximum flow rate for methanol, isopropanol, and water is approximately 19 m³/h, 14 m³/h, and 13 m³/h, respectively. Methanol exhibits the highest thermal inbreathing flow rate due to its high volatility.

6.3 Chakra (2016)

Abou-Chakra [4] conducted a study in which is compared the primary research conducted over recent decades regarding the thermal effects on low-pressure tanks. The study emphasized the challenges associated with these types of tanks due to their vulnerability.

Abou-Chakra calculates various thermal inbreathing flow rates using dynamic simulations with ioMosaics Super Chems Expert™ software for different tanks. This is particularly relevant when abrupt temperature changes occur, such as the case of cooling inside the tank due to a summer storm. Furthermore, these calculated flow rates are compared to the API 2000 7th Edition standard for assessment.

Finally, with this research, the author aims to analyze the impact of solar radiation on venting flow rates, depending on the tank's location. For these simulations, it is assumed that the tank is completely empty and is located in Montreal, Canada, and Jubail City, KSA. Solar radiation and ambient temperature are adjusted according to the respective locations.

However, in this case, the rainfall intensity has not been specified and is maintained as per the value considered by API 2000.

6.3.1 Conclusions

After analyzing various scenarios, Chakra's thesis concludes that API 2000 provides conservative equations when the tank stores non-condensable gases. According to the author, in this case, API 2000 overestimates relief devices by 60%. However, API 2000 does not correctly size relief devices for tanks containing condensable vapors. According to the study, using API 2000 can lead to an underestimation of relief devices by up to 270%. To ensure proper sizing, the proposal is to adjust the free-convection heat transfer coefficients according to the type of vapor.

On the other hand, the tank located in Jubail City experiences 10% more inbreathing and 8% more outbreathing compared to the tank located in Montreal.

Below is a comparison between the results obtained using SuperChems™ and API 2000.

Table 6.3.1. Comparison between breathing requirements in SuperChems™ simulation and API 2000.

Site	Chakra Simulation		API 2000 7 th Ed.	
	Thermal inbreathing [Nm ³ /h]	Thermal outbreathing [Nm ³ /h]	Thermal inbreathing [Nm ³ /h]	Thermal outbreathing [Nm ³ /h]
Montreal	134.5	30.3	264.1	79.1
Jubail City	148.8	32.6	352.2	101.3

The thermal breathing flow rates from the simulation, when compared to API 2000, are lower. Therefore, it could be considered that API 2000 overestimates safety devices and presents very conservative flow rate values.

The author examines two wide-boiling point mixtures in order to quantify the impact of storing such mixtures on the thermal inbreathing. The first mixture had a molar 60% water and 40% ethanol, the second mixture had a molar 60% gasoline 40% ethanol. The inbreathing of the gasoline/ethanol mixture recorded the highest inbreathing rate when compared to the water/ethanol and pure water vapor systems. The API 2000 method predictions were incapable of protecting the storage tank from the vacuum caused by the condensation and contraction of both mixtures as was shown using the proposed SuperChems model. [4]

As a result, in Chakra's study (reference), it is concluded that the inbreathing and outbreathing requirements calculated according to API 2000 are suitable for tanks storing non-condensable vapors. However, for condensable vapors such as methanol, ethanol, and isopropanol, API 2000 underestimates the thermal effect caused by condensation.

Moreover, Chakra [4] investigated the validity of the heat transfer coefficients used by API 2000, it was found that the gas/wall free convection heat transfer coefficient of 5 W/(m² K), specified by API 2000 was adequate when the tank was empty. However, higher values were suggested for condensable gases and range between 10 W/(m² K) to 45 W/(m² K) depending on the type and volatility of the vapor.

6.4 Davies and Moncalvo (2016)

In 2016, the article "*Breathing losses from low-pressure storage tanks due to atmospheric weather change*" [21] was published, aiming to provide a guide that can help address the issue of condensable vapors and the requirements that should be considered to avoid potential deformations in these types of tanks.

Low-pressure tanks generally lack insulation, making thermal effects on ventilation rates significantly influential. In this case, the authors develop an analytical model for an uninsulated tank filled with a mixture of non-condensable gases, saturated with condensable vapors, and exposed to a realistic severe rain following prolonged and uninterrupted solar exposure.

6.4.1 Assumptions and approximations

In a preliminary analysis, it is considered that the rain layer on the external walls of the tank has a constant thickness on all lateral walls and the ceiling. In this model, it is assumed that the condensed phase is at the same temperature as the gaseous phase, even though it spreads along the cold metal surface. Another consideration made by the authors is the neglect of a non-uniform temperature distribution on the tank wall.

The following equation is presented as the energy balance of the product inside the tank:

$$(M_{\text{vap}}c_{\text{vap}} + M_{\text{liq}}c_{\text{liq}} + M_{\text{air}}c_{\text{air}}) \frac{dT_{\text{B}}}{dt} = -h_{\text{int}}A(T_{\text{B}} - T_{\text{E}}) - \dot{M}_{\text{air}}c_{\text{air}}(T_{\text{B}} - T_{\text{amb}}) \quad (50)$$

Where:

M_{vap} = vapor phase mass [kg]

c_{vap} = vapor phase specific heat [J/(kg K)]

M_{liq} = liquid phase mass [kg]

c_{liq} = liquid phase specific heat [J/(kg K)]

M_{air} = air mass [kg]

c_{air} = air specific heat [J/(kg K)]

T_{B} = temperature of the bulk gaseous phase in the tank (mixture of air and vapors) [K]

h_{int} = internal heat transfer between walls and bulk product [W/(m² K)]

A = lateral tank surface area and tank roof [m²]

T_{E} = temperature of the tank walls [K]

\dot{M}_{air} = air mass flow rate [kg/s]

T_{amb} = ambient temperature [K]

From the preceding energy balance, it can be determined that the cooling rate of the tank's product accelerates with the internal heat transfer towards the walls and towards the inbreathed ambient air.

Next, the equation corresponding to the energy balance of the tank's walls is presented:

$$M_E c_E \frac{dT_B}{dt} = h_{int} A (T_B - T_E) - h_{rain} A (T_E - T_{rain}) + \rho_B \dot{V}_{cond} \Delta h_{cond} \quad (51)$$

$$\dot{V}_{cond} = \beta [y_{vap}(T_B) - y_{vap}(T_E)] A \quad (52)$$

Where:

M_E = tank walls mass [kg]

c_E = tank walls specific heat [J/(kg K)]

h_{rain} = heat transfer coefficient of the rain [W/(m² K)]

T_{rain} = rain temperature [K]

ρ_B = bulk phase density [kg/m³]

\dot{V}_{cond} = condensation volume flow rate [m³/s]

Δh_{cond} = condensation specific latent heat [J/kg]

β = vapor mass transfer coefficient [m/s]

y_{vap} = vapor phase mass fraction [-]

It should be noted that in the previous equation, the rate of cooling due to heat transfer to the rain film is dampened by vapor condensation. This equation might resemble the one presented by Fullarton [14], except for the introduction of an explicit formulation for the volumetric condensation rate within the tank, which is proportional to the difference between the vapor concentration at the walls and inside the tank.

The integrity of the tank imposes that the volume shrinkage caused by gaseous phase compression and vapor condensation inside the tank must be compensated by ambient air inbreathing. In this way, the incoming air low into the tank compensates for the vacuum caused by the contraction of the gas mixture from the tank's headspace and the potential condensation.

$$-\frac{V_{vap} + V_{air}}{T_B} \cdot \frac{dT_B}{dt} + \dot{V}_{cond} = \dot{V}_{air} \quad (53)$$

Where:

V_{vap} = vapor volume [m³]

V_{air} = air volume [m³]

\dot{V}_{air} = air volume flow rate [m³/s]

Finally, an equation for the rain film temperature over time is necessary. Förster [13] proposed a general balance considering that the heat either exits the tank, is dissipated towards the rain film, or is released to the surroundings. Typically, this rain film deposited on the tank's surface has a thinner layer compared to the thickness of the tank walls. As a result, the heat from the walls is mainly used to increase the temperature of the water droplets in the film, as depicted in equation (54). On the other hand, the relationship between the mass flux of rain impacting the tank (\dot{m}_{film}) and that impacting the ground is shown in equation (56).

$$h_{\text{rain}}A(T_E - T_{\text{rain}}) - \dot{m}_{\text{film}}c_{\text{rain}}(T_{\text{rain}} - T_{\text{amb}}) = 0 \quad (54)$$

$$\dot{m}_{\text{film}} = \dot{m}_{\text{rain}} \frac{\left[\frac{\pi D^2}{4} + DH \cot \omega \right]}{\left[\frac{\pi D^2}{4} + \pi DH \right]} \quad (55)$$

Where:

\dot{m}_{film} = rain film mass flow rate [kg/s]

\dot{m}_{rain} = rain mass flow rate [kg/s]

D = tank diameter [m]

H = tank height [m]

ω = rain impingement angle [-]

6.4.2 Results

The authors indicate that for a given tank size, wall thickness, ambient temperature, as well as rain intensity and angle of incidence, equations (50, 51, 52) can be numerically integrated. This integration of the equations is employed to estimate temperature profiles of the product, walls, and rain film, along with inbreathing rates as a function of time.

In cases where vapor is a pure component, the authors present a simplified formula that allows the calculation of the condensation-induced flow rate.

This formula transforms the tank wall energy balances into a linear PDE (Partial Differential Equation).

$$\dot{V}_{\text{cond}} = \frac{\beta_1}{\rho_B} |dp_{\text{sat}}/dT|_{T_E} [T_B - T_E]A \quad (56)$$

Subsequently, inbreathing rates obtained from applying this study to a 2651 m³ tank are presented, assuming an initial temperature of 49 °C. It is noteworthy that an initial temperature of 49 °C is considered, as per API2000 Annex A, this is the maximum allowable temperature for applying this standard.

This tank, in one case, is filled with saturated dry air with steam, and in another case, it is filled with heptane vapor. Initially, the presence of liquid level is not considered, as empty tanks, due to their low thermal capacity, experience greater cooling, higher condensation, and consequently, a higher required inbreathing flow rate compared to the case when the tank is filled with liquid.

For this experiment, a flat-roofed tank with a diameter and height of 15 meters is considered. Different rain intensities (75, 150, and 225 kg/(m² h)) are applied to the tank with an angle of incidence of 68° from the horizontal. On the other hand, the tank wall is made of steel with a thickness of 5 mm, and the external temperature is 15°C.

In the calculations performed in the study, constant densities, specific heats, and thermal conductivities are assumed for the gas phase. On the other hand, the fractions of condensable vapor in the gas mixture are determined based on initial partial pressures, resulting in a 11.7% volume fraction for saturated dry air with vapor and an 18.1% volume fraction for heptane vapor.

Next, in the following figure, the results obtained for the two analyzed cases are graphically presented, and in tables 6.4.1. and 6.4.2., the numerical results are shown:

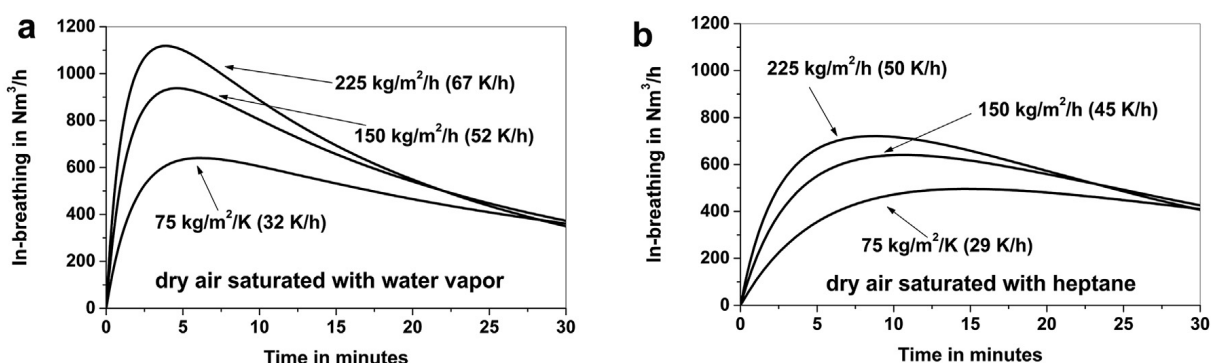


Figure 16: Inbreathing flow rate in function of time for the different cases. [21]

Table 6.4.1. Calculated inbreathing and cooling rates for the tank described filled with humid air.

Rain intensity (kg/m ² /h)	Maximum inbreathing (Nm ³ /h)		Maximum cooling rate (K/h)	
	With Condensation	No condensation	With condensation	No condensation
75	640	528	32	63
150	937	738	52	87
225	1097	863	67	102

Table 6.4.2. Calculated inbreathing and cooling rates for the tank described filled with air and heptane vapors.

Rain intensity (kg/m ² /h)	Maximum inbreathing (Nm ³ /h)		Maximum cooling rate (K/h)	
	With Condensation	No condensation	With condensation	No condensation
75	496	273	29	32
150	640	382	45	42
225	721	446	50	53

It can be observed that a higher rain intensity directly increases, but not in a linear manner, the cooling rate and consequently leads to higher inbreathing flow rates due to condensation.

When comparing the required flow rate of 448 Nm³/h and the cooling rate of 56 K/h suggested by API2000 Annex A for the previous tank, it can be determined that, in the case of heptane vapors, there wouldn't be a very noticeable difference if condensation is not considered. On the other hand, when comparing the API2000 Annex A required flow rate with the case of saturated dry air with vapor, it is concluded that the 448 Nm³/h is significantly lower than the results obtained, even without considering condensation.

6.4.3 Conclusions

The study aimed to address the issue of condensable vapors in low-pressure storage tanks exposed to atmospheric weather changes, as these condensable vapors inside the tank can cause tank deformation and collapse. The authors developed an analytical model for tanks lacking insulation, subjected to rain after extended solar exposure.

The research considered the impact of rainfall on tank walls. While assuming a constant rain layer thickness, the study acknowledged the complexities of how condensate spreads along cold surfaces and how this can influence the tank's behavior.

Nevertheless, the authors recognized that their model did not incorporate a non-uniform temperature distribution on the tank walls. This omission could impact the accuracy of predictions, particularly in situations with varying thermal conditions.

Moreover, the article introduced an energy balance equation to describe the behavior of the product inside the tank. This equation serves as a foundation for understanding how temperature changes and condensation influences the tank's internal dynamics.

The conclusions of the article suggested that additional research is required to refine the model, considering more complex factors such as non-uniform temperature distribution and variable rain conditions. This would enhance the accuracy of predictions and the applicability of the findings to real-world scenarios.

In essence, the study emphasized the importance of considering condensable vapors and the effect of atmospheric weather changes on low-pressure storage tanks. While providing initial insights, the authors acknowledged the limitations of their model and the necessity for future research to create a more comprehensive understanding of the issue.

7 Practical case studies

Throughout this practical part of the study, the peculiarities of the selected standards will be explored, examining their theoretical foundations and calculation formulas. Additionally, concrete examples of venting calculations for different types of liquids and operational scenarios will be performed using each of the standards considered in the analysis. These practical examples will allow evaluating the effectiveness and accuracy of the standards in various situations and offer a clear insight into how the calculation results can influence decisions related to the design, operation, and maintenance of low-pressure tanks.

In summary, this research aims to provide an informed perspective on available venting calculations standards, their advantages, limitations, and how they can be applied in the context of low-pressure or atmospheric storage tanks. Furthermore, the study includes the calculation of inbreathing flow rates due to condensation for different stored products, following the approximate method of Fullarton previously studied.

By the end of this comparative study, it is expected that practitioners will gain a deeper understanding of the practical implications of venting calculations standards, contributing to safer and more efficient management of industrial facilities.

7.1 Design Basis

One of the main objectives of this thesis is to compare the different required flow rates obtained according to the standards analyzed throughout this work. Therefore, in this section, design foundations are proposed with the aim of numerically analyzing the results of the volumetric flow rates obtained.

For the study, a tank farm located in Tarragona, Spain, is considered, consisting of 5 tanks with identical dimensions. It is assumed that all 5 tanks are of a fixed roof, flat-bottomed, vertical, non-insulated, carbon steel and above-ground design with a design pressure of +25/-8.5 mbarg. API 650 is considered to have been followed for the design of these tanks. The stored products include acrylic acid, methyl acrylate, hexane, ethanol, and methanol.

The following table shows all the design foundations considered for the study.

Table 7.1. Design basis for the practical cases.

Parameters	
Site	Tarragona
Tank height	10 m
Tank diameter	4 m
Filling flow rate	25 m ³ /h (25 °C)
Discharging flow rate	25 m ³ /h (25 °C)
Operating temperature	25 °C

Operating pressure	0 mbarg
Design Pressure	+25/-8.5 mbarg

In the following sections, the different flow rates required for normal operation venting (outbreathing and inbreathing) and for emergency venting (external fire case) are presented.

7.2 Acrylic Acid case

Acrylic acid is a corrosive and pungent-smelling chemical compound. It is used in the production of acrylic polymers for products such as paints, adhesives, and coatings, as well as in the manufacturing of synthetic fibers and plastics.

In this section, the venting flow rates required are shown according to the different regulations and codes analyzed in this thesis. Next, a table with the necessary parameters related to acrylic acid for the flow rate calculations is provided. It's worth noting that all properties have been extracted from ASPEN HYSYS V14 software.

Table 7.2.1. Acrylic acid parameters.

Parameters	
Boiling point	141 °C
Flash point	55 °C
Vapor pressure	5.71 mbara
Latent heat of vaporization	595 kJ/kg
Molecular weight	72.1 kg/kmol
Temperature of relieving vapor (fire case)	141 °C
Operating temperature	25 °C

Given the tank characteristics detailed above, along with the parameters corresponding to acrylic acid, the various standards and regulations detailed in Section 4 of this thesis are applied.

Table 7.2.1. Acrylic acid required venting flow rates according to the different standards.

Standard	Venting flow rates [Nm ³ /h]		
	Outbreathing	Inbreathing	Emergency
API 2000 7 th Edition	50	217	11441
API 2000 Annex A	38	45	11441
ISO 28300	50	217	11441
EN 14015	50	217	7880
TRGS 509	33	174	-

From the previous table, it can be observed that the required outbreathing flow rate obtained from different standards is very similar, except for the TRGS 509 regulation, which suggests a slightly lower value compared to the others.

Regarding inbreathing, the API 2000, ISO 28300, and EN 14015 standards propose the same required venting flow rate, as previously mentioned in this thesis, as they use the same formulas for this calculation. The TRGS 509 regulation provides a lower flow rate, specifically 20% less, despite this difference, it follows the trend of values from the other standards. However, applying API 2000 Annex A results in significantly lower flow rates, nearly 5 times lower than the flow rate calculated using API 2000, ISO 28300, and EN 14015.

Finally, for the emergency venting flow rate due to an external fire scenario, it is observed that API 2000 and ISO 28300 indicate the same required flow rate since they use the same equations. However, the required venting flow rate calculated using the formulas proposed by EN 14015 is lower. It is worth noting TRGS 509 cannot be compared because this standard does not provide any calculation methodology for emergency cases.

The details of these calculations are presented in Annex 11.1.

7.3 Methyl Acrylate case

Methyl acrylate is a chemical compound belonging to the ester family and derived from acrylic acid. Furthermore, methyl acrylate is a flammable and colorless liquid with a characteristic odor. It is primarily used as a raw material in the production of acrylic polymers and resins. These polymers have a wide range of applications, including coatings, adhesives, paints, sealants and plastic materials. Methyl acrylate is valued for its ability to form polymers with adhesive properties and fast curing.

In this section, the venting flow rates required are shown according to the different regulations and codes analyzed in this thesis. Next, a table with the necessary parameters related to methyl acrylate for the flow rate calculations is provided. It's worth noting that all properties have been extracted from ASPEN HYSYS V14 software.

Table 7.3.1. Methyl acrylate parameters.

Parameters	
Boiling point	80 °C
Flash point	-3 °C
Vapor pressure	122 mbara
Latent heat of vaporization	372 kJ/kg
Molecular weight	86.1 kg/kmol
Temperature of relieving vapor (fire case)	80 °C
Operating temperature	25 °C

Given the tank characteristics detailed above, along with the parameters corresponding to methyl acrylate, the various standards and regulations detailed in Section 4 of this thesis are applied.

Table 7.3.2. Methyl acrylate required venting flow rates according to the different standards.

Standard	Venting flow rates [Nm ³ /h]		
	Outbreathing	Inbreathing	Emergency
API 2000 7 th Edition	75	217	15464
API 2000 Annex A	72	45	15464
ISO 28300	58	217	15464
EN 14015	58	217	10650
TRGS 509	33	174	-

From the previous table, it can be observed that the required normal operation and emergency venting flow rates obtained from different standards show two distinct trends.

There are two noticeable trends in the required outbreathing flow rates. API 2000 and API 2000 Annex apply a factor of 2 to the outbreathing flow rate due to tank filling. This factor is attributed to the volatility of methyl acrylate, as its vapor pressure exceeds 50 mbara (API 2000) and it has a flashpoint below 38°C (API 2000 Annex A). Consequently, these standards provide very similar flow rates. On the other hand, ISO 28300 and EN 14015 do not specify any factor when dealing with volatile products but recommend considering an evaporation ratio, which can often be challenging to determine and may have a wide range of values. In

this case, it has been determined through literature that the evaporation ratio for methyl acrylate is 1.3. [7]

Finally, TRGS specifies a significantly lower required outbreathing flow rate compared to other standards, and it does not take into account the volatility of the product.

Regarding inbreathing, all the standards analyzed in this thesis specify the same required flow rates. This is because all the standards primarily rely on equations that depend mainly on the tank volume. Therefore, the required inbreathing flow rates will be the same for all products according to each of these standards.

Finally, for the emergency venting flow rate due to an external fire scenario, it is noted that API 2000 and ISO 28300 specify the same required flow rate as they use the same equations. However, the required venting flow rate calculated using the formulas proposed by EN 14015 is lower. It is important to highlight that TRGS 509 cannot be compared because this standard does not provide any calculation methodology for the emergency case.

The details of these calculations are presented in Annex 11.1.

7.4 Hexane case

Hexane is an aliphatic hydrocarbon that belongs to the alkane family. It is a colorless, flammable liquid, naturally found in crude oil and is a common component of industrial solvents. Hexane is primarily used as a solvent in industrial applications such as vegetable oil extraction and the production of rubber adhesives.

In this section, the venting flow rates required are shown according to the different regulations and codes analyzed in this thesis. Next, a table with the necessary parameters related to hexane for the flow rate calculations is provided. It's worth noting that all properties have been extracted from ASPEN HYSYS V14 software.

Table 7.4.1. Hexane parameters.

Parameters	
Boiling point	69 °C
Flash point	-22 °C
Vapor pressure	194 mbara
Latent heat of vaporization	335 kJ/kg
Molecular weight	86.2 kg/kmol
Temperature of relieving vapor (fire case)	69 °C
Operating temperature	25 °C

Given the tank characteristics detailed above, along with the parameters corresponding to hexane, the various standards and regulations detailed in Section 4 of this thesis are applied.

Table 7.4.2. Hexane required venting flow rates according to the different standards.

Standard	Venting flow rates [Nm ³ /h]		
	Outbreathing	Inbreathing	Emergency
API 2000 7 th Edition	75	217	16892
API 2000 Annex A	72	45	16892
ISO 28300	70	217	16892
EN 14015	70	217	11634
TRGS 509	33	174	-

From the previous table, it can be observed that the required flow rates for normal operation and emergency cases obtained from different standards vary.

In this case, the required outbreathing flow rates are very similar, except for TRGS. This similarity arises because the hexane's evaporation ratio is very close to the factor of 2 applied in API 2000 for products with vapor pressures exceeding 50 mbara. It has been determined through literature that the evaporation ratio for hexane corresponds to 1.8. [19]

Regarding inbreathing, the same situation applies as for the rest of the products analyzed in this thesis.

Finally, for the emergency venting flow rate due to an external fire scenario, it is observed that API 2000 and ISO 28300 specify the same required flow rate as they use the same equations. However, the required venting flow rate calculated using the formulas proposed by EN 14015 is lower. It is important to highlight that TRGS 509 cannot be compared because this standard does not provide any calculation methodology for the emergency case.

The details of these calculations are presented in Annex 11.1.

7.5 Ethanol case

Ethanol is an organic chemical compound, it is a colorless, volatile liquid with a characteristic alcohol smell. Ethanol is the type of alcohol found in alcoholic beverages, and it is the only type of alcohol safe for human consumption in moderate amounts.

In addition, ethanol has a wide range of industrial and chemical applications. It is used as a solvent in the manufacture of chemicals, perfumes, medicines, and cleaning products. It is also employed as a fuel in vehicles, especially in blends like ethanol-gasoline mixtures to reduce pollutant emissions. Ethanol is also used in the production of hand sanitizers and as a component in the fragrance and cosmetics industry.

In this section, the venting flow rates required are shown according to the different regulations and codes analyzed in this thesis. Next, a table with the necessary parameters related to ethanol for the flow rate calculations is provided. It's worth noting that all properties have been extracted from ASPEN HYSYS V14 software.

Table 7.5.1. Ethanol parameters.

Parameters	
Boiling point	78.2 °C
Flash point	12 °C
Vapor pressure	78 mbara
Latent heat of vaporization	834.2 kJ/kg
Molecular weight	46.1 kg/kmol
Temperature of relieving vapor (fire case)	78.2 °C
Operating temperature	25 °C

Given the tank characteristics detailed above, along with the parameters corresponding to ethanol, the various standards and regulations detailed in Section 4 of this thesis are applied.

Table 7.5.2. Ethanol required venting flow rates according to the different standards.

Standard	Venting flow rates [Nm ³ /h]		
	Outbreathing	Inbreathing	Emergency
API 2000 7 th Edition	75	217	9403
API 2000 Annex A	72	45	9403
ISO 28300	60	217	9403
EN 14015	60	217	6476
TRGS 509	33	174	-

From the previous table, it can be observed that the required flow rates for normal operation and emergency cases obtained from different standards vary.

In this case, the required outbreathing flow rates are not as similar as in other products. This discrepancy is due to the evaporation ratio of ethanol, with a determined value from literature of 1.4. [19]

Regarding inbreathing, the same situation applies as for the rest of the products analyzed in this thesis.

Finally, for the emergency venting flow rate due to an external fire scenario, it is observed that API 2000 and ISO 28300 specify the same required flow rate as they use the same equations. However, the required venting flow rate calculated using the formulas

proposed by EN 14015 is lower. It is important to highlight that TRGS 509 cannot be compared because this standard does not provide any calculation methodology for the emergency case.

The details of these calculations are presented in Annex 11.1.

7.6 Methanol case

Methanol is a chemical compound, colorless and flammable liquid with slightly sweet odor. This product is primarily produced from natural gas or biomass and is used in various industrial and chemical applications. For example, it is used as a fuel in industrial and transportation applications, is a versatile solvent used in manufacturing of chemicals, resins, inks, paints and adhesives, and also is used as a raw material in the production of formaldehyde.

In this section, the venting flow rates required are shown according to the different regulations and codes analyzed in this thesis. Next, a table with the necessary parameters related to methanol for the flow rate calculations is provided. It's worth noting that all properties have been extracted from ASPEN HYSYS V14 software.

Table 7.6.1. Methanol parameters.

Parameters	
Boiling point	64.5 °C
Flash point	9 °C
Vapor pressure	169.7 mbara
Latent heat of vaporization	1100 kJ/kg
Molecular weight	32 kg/kmol
Temperature of relieving vapor (fire case)	64.5 °C
Operating temperature	25 °C

Given the tank characteristics detailed above, along with the parameters corresponding to methanol, the various standards and regulations detailed in Section 4 of this thesis are applied.

Table 7.6.2. Methanol required venting flow rates according to the different standards.

Standard	Venting flow rates [Nm ³ /h]		
	Outbreathing	Inbreathing	Emergency
API 2000 7 th Edition	75	217	8383
API 2000 Annex A	72	45	8383

ISO 28300	100	217	8383
EN 14015	100	217	5773
TRGS 509	33	174	-

From the previous table, it can be observed that the required flow rates for normal operation and emergency cases obtained from different standards vary.

In this case, it is observed that the required outbreathing flow rate for the EN 14015 and ISO 28300 standards is higher than that of API 2000. This is because methanol has an evaporation ratio of 3. [19]

Regarding inbreathing, the same situation applies as for the rest of the products analyzed in this thesis.

Finally, for the emergency venting flow rate due to an external fire scenario, it is observed that API 2000 and ISO 28300 specify the same required flow rate as they use the same equations. However, the required venting flow rate calculated using the formulas proposed by EN 14015 is lower. It is important to highlight that TRGS 509 cannot be compared because this standard does not provide any calculation methodology for the emergency case.

The details of these calculations are presented in Annex 11.1.

7.7 The impact of condensation

Throughout the thesis, the main studies analyzing the impact that condensation can have on atmospheric and low-pressure tanks have been examined. These studies emphasize that the current main standards for designing venting systems for such tanks do not take into account these potential effects that can occur if vapor condensation from the tank contents is not considered.

With the aim of ensuring a safe design of the tank venting system and avoiding possible deformations and collapses considering the effect caused by condensation, the simplified method provided by Fullarton [14], which was discussed earlier in Section 6.1 of this thesis, is applied. This method is applied for each product considered in the practical cases.

It is important to note that, for the application of this method, the same assumptions as those used as a reference in the study conducted by the authors themselves have been considered. All calculations and the process followed in applying this method are shown in Annex 11.1.

Next, the results obtained from the Fullarton method for the different stored products are presented. All the parameters required for the calculation have been extracted from the ASPEN HYSYS V14 software.

Table 7.7. Inbreathing venting flow rates according to the approximate method of Fullarton.

Product	Total inbreathing venting flow rate [Nm ³ /h]
Acrylic Acid	92

Methyl Acrylate	218
Hexane	225
Ethanol	214
Methanol	290

From the inbreathing flow rates obtained using the approximate Fullarton method, it can be determined that in cases where the stored product is non-volatile, such as acrylic acid, the total inbreathing flow rate is lower than what is proposed by the various standards analyzed, except for API 2000 Annex A.

On the other hand, those volatile products that are slightly condensable, such as methyl acrylate and ethanol, have inbreathing flow rates that are very close to those proposed by the API 2000, ISO 28300, and EN 14015 standards. Finally, products whose vapors can condense more easily and are highly volatile obtain significantly higher flow rates compared to those calculated using current standards, especially in the case of methanol.

Another important consideration is the units in which the authors present the required inbreathing flow rates, which are in m^3/h , while the various standards specify flow rates in Nm^3/h ($0^\circ C$ and 1 atm), for this reason the units have been converted to Nm^3/h .

Annex 11.2. provides all the assumptions made throughout the various calculations.

7.8 General conclusions

The analyzed standards propose different equations for calculating the required venting flow rates, depending on the approaches and considerations that are taken into account. All of these assumed parameters are detailed in Section 4 of this thesis.

This section aims to analyze the determination of the total breathing flow rates for different products according to each of the standards.

The tank proposed for the study could be considered a small tank due to its limited capacity. Additionally, the site where the tank is located is in Tarragona, Spain. This area is situated at latitude $41^\circ 7'$, and since it is below 42° , higher factors are applied, which increase the required flow rates. As a result, the total required breathing flow rate is conservative.

The following table shows the required flow rates for various products in accordance with the analyzed regulations. It is worth noting that all flow values are in Nm^3/h . There are three columns for each product, denoted as O, I, and E, representing outbreathing flow rate, inbreathing flow rate, and emergency venting flow rate, respectively.

Table 7.8. Required venting flow rates for the different products [Nm³/h].

Standard	Acrylic Acid			Methyl Acrylate			Hexane			Ethanol			Methanol		
	O	I	E	O	I	E	O	I	E	O	I	E	O	I	E
API 2000	50	217	11441	75	217	15464	75	217	16892	75	217	9403	75	217	8383
API 2000 Annex A	38	45	11441	72	45	15464	72	45	16892	72	45	9403	72	45	8383
ISO 28300	50	217	11441	58	217	15464	70	217	16892	60	217	9403	100	217	8383
EN 14015	50	217	7880	58	217	10650	70	217	11634	60	217	6476	100	217	5773
TRGS 509	33	174	-	33	174	-	33	174	-	33	174	-	33	174	-
Fullarton	-	92	-	-	218	-	-	225	-	-	214	-	-	290	-

In this study, it has been observed that TRGS 509 does not provide equations for emergency cases. However, API 2000, ISO 28300, and EN 14015 do provide equations to calculate the required venting flow rate for the case of an external fire emergency. It is worth noting that API 2000 and ISO 28300 share the same equations, and the flow rate they calculate is 45% higher than that of EN 14015.

The requirements for normal operation venting show discrepancies among the different standards. Primarily for outbreathing, there is a similarity in flow rate values for products that are not considered volatile, such as acrylic acid. In this case, all standards propose very similar values, except for TRGS, which suggests a flow rate that is approximately 50% lower than the others, making it less conservative.

On the other hand, in cases where the product is volatile, API 2000 generally calculates a conservative outbreathing flow rate. However, in cases where volatility is very high and the product has a very high evaporation ratio, such as methanol, EN 14015 and ISO 28300 obtain values higher than API 2000. It is important to note that determining the evaporation ratio is not always straightforward, as many product safety data sheets do not include this parameter.

Next, when analyzing the flow rate requirements for inbreathing, it is observed that all the regulations specify the same flow rates for all products. This is because these equations take into account parameters that are common to all practical cases, such as tank dimensions, the latitude at which the tank is located, operating temperature, and the product discharge rate.

The inbreathing flow rates determined by API 2000, EN 14015, and ISO 28300 are the same because they use the same equations, and they are also the most conservative. On the other hand, API 2000 Annex A and TRGS 509 underestimate the required flow rates, up to 5 times and 20% less, respectively. For this reason, API 2000 Annex A and TRGS 509 may not be the best options to consider when sizing the pressure-vacuum relief valves for the tank.

Finally, after analyzing the standards applicable to the protection of low-pressure tanks, it can be concluded that API 2000 7th Edition is the most recommended standard for designing such safety devices.

API 2000 provides venting flow rates that are conservative even under extreme conditions, both for outbreathing and inbreathing. It also provides a methodology for calculating the relief flow rate required for external fire cases. It should be noted that ISO 28300 has very similar characteristics to API 2000, but determining the evaporation ratio can

sometimes introduce errors in the outbreathing flow rate calculation because in some instances, depending on the product, it can be complicated to find this value. For this reason, in cases where the product is highly volatile, it is recommended to conduct a more in-depth study to determine if the factor of 2 indicated by API 2000 is sufficient or not.

However, a review of the most important studies on thermal effects in low-pressure tanks indicates that API 2000 is conservative only when the stored product is non-condensable. Over the past decades, numerous studies have highlighted the importance of considering the effects that condensation can have inside the tank, emphasizing that current standards like API 2000 do not account for these effects, which can be problematic for tank integrity.

For this reason, it is recommended to apply the Fullarton method [14] in tanks that store products with condensable vapors to account for this effect.

8 Sizing of the pressure-vacuum relief valves

In the industry, where safety, efficiency, and reliability are paramount, the proper design and sizing of pressure-vacuum relief valves become a critical factor.

In this context, it is evident that ensuring precise design and sizing of pressure-vacuum relief valves is essential for safety, equipment integrity, and efficiency in the industry.

In the design and sizing of pressure-vacuum relief valves for low-pressure tanks, one of the crucial factors that often goes unnoticed is the proper consideration of pressure drop. These energy losses, caused by friction and flow resistance through pipes and system components, can introduce significant variations when designing these safety devices.

Omitting pressure drop considerations in the sizing process can lead to either undersized or oversized pressure-vacuum relief valve designs. An undersized design may result in insufficient flow through the valve, which, in turn, can create overpressure or underpressure situations within the equipment or system, jeopardizing asset integrity and personnel safety. On the other hand, an oversized design can lead to energy and resource wastage, along with increased operational and maintenance costs. [8]

In this context, giving due consideration to pressure drop becomes a critical aspect of pressure-vacuum relief valve sizing. By integrating this factor into the design process, it becomes possible to achieve an optimal balance between safety, efficiency, and the reliability of the industrial system.

8.1 Review of the software available for sizing

Many companies in the chemical industry sector have specialized in the design and manufacturing of safety devices such as pressure-vacuum relief valves. In this section, some of the major leaders in the design and construction of safety elements are introduced.

Companies like CSE (Center of Safety Excellence), KITO, Emerson, or PROTEGO are among the companies that offer software for sizing safety elements.

CSE offers the PROSaR™ software, which allows for the sizing and review of safety valves, pressure-vacuum relief valves and rupture discs. It also recommends a model based on the requirements.

Emerson offers the PRV²Size™ software. This software is an easy-to-use and comprehensive program that provides sizing, selection, and configuration capabilities for Anderson Greenwood, Crosby, and Varec brand Overpressure Protection Valves and for Yarway brand Automatic Recirculation Control Valves.

KITO™ provides an online platform where different types of pressure-vacuum relief valves and flame arresters can be sized and selected.

All of the above applications are very useful for sizing, validating, and selecting safety devices for our processes. It should be noted that not all software allows for calculating pressure losses, except for CSE PROSaR™.

Finally, the PROTEGO QuEST™ software is used for the sizing and selection of pressure-vacuum relief valves. PROTEGO is a leading company in the field of industrial safety and is recognized worldwide.

8.2 Design Basis

The required flow rates, both for normal operational venting and for external fire cases, calculated in the previous section 7 of this thesis, are taken as a reference for sizing the pressure-vacuum relief valves of the specified tank.

It should be noted that, in order to account for the potential effect of condensation that may occur inside the tank, the design flow rates will be determined as the larger values between those from API 2000 or the flow rates calculated using the Fullarton method. This is done to avoid potential adverse situations that could compromise the tank's integrity.

When the required inbreathing flow rate obtained using the Fullarton method exceeds the flow rate obtained according to API 2000, the flow rate to be considered for the sizing of the pressure-vacuum relief valve will be that of the Fullarton method. To account for this additional flow rate due to Fullarton method, an additional load (vapor condensation) is introduced into the PROTEGO QuEST™, because the program is incapable of performing this calculation. This additional load will be the difference between the flow rate proposed by the Fullarton method and the flow rate proposed by API 2000.

The design bases shown in Table 8.2.1. from section 7 are retained. Below are the considered required flow rates for valve sizing.

Table 8.2.1. Design Flow Rates for Sizing Pressure-Vacuum relief Valves.

Tank product	Venting flow rates [Nm ³ /h]		
	Outbreathing	Inbreathing	Emergency
Acrylic Acid	50	217	11441
Methyl Acrylate	75	218	15464
Hexane	75	225	16892
Ethanol	75	217	9403
Methanol	75	290	8383

In order to analyze the impact of pressure drop on the sizing of pressure-vacuum relief valves, it is considered that the PVRV is an in-line device instead of an end-of-line device, and the tank has one valve for pressure and another for vacuum. Additionally, a series of fittings are considered to create a pressure drop greater than what is generally encountered in the industry. In this case, the system set up is solely for academic purposes, as in a real installation, it might not be an optimized design.

The hydraulic calculation is performed using PALS R6™ software. [24]

Table 8.2.2. Lengths and fittings considered for the sizing of PVRVs.

Fitting	Upstream valve (Tank – Valve)	Downstream valve (Valve – Atmosphere)
Pipe	2.5 m	3 m
Elbow 90° LR	2	2

It is considered that the pipeline is made of carbon steel with an absolute roughness of 0.07 mm. Additionally, sharp-edged entrances ($K=0.5$) are taken into account at the pipe inlets, and a pressure drop is considered at the pipe outlet ($K=1$). All friction factors (K) are extracted from Crane [9].

In this practical exercise, it is considered that emergency devices do not have pressure drop.

Another important aspect to consider in the sizing of pressure-vacuum relief valves is the percentage of overpressure that the device allows. In this case, PROTEGO technology with a 10% overpressure setting is selected, as it offers several advantages such as maintaining pressure very close to the maximum allowable tank pressure, minimizing product losses, and reducing vapor emissions into the atmosphere.

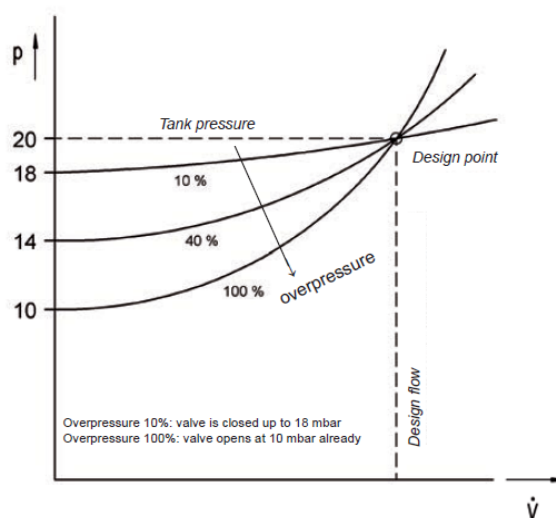


Figure 17: Opening characteristics of valves with different overpressure levels. [25]

The considered design pressure of the tank is +25/-8.5 mbarg. Therefore, in terms of overpressure protection, the valve with the highest set pressure corresponds to the emergency relief device. Since it's 10% technology, the set pressure of the emergency relief device corresponds to:

$$P_{\text{set}_{\text{ERV}}} = \frac{\text{MAWP}}{1.1} \quad (57)$$

$$P_{\text{set}_{\text{ERV}}} = \frac{25}{1.1} = 22.72 \text{ mbarg}$$

The set pressure for the pressure and vacuum relief devices due to normal tank operation will be determined based on the hydraulic calculations of pressure drop.

The sizing procedure for these devices is based on an iterative process, which can be divided into phases:

- Step 1:

The required flow rates and set pressures are entered into the PROTEGO QuEST™ software to obtain an initial valve size. The initially selected set pressures for the normal tank

operation venting devices correspond to 20.65/-7.72 mbarg, considering that for the vacuum device, the maximum set pressure value will be the MAWV (Maximum Allowable Vacuum) divided by the overpressure (10% PROTEGO technology).

On the other hand, for the normal overpressure protection device, since there is an emergency device set at a higher pressure, the set pressure will be the set pressure of the emergency device divided by the allowed overpressure percentage of 10%. It is worth noting that blowdown has not been considered in this practical exercise.

Finally, initial valve sizes are obtained.

- Step 2:

With the initially obtained valve sizes, the pressure drop calculations are performed for both upstream and downstream of the valve, both for pressure and vacuum relief valves. No pressure drop is considered for the emergency relief device.

- Step 3:

Once the initial pressure drops are known, the new set pressures are determined following the PROTEGO procedure. Applying these losses, it is checked whether it is a case of low or high built-up backpressure.

Low built-up backpressure:

$$P_{\text{built-up(gauge)}} \leq 15\% \cdot P_{\text{set(gauge)}} \text{ AND } \Delta P_{\text{inlet}} \leq 10\% \cdot P_{\text{set(gauge)}} \quad (58)$$

High built-up backpressure:

$$P_{\text{built-up(gauge)}} \leq 15\% \cdot P_{\text{set(gauge)}} \text{ OR } \Delta P_{\text{inlet}} \leq 10\% \cdot P_{\text{set(gauge)}} \quad (59)$$

With the newly determined set pressures, they are re-entered into PROTEGO QuEST™ in order to obtain the recommended valve dimensions.

- Step 4:

It is checked whether the dimensions recommended by the software match the initial ones; if they do, further iterations are not needed as the valve sizes have been confirmed considering the generated pressure losses. In case they do not match, the same steps described in this iterative process are repeated until a definitive valve size is obtained.

Finally, it is necessary to define some concepts before starting with the valve sizing, such as backpressure, built-up backpressure, and superimposed backpressure.

Backpressure is the pressure that exists at the outlet of a pressure-relief device as a result of the pressure in the discharge system. Backpressure is the sum of the superimposed and built-up backpressures.

Built-up backpressure is the increase in pressure at the outlet of a pressure-relief device that develops as a result of flow after the pressure-relief device opens.

Superimposed backpressure is the static pressure that exists at the outlet of a pressure-relief device at the time the device is required to operate. Superimposed backpressure is the

result of pressure in the discharge system coming from other sources and may be constant or variable.

8.3 Acrylic Acid case

In this section, the sizing of the pressure-vacuum relief valves responsible for protecting and ensuring the proper operation of the acrylic acid tank is carried out. Both the tank dimensions and other parameters necessary for the design of safety devices have been previously introduced in the thesis.

The considered required flow rates for normal outbreathing, normal inbreathing, and the emergency case are 50, 217, and 11441 Nm³/h, respectively.

Below is the iterative process followed for the sizing of the valves for the acrylic acid tank.

Table 8.3.1. Iterative process for sizing the pressure relief valve for the acrylic acid tank.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	20.65	DN25
Iteration 1	18	19	-	dP>MAWP (DN40)
Iteration 2	3	2	16.11	DN40

Table 8.3.2. Iterative process for sizing the vacuum relief valve for the acrylic acid tank.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	-7.72	DN80
Iteration 1	3	2	-3.18	DN125
Iteration 2	0	1	-6.81	DN100
Iteration 3	1	1	-5.90	DN100

Finally, the normal pressure relief valve is DN40 with a set pressure of 16.11 mbarg, while the normal vacuum relief valve is DN100 with a set pressure of -5.90 mbarg. In the case of the emergency valve, a size of DN400 is considered.

Table 8.3.3. Selected safety devices for the acrylic acid tank.

Valve	Pset (mbarg)	Model	Size
Pressure relief	16.11	DZ/T	DN40
Vacuum relief	-5.90	DZ/T	DN100
Emergency relief	22.72	ER/V	DN400

The annex 11.2 provides a more detailed procedure and includes the technical specification sheets for the pressure-vacuum relief valves and hydraulic calculations.

8.4 Methyl Acrylate case

In this section, the sizing of the pressure-vacuum relief valves responsible for protecting and ensuring the proper operation of the methyl acrylate tank is carried out. Both the tank dimensions and other parameters necessary for the design of safety devices have been previously introduced in the thesis.

The considered required flow rates for normal outbreathing, normal inbreathing, and the emergency case are 75, 218, and 15464 Nm³/h, respectively.

Below is the iterative process followed for the sizing of the valves for the methyl acrylate tank.

Table 8.4.1. Iterative process for sizing the pressure relief valve for the methyl acrylate.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	20.65	DN40
Iteration 1	6	6	9.75	DN40

Table 8.4.2. Iterative process for sizing the vacuum relief valve for the methyl acrylate.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	-7.72	DN80
Iteration 1	3	2	-3.18	DN125
Iteration 2	0	1	-6.81	DN100
Iteration 3	1	1	-5.90	DN100

Finally, the normal pressure relief valve is DN40 with a set pressure of 9.75 mbarg, while the normal vacuum relief valve is DN100 with a set pressure of -5.90 mbarg. In the case of the emergency relief valve, a size of DN500 is considered.

Table 8.4.3. Selected safety devices for the methyl acrylate tank.

Valve	Pset (mbarg)	Model	Size
Pressure relief	9.75	DZ/T	DN40
Vacuum relief	-5.90	DZ/T	DN100
Emergency relief	22.72	ER/V	DN500

The annex 11.2 provides a more detailed procedure and includes the technical specification sheets for the pressure-vacuum relief valves and hydraulic calculations.

8.5 Hexane case

In this section, the sizing of the pressure-vacuum relief valves responsible for protecting and ensuring the proper operation of the hexane tank is carried out. Both the tank dimensions and other parameters necessary for the design of safety devices have been previously introduced in the thesis.

The considered required flow rates for normal outbreathing, normal inbreathing, and the emergency case are 75, 225, and 16892 Nm³/h, respectively.

Below is the iterative process followed for the sizing of the valves for the hexane tank.

Table 8.5.1. Iterative process for sizing the pressure relief valve for the hexane.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	20.65	DN40
Iteration 1	6	6	9.75	DN40

Table 8.5.2. Iterative process for sizing the vacuum relief valve for the hexane.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	-7.72	DN80
Iteration 1	3	2	-3.18	DN125
Iteration 2	0	1	-6.81	DN100
Iteration 3	1	1	-5.90	DN100

Finally, the normal pressure relief valve is DN40 with a set pressure of 9.75 mbarg, while the normal vacuum relief valve is DN100 with a set pressure of -5.90 mbarg. In the case of the emergency relief valve, a size of DN500 is considered.

Table 8.5.3. Selected safety devices for the hexane tank.

Valve	Pset (mbarg)	Model	Size
Pressure relief	9.75	DZ/T	DN40
Vacuum relief	-5.90	DZ/T	DN100
Emergency relief	22.72	ER/V	DN500

The annex 11.2 provides a more detailed procedure and includes the technical specification sheets for the pressure-vacuum relief valves and hydraulic calculations.

8.6 Ethanol case

In this section, the sizing of the pressure-vacuum relief valves responsible for protecting and ensuring the proper operation of the ethanol tank is carried out. Both the tank dimensions and other parameters necessary for the design of safety devices have been previously introduced in the thesis.

The considered required flow rates for normal outbreathing, normal inbreathing, and the emergency case are 75, 217, and 9403 Nm³/h, respectively.

Below is the iterative process followed for the sizing of the valves for the ethanol tank.

Table 8.6.1. Iterative process for sizing the pressure relief valve for ethanol.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	20.65	DN40
Iteration 1	6	6	9.75	DN40

Table 8.6.2. Iterative process for sizing the vacuum relief valve for ethanol.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	-7.72	DN80
Iteration 1	3	2	-3.18	DN125
Iteration 2	0	1	-6.81	DN100
Iteration 3	1	1	-5.90	DN100

Finally, the normal pressure relief valve is DN40 with a set pressure of 9.75 mbarg, while the normal vacuum relief valve is DN100 with a set pressure of -5.90 mbarg. In the case of the emergency relief valve, PROTEGO QuEST™ suggests a size of DN350, but it is decided to increase it to DN400 because the previous size had a relief capacity 0.54% higher than the required flow for external fire case. Therefore, for safety reasons, the size is increased from DN350 to DN400.

Table 8.6.3. Selected safety devices for the ethanol tank.

Valve	Pset (mbarg)	Model	Size
Pressure relief	9.75	DZ/T	DN40
Vacuum relief	-5.90	DZ/T	DN100
Emergency relief	22.72	ER/V	DN400

The annex 11.2 provides a more detailed procedure and includes the technical specification sheets for the pressure-vacuum relief valves and hydraulic calculations.

8.7 Methanol case

In this section, the sizing of the pressure-vacuum relief valves responsible for protecting and ensuring the proper operation of the methanol tank is carried out. Both the tank dimensions and other parameters necessary for the design of safety devices have been previously introduced in the thesis.

The considered required flow rates for normal outbreathing, normal inbreathing, and the emergency case are 75, 290, and 8383 Nm³/h, respectively.

Below is the iterative process followed for the sizing of the valves for the methanol tank.

Table 8.7.1. Iterative process for sizing the pressure relief valve for the methanol.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	20.65	DN40
Iteration 1	6	6	9.75	DN40

Table 8.7.2. Iterative process for sizing the vacuum relief valve for the methanol.

Iteration	Upstream valve dP (mbarg)	Downstream valve dP (mbarg)	Pset (mbarg)	Valve size
No dP	0	0	-7.72	DN100
Iteration 1	2	1	-5	DN125
Iteration 2	1	1	-5.90	DN125

Finally, the normal pressure relief valve is DN40 with a set pressure of 9.75 mbarg, while the normal vacuum relief valve is DN125 with a set pressure of -5.90 mbarg. In the case of the emergency relief valve, PROTEGO QuEST™ suggests a size of DN350.

Table 8.7.3. Selected safety devices for the methanol tank.

Valve	Pset (mbarg)	Model	Size
Pressure relief	9.75	DZ/T	DN40
Vacuum relief	-5.90	DZ/T	DN125
Emergency relief	22.72	ER/V	DN350

The annex 11.2 provides a more detailed procedure and includes the technical specification sheets for the pressure-vacuum relief valves and hydraulic calculations.

For all practical cases, the same pressure-vacuum relief and emergency relief valve model has been selected.

The pressure-vacuum valve responsible for relieving the normal operating flow corresponds to the DZ/T model from PROTEGO. The PROTEGO in-line valve DZ/T is a state-of-the-art pressure or vacuum relief valve. The device will start to open as soon as the set pressure is reached and only requires 10% overpressure to full lift. The valve pallet is weight-loaded.

The valve responsible for relieving the flow in the case of an external fire emergency corresponds to the ER/V model. It is designed to relief particularly large amounts to prevent the vessel from rupturing in emergency case. The device will start to open as soon as the set pressure is reached and only requires 10% overpressure to full lift. The valve pallet is weight-loaded. [25]

9 Conclusions and future lines of continuation of research

A comparison of the main standards for the design of venting systems for atmospheric or low-pressure storage tanks was performed in order to recommend a suitable standard for future pressure-vacuum relief valve designs. After analyzing all the standards, API 2000 7th Edition is selected as the best option for designing this type of safety device.

API 2000 is quite conservative in cases where the product stored in the tank is non-volatile and exhibits non-condensable vapors. However, for volatile products with condensable vapors, both API 2000 and the rest of the current standards do not provide methods or calculations to account for the potential vacuum generated by product condensation. For this reason, important studies have been conducted over the past decades regarding effects of condensation and the impact it can have on thermal inbreathing flow rates.

A literature review of the tank breathing main studies is conducted performed in order to analyze the different methods for calculating inbreathing flow rates while considering the condensation effect. Analyzed the different calculation methods, it is recommended to apply the simplified Fullarton method for volatile products with condensable vapors. This thesis recommends the application of this method due to its ease of implementation, as it does not rely on complex numerical methods. Additionally, it provides conservative inbreathing flow rates that would address the under-sizing of pressure-vacuum relief valves in potential condensation scenarios.

In the thesis, various case studies with products of different volatilities have been proposed. Furthermore, a tank located in Tarragona (Spain) is considered as the object of study. Applying API 2000 and the simplified Fullarton method, the pressure-vacuum relief valve and emergency relief valves responsible for protecting the tank are sized. Additionally, a series of fittings are considered to analyze the impact they cause in terms of pressure drop on the sizing of these devices.

After sizing the pressure-vacuum relief valves for the tanks containing different products, it is found that no accounting for pressure drop in the design results in smaller valve sizes. Therefore, if there losses are not considered, the designed devices will not have the capacity to adequately relieve the required venting flows, jeopardizing the tank's integrity.

Finally, with the justification for the selection of the standard for venting systems, the analysis of numerical methods to consider the condensation effect, and the sizing of pressure-vacuum relief valves this thesis provides a valuable guide for preserving integrity and ensuring a proper design of tank safety devices.

However, all models analyzed in this thesis are derived for single components, predominantly water and air. In industry, liquids like naphtha, gasoline or other multi components are stored in those tanks. The impact of mixing properties on inbreathing and the transferability to common breathing models needs to be validated. Currently there is no multi component model published in literature. The influence of those effects shall be verified in subsequent models. [30]

On the other hand, different storage capacities would complement the study conducted in this thesis.

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11 Annex

In this annex, the calculations carried out throughout this study are detailed, including the considerations, assumptions, and methodologies adopted for various practical cases. Mainly, it includes different developments of the calculations for the required venting for different products, the analysis of the corresponding condensation effect, and finally, the selection of the safety devices for each tank.

11.1 Development of practical cases

In this section of the annex, the calculations for determining the required venting flow rates according to the regulations analyzed in the thesis are presented, as well as the Fullarton method for a particular case.

11.1.1 Acrylic Acid case

11.1.1.1 API 2000

The procedure for calculating the required normal and emergency venting is shown in section 4.1.

- Normal venting Flow rates:

First of all, the total outbreathing flow rate is calculated:

The outbreathing flow rate due to pump-in, in this case, corresponds to equation (1) since acrylic acid has a vapor pressure lower than 50 mbara.

$$\dot{V}_{op}=25 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{OT}=0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{out}=25 + 25 = 50 \text{ Nm}^3/\text{h}$$

For the required inbreathing:

The inbreathing flow rate due to pump-out corresponds directly to the tank discharge flow rate.

$$\dot{V}_{ip}= 25 \text{ Nm}^3/\text{h}$$

The inbreathing flow rate due to thermal effects, in this case, the factor "C" has a value of 6.5 since the tank's latitude is below 42°C, the vapor pressure of the product is below 50 mbarg, and the operating temperature is 25 °C. Additionally, since it's a non-insulated tank, the reduction factor is 1.

$$\dot{V}_{IT}= 6.5 \cdot 1 \cdot 125.67^{0.7} = 192 \text{ Nm}^3/\text{h}$$

The total inbreathing flow rate corresponds to the sum of the effects of discharging out the tank and the thermal effects due to cooling of the tank.

$$\dot{V}_{IT} = 25 + 192 = 217 \text{ Nm}^3/\text{h}$$

To calculate the emergency flow rate due to the fire case:

First, it is necessary to determine the wetted area of the tank. In this case, since the tank height of 10 m exceeds 9.14 m, it is considered that the maximum height is 9.14 m.

$$A_{TWS} = 9.14 \cdot 4 \cdot \pi^2 = 114.86 \text{ m}^2$$

From table 4.1.3., the value of Q can be determined using the following expression:

$$Q = 630400(114.86^{0.338}) = 3132917 \text{ W}$$

Finally, the required flow rate for the external fire case is:

$$q = 906.6 \cdot \frac{3132917 \cdot 1}{595000} \left(\frac{273 + 141}{72.1} \right)^{0.5} = 11441 \text{ Nm}^3/\text{h}$$

11.1.1.2 API 2000 Annex A

The procedure for calculating the required normal venting is shown in section 4.2.

Acrylic acid has a flash point of 55°C, therefore, applying the table 4.2.1. from this thesis, the following required pump-in and pump-out flow rates are obtained.

$$\dot{V}_{ip} = 25 \cdot 0.94 = 23.5 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{op} = 25 \cdot 1.01 = 25.25 \text{ Nm}^3/\text{h}$$

For the part of the required flow rates due to thermal effects, based on table 4.2.2. from this thesis, these flow rates can be determined. Interpolation between the values in the table is allowed with a tank volume of 125.67 m³.

$$\dot{V}_{OT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (20.3 - 10.1) \right) = 12.72 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

Finally, the total required outbreathing and inbreathing flow rates correspond to:

$$\dot{V}_{out} = 25.25 + 12.72 = 38 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 23.5 + 21.24 = 45 \text{ Nm}^3/\text{h}$$

For the required emergency flow rate, the API 2000 main body methodology is used.

11.1.1.3 ISO 28300

The procedure for calculating the required normal venting is shown in section 4.3.

In this case, since acrylic acid has a vapor pressure lower than 50 mbara, the evaporation ratio factor is not applied. Therefore, the same equations and calculation methodology as in API 2000 are used for both normal and emergency venting flow rates.

11.1.1.4 EN 14015

The procedure for calculating the required normal venting is shown in section 4.4.

In this case, since acrylic acid has a vapor pressure lower than 50 mbara, the evaporation ratio factor is not applied. Therefore, the same equations and calculation methodology as in API 2000 are used for both normal venting flow rates. Additionally, in equations (14, 16), a reduction factor of 1 is considered.

On the other hand, to determine the required flow rate for the emergency case, the following expression is followed:

$$U_{FB} = 4 \cdot 10^4 \cdot 114.86^{0.82} \cdot \frac{1}{595} \sqrt{\frac{273 + 141}{72.1}} = 7880 \text{ Nm}^3/\text{h}$$

11.1.1.5 TRGS 509

The procedure for calculating the required normal venting is shown in section 4.5.

The TRGS 509 does not provide any guidance on how to consider the tank filling and emptying flow rates. As for the required flow rate due to thermal effects, the following equations are used.

- Total outbreathing:

$$\dot{V}_E = 0.17 \cdot \left(\frac{10}{4}\right)^{-0.52} \cdot 125.67^{0.89} = 7.8 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{out} = \dot{V}_E + \dot{V}_{pump-in} = 7.8 + 25 = 33 \text{ Nm}^3/\text{h}$$

-Total inbreathing:

$$\dot{V}_A = 4.8 \cdot 125.67^{0.71} = 148.49 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{in} = \dot{V}_A + \dot{V}_{pump-out} = 148.49 + 25 = 174 \text{ Nm}^3/\text{h}$$

TRGS 509 does not provide equations for calculating the required emergency flow rate.

11.1.1.6 Fullarton Simplified Method

The Fullarton method is shown in section 6.1.

Fullarton considers the tank to be filled with acrylic acid phase gas, with a negligible amount of liquid.

The temperature of the wall at the beginning of the sudden rain is 55 °C, with 15 °C being the temperature of the rain.

The tank has a capacity of 125.67 m³ and exposure area of 138.23 m².

- Gas composition:

Fullarton takes 50 °C as a reference temperature because it considers that this is where the maximum air intake occurs.

The vapor pressure of acrylic acid at 50 °C is 24.5 mbara; value extracted from ASPEN HYSYS V14.

The gas compositions inside the tank correspond to:

$$y_{molar,acrylic\ acid} = \frac{24.5}{1013} = 0.025$$

$$y_{molar,air} = 1 - 0.025 = 0.975$$

To know the mass composition, the molecular weights must be taken into account:

$$y_{mass,acrylic\ acid} = 0.025 \cdot 72.1 = 1.75 \text{ g acrylic acid} = \frac{1.75}{1.75 + 28.25} = 0.06$$

$$y_{mass,air} = 0.975 \cdot 28.96 = 28.25 \text{ g air} = \frac{28.25}{1.75 + 28.25} = 0.94$$

- Physical properties of gas:

Air density at 50 °C (normal conditions 1.293 kg/m³):

$$\rho_{air} = 1.293 \cdot \left(\frac{273}{273 + 50} \right) = 1.093 \text{ kg/m}^3$$

Density of acrylic acid at 50 °C:

$$\rho_{acrylic\ acid} = \left(\frac{P \cdot PM}{0.082 \cdot T} \right) = \left(\frac{1 \cdot 72.1}{0.082 \cdot (273 + 50)} \right) = 2.722 \text{ kg/m}^3$$

Density of the mixture:

$$\rho_{mixture} = \left(\frac{1}{(0.94/1.093) + (0.06/2.722)} \right) = 1.132 \text{ kg/m}^3$$

Mass heat capacity:

The value for air at 50 °C corresponds to 1.01 kJ/(kg K), while for acrylic acid it is 1.154 kJ/(kg·K). Values extracted from ASPEN HYSYS V14.

$$Cp_{mixture} = 0.06 \cdot 1.154 + 0.94 \cdot 1.01 = 1.018 \text{ kJ}/(\text{kg} \cdot \text{K})$$

Mass heat of vaporization:

The mass heat of vaporization value is 692 kJ/kg at 50 °C. Value extracted from ASPEN HYSYS V14.

- Lewis Number:

The thermal conductivity of acrylic acid at 50 °C is 0.00257 W/(m·K). The thermal conductivity and diffusion coefficient values are extracted from ASPEN HYSYS V14.

$$Le = \lambda_G / \rho_G c_G \delta_G = 1.9367$$

$$Le^{0.66} = 1.9367^{0.66} = 1.5469$$

- Calculation of the factor $\left(\frac{1}{p_G} \frac{dp^*}{dT}\right)$:

Since the tangent is the derivative at this point 50 °C, if the vapor pressure at 51 °C and 49 °C are considered as an interval:

The vapor pressure of acrylic acid at 49 °C corresponds to 0.0236 bar.

The vapor pressure of acrylic acid at 51 °C corresponds to 0.0258 bar.

$$tg\alpha = \frac{0.0258 - 0.0236}{2} = 0.0011$$

$$Factor \frac{1}{p_G} \frac{dp^*}{dT} = \frac{1}{1.013} \cdot 0.0011 = 0.00105888 K^{-1}$$

- Calculation of the capacity ratio:

The tank walls are made of steel with a thickness of 5 mm. The steel density is 7850 kg/m³ and the mass heat capacity is 0.469 kJ/(kg·K).

$$C = \frac{\rho_w c_w s_w}{\rho_G c_G} \cdot \frac{1 + 4H/D}{H}$$

$$C = \frac{7850 \cdot 0.005 \cdot 0.469}{1.01 \cdot 1.093} \cdot \frac{1 + 4 \cdot 10/4}{10} = 18.35$$

- Calculation of $\frac{\alpha_{g,wet}}{\alpha_g}$:

$$\frac{\alpha_{g,wet}}{\alpha_g} = \frac{692.3}{1.018} \cdot 0.00105888 \cdot \frac{1}{1.5469} = 0.477$$

- Calculation of the maximum condensation volume:

Fullarton considers the following heat transfer coefficients:

$$\alpha_g = 5 \text{ W/(m}^2 \text{ K)}$$

$$\alpha_a / \alpha_g = 10$$

$$\dot{V}_N = \frac{\alpha_G A}{\rho_G c_G} \frac{T_0 - T_A}{T_0}$$

$$\dot{V}_N = \frac{5 \cdot 138.23}{1.093 \cdot 1.01} \cdot \frac{328 - 288}{328} = 274.90 \text{ m}^3/h$$

- Calculation of the reduction factor η :

Fullarton considers that $\theta_{\max} = 0.85$ is a valid value, without providing any further clarification or explanation regarding this specific choice.

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + \alpha_G / \alpha_A (C + 1)} \theta_{\max}$$

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + 0.1(18.35 + 1)} \cdot 0.85 = 0.341$$

- Calculation of condensation factor χ :

$$K = 1 + \frac{\alpha_{G,\text{wet}}}{\alpha_G}$$

$$K = 1 + 0.477 = 1.477$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_0\right) \left(\frac{p_{\text{air}} c_{\text{air}}}{p_G c_G}\right) \left[\frac{1 + \alpha_G/\alpha_A(C + 1)}{1 + \alpha_G/\alpha_A(C + K)}\right]$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{1.5469} \cdot 0.00105888 \cdot 328\right) \left(\frac{1.093 \cdot 1.01}{1.132 \cdot 1.018}\right) \left[\frac{1 + 0.1(18.35 + 1)}{1 + 0.1(18.35 + 1.477)}\right] = 1.159$$

- Calculation of the volumetric flow rate:

$$\dot{V}_{K,\max} = \dot{V}_N \cdot \eta \cdot \chi$$

$$\dot{V}_{K,\max} = 274.90 \cdot 0.341 \cdot 1.159 = 108.56 \text{ m}^3/\text{h}$$

This air flow at 50 °C must be converted to normal conditions units:

$$\dot{V}_{N,\text{gas}} = \dot{V}_{B,\text{gas}} \cdot \frac{T_N \cdot P_B}{T_B \cdot P_N} = \dot{V}_{B,\text{gas}} \cdot \frac{273.15 \cdot P_B}{T_B \cdot 1.013}$$

$$\dot{V}_{N,\text{gas}} = 108.56 \cdot \frac{273.15 \cdot 1.013}{323 \cdot 1.013} = 91.7 \text{ Nm}^3/\text{h}$$

11.1.2 Methyl Acrylate case

11.1.2.1 API 2000

The procedure for calculating the required normal and emergency venting is shown in section 4.1.

- Normal venting Flow rates:

First of all, the total outbreathing flow rate is calculated:

The outbreathing flow rate due to pump-in, in this case, corresponds to equation (2) since methyl acrylate has a vapor pressure higher than 50 mbara.

$$\dot{V}_{\text{op}} = 2 \cdot 25 = 50 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{\text{OT}} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{\text{out}} = 25 + 25 = 50 \text{ Nm}^3/\text{h}$$

For the required inbreathing:

The inbreathing flow rate due to pump-out corresponds directly to the tank discharge flow rate.

$$\dot{V}_{ip} = 25 \text{ Nm}^3/\text{h}$$

The inbreathing flow rate due to thermal effects, in this case, the factor "C" has a value of 6.5 since the tank's latitude is below 42°C, the vapor pressure of the product is below 50 mbarg, and the operating temperature is 25 °C. Additionally, since it's a non-insulated tank, the reduction factor is 1.

$$\dot{V}_{IT} = 6.5 \cdot 1 \cdot 125.67^{0.7} = 192 \text{ Nm}^3/\text{h}$$

The total inbreathing flow rate corresponds to the sum of the effects of discharging out the tank and the thermal effects due to cooling of the tank.

$$\dot{V}_{IT} = 25 + 192 = 217 \text{ Nm}^3/\text{h}$$

To calculate the emergency flow rate due to the fire case:

First, it is necessary to determine the wetted area of the tank. In this case, since the tank height of 10 m exceeds 9.14 m, it is considered that the maximum height is 9.14 m.

$$A_{TWS} = 9.14 \cdot 4 \cdot \pi^2 = 114.86 \text{ m}^2$$

From table 4.1.3., the value of Q can be determined using the following expression:

$$Q = 630400(114.86^{0.338}) = 3132917 \text{ W}$$

Finally, the required flow rate for the external fire case is:

$$q = 906.6 \cdot \frac{3132917 \cdot 1}{372000} \left(\frac{273 + 80}{86.1} \right)^{0.5} = 15464 \text{ Nm}^3/\text{h}$$

11.1.2.2 API 2000 Annex A

The procedure for calculating the required normal venting is shown in section 4.2.

Methyl acrylate has a flash point of -3°C, therefore, applying the table 4.2.1. from this thesis, the following required pump-in and pump-out flow rates are obtained.

$$\dot{V}_{ip} = 25 \cdot 0.94 = 23.5 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{op} = 25 \cdot 2.02 = 50.5 \text{ Nm}^3/\text{h}$$

For the part of the required flow rates due to thermal effects, based on table 4.2.2. from this thesis, these flow rates can be determined. Interpolation between the values in the table is allowed with a tank volume of 125.67 m³.

$$\dot{V}_{OT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

Finally, the total required outbreathing and inbreathing flow rates correspond to:

$$\dot{V}_{\text{out}} = 50.5 + 21.24 = 72 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{IT}} = 23.5 + 21.24 = 45 \text{ Nm}^3/\text{h}$$

For the required emergency flow rate, the API 2000 main body methodology is used.

11.1.2.3 ISO 28300

The procedure for calculating the required normal venting is shown in section 4.3.

In this case, since methyl acrylate has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. In this case, the evaporation rate of methyl acrylate is 1.3. [7].

$$\dot{V}_{\text{op}} = 1.3 \cdot 25 = 32.5 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{\text{OT}} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{\text{out}} = 32.5 + 25 = 58 \text{ Nm}^3/\text{h}$$

Therefore, the same equations and calculation methodology as in API 2000 are used for rest of normal and emergency venting flow rates.

11.1.2.4 EN 14015

The procedure for calculating the required normal venting is shown in section 4.4.

In this case, since methyl acrylate has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. The same calculation of ISO 28300 is performed.

Therefore, the same equations and calculation methodology as in API 2000 are used for both normal venting flow rates. Additionally, in equations (14, 16), a reduction factor of 1 is considered.

On the other hand, to determine the required flow rate for the emergency case, the following expression is followed:

$$U_{\text{FB}} = 4 \cdot 10^4 \cdot 114.86^{0.82} \cdot \frac{1}{372} \sqrt{\frac{273 + 80}{86.1}} = 10650 \text{ Nm}^3/\text{h}$$

11.1.2.5 TRGS 509

The procedure for calculating the required normal venting is shown in section 4.5.

The TRGS 509 does not provide any guidance on how to consider the tank filling and emptying flow rates. As for the required flow rate due to thermal effects, the following equations are used.

- Total outbreathing:

$$\dot{V}_E = 0.17 \cdot \left(\frac{10}{4}\right)^{-0.52} \cdot 125.67^{0.89} = 7.8 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{out}} = \dot{V}_E + \dot{V}_{\text{pump-in}} = 7.8 + 25 = 33 \text{ Nm}^3/\text{h}$$

-Total inbreathing:

$$\dot{V}_A = 4.8 \cdot 125.67^{0.71} = 148.49 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{in}} = \dot{V}_A + \dot{V}_{\text{pump-out}} = 148.49 + 25 = 174 \text{ Nm}^3/\text{h}$$

TRGS 509 does not provide equations for calculating the required emergency flow rate.

11.1.2.6 Fullarton Simplified Method

The Fullarton method is shown in section 6.1.

Fullarton considers the tank to be filled with methyl acrylate phase gas, with a negligible amount of liquid.

The temperature of the wall at the beginning of the sudden rain is 55 °C, with 15 °C being the temperature of the rain.

The tank has a capacity of 125.67 m³ and exposure area of 138.23 m².

- Gas composition:

Fullarton takes 50 °C as a reference temperature because it considers that this is where the maximum air intake occurs.

The vapor pressure of methyl acrylate at 50 °C is 360 mbara; value extracted from ASPEN HYSYS V14.

The gas compositions inside the tank correspond to:

$$y_{\text{molar,methyl acrylate}} = \frac{360}{1013} = 0.355$$

$$y_{\text{molar,air}} = 1 - 0.355 = 0.645$$

To know the mass composition, the molecular weights must be taken into account:

$$y_{\text{mass,methyl acrylate}} = 0.355 \cdot 86.1 = 30.6 \text{ g methyl acrylate} = \frac{30.6}{30.6 + 18.7} = 0.62$$

$$y_{\text{mass,air}} = 0.645 \cdot 28.96 = 18.7 \text{ g air} = \frac{18.7}{18.7 + 30.6} = 0.38$$

- Physical properties of gas:

Air density at 50 °C (normal conditions 1.293 kg/m³):

$$\rho_{\text{air}} = 1.293 \cdot \left(\frac{273}{273 + 50}\right) = 1.093 \text{ kg/m}^3$$

Density of methyl acrylate at 50 °C:

$$\rho_{methyl\ acrylate} = \left(\frac{P \cdot PM}{0.082 \cdot T} \right) = \left(\frac{1 \cdot 86.1}{0.082 \cdot (273 + 50)} \right) = 3.25\ kg/m^3$$

Density of the mixture:

$$\rho_{mixture} = \left(\frac{1}{(0.38/1.093) + (0.62/3.25)} \right) = 1.86\ kg/m^3$$

Mass heat capacity:

The value for air at 50 °C corresponds to 1.01 kJ/(kg K), while for methyl acrylate it is 1.231 kJ/(kg·K). Values extracted from ASPEN HYSYS V14.

$$Cp_{mixture} = 0.62 \cdot 1.231 + 0.38 \cdot 1.01 = 1.147\ kJ/(kg \cdot K)$$

Mass heat of vaporization:

The mass heat of vaporization value is 372.9 kJ/kg at 50 °C. Value extracted from ASPEN HYSYS V14.

- Lewis Number:

The thermal conductivity of methyl acrylate at 50 °C is 0.002 W/(m·K). The thermal conductivity and diffusion coefficient values are extracted from ASPEN HYSYS V14.

$$Le = \lambda_G / \rho_G c_G \delta_G = 0.815$$

$$Le^{0.66} = 0.815^{0.66} = 0.87$$

- Calculation of the factor $\left(\frac{1}{p_G} \frac{dp^*}{dT} \right)$:

Since the tangent is the derivative at this point 50 °C, if the vapor pressure at 51 °C and 49 °C are considered as an interval:

The vapor pressure of methyl acrylate at 49 °C corresponds to 0.3462 bar.

The vapor pressure of methyl acrylate at 51 °C corresponds to 0.3746 bar.

$$tg_{\alpha} = \frac{0.3746 - 0.3462}{2} = 0.0142$$

$$Factor\ \frac{1}{p_G} \frac{dp^*}{dT} = \frac{1}{1.013} \cdot 0.0142 = 0.0140177\ K^{-1}$$

- Calculation of the capacity ratio:

The tank walls are made of steel with a thickness of 5 mm. The steel density is 7850 kg/m³ and the mass heat capacity is 0.469 kJ/(kg·K).

$$C = \frac{\rho_w c_w s_w}{\rho_G c_G} \cdot \frac{1 + 4H/D}{H}$$

$$C = \frac{7850 \cdot 0.005 \cdot 0.469}{1.01 \cdot 1.093} \cdot \frac{1 + 4 \cdot 10/4}{10} = 18.35$$

- Calculation of $\frac{\alpha_{g,wet}}{\alpha_g}$:

$$\frac{\alpha_{g,wet}}{\alpha_g} = \frac{372.9}{1.147} \cdot 0.0140177 \cdot \frac{1}{0.87} = 5.21$$

- Calculation of the maximum condensation volume:

Fullarton considers the following heat transfer coefficients:

$$\alpha_g = 5 \text{ W/(m}^2 \text{ K)}$$

$$\alpha_a / \alpha_g = 10$$

$$\dot{V}_N = \frac{\alpha_G A T_0 - T_A}{\rho_G c_G T_0}$$

$$\dot{V}_N = \frac{5 \cdot 138.23}{1.093 \cdot 1.01} \cdot \frac{328 - 288}{328} = 274.90 \text{ m}^3/\text{h}$$

- Calculation of the reduction factor η :

Fullarton considers that $\theta_{\max} = 0.85$ is a valid value, without providing any further clarification or explanation regarding this specific choice.

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + \alpha_G / \alpha_A (C + 1)} \theta_{\max}$$

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + 0.1(18.35 + 1)} \cdot 0.85 = 0.341$$

- Calculation of condensation factor χ :

$$K = 1 + \frac{\alpha_{G,wet}}{\alpha_G}$$

$$K = 1 + 5.21 = 6.21$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_0 \right) \left(\frac{p_{\text{air}} c_{\text{air}}}{p_G c_G} \right) \left[\frac{1 + \alpha_G / \alpha_A (C + 1)}{1 + \alpha_G / \alpha_A (C + K)} \right]$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{0.87} \cdot 0.0140177 \cdot 328 \right) \left(\frac{1.093 \cdot 1.01}{1.132 \cdot 1.147} \right) \left[\frac{1 + 0.1(18.35 + 1)}{1 + 0.1(18.35 + 6.21)} \right] = 2.75$$

- Calculation of the volumetric flow rate:

$$\dot{V}_{K,\max} = \dot{V}_N \cdot \eta \cdot \chi$$

$$\dot{V}_{K,\max} = 274.90 \cdot 0.341 \cdot 2.75 = 258 \text{ m}^3/\text{h}$$

This air flow at 50 °C must be converted to normal conditions units:

$$\dot{V}_{N,gas} = \dot{V}_{B,gas} \cdot \frac{T_N \cdot P_B}{T_B \cdot P_N} = \dot{V}_{B,gas} \cdot \frac{273.15 \cdot P_B}{T_B \cdot 1.013}$$

$$\dot{V}_{N,gas} = 258 \cdot \frac{273.15 \cdot 1.013}{323 \cdot 1.013} = 218 \text{ Nm}^3/\text{h}$$

11.1.3 Hexane case

11.1.3.1 API 2000

The procedure for calculating the required normal and emergency venting is shown in section 4.1.

- Normal venting Flow rates:

First of all, the total outbreathing flow rate is calculated:

The outbreathing flow rate due to pump-in, in this case, corresponds to equation (2) since hexane has a vapor pressure higher than 50 mbara.

$$\dot{V}_{op} = 2 \cdot 25 = 50 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{OT} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{out} = 25 + 25 = 75 \text{ Nm}^3/\text{h}$$

For the required inbreathing:

The inbreathing flow rate due to pump-out corresponds directly to the tank discharge flow rate.

$$\dot{V}_{ip} = 25 \text{ Nm}^3/\text{h}$$

The inbreathing flow rate due to thermal effects, in this case, the factor "C" has a value of 6.5 since the tank's latitude is below 42°C, the vapor pressure of the product is below 50 mbarg, and the operating temperature is 25 °C. Additionally, since it's a non-insulated tank, the reduction factor is 1.

$$\dot{V}_{IT} = 6.5 \cdot 1 \cdot 125.67^{0.7} = 192 \text{ Nm}^3/\text{h}$$

The total inbreathing flow rate corresponds to the sum of the effects of discharging out the tank and the thermal effects due to cooling of the tank.

$$\dot{V}_{IT} = 25 + 192 = 217 \text{ Nm}^3/\text{h}$$

To calculate the emergency flow rate due to the fire case:

First, it is necessary to determine the wetted area of the tank. In this case, since the tank height of 10 m exceeds 9.14 m, it is considered that the maximum height is 9.14 m.

$$A_{TWS} = 9.14 \cdot 4 \cdot \pi^2 = 114.86 \text{ m}^2$$

From table 4.1.3., the value of Q can be determined using the following expression:

$$Q = 630400(114.86^{0.338}) = 3132917 \text{ W}$$

Finally, the required flow rate for the external fire case is:

$$q = 906.6 \cdot \frac{3132917 \cdot 1}{335000} \left(\frac{273 + 69}{86.2} \right)^{0.5} = 16892 \text{ Nm}^3/\text{h}$$

11.1.3.2 API 2000 Annex A

The procedure for calculating the required normal venting is shown in section 4.2.

Hexane has a flash point of -22 °C, therefore, applying the table 4.2.1. from this thesis, the following required pump-in and pump-out flow rates are obtained.

$$\dot{V}_{ip} = 25 \cdot 0.94 = 23.5 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{op} = 25 \cdot 2.02 = 50.5 \text{ Nm}^3/\text{h}$$

For the part of the required flow rates due to thermal effects, based on table 4.2.2. from this thesis, these flow rates can be determined. Interpolation between the values in the table is allowed with a tank volume of 125.67 m³.

$$\dot{V}_{OT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

Finally, the total required outbreathing and inbreathing flow rates correspond to:

$$\dot{V}_{out} = 50.5 + 21.24 = 72 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 23.5 + 21.24 = 45 \text{ Nm}^3/\text{h}$$

For the required emergency flow rate, the API 2000 main body methodology is used.

11.1.3.3 ISO 28300

The procedure for calculating the required normal venting is shown in section 4.3.

In this case, since hexane has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. In this case, the evaporation rate of hexane is 1.8. [19].

$$\dot{V}_{op} = 1.8 \cdot 25 = 45 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{OT} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{out} = 45 + 25 = 70 \text{ Nm}^3/\text{h}$$

Therefore, the same equations and calculation methodology as in API 2000 are used for rest of normal and emergency venting flow rates.

11.1.3.4 EN 14015

The procedure for calculating the required normal venting is shown in section 4.4.

In this case, since hexane has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. The same calculation of ISO 28300 is performed.

Therefore, the same equations and calculation methodology as in API 2000 are used for both normal venting flow rates. Additionally, in equations (14, 16), a reduction factor of 1 is considered.

On the other hand, to determine the required flow rate for the emergency case, the following expression is followed:

$$U_{FB} = 4 \cdot 10^4 \cdot 114.86^{0.82} \cdot \frac{1}{335} \sqrt{\frac{273 + 69}{86.2}} = 11634 \text{ Nm}^3/\text{h}$$

11.1.3.5 TRGS 509

The procedure for calculating the required normal venting is shown in section 4.5.

The TRGS 509 does not provide any guidance on how to consider the tank filling and emptying flow rates. As for the required flow rate due to thermal effects, the following equations are used.

- Total outbreathing:

$$\dot{V}_E = 0.17 \cdot \left(\frac{10}{4}\right)^{-0.52} \cdot 125.67^{0.89} = 7.8 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{out}} = \dot{V}_E + \dot{V}_{\text{pump-in}} = 7.8 + 25 = 33 \text{ Nm}^3/\text{h}$$

-Total inbreathing:

$$\dot{V}_A = 4.8 \cdot 125.67^{0.71} = 148.49 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{in}} = \dot{V}_A + \dot{V}_{\text{pump-out}} = 148.49 + 25 = 174 \text{ Nm}^3/\text{h}$$

TRGS 509 does not provide equations for calculating the required emergency flow rate.

11.1.3.6 Fullarton Simplified Method

The Fullarton method is shown in section 6.1.

Fullarton considers the tank to be filled with hexane phase gas, with a negligible amount of liquid.

The temperature of the wall at the beginning of the sudden rain is 55 °C, with 15 °C being the temperature of the rain.

The tank has a capacity of 125.67 m³ and exposure area of 138.23 m².

- Gas composition:

Fullarton takes 50 °C as a reference temperature because it considers that this is where the maximum air intake occurs.

The vapor pressure of hexane at 50 °C is 527 mbara; value extracted from ASPEN HYSYS V14.

The gas compositions inside the tank correspond to:

$$y_{molar,hexane} = \frac{527}{1013} = 0.52$$

$$y_{molar,air} = 1 - 0.52 = 0.48$$

To know the mass composition, the molecular weights must be taken into account:

$$y_{mass,hexane} = 0.52 \cdot 86.2 = 44.85 \text{ g hexane} = \frac{44.85}{30.6 + 44.85} = 0.76$$

$$y_{mass,air} = 0.48 \cdot 28.96 = 13.90 \text{ g air} = \frac{13.90}{13.90 + 30.6} = 0.24$$

- Physical properties of gas:

Air density at 50 °C (normal conditions 1.293 kg/m³):

$$\rho_{air} = 1.293 \cdot \left(\frac{273}{273 + 50} \right) = 1.093 \text{ kg/m}^3$$

Density of hexane at 50 °C:

$$\rho_{hexane} = \left(\frac{P \cdot PM}{0.082 \cdot T} \right) = \left(\frac{1 \cdot 86.2}{0.082 \cdot (273 + 50)} \right) = 3.26 \text{ kg/m}^3$$

Density of the mixture:

$$\rho_{mixture} = \left(\frac{1}{(0.24/1.093) + (0.76/3.26)} \right) = 2.22 \text{ kg/m}^3$$

Mass heat capacity:

The value for air at 50 °C corresponds to 1.01 kJ/(kg K), while for hexane it is 1.77 kJ/(kg·K). Values extracted from ASPEN HYSYS V14.

$$Cp_{mixture} = 0.76 \cdot 1.77 + 0.24 \cdot 1.01 = 1.590 \text{ kJ/(kg} \cdot \text{K)}$$

Mass heat of vaporization:

The mass heat of vaporization value is 347 kJ/kg at 50 °C. Value extracted from ASPEN HYSYS V14.

- Lewis Number:

The thermal conductivity of hexane at 50 °C is 0.01915 W/(m·K). The thermal conductivity and diffusion coefficient values are extracted from ASPEN HYSYS V14.

$$Le = \lambda_G / \rho_G c_G \delta_G = 0.4723$$

$$Le^{0.66} = 0.4723^{0.66} = 0.61$$

- Calculation of the factor $\left(\frac{1}{p_G} \frac{dp^*}{dT}\right)$:

Since the tangent is the derivative at this point 50 °C, if the vapor pressure at 51 °C and 49 °C are considered as an interval:

The vapor pressure of hexane at 49 °C corresponds to 0.5085 bar.

The vapor pressure of hexane at 51 °C corresponds to 0.5468 bar.

$$tg_{\alpha} = \frac{0.5468 - 0.5085}{2} = 0.01915$$

$$Factor \frac{1}{p_G} \frac{dp^*}{dT} = \frac{1}{1.013} \cdot 0.01915 = 0.018904 K^{-1}$$

- Calculation of the capacity ratio:

The tank walls are made of steel with a thickness of 5 mm. The steel density is 7850 kg/m³ and the mass heat capacity is 0.469 kJ/(kg·K).

$$C = \frac{\rho_w c_w s_w}{\rho_G c_G} \cdot \frac{1 + 4H/D}{H}$$

$$C = \frac{7850 \cdot 0.005 \cdot 0.469}{1.01 \cdot 1.093} \cdot \frac{1 + 4 \cdot 10/4}{10} = 18.35$$

- Calculation of $\frac{\alpha_{g,wet}}{\alpha_g}$:

$$\frac{\alpha_{g,wet}}{\alpha_g} = \frac{347}{1.509} \cdot 0.018904 \cdot \frac{1}{0.61} = 6.77$$

- Calculation of the maximum condensation volume:

Fullarton considers the following heat transfer coefficients:

$$\alpha_g = 5 \text{ W/(m}^2 \text{ K)}$$

$$\alpha_a / \alpha_g = 10$$

$$\dot{V}_N = \frac{\alpha_G A}{\rho_G c_G} \frac{T_0 - T_A}{T_0}$$

$$\dot{V}_N = \frac{5 \cdot 138.23}{1.093 \cdot 1.01} \cdot \frac{328 - 288}{328} = 274.90 \text{ m}^3/h$$

- Calculation of the reduction factor η :

Fullarton considers that $\theta_{max} = 0.85$ is a valid value, without providing any further clarification or explanation regarding this specific choice.

$$\eta = \frac{\dot{V}_{max}}{\dot{V}_N} = \frac{1}{1 + \alpha_G / \alpha_A (C + 1)} \theta_{max}$$

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + 0.1(18.35 + 1)} \cdot 0.85 = 0.341$$

- Calculation of condensation factor χ :

$$K = 1 + \frac{\alpha_{G,\text{wet}}}{\alpha_G}$$

$$K = 1 + 6.77 = 7.77$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_0\right) \left(\frac{p_{\text{air}} c_{\text{air}}}{p_G c_G}\right) \left[\frac{1 + \alpha_G/\alpha_A(C + 1)}{1 + \alpha_G/\alpha_A(C + K)}\right]$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{0.61} \cdot 0.018904 \cdot 328\right) \left(\frac{1.093 \cdot 1.01}{2.22 \cdot 1.590}\right) \left[\frac{1 + 0.1(18.35 + 1)}{1 + 0.1(18.35 + 7.77)}\right] = 2.84$$

- Calculation of the volumetric flow rate:

$$\dot{V}_{K,\max} = \dot{V}_N \cdot \eta \cdot \chi$$

$$\dot{V}_{K,\max} = 274.90 \cdot 0.341 \cdot 2.84 = 267 \text{ m}^3/\text{h}$$

This air flow at 50 °C must be converted to normal conditions units:

$$\dot{V}_{N,\text{gas}} = \dot{V}_{B,\text{gas}} \cdot \frac{T_N \cdot P_B}{T_B \cdot P_N} = \dot{V}_{B,\text{gas}} \cdot \frac{273.15 \cdot P_B}{T_B \cdot 1.013}$$

$$\dot{V}_{N,\text{gas}} = 267 \cdot \frac{273.15 \cdot 1.013}{323 \cdot 1.013} = 225 \text{ Nm}^3/\text{h}$$

11.1.4 Ethanol case

11.1.4.1 API 2000

The procedure for calculating the required normal and emergency venting is shown in section 4.1.

- Normal venting Flow rates:

First of all, the total outbreathing flow rate is calculated:

The outbreathing flow rate due to pump-in, in this case, corresponds to equation (2) since ethanol has a vapor pressure higher than 50 mbara.

$$\dot{V}_{\text{op}} = 2 \cdot 25 = 50 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{\text{OT}} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{\text{out}} = 25 + 25 = 50 \text{ Nm}^3/\text{h}$$

For the required inbreathing:

The inbreathing flow rate due to pump-out corresponds directly to the tank discharge flow rate.

$$\dot{V}_{ip} = 25 \text{ Nm}^3/\text{h}$$

The inbreathing flow rate due to thermal effects, in this case, the factor "C" has a value of 6.5 since the tank's latitude is below 42°C, the vapor pressure of the product is below 50 mbarg, and the operating temperature is 25 °C. Additionally, since it's a non-insulated tank, the reduction factor is 1.

$$\dot{V}_{IT} = 6.5 \cdot 1 \cdot 125.67^{0.7} = 192 \text{ Nm}^3/\text{h}$$

The total inbreathing flow rate corresponds to the sum of the effects of discharging out the tank and the thermal effects due to cooling of the tank.

$$\dot{V}_{IT} = 25 + 192 = 217 \text{ Nm}^3/\text{h}$$

To calculate the emergency flow rate due to the fire case:

First, it is necessary to determine the wetted area of the tank. In this case, since the tank height of 10 m exceeds 9.14 m, it is considered that the maximum height is 9.14 m.

$$A_{TWS} = 9.14 \cdot 4 \cdot \pi^2 = 114.86 \text{ m}^2$$

From table 4.1.3., the value of Q can be determined using the following expression:

$$Q = 630400(114.86^{0.338}) = 3132917 \text{ W}$$

Finally, the required flow rate for the external fire case is:

$$q = 906.6 \cdot \frac{3132917 \cdot 1}{834200} \left(\frac{273 + 78.2}{46.1} \right)^{0.5} = 9403 \text{ Nm}^3/\text{h}$$

11.1.4.2 API 2000 Annex A

The procedure for calculating the required normal venting is shown in section 4.2.

Ethanol has a flash point of 12 °C, therefore, applying the table 4.2.1. from this thesis, the following required pump-in and pump-out flow rates are obtained.

$$\dot{V}_{ip} = 25 \cdot 0.94 = 23.5 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{op} = 25 \cdot 2.02 = 50.5 \text{ Nm}^3/\text{h}$$

For the part of the required flow rates due to thermal effects, based on table 4.2.2. from this thesis, these flow rates can be determined. Interpolation between the values in the table is allowed with a tank volume of 125.67 m³.

$$\dot{V}_{OT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

Finally, the total required outbreathing and inbreathing flow rates correspond to:

$$\dot{V}_{\text{out}} = 50.5 + 21.24 = 72 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{IT}} = 23.5 + 21.24 = 45 \text{ Nm}^3/\text{h}$$

For the required emergency flow rate, the API 2000 main body methodology is used.

11.1.4.3 ISO 28300

The procedure for calculating the required normal venting is shown in section 4.3.

In this case, since ethanol has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. In this case, the evaporation rate of ethanol is 1.4. [19].

$$\dot{V}_{\text{op}} = 1.4 \cdot 25 = 35 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{\text{OT}} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{\text{out}} = 35 + 25 = 60 \text{ Nm}^3/\text{h}$$

Therefore, the same equations and calculation methodology as in API 2000 are used for rest of normal and emergency venting flow rates.

11.1.4.4 EN 14015

The procedure for calculating the required normal venting is shown in section 4.4.

In this case, since ethanol has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. The same calculation of ISO 28300 is performed.

Therefore, the same equations and calculation methodology as in API 2000 are used for both normal venting flow rates. Additionally, in equations (14, 16), a reduction factor of 1 is considered.

On the other hand, to determine the required flow rate for the emergency case, the following expression is followed:

$$U_{\text{FB}} = 4 \cdot 10^4 \cdot 114.86^{0.82} \cdot \frac{1}{834.2} \sqrt{\frac{273 + 78.2}{46.1}} = 6476 \text{ Nm}^3/\text{h}$$

11.1.4.5 TRGS 509

The procedure for calculating the required normal venting is shown in section 4.5.

The TRGS 509 does not provide any guidance on how to consider the tank filling and emptying flow rates. As for the required flow rate due to thermal effects, the following equations are used.

- Total outbreathing:

$$\dot{V}_E = 0.17 \cdot \left(\frac{10}{4}\right)^{-0.52} \cdot 125.67^{0.89} = 7.8 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{out}} = \dot{V}_E + \dot{V}_{\text{pump-in}} = 7.8 + 25 = 33 \text{ Nm}^3/\text{h}$$

-Total inbreathing:

$$\dot{V}_A = 4.8 \cdot 125.67^{0.71} = 148.49 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{in}} = \dot{V}_A + \dot{V}_{\text{pump-out}} = 148.49 + 25 = 174 \text{ Nm}^3/\text{h}$$

TRGS 509 does not provide equations for calculating the required emergency flow rate.

11.1.4.6 Fullarton Simplified Method

The Fullarton method is shown in section 6.1.

Fullarton considers the tank to be filled with ethanol phase gas, with a negligible amount of liquid.

The temperature of the wall at the beginning of the sudden rain is 55 °C, with 15 °C being the temperature of the rain.

The tank has a capacity of 125.67 m³ and exposure area of 138.23 m².

- Gas composition:

Fullarton takes 50 °C as a reference temperature because it considers that this is where the maximum air intake occurs.

The vapor pressure of ethanol at 50 °C is 294 mbara; value extracted from ASPEN HYSYS V14.

The gas compositions inside the tank correspond to:

$$y_{\text{molar,ethanol}} = \frac{294}{1013} = 0.29$$

$$y_{\text{molar,air}} = 1 - 0.29 = 0.71$$

To know the mass composition, the molecular weights must be taken into account:

$$y_{\text{mass,ethanol}} = 0.29 \cdot 46.1 = 13.37 \text{ g ethanol} = \frac{13.37}{13.37 + 20.56} = 0.39$$

$$y_{\text{mass,air}} = 0.71 \cdot 28.96 = 20.56 \text{ g air} = \frac{20.56}{13.90 + 20.56} = 0.61$$

- Physical properties of gas:

Air density at 50 °C (normal conditions 1.293 kg/m³):

$$\rho_{\text{air}} = 1.293 \cdot \left(\frac{273}{273 + 50}\right) = 1.093 \text{ kg/m}^3$$

Density of ethanol at 50 °C:

$$\rho_{ethanol} = \left(\frac{P \cdot PM}{0.082 \cdot T} \right) = \left(\frac{1 \cdot 46.2}{0.082 \cdot (273 + 50)} \right) = 1.74 \text{ kg/m}^3$$

Density of the mixture:

$$\rho_{mixture} = \left(\frac{1}{(0.61/1.093) + (0.39/1.74)} \right) = 1.28 \text{ kg/m}^3$$

Mass heat capacity:

The value for air at 50 °C corresponds to 1.01 kJ/(kg K), while for ethanol it is 1.51 kJ/(kg·K). Values extracted from ASPEN HYSYS V14.

$$Cp_{mixture} = 0.39 \cdot 1.51 + 0.61 \cdot 1.01 = 1.207 \text{ kJ/(kg} \cdot \text{K)}$$

Mass heat of vaporization:

The mass heat of vaporization value is 892 kJ/kg at 50 °C. Value extracted from ASPEN HYSYS V14.

- Lewis Number:

The thermal conductivity of ethanol at 50 °C is 0.0225 W/(m·K). The thermal conductivity and diffusion coefficient values are extracted from ASPEN HYSYS V14.

$$Le = \lambda_G / \rho_G c_G \delta_G = 1.2659$$

$$Le^{0.66} = 1.2659^{0.66} = 1.17$$

- Calculation of the factor $\left(\frac{1}{p_G} \frac{dp^*}{dT} \right)$:

Since the tangent is the derivative at this point 50 °C, if the vapor pressure at 51 °C and 49 °C are considered as an interval:

The vapor pressure of ethanol at 49 °C corresponds to 0.2804 bar.

The vapor pressure of ethanol at 51 °C corresponds to 0.3087 bar.

$$tg_{\alpha} = \frac{0.3087 - 0.2804}{2} = 0.01415$$

$$Factor \frac{1}{p_G} \frac{dp^*}{dT} = \frac{1}{1.013} \cdot 0.01415 = 0.013968 \text{ K}^{-1}$$

- Calculation of the capacity ratio:

The tank walls are made of steel with a thickness of 5 mm. The steel density is 7850 kg/m³ and the mass heat capacity is 0.469 kJ/(kg·K).

$$C = \frac{\rho_w c_w s_w}{\rho_G c_G} \cdot \frac{1 + 4H/D}{H}$$

$$C = \frac{7850 \cdot 0.005 \cdot 0.469}{1.01 \cdot 1.093} \cdot \frac{1 + 4 \cdot 10/4}{10} = 18.35$$

- Calculation of $\frac{\alpha_{g,wet}}{\alpha_g}$:

$$\frac{\alpha_{g,wet}}{\alpha_g} = \frac{892}{1.207} \cdot 0.013968 \cdot \frac{1}{1.17} = 8.83$$

- Calculation of the maximum condensation volume:

Fullarton considers the following heat transfer coefficients:

$$\alpha_g = 5 \text{ W/(m}^2 \text{ K)}$$

$$\alpha_a/\alpha_g = 10$$

$$\dot{V}_N = \frac{\alpha_G A T_0 - T_A}{\rho_G c_G T_0}$$

$$\dot{V}_N = \frac{5 \cdot 138.23}{1.093 \cdot 1.01} \cdot \frac{328 - 288}{328} = 274.90 \text{ m}^3/\text{h}$$

- Calculation of the reduction factor η :

Fullarton considers that $\theta_{\max} = 0.85$ is a valid value, without providing any further clarification or explanation regarding this specific choice.

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + \alpha_G/\alpha_A(C + 1)} \theta_{\max}$$

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + 0.1(18.35 + 1)} \cdot 0.85 = 0.341$$

- Calculation of condensation factor χ :

$$K = 1 + \frac{\alpha_{G,wet}}{\alpha_G}$$

$$K = 1 + 8.83 = 9.83$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_0\right) \left(\frac{p_{\text{air}} c_{\text{air}}}{p_G c_G}\right) \left[\frac{1 + \alpha_G/\alpha_A(C + 1)}{1 + \alpha_G/\alpha_A(C + K)}\right]$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{1.17} \cdot 0.013968 \cdot 328\right) \left(\frac{1.093 \cdot 1.01}{1.28 \cdot 1.207}\right) \left[\frac{1 + 0.1(18.35 + 1)}{1 + 0.1(18.35 + 9.83)}\right] = 2.70$$

- Calculation of the volumetric flow rate:

$$\dot{V}_{K,\max} = \dot{V}_N \cdot \eta \cdot \chi$$

$$\dot{V}_{K,\max} = 274.90 \cdot 0.341 \cdot 2.70 = 253 \text{ m}^3/\text{h}$$

This air flow at 50 °C must be converted to normal conditions units:

$$\dot{V}_{N,gas} = \dot{V}_{B,gas} \cdot \frac{T_N \cdot P_B}{T_B \cdot P_N} = \dot{V}_{B,gas} \cdot \frac{273.15 \cdot P_B}{T_B \cdot 1.013}$$

$$\dot{V}_{N,gas} = 253 \cdot \frac{273.15 \cdot 1.013}{323 \cdot 1.013} = 214 \text{ Nm}^3/\text{h}$$

11.1.5 Methanol case

11.1.5.1 API 2000

The procedure for calculating the required normal and emergency venting is shown in section 4.1.

- Normal venting Flow rates:

First of all, the total outbreathing flow rate is calculated:

The outbreathing flow rate due to pump-in, in this case, corresponds to equation (2) since methanol has a vapor pressure higher than 50 mbara.

$$\dot{V}_{op} = 2 \cdot 25 = 50 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{OT} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{out} = 25 + 25 = 75 \text{ Nm}^3/\text{h}$$

For the required inbreathing:

The inbreathing flow rate due to pump-out corresponds directly to the tank discharge flow rate.

$$\dot{V}_{ip} = 25 \text{ Nm}^3/\text{h}$$

The inbreathing flow rate due to thermal effects, in this case, the factor "C" has a value of 6.5 since the tank's latitude is below 42°C, the vapor pressure of the product is below 50 mbarg, and the operating temperature is 25 °C. Additionally, since it's a non-insulated tank, the reduction factor is 1.

$$\dot{V}_{IT} = 6.5 \cdot 1 \cdot 125.67^{0.7} = 192 \text{ Nm}^3/\text{h}$$

The total inbreathing flow rate corresponds to the sum of the effects of discharging out the tank and the thermal effects due to cooling of the tank.

$$\dot{V}_{IT} = 25 + 192 = 217 \text{ Nm}^3/\text{h}$$

To calculate the emergency flow rate due to the fire case:

First, it is necessary to determine the wetted area of the tank. In this case, since the tank height of 10 m exceeds 9.14 m, it is considered that the maximum height is 9.14 m.

$$A_{TWS} = 9.14 \cdot 4 \cdot \pi^2 = 114.86 \text{ m}^2$$

From table 4.1.3., the value of Q can be determined using the following expression:

$$Q = 630400(114.86^{0.338}) = 3132917 \text{ W}$$

Finally, the required flow rate for the external fire case is:

$$q = 906.6 \cdot \frac{3132917 \cdot 1}{1100000} \left(\frac{273 + 64.5}{32} \right)^{0.5} = 8383 \text{ Nm}^3/\text{h}$$

11.1.5.2 API 2000 Annex A

The procedure for calculating the required normal venting is shown in section 4.2.

Methanol has a flash point of 9 °C, therefore, applying the table 4.2.1. from this thesis, the following required pump-in and pump-out flow rates are obtained.

$$\dot{V}_{ip} = 25 \cdot 0.94 = 23.5 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{op} = 25 \cdot 2.02 = 50.5 \text{ Nm}^3/\text{h}$$

For the part of the required flow rates due to thermal effects, based on table 4.2.2. from this thesis, these flow rates can be determined. Interpolation between the values in the table is allowed with a tank volume of 125.67 m³.

$$\dot{V}_{OT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 125.67 + \left(\frac{(125.67 - 100)}{(200 - 100)} \cdot (33.8 - 16.9) \right) = 21.24 \text{ Nm}^3/\text{h}$$

Finally, the total required outbreathing and inbreathing flow rates correspond to:

$$\dot{V}_{out} = 50.5 + 21.24 = 72 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{IT} = 23.5 + 21.24 = 45 \text{ Nm}^3/\text{h}$$

For the required emergency flow rate, the API 2000 main body methodology is used.

11.1.5.3 ISO 28300

The procedure for calculating the required normal venting is shown in section 4.3.

In this case, since methanol has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. In this case, the evaporation rate of methanol is 3. [19].

$$\dot{V}_{op} = 3 \cdot 25 = 75 \text{ Nm}^3/\text{h}$$

The outbreathing flow rate due to thermal effects, in this case, the value of the latitude factor Y corresponds to 0.32, as the site where the tanks are located is Tarragona. The latitude of Tarragona is 41°7'. Additionally, the tank has no insulation, so the reduction factor is 1.

$$\dot{V}_{OT} = 0.32 \cdot 1 \cdot 125.67^{0.9} = 25 \text{ Nm}^3/\text{h}$$

The total outbreathing flow rate corresponds to the sum of the effects of tank filling and the thermal effects due to tank heating.

$$\dot{V}_{out} = 75 + 25 = 100 \text{ Nm}^3/\text{h}$$

Therefore, the same equations and calculation methodology as in API 2000 are used for rest of normal and emergency venting flow rates.

11.1.5.4 EN 14015

The procedure for calculating the required normal venting is shown in section 4.4.

In this case, since methanol has a vapor pressure higher than 50 mbara, the evaporation ratio factor is applied. The same calculation of ISO 28300 is performed.

Therefore, the same equations and calculation methodology as in API 2000 are used for both normal venting flow rates. Additionally, in equations (14, 16), a reduction factor of 1 is considered.

On the other hand, to determine the required flow rate for the emergency case, the following expression is followed:

$$U_{FB} = 4 \cdot 10^4 \cdot 114.86^{0.82} \cdot \frac{1}{1100} \sqrt{\frac{273 + 64.5}{32}} = 5773 \text{ Nm}^3/\text{h}$$

11.1.5.5 TRGS 509

The procedure for calculating the required normal venting is shown in section 4.5.

The TRGS 509 does not provide any guidance on how to consider the tank filling and emptying flow rates. As for the required flow rate due to thermal effects, the following equations are used.

- Total outbreathing:

$$\dot{V}_E = 0.17 \cdot \left(\frac{10}{4}\right)^{-0.52} \cdot 125.67^{0.89} = 7.8 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{out}} = \dot{V}_E + \dot{V}_{\text{pump-in}} = 7.8 + 25 = 33 \text{ Nm}^3/\text{h}$$

-Total inbreathing:

$$\dot{V}_A = 4.8 \cdot 125.67^{0.71} = 148.49 \text{ Nm}^3/\text{h}$$

$$\dot{V}_{\text{in}} = \dot{V}_A + \dot{V}_{\text{pump-out}} = 148.49 + 25 = 174 \text{ Nm}^3/\text{h}$$

TRGS 509 does not provide equations for calculating the required emergency flow rate.

11.1.5.6 Fullarton Simplified Method

The Fullarton method is shown in section 6.1.

Fullarton considers the tank to be filled with methanol phase gas, with a negligible amount of liquid.

The temperature of the wall at the beginning of the sudden rain is 55 °C, with 15 °C being the temperature of the rain.

The tank has a capacity of 125.67 m³ and exposure area of 138.23 m².

- Gas composition:

Fullarton takes 50 °C as a reference temperature because it considers that this is where the maximum air intake occurs.

The vapor pressure of methanol at 50 °C is 557 mbara; value extracted from ASPEN HYSYS V14.

The gas compositions inside the tank correspond to:

$$y_{molar, methanol} = \frac{557}{1013} = 0.55$$

$$y_{molar, air} = 1 - 0.55 = 0.45$$

To know the mass composition, the molecular weights must be taken into account:

$$y_{mass, methanol} = 0.55 \cdot 32 = 17.61 \text{ g methanol} = \frac{17.61}{17.61 + 13.04} = 0.58$$

$$y_{mass, air} = 0.45 \cdot 28.96 = 13.04 \text{ g air} = \frac{13.04}{13.04 + 17.61} = 0.42$$

- Physical properties of gas:

Air density at 50 °C (normal conditions 1.293 kg/m³):

$$\rho_{air} = 1.293 \cdot \left(\frac{273}{273 + 50} \right) = 1.093 \text{ kg/m}^3$$

Density of methanol at 50 °C:

$$\rho_{methanol} = \left(\frac{P \cdot PM}{0.082 \cdot T} \right) = \left(\frac{1 \cdot 32}{0.082 \cdot (273 + 50)} \right) = 1.21 \text{ kg/m}^3$$

Density of the mixture:

$$\rho_{mixture} = \left(\frac{1}{(0.42/1.093) + (0.58/1.21)} \right) = 1.16 \text{ kg/m}^3$$

Mass heat capacity:

The value for air at 50 °C corresponds to 1.01 kJ/(kg K), while for methanol it is 1.43 kJ/(kg·K). Values extracted from ASPEN HYSYS V14.

$$Cp_{mixture} = 0.58 \cdot 1.43 + 0.42 \cdot 1.01 = 1.25 \text{ kJ/(kg} \cdot \text{K)}$$

Mass heat of vaporization:

The mass heat of vaporization value is 1134 kJ/kg at 50 °C. Value extracted from ASPEN HYSYS V14.

- Lewis Number:

The thermal conductivity of methanol at 50 °C is 0.01987 W/(m·K). The thermal conductivity and diffusion coefficient values are extracted from ASPEN HYSYS V14.

$$Le = \lambda_G / \rho_G C_G \delta_G = 1.1933$$

$$Le^{0.66} = 1.1933^{0.66} = 1.12$$

- Calculation of the factor $\left(\frac{1}{p_G} \frac{dp^*}{dT}\right)$:

Since the tangent is the derivative at this point 50 °C, if the vapor pressure at 51 °C and 49 °C are considered as an interval:

The vapor pressure of methanol at 49 °C corresponds to 0.5332 bar.

The vapor pressure of methanol at 51 °C corresponds to 0.5815 bar.

$$tg_{\alpha} = \frac{0.5332 - 0.5815}{2} = 0.02415$$

$$Factor \frac{1}{p_G} \frac{dp^*}{dT} = \frac{1}{1.013} \cdot 0.02415 = 0.02384 K^{-1}$$

- Calculation of the capacity ratio:

The tank walls are made of steel with a thickness of 5 mm. The steel density is 7850 kg/m³ and the mass heat capacity is 0.469 kJ/(kg·K).

$$C = \frac{\rho_w c_w s_w}{\rho_G c_G} \cdot \frac{1 + 4H/D}{H}$$

$$C = \frac{7850 \cdot 0.005 \cdot 0.469}{1.01 \cdot 1.093} \cdot \frac{1 + 4 \cdot 10/4}{10} = 18.35$$

- Calculation of $\frac{\alpha_{g,wet}}{\alpha_g}$:

$$\frac{\alpha_{g,wet}}{\alpha_g} = \frac{1134}{1.25} \cdot 0.02384 \cdot \frac{1}{1.12} = 19.23$$

- Calculation of the maximum condensation volume:

Fullarton considers the following heat transfer coefficients:

$$\alpha_g = 5 \text{ W/(m}^2 \text{ K)}$$

$$\alpha_a / \alpha_g = 10$$

$$\dot{V}_N = \frac{\alpha_G A}{\rho_G c_G} \frac{T_0 - T_A}{T_0}$$

$$\dot{V}_N = \frac{5 \cdot 138.23}{1.093 \cdot 1.01} \cdot \frac{328 - 288}{328} = 274.90 \text{ m}^3/\text{h}$$

- Calculation of the reduction factor η :

Fullarton considers that $\theta_{max} = 0.85$ is a valid value, without providing any further clarification or explanation regarding this specific choice.

$$\eta = \frac{\dot{V}_{max}}{\dot{V}_N} = \frac{1}{1 + \alpha_G / \alpha_A (C + 1)} \theta_{max}$$

$$\eta = \frac{\dot{V}_{\max}}{\dot{V}_N} = \frac{1}{1 + 0.1(18.35 + 1)} \cdot 0.85 = 0.341$$

- Calculation of condensation factor χ :

$$K = 1 + \frac{\alpha_{G,\text{wet}}}{\alpha_G}$$

$$K = 1 + 19.23 = 20.23$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{Le^{0.66}} \frac{1}{p_G} \frac{dp^*}{dT} T_0\right) \left(\frac{p_{\text{air}} c_{\text{air}}}{p_G c_G}\right) \left[\frac{1 + \alpha_G/\alpha_A(C + 1)}{1 + \alpha_G/\alpha_A(C + K)}\right]$$

$$\chi = \frac{\dot{V}_{K,\max}}{\dot{V}_{\max}} = \left(1 + \frac{1}{1.12} \cdot 0.02384 \cdot 328\right) \left(\frac{1.093 \cdot 1.01}{1.16 \cdot 1.25}\right) \left[\frac{1 + 0.1(18.35 + 1)}{1 + 0.1(18.35 + 20.23)}\right] = 3.67$$

- Calculation of the volumetric flow rate:

$$\dot{V}_{K,\max} = \dot{V}_N \cdot \eta \cdot \chi$$

$$\dot{V}_{K,\max} = 274.90 \cdot 0.341 \cdot 3.67 = 344 \text{ m}^3/\text{h}$$

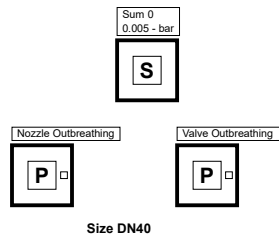
This air flow at 50 °C must be converted to normal conditions units:

$$\dot{V}_{N,\text{gas}} = \dot{V}_{B,\text{gas}} \cdot \frac{T_N \cdot P_B}{T_B \cdot P_N} = \dot{V}_{B,\text{gas}} \cdot \frac{273.15 \cdot P_B}{T_B \cdot 1.013}$$

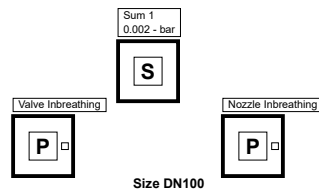
$$\dot{V}_{N,\text{gas}} = 344 \cdot \frac{273.15 \cdot 1.013}{323 \cdot 1.013} = 290 \text{ Nm}^3/\text{h}$$

11.2 Hydraulic calculations report and technical data sheet of PVRVs

In this annex section are included the different hydraulic calculations and technical data sheet of PVRVs.



The required outbreathing flowrate (pump in + thermal effect) is 50 Nm³/h



The required inbreathing flowrate (API2000 > Fullarton; 217 > 108) is 217 Nm³/h.

Acrylic Acid

Design Basis:

Upstream Valve:

- Pipeline = 2.5 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

Downstream Valve:

- Pipeline = 3 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

*For outbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

*For inbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Acrylic Acid Case)

Contract: Acrylic Acid Case
 Date: 8/9/2023
 By: _____ Chk'd: _____ App'd: _____
 Engineer: JLG
 Page 1 of 2

General										
Name		Valve Inbreathing		Nozzle Outbreathing		Nozzle Inbreathing		Valve Outbreathing		Sum 0
Line No.										
Process Conditions										
Mass Flow	kg/hr		280.7		64.6		280.4		64.6	
Std. Volume Flow	Nm³/hr		217.0		50.0		217.0		50.0	
Viscosity	cP		0.019		0.019		0.019		0.019	
Temperature	°C		25.0		25.0		25.0		25.0	
Molecular Weight			29.0		29.0		29.0		29.0	
Compressibility			1.00		1.00		1.00		1.00	
Cp/Cv			1.40		1.41		1.40			
Inlet-Outlet Conditions										
Density (In Out)	kg/m³	1.187	1.186	1.187	1.184	1.186	1.185	1.187	1.184	
Velocity (In Out)	m/s	0.00	7.30	0.00	10.39	7.29	7.29	10.36	10.39	
% Critical Flow - (In Out)	%	0.00	2.50	0.00	3.55	2.49	2.49	3.54	3.55	
Mach Number - (In Out)		0.00	0.02	0.00	0.03	0.02	0.02			
Velocity Head (In Out)	bar	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	
Dynamic Pressure (In Out)	barg	0.001	0.000	0.003	0.001	0.002	0.001	0.003	0.001	
Static Pressure (In Out)	barg	0.001	0.000	0.003	0.000	0.001	0.001	0.003	0.000	
Details										
Design Factor - Frictional Only	%		120.00		120.00		120.00		120.00	
Connect Effect	bar		0.000		0.000		0.000		0.000	0.000
Pipe Data										
Size (Nominal Schedule)	mm		User		User		User		User	
Inside Diameter	mm		107.100		43.100		107.100		43.100	
Length	m		3.0		2.5		2.5		3.0	
Roughness	mm		0.07000		0.07000		0.07000		0.07000	
Friction Factor - (Moody Fully Turbulent)		0.02312	0.01775	0.02764	0.02218	0.02313	0.01775	0.02762	0.02218	
Density (In Out)	kg/m³	1.186	1.186	1.186	1.184	1.186	1.185	1.187	1.184	
Velocity (In Out)	m/s	7.30	7.30	10.37	10.39	7.29	7.29	10.36	10.39	
Velocity Head (In Out)	bar	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.001	
Rho*v² (In Out)	kg/m-s²	63.2	63.2	127.5	127.7	63.0	63.1	127.4	127.7	
Reynold's No.			48,797		27,784		48,730		27,901	
% Critical Flow - (In Out)	%	2.50	2.50	3.54	3.55	2.49	2.49	3.54	3.55	
Mach Number - (In Out)		0.02	0.02	0.03	0.03	0.02	0.02			
Pressure Drop	bar/100-m		0.008		0.049		0.008		0.049	
Pipe Angle	°		-7.66		9.21		-9.21		7.66	
Elevation (In Out)	m	10.8	10.4	10.0	10.4	10.4	10.0	10.4	10.8	
Fittings										
45° Elbow (LR SR)	Qty									
90° Elbow (LR SR)	Qty	2		2		2		2		
180° Elbow (LR SR)	Qty									
Flanged Tee (Branch Run)	Qty									
Threaded Tee (Branch Run)	Qty									
Valve (Ball Gate)	Qty									
Valve (Globe Butterfly)	Qty									
Check Valve (Swing Lift)	Qty									
Control Valve CV	CV									
Additional K	K						1.0		1.0	
Crane X (K=X*ft)										
Additional Length	m									
Additional Drop	bar									
Inlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Entrance		Flush (Sharp Edged)		Flush (Sharp Edged)		(none)		(none)		
Outlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Exit		(none)		(none)		(none)		(none)		
Pressure Drops By Component										
Frictional	bar		0.001		0.002		0.001		0.003	0.005
Static Head	bar		0.000		0.000		0.000		0.000	0.000
Velocity Head	bar		0.000		0.001		0.000		0.000	0.001
Static Pressure Drops										
Pipe	bar		0.000		0.001		0.000		0.002	0.003
Fittings	bar		0.000		0.000		0.001		0.001	0.002
Inlet Effect	bar		0.000		0.001		0.000		0.000	0.001
Outlet Effect	bar		0.000		0.000		0.000		0.000	0.000
Total	bar		0.001		0.003		0.001		0.003	0.005

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY
 (Acrylic Acid Case)

Contract: Acrylic Acid Case
 Date: 8/9/2023
 By: _____ Chk'd: _____ App'd: _____
 Engineer: JLG
 Page 2 of 2

General					
Name		Sum 1			
Line No.					
Process Conditions					
Mass Flow	kg/hr				
Std. Volume Flow	Nm³/hr				
Viscosity	cP				
Temperature	°C				
Molecular Weight					
Compressibility					
Cp/Cv					
Inlet-Outlet Conditions					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Velocity Head (In Out)	bar				
Dynamic Pressure (In Out)	barg				
Static Pressure (In Out)	barg				
Details					
Design Factor - Frictional Only	%				
Connect Effect	bar	0.000			
Pipe Data					
Size (Nominal Schedule)	mm				
Inside Diameter	mm				
Length	m				
Roughness	mm				
Friction Factor - (Moody Fully Turbulent)					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
Velocity Head (In Out)	bar				
Rho*v² (In Out)	kg/m-s²				
Reynold's No.					
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Pressure Drop	bar/100-m				
Pipe Angle	°				
Elevation (In Out)	m				
Fittings					
45° Elbow (LR SR)	Qty				
90° Elbow (LR SR)	Qty				
180° Elbow (LR SR)	Qty				
Flanged Tee (Branch Run)	Qty				
Threaded Tee (Branch Run)	Qty				
Valve (Ball Gate)	Qty				
Valve (Globe Butterfly)	Qty				
Check Valve (Swing Lift)	Qty				
Control Valve CV	CV				
Additional K	K				
Crane X (K=X*ft)					
Additional Length	m				
Additional Drop	bar				
Inlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Entrance					
Outlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Exit					
Pressure Drops By Component					
Frictional	bar	0.001			
Static Head	bar	0.000			
Velocity Head	bar	0.000			
Static Pressure Drops					
Pipe	bar	0.000			
Fittings	bar	0.001			
Inlet Effect	bar	0.000			
Outlet Effect	bar	0.000			
Total	bar	0.002			

Sizing of a pressure relief valve PRV (high build-up back pressures)

ACRYLIC ACID

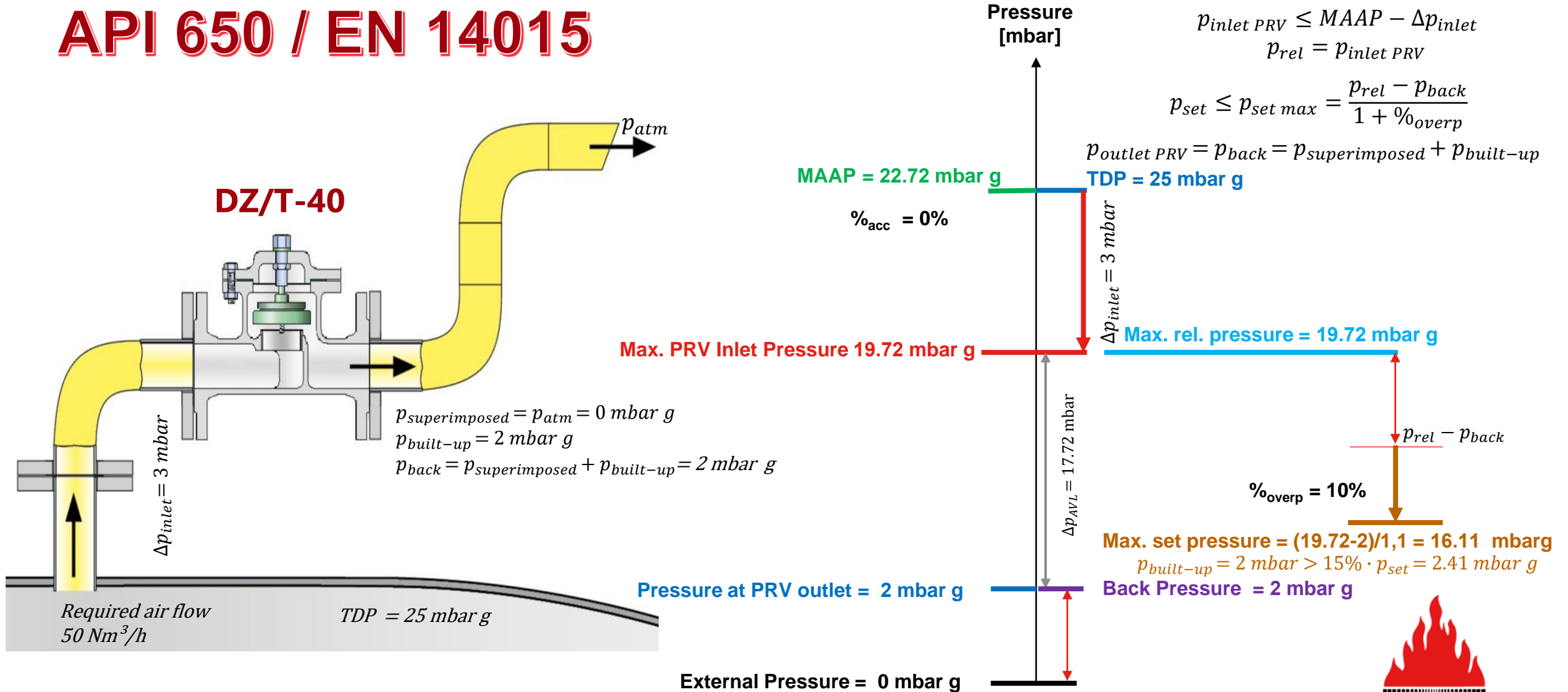
$$p_{built-up (gauge)} > 15\% \cdot p_{set (gauge)}$$

OR

$$\Delta p_{inlet} > 10\% \cdot p_{set (gauge)}$$

Approved for QuEST 3.0

API 650 / EN 14015

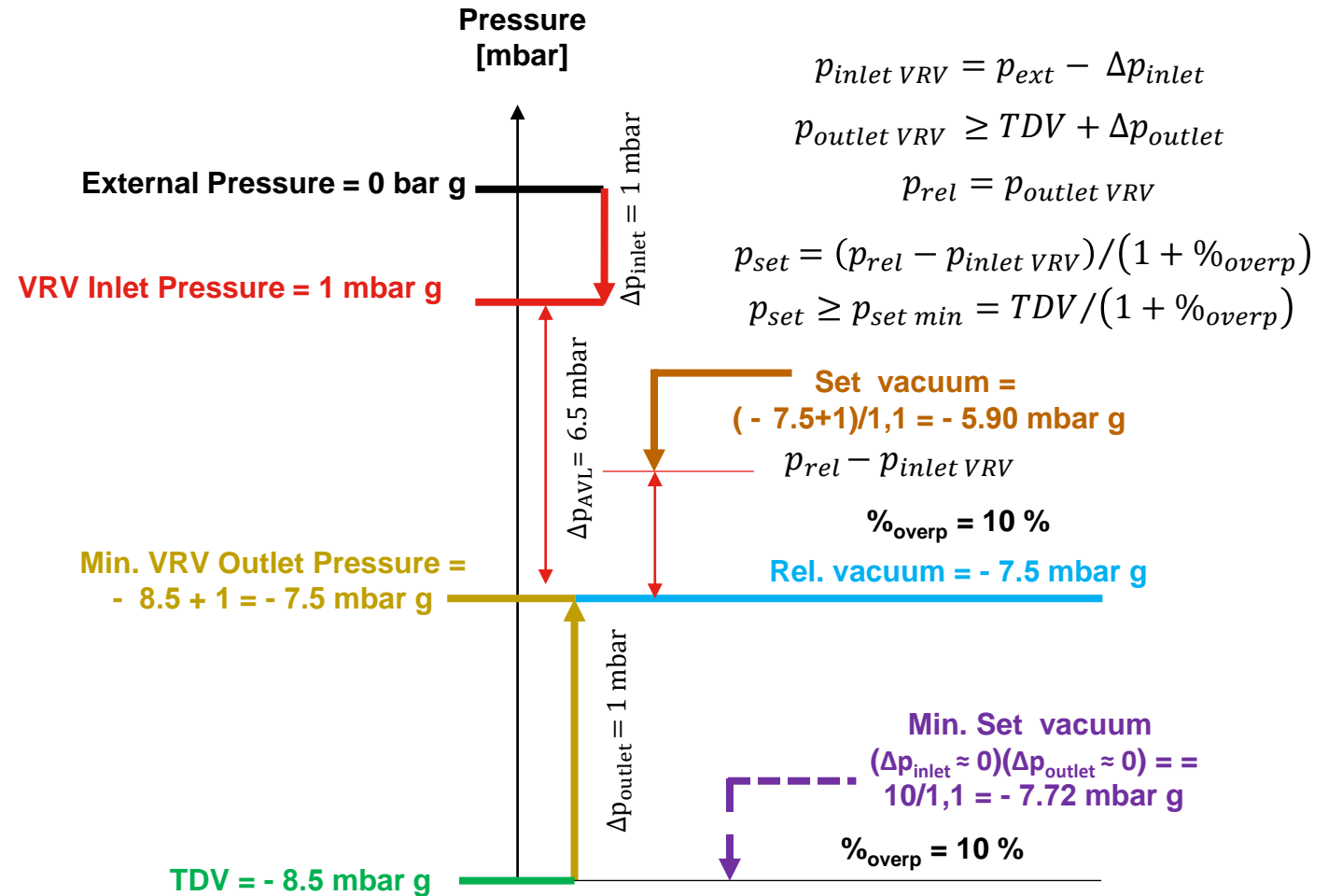
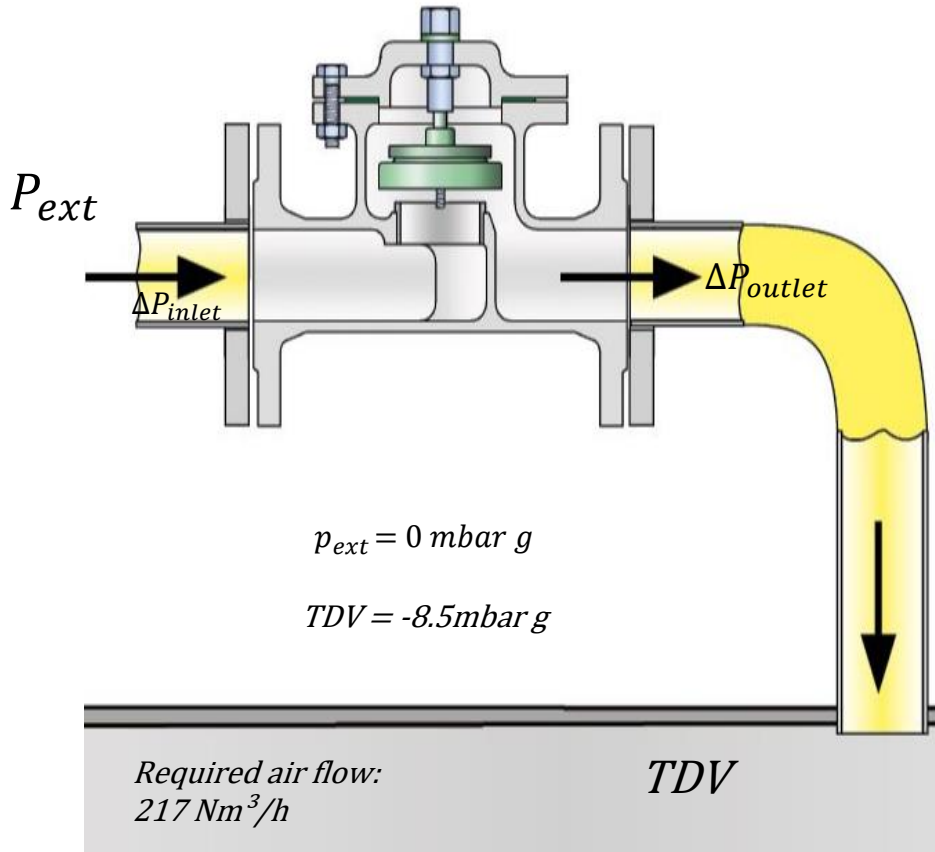


Sizing of a vacuum relief valve VRV

ACRYLIC ACID

Approved for QuEST 3.0

DZ/T-100





Project		API 2000 - TFM			
Revision	0.0	Tank location		TARRAGONA	
Atmospheric pressure	1013.25	mbar-a	Tank label		
Quotation number			Tank number		ACRYLIC ACID TANK
Job number			Job number by Customer		
Editor	Mr. Joel Lopez		Date		08/09/2023
Notes:					
Tank data					
Tank type	vertical, cylindrical		Height of elevation		0.0 m
Tank height	10.0	m	Tank diameter		4.0 m
Tank volume	125.7	m³	Tank Wetted Surface area ATWS		114.9 m²
Tank design pressure	25.0	mbar-g	Tank design vacuum		-8.5 mbar-g
Max. filling rate	25.0	m³/h	Max. rate of liquid discharge		25.0 m³/h
Product data for normal breathing					
Product	ACRYLIC ACID				
Molar mass	-		Explosion Group		-
C factor	6.50		Y factor		0.32
Operating temperature	25.0	°C	Vapor pressure ≤ 5.0 kPa (0.73 psi)		
Notes					
Product data for emergency breathing					
Product	Acrylic acid				
Molar mass	72.1	kg/kmol	Environmental factor		1.0
Boiling point / bubble point	141.0	°C	Latent heat		595.0 KJ/kg
Notes					
Device data					
Max. relieving pressure acc. to	API 650 12th Ed. (EN 14015)		Burn rating		not burning proof
Operating temperature	25.0	°C			



Venting calculation results			Outbreathing	Inbreathing
Normal venting capacity		m³/h	50	217
Load due to filling -in / out		m³/h	25	25
Thermal out- / inbreathing		m³/h	25	192
Emergency relief load		m³/h	11441	-
C factor	6.50		Y factor	0.32
Tank volume	125.7	m³	Tank Wetted Surface area ATWS	114.9 m²
Notes:				
Signatures and Stamps or Company logo:				

Loads are expressed in Air at Normal conditions (0.00 °C, 101.325 kPa-a)
 For the calculation herein the conservative assumption of a tank design pressure equal to the upper application range of API 2000 7th Ed. has been taken.

Venting calculation results converted into PROTEGO® diagram conditions			Outbreathing	Inbreathing
Normal venting capacity		m³/h	55	236
Emergency relief load		m³/h	12442	-

Loads are expressed in Air at PROTEGO® diagram conditions (20°C, 1 bar)



Device selection / Basic data			
Device		DZ/T-40	DZ/T-100
Manufacturer		Braunschweiger Flammenfilter GmbH	Braunschweiger Flammenfilter GmbH
Type of device		In-line device	In-line device
Inlet flange	DN	40	100
Outlet flange	DN	40	100
Nominal width NG		-	-
Function		Pressure or Vacuum Relief Valve	Pressure or Vacuum Relief Valve
Set pressure P	mbar-g	16.11	-
Set pressure V	mbar-g	-	-5.9
Relieving pressure minus back pressure (P)	mbar	17.73	-
Relieving pressure minus inlet pressure (V)	mbar	-	-6.49
Adjusted set pressure (P)	mbar-g	16.11	-
Adjusted set pressure (V)	mbar-g	-	-5.9
Overpressure P / V	%	10.0 / -	- / 10.0
Capacity air at normal condition P	m³/h	105	-
Capacity air at normal condition V	m³/h	-	255
Back pressure	mbar-g	2.0	-
Inlet line pressure loss (P)	mbar	3.0	-
External pressure	mbar	-	0.0
Pressure loss to VRV inlet	mbar	-	1.0
Pressure loss between VRV outlet and tank	mbar	-	1.0
Capacity as per PROTEGO® Diagramm (P)	m³/h	115	-
Capacity as per PROTEGO® Diagramm (V)	m³/h	-	277
Number of required devices		1	1
Excess capacity air at normal condition P	%	112.42	-
Excess capacity air at normal condition V	%	-	17.9
Notes: The pressure loss is considered.			
Signatures and Stamps or Company logo:			

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



Device selection / Basic data			
Device		ER/V-400	
Manufacturer		Braunschweiger Flammenfilter GmbH	
Type of device		End-of-line device	
Inlet flange	DN	400	
Outlet flange	DN	-	
Nominal width NG		-	
Function		Pressure Relief Valve	
Set pressure P	mbar-g	22.72	
Relieving pressure minus back pressure (P)	mbar	25.0	
Adjusted set pressure (P)	mbar-g	22.72	
Overpressure P / V	%	10.0 / -	
Capacity air at normal condition P	m³/h	11584	
Back pressure		-	
Inlet line pressure loss (P)	mbar	0.0	
Capacity as per PROTEGO® Diagramm (P)	m³/h	12597	
Number of required devices		1	
Excess capacity air at normal condition P	%	1.7	
Notes:			
Signatures and Stamps or Company logo:			

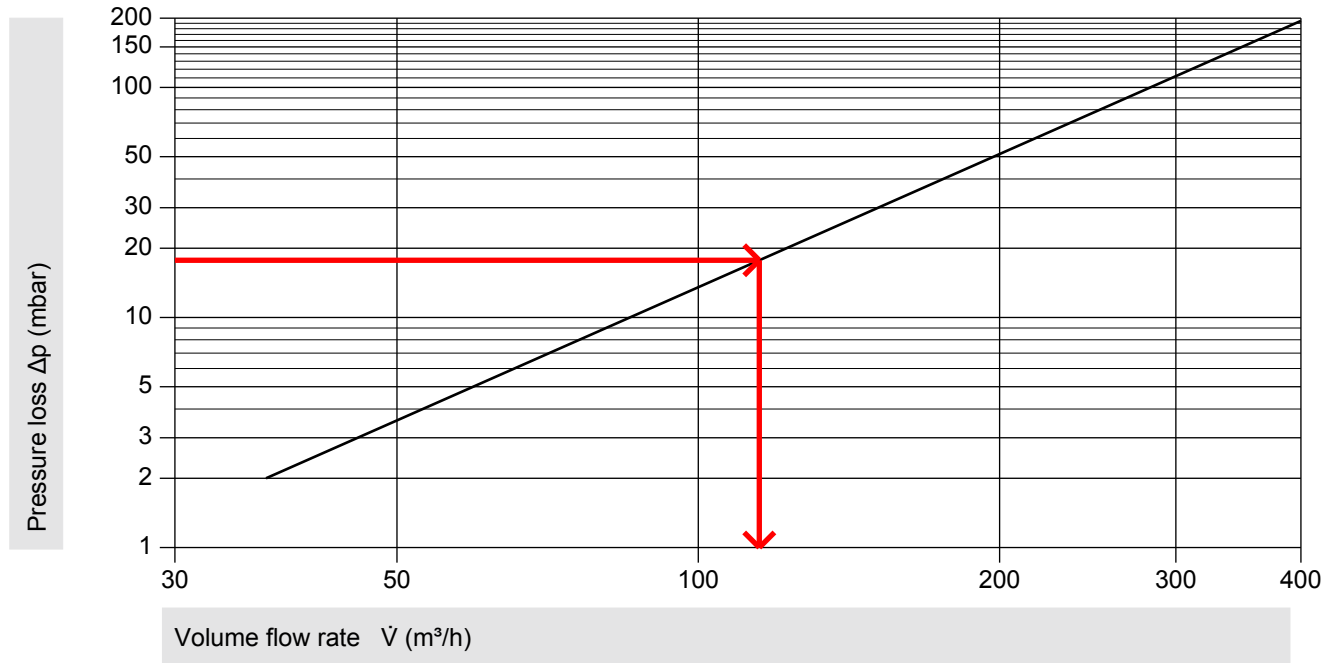
The required flow capacity for the emergency venting device is the difference between the emergency and the normal outbreathing requirement.

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



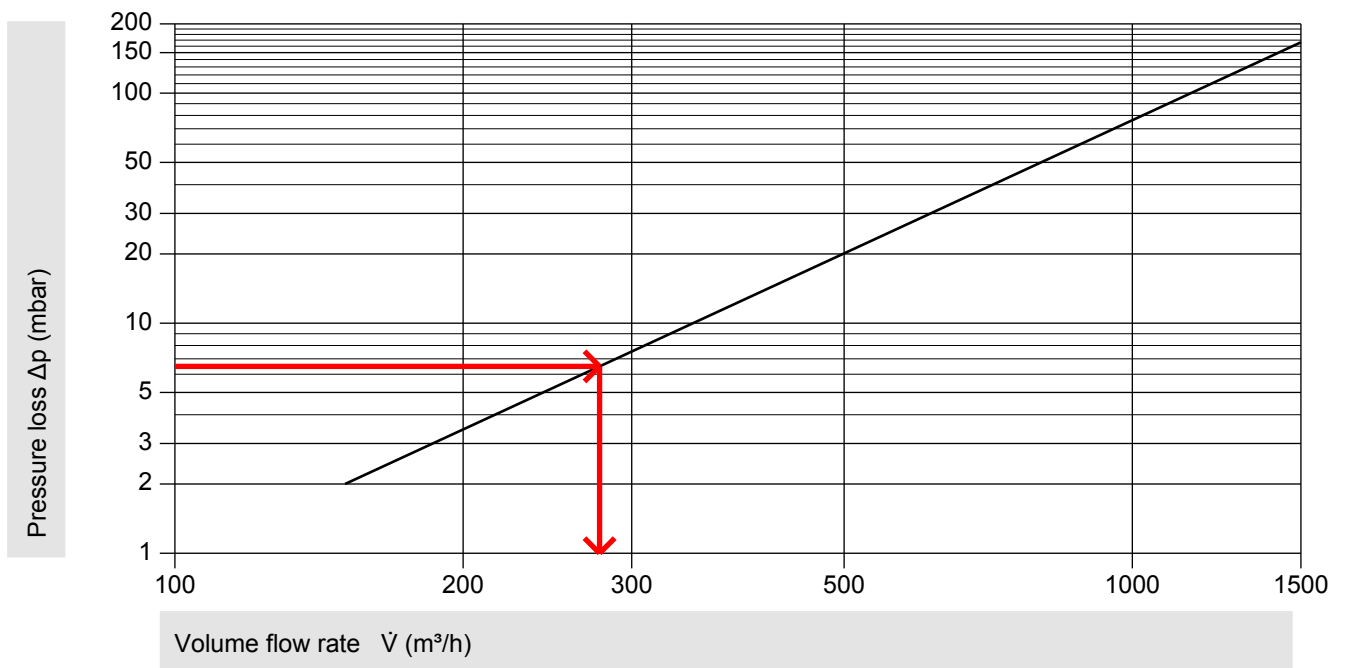
PROTEGO® capacity diagram

DZ/T-40, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

DZ/T-100, Vacuum

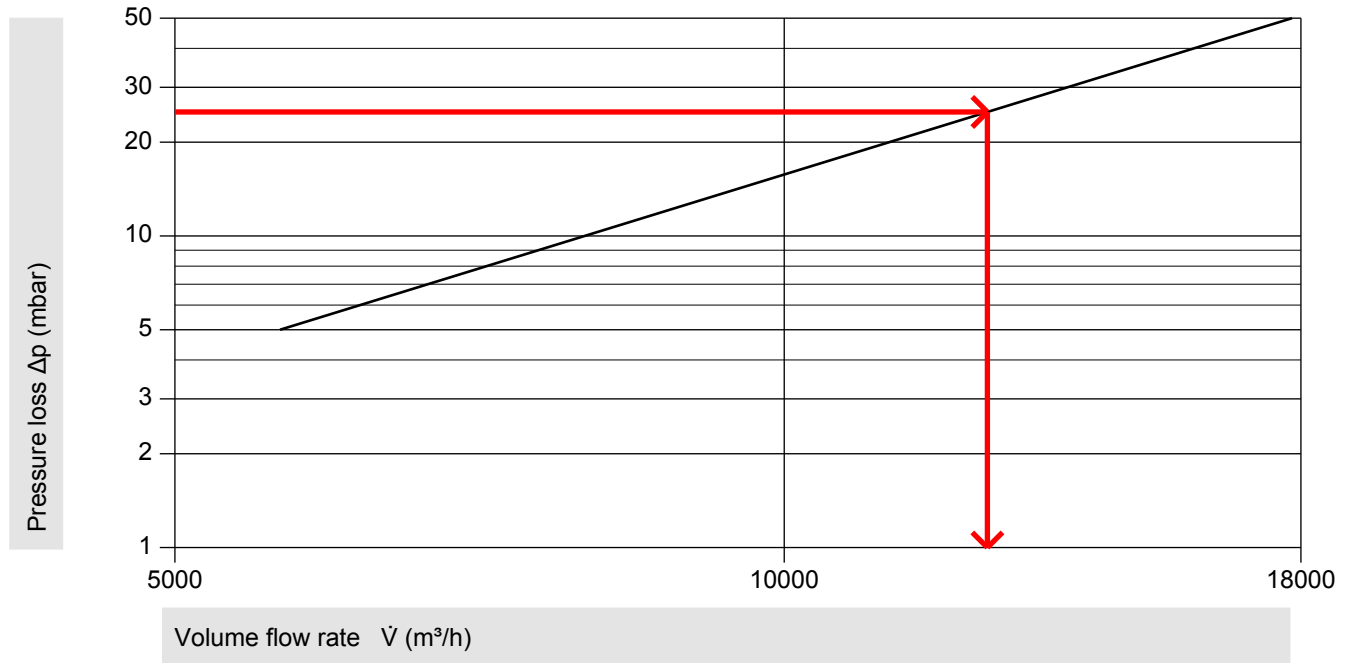


Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

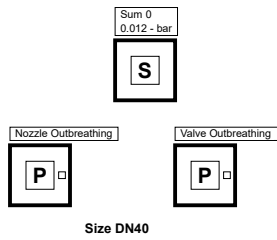


PROTEGO® capacity diagram

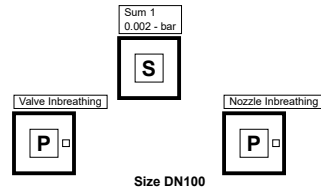
ER/V-400, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar



The required outbreathing flowrate (pump in + thermal effect) is 75 Nm³/h



The required inbreathing flowrate (API2000 < Fullarton; 217 < 218) is 218 Nm³/h.

Methyl Acrylate

Design Basis:

Upstream Valve:

- Pipeline = 2.5 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

Downstream Valve:

- Pipeline = 3 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

*For outbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

*For inbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Methyl Acrylate Case)

Contract: Methyl Acrylate Case

Date: 8/9/2023

By: JLG	Chk'd:	App'd:
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Engineer: _____
 Page 1 of 2

General											
Name		Valve Inbreathing		Nozzle Outbreathing		Nozzle Inbreathing		Valve Outbreathing		Sum 0	
Line No.											
Process Conditions											
Mass Flow	kg/hr	282.0		96.9		281.7		96.9			
Std. Volume Flow	Nm³/hr	218.0		75.0		218.0		75.0			
Viscosity	cP	0.019		0.019		0.019		0.019			
Temperature	°C	25.0		25.0		25.0		25.0			
Molecular Weight		29.0		29.0		29.0		29.0			
Compressibility		1.00		1.00		1.00		1.00			
Cp/Cv		1.40		1.41		1.40					
Inlet-Outlet Conditions											
Density (In Out)	kg/m³	1.187	1.186	1.191	1.184	1.186	1.185	1.191	1.184		
Velocity (In Out)	m/s	0.00	7.33	0.00	15.58	7.32	7.33	15.49	15.58		
% Critical Flow - (In Out)	%	0.00	2.51	0.00	5.33	2.50	2.50	5.29	5.33		
Mach Number - (In Out)		0.00	0.02	0.00	0.04	0.02	0.02				
Velocity Head (In Out)	bar	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001		
Dynamic Pressure (In Out)	kPa_g	0.087	0.032	0.589	0.144	0.179	0.106	0.741	0.144		
Static Pressure (In Out)	kPa_g	0.087	0.000	0.589	0.000	0.147	0.074	0.598	0.000		
Details											
Design Factor - Frictional Only	%	120.00		120.00		120.00		120.00			
Connect Effect	bar	0.000		0.000		0.000		0.000		0.000	
Pipe Data											
Size (Nominal Schedule)	mm	User		User		User		User			
Inside Diameter	mm	107.100		43.100		107.100		43.100			
Length	m	3.0		2.5		2.5		3.0			
Roughness	mm	0.07000		0.07000		0.07000		0.07000			
Friction Factor - (Moody Fully Turbulent)		0.02311	0.01775	0.02617	0.02218	0.02311	0.01775	0.02616	0.02218		
Density (In Out)	kg/m³	1.186	1.186	1.189	1.184	1.186	1.185	1.191	1.184		
Velocity (In Out)	m/s	7.33	7.33	15.52	15.58	7.32	7.33	15.49	15.58		
Velocity Head (In Out)	bar	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.001		
Rho*v² (In Out)	kg/m-s²	63.8	63.8	286.4	287.4	63.6	63.6	285.7	287.4		
Reynold's No.		49,022		41,676		48,954		41,851			
% Critical Flow - (In Out)	%	2.51	2.51	5.31	5.33	2.50	2.50	5.29	5.33		
Mach Number - (In Out)		0.02	0.02	0.04	0.04	0.02	0.02				
Pressure Drop	bar/100-m	0.008		0.105		0.008		0.105			
Pipe Angle	°	-7.66		9.21		-9.21		7.66			
Elevation (In Out)	m	10.8	10.4	10.0	10.4	10.4	10.0	10.4	10.8		
Fittings											
45° Elbow (LR SR)	Qty										
90° Elbow (LR SR)	Qty	2		2		2		2			
180° Elbow (LR SR)	Qty										
Flanged Tee (Branch Run)	Qty										
Threaded Tee (Branch Run)	Qty										
Valve (Ball Gate)	Qty										
Valve (Globe Butterfly)	Qty										
Check Valve (Swing Lift)	Qty										
Control Valve CV	CV										
Additional K	K					1.0		1.0			
Crane X (K=X*ft)											
Additional Length	m										
Additional Drop	bar										
Inlet Effect											
R/E Inside Diameter	mm										
R/E Length (User Default)	mm										
Pipe Entrance		Flush (Sharp Edged)		Flush (Sharp Edged)		(none)		(none)			
Outlet Effect											
R/E Inside Diameter	mm										
R/E Length (User Default)	mm										
Pipe Exit		(none)		(none)		(none)		(none)			
Pressure Drops By Component											
Frictional	bar	0.001		0.004		0.001		0.006		0.010	
Static Head	bar	0.000		0.000		0.000		0.000		0.000	
Velocity Head	bar	0.000		0.001		0.000		0.000		0.001	
Static Pressure Drops											
Pipe	bar	0.000		0.003		0.000		0.003		0.006	
Fittings	bar	0.000		0.001		0.001		0.003		0.004	
Inlet Effect	bar	0.000		0.002		0.000		0.000		0.002	
Outlet Effect	bar	0.000		0.000		0.000		0.000		0.000	
Total	bar	0.001		0.006		0.001		0.006		0.012	

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Methyl Acrylate Case)

Contract: Methyl Acrylate Case
 Date: 8/9/2023

By:	Chk'd:	App'd:
JLG		

Engineer: _____
 Page 2 of 2

General					
Name		Sum 1			
Line No.					
Process Conditions					
Mass Flow	kg/hr				
Std. Volume Flow	Nm³/hr				
Viscosity	cP				
Temperature	°C				
Molecular Weight					
Compressibility					
Cp/Cv					
Inlet-Outlet Conditions					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Velocity Head (In Out)	bar				
Dynamic Pressure (In Out)	kPa_g				
Static Pressure (In Out)	kPa_g				
Details					
Design Factor - Frictional Only	%				
Connect Effect	bar	0.000			
Pipe Data					
Size (Nominal Schedule)	mm				
Inside Diameter	mm				
Length	m				
Roughness	mm				
Friction Factor - (Moody Fully Turbulent)					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
Velocity Head (In Out)	bar				
Rho*v² (In Out)	kg/m-s²				
Reynold's No.					
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Pressure Drop	bar/100-m				
Pipe Angle	°				
Elevation (In Out)	m				
Fittings					
45° Elbow (LR SR)	Qty				
90° Elbow (LR SR)	Qty				
180° Elbow (LR SR)	Qty				
Flanged Tee (Branch Run)	Qty				
Threaded Tee (Branch Run)	Qty				
Valve (Ball Gate)	Qty				
Valve (Globe Butterfly)	Qty				
Check Valve (Swing Lift)	Qty				
Control Valve CV	CV				
Additional K	K				
Crane X (K=X*ft)					
Additional Length	m				
Additional Drop	bar				
Inlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Entrance					
Outlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Exit					
Pressure Drops By Component					
Frictional	bar	0.001			
Static Head	bar	0.000			
Velocity Head	bar	0.000			
Static Pressure Drops					
Pipe	bar	0.000			
Fittings	bar	0.001			
Inlet Effect	bar	0.000			
Outlet Effect	bar	0.000			
Total	bar	0.002			

Sizing of a pressure relief valve PRV (high build-up back pressures)

METHYL ACRYLATE

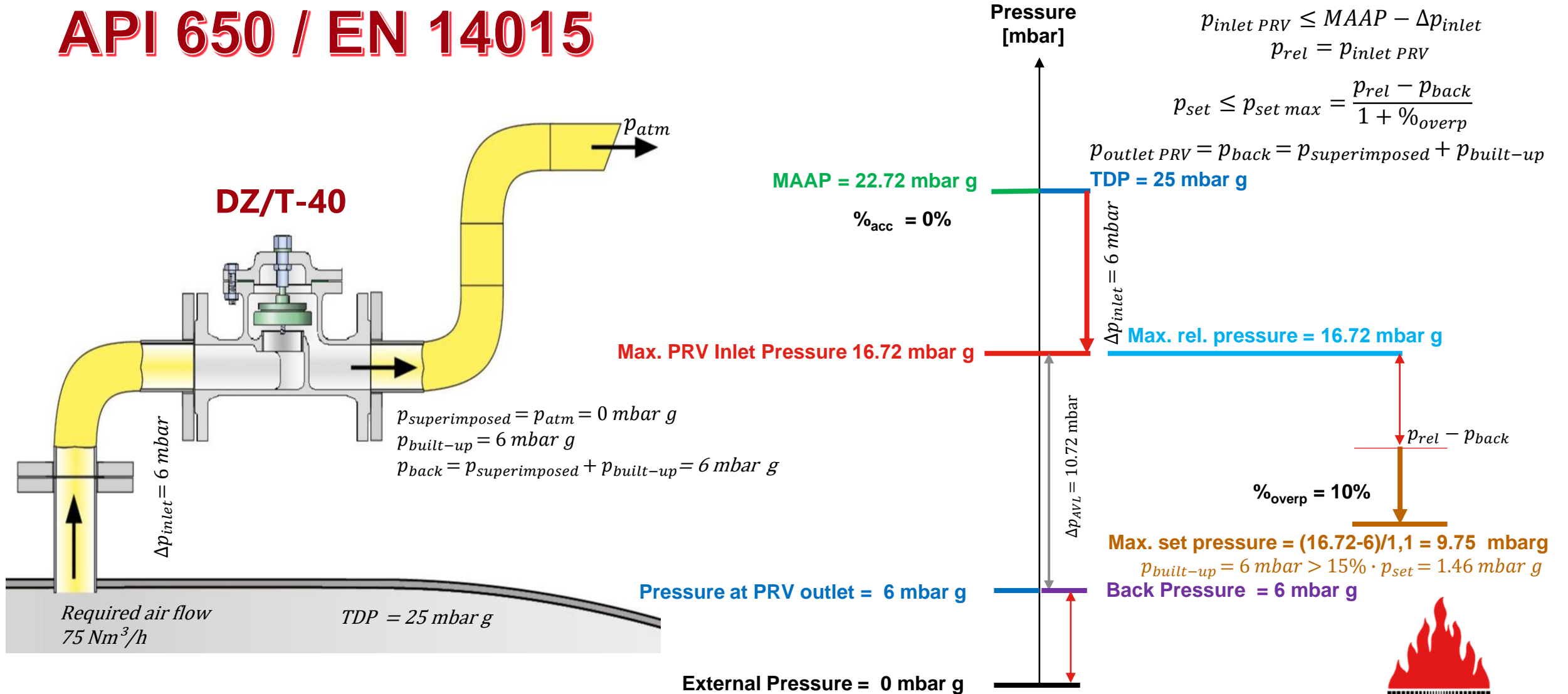
$$p_{built-up (gauge)} > 15\% \cdot p_{set (gauge)}$$

OR

$$\Delta p_{inlet} > 10\% \cdot p_{set (gauge)}$$

Approved for QuEST 3.0

API 650 / EN 14015

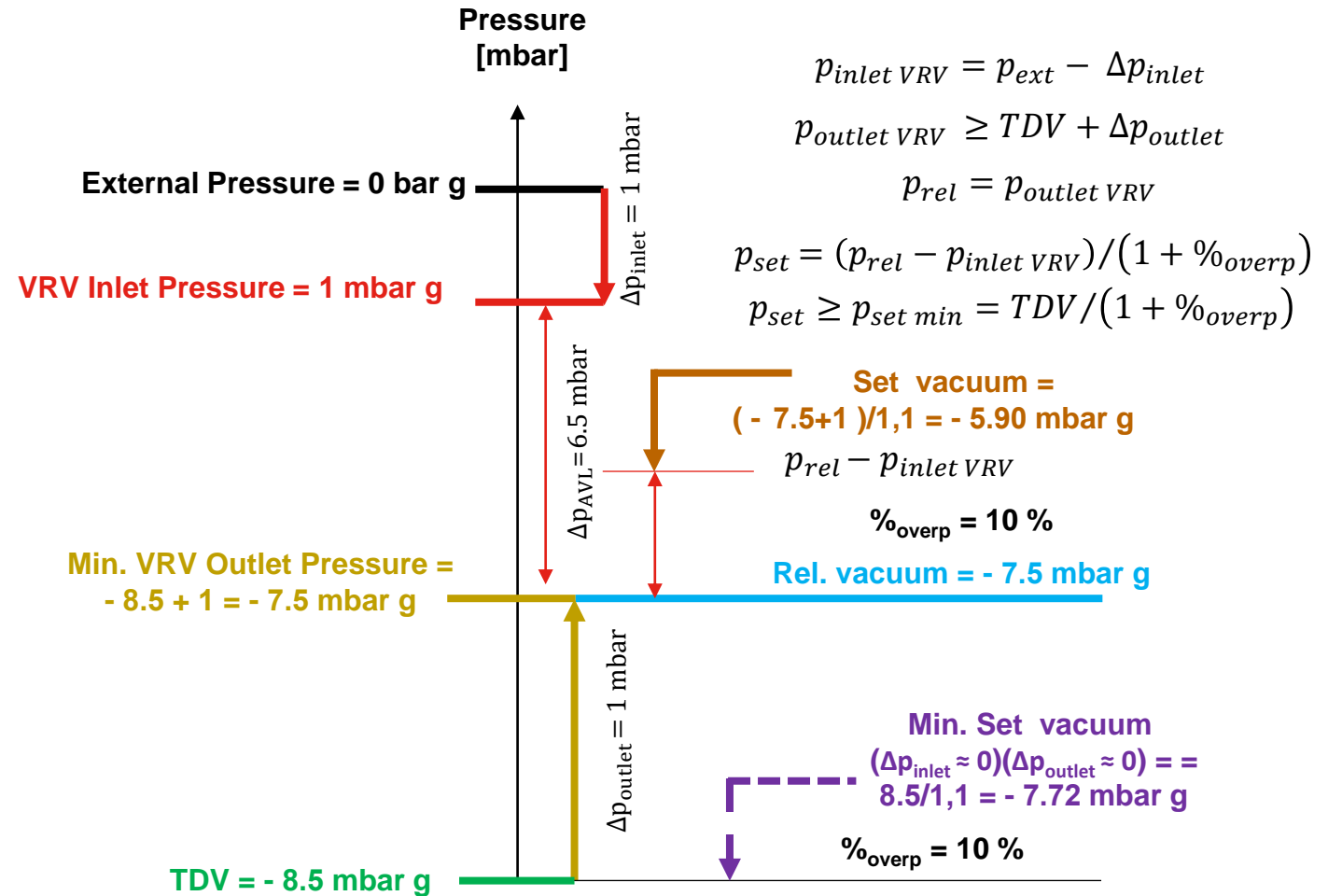
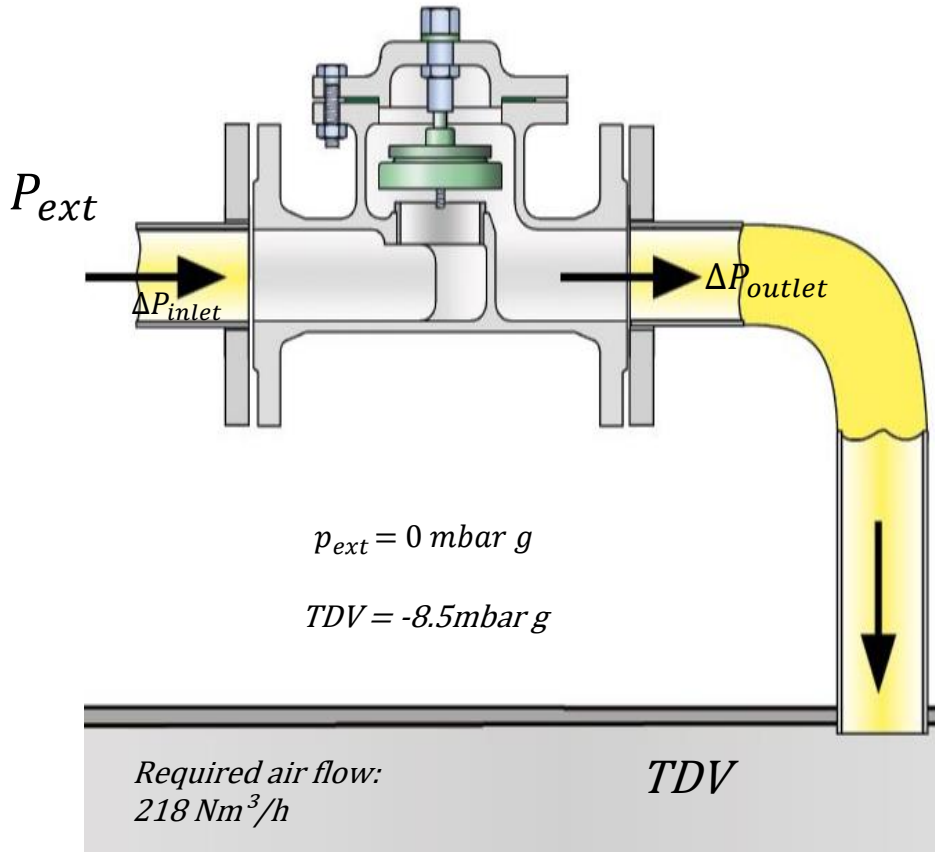


Sizing of a vacuum relief valve VRV

METHYL ACRYLATE

Approved for QuEST 3.0

DZ/T-100





Project		API 2000 - TFM			
Revision	0.0	Tank location		TARRAGONA	
Atmospheric pressure	1013.25	mbar-a	Tank label		
Quotation number			Tank number		METHYL ACRYLATE TANK
Job number			Job number by Customer		
Editor	Mr. Joel Lopez		Date		08/09/2023
Notes:					
Tank data					
Tank type	vertical, cylindrical		Height of elevation		0.0 m
Tank height	10.0	m	Tank diameter		4.0 m
Tank volume	125.7	m³	Tank Wetted Surface area ATWS		114.9 m²
Tank design pressure	25.0	mbar-g	Tank design vacuum		-8.5 mbar-g
Max. filling rate	25.0	m³/h	Max. rate of liquid discharge		25.0 m³/h
Product data for normal breathing					
Product	Methyl Acrylate				
Molar mass	-		Explosion Group		-
C factor	6.50		Y factor		0.32
Operating temperature	25.0	°C	Vapor pressure		> 5.0 kPa (0.73 psi)
Notes					
Product data for emergency breathing					
Product	Methyl Acrylate				
Molar mass	86.1	kg/kmol	Environmental factor		1.0
Boiling point / bubble point	80.0	°C	Latent heat		372.0 KJ/kg
Notes					
Device data					
Max. relieving pressure acc. to	API 650 12th Ed. (EN 14015)		Burn rating		not burning proof
Operating temperature	25.0	°C			



Venting calculation results			Outbreathing	Inbreathing
Normal venting capacity		m ³ /h	75	218
Load due to filling -in / out		m ³ /h	50	25
Thermal out- / inbreathing		m ³ /h	25	192
Uninsulated hot tanks (Vapor condensation)		m ³ /h	-	1.0
Emergency relief load		m ³ /h	15464	-
C factor	6.50	Y factor	0.32	
Tank volume	125.7	m ³	Tank Wetted Surface area ATWS	114.9 m ²
Notes:				
Signatures and Stamps or Company logo:				

Loads are expressed in Air at Normal conditions (0.00 °C, 101.325 kPa-a)

Venting calculation results converted into PROTEGO® diagram conditions		Outbreathing	Inbreathing
Normal venting capacity	m ³ /h	82	237
Emergency relief load	m ³ /h	16816	-

Loads are expressed in Air at PROTEGO® diagram conditions (20°C, 1 bar)



Device selection / Basic data			
Device		DZ/T-40	DZ/T-100
Manufacturer		Braunschweiger Flammenfilter GmbH	Braunschweiger Flammenfilter GmbH
Type of device		In-line device	In-line device
Inlet flange	DN	40	100
Outlet flange	DN	40	100
Nominal width NG		-	-
Function		Pressure or Vacuum Relief Valve	Pressure or Vacuum Relief Valve
Set pressure P	mbar-g	9.75	-
Set pressure V	mbar-g	-	-5.9
Relieving pressure minus back pressure (P)	mbar	10.73	-
Relieving pressure minus inlet pressure (V)	mbar	-	-6.49
Adjusted set pressure (P)	mbar-g	9.75	-
Adjusted set pressure (V)	mbar-g	-	-5.9
Overpressure P / V	%	10.0 / -	- / 10.0
Capacity air at normal condition P	m³/h	81	-
Capacity air at normal condition V	m³/h	-	255
Back pressure	mbar-g	6.0	-
Inlet line pressure loss (P)	mbar	6.0	-
External pressure	mbar	-	0.0
Pressure loss to VRV inlet	mbar	-	1.0
Pressure loss between VRV outlet and tank	mbar	-	1.0
Capacity as per PROTEGO® Diagramm (P)	m³/h	88	-
Capacity as per PROTEGO® Diagramm (V)	m³/h	-	277
Number of required devices		1	1
Excess capacity air at normal condition P	%	8.92	-
Excess capacity air at normal condition V	%	-	17.36
Notes: The pressure loss is considered. An additional inbreathing load is taken into account according to Fullarton calculation (see explanation in Section 8.2)			
Signatures and Stamps or Company logo:			

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



Device selection / Basic data			
Device		ER/V-500	
Manufacturer		Braunschweiger Flammenfilter GmbH	
Type of device		End-of-line device	
Inlet flange	DN	500	
Outlet flange	DN	-	
Nominal width NG		-	
Function		Pressure Relief Valve	
Set pressure P	mbar-g	22.72	
Relieving pressure minus back pressure (P)	mbar	25.0	
Adjusted set pressure (P)	mbar-g	22.72	
Overpressure P / V	%	10.0 / -	
Capacity air at normal condition P	m³/h	18102	
Back pressure		-	
Inlet line pressure loss (P)	mbar	0.0	
Capacity as per PROTEGO® Diagramm (P)	m³/h	19685	
Number of required devices		1	
Excess capacity air at normal condition P	%	17.64	
Notes:			
Signatures and Stamps or Company logo:			

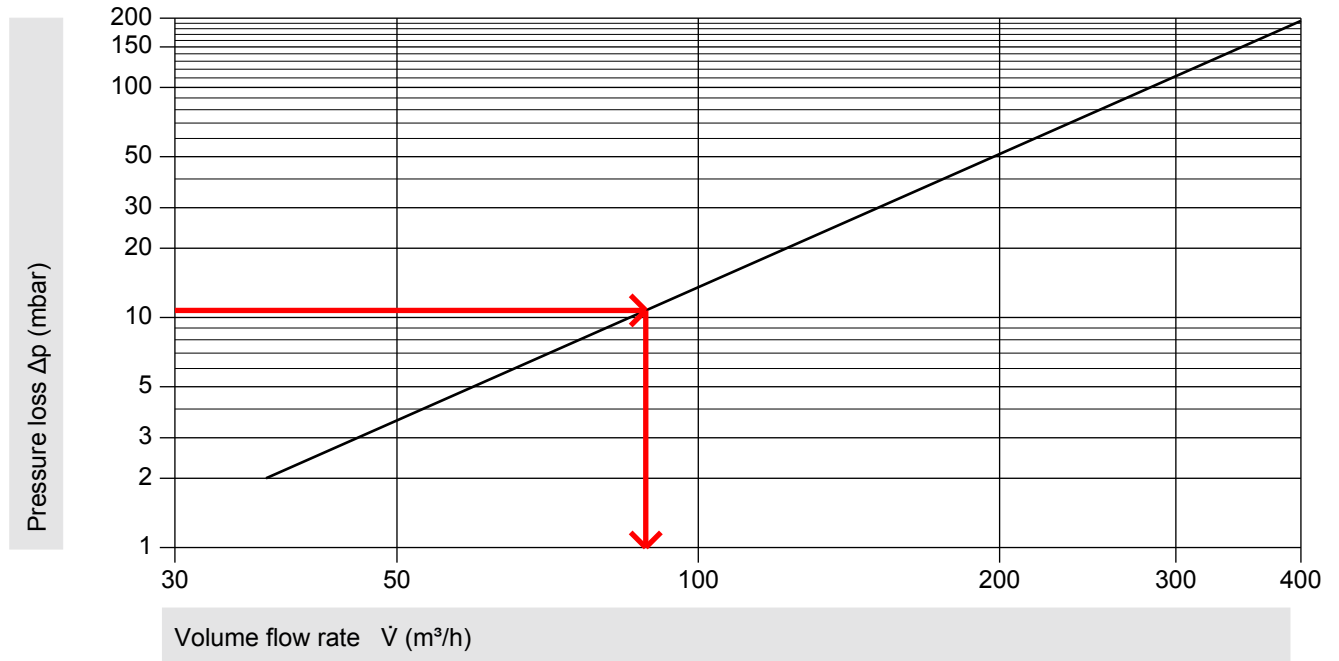
The required flow capacity for the emergency venting device is the difference between the emergency and the normal outbreathing requirement.

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



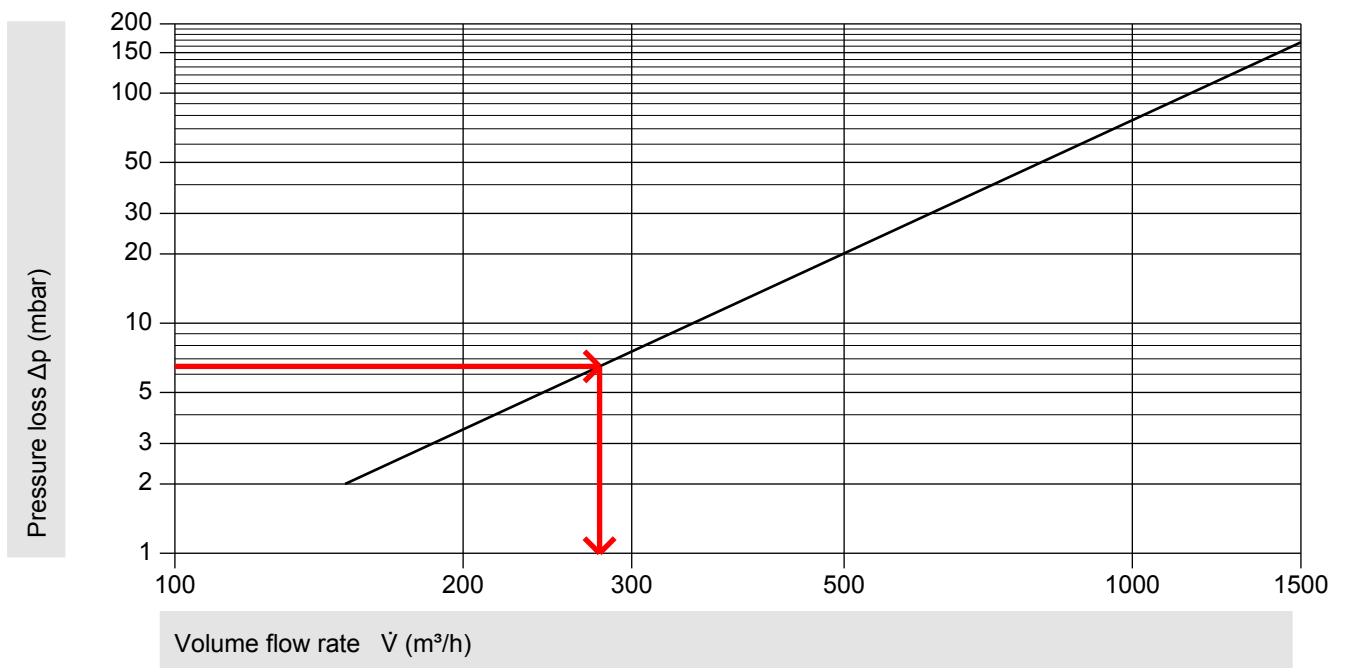
PROTEGO® capacity diagram

DZ/T-40, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

DZ/T-100, Vacuum

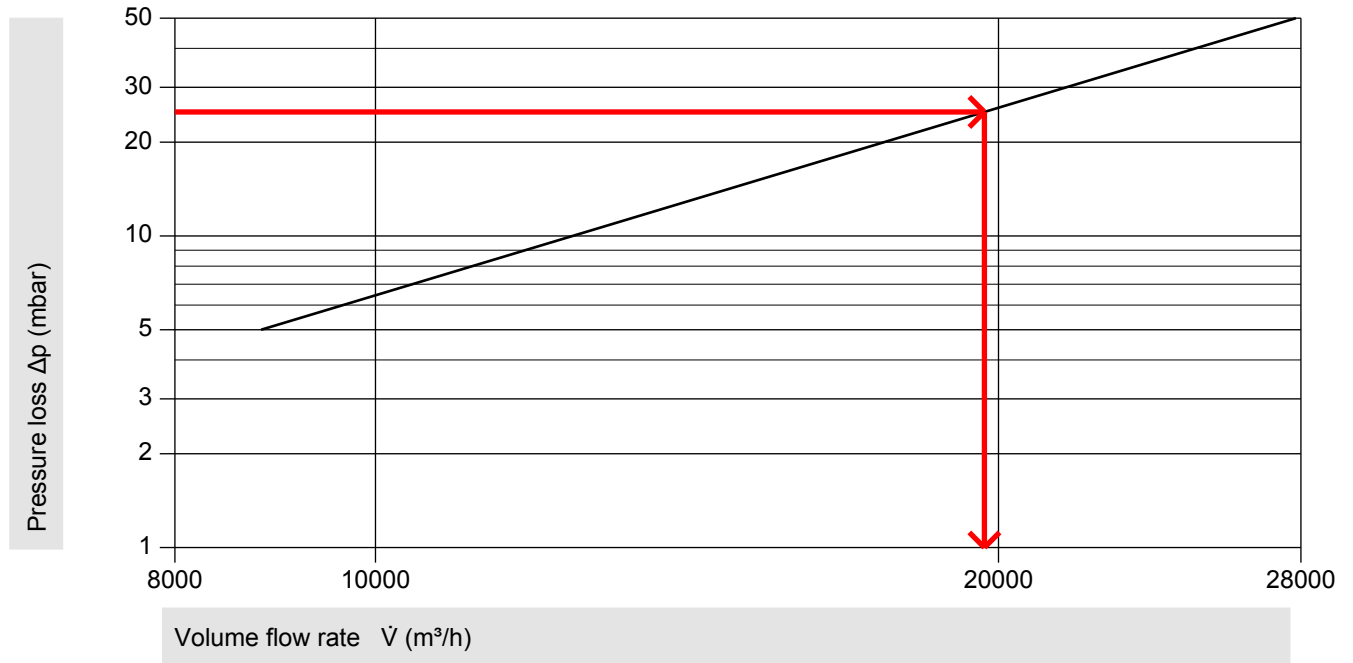


Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

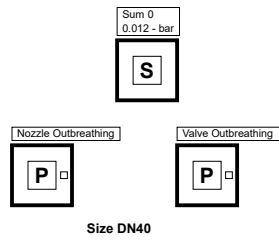


PROTEGO® capacity diagram

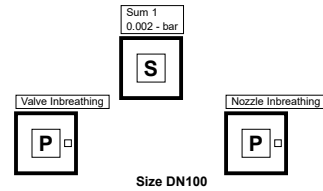
ER/V-500, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar



The required outbreathing flowrate (pump in + thermal effect) is 75 Nm³/h



The required inbreathing flowrate (API2000 < Fullarton; 217 < 225) is 225 Nm³/h.

Hexane

Design Basis:

Upstream Valve:

- Pipeline = 2.5 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

Downstream Valve:

- Pipeline = 3 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

*For outbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

*For inbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Hexane Case)

Contract: Hexane Case
 Date: 8/8/2023

By:	Chk'd:	App'd:
JLG		

Engineer: _____
 Page 1 of 2

General										
Name	Valve Inbreathing		Nozzle Outbreathing		Nozzle Inbreathing		Valve Outbreathing		Sum 0	
Line No.										
Process Conditions										
Mass Flow	kg/hr	291.1	96.9	290.7	96.9					
Std. Volume Flow	Nm³/hr	225.0	75.0	225.0	75.0					
Viscosity	cP	0.019	0.019	0.019	0.019					
Temperature	°C	25.0	25.0	25.0	25.0					
Molecular Weight		29.0	29.0	29.0	29.0					
Compressibility		1.00	1.00	1.00	1.00					
Cp/Cv		1.40	1.41	1.40	1.40					
Inlet-Outlet Conditions										
Density (In Out)	kg/m³	1.187	1.186	1.191	1.184	1.186	1.185	1.191	1.184	
Velocity (In Out)	m/s	0.00	7.57	0.00	15.58	7.56	7.56	15.49	15.58	
% Critical Flow - (In Out)	%	0.00	2.59	0.00	5.33	2.58	2.59	5.29	5.33	
Mach Number - (In Out)		0.00	0.02	0.00	0.04	0.02	0.02			
Velocity Head (In Out)	bar	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	
Dynamic Pressure (In Out)	kPa_g	0.093	0.034	0.589	0.144	0.181	0.103	0.741	0.144	
Static Pressure (In Out)	kPa_g	0.093	0.000	0.589	0.000	0.147	0.069	0.598	0.000	
Details										
Design Factor - Frictional Only	%	120.00		120.00		120.00		120.00		
Connect Effect	bar	0.000		0.000		0.000		0.000		0.000
Pipe Data										
Size (Nominal Schedule)	mm	User	User	User	User					
Inside Diameter	mm	107.100	43.100	107.100	43.100					
Length	m	3.0	2.5	3.0	2.5					
Roughness	mm	0.07000	0.07000	0.07000	0.07000					
Friction Factor - (Moody Fully Turbulent)		0.02299	0.01775	0.02617	0.02218	0.02300	0.01775	0.02616	0.02218	
Density (In Out)	kg/m³	1.186	1.186	1.189	1.184	1.186	1.185	1.191	1.184	
Velocity (In Out)	m/s	7.57	7.57	15.52	15.58	7.56	7.56	15.49	15.58	
Velocity Head (In Out)	bar	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.001	
Rho*v² (In Out)	kg/m-s²	67.9	67.9	286.4	287.4	67.7	67.8	285.7	287.4	
Reynold's No.		50,596	41,676	50,526	41,851					
% Critical Flow - (In Out)	%	2.59	2.59	5.31	5.33	2.58	2.59	5.29	5.33	
Mach Number - (In Out)		0.02	0.02	0.04	0.04	0.02	0.02			
Pressure Drop	bar/100-m	0.009	0.105	0.009	0.105					
Pipe Angle	°	-7.66	9.21	-9.21	7.66					
Elevation (In Out)	m	10.8	10.4	10.0	10.4	10.4	10.0	10.4	10.8	
Fittings										
45° Elbow (LR SR)	Qty									
90° Elbow (LR SR)	Qty	2		2		2		2		
180° Elbow (LR SR)	Qty									
Flanged Tee (Branch Run)	Qty									
Threaded Tee (Branch Run)	Qty									
Valve (Ball Gate)	Qty									
Valve (Globe Butterfly)	Qty									
Check Valve (Swing Lift)	Qty									
Control Valve CV	CV									
Additional K	K					1.0		1.0		
Crane X (K=X*ft)										
Additional Length	m									
Additional Drop	bar									
Inlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Entrance		Flush (Sharp Edged)	Flush (Sharp Edged)	(none)	(none)					
Outlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Exit		(none)	(none)	(none)	(none)					
Pressure Drops By Component										
Frictional	bar	0.001	0.004	0.001	0.006					0.010
Static Head	bar	0.000	0.000	0.000	0.000					0.000
Velocity Head	bar	0.000	0.001	0.000	0.000					0.001
Static Pressure Drops										
Pipe	bar	0.000	0.003	0.000	0.003					0.006
Fittings	bar	0.000	0.001	0.001	0.003					0.004
Inlet Effect	bar	0.001	0.002	0.000	0.000					0.002
Outlet Effect	bar	0.000	0.000	0.000	0.000					0.000
Total	bar	0.001	0.006	0.001	0.006					0.012

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Hexane Case)

Contract: Hexane Case
 Date: 8/8/2023

By:	Chk'd:	App'd:
JLG		

Engineer: _____
 Page 2 of 2

General					
Name		Sum 1			
Line No.					
Process Conditions					
Mass Flow	kg/hr				
Std. Volume Flow	Nm³/hr				
Viscosity	cP				
Temperature	°C				
Molecular Weight					
Compressibility					
Cp/Cv					
Inlet-Outlet Conditions					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Velocity Head (In Out)	bar				
Dynamic Pressure (In Out)	kPa_g				
Static Pressure (In Out)	kPa_g				
Details					
Design Factor - Frictional Only	%				
Connect Effect	bar	0.000			
Pipe Data					
Size (Nominal Schedule)	mm				
Inside Diameter	mm				
Length	m				
Roughness	mm				
Friction Factor - (Moody Fully Turbulent)					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
Velocity Head (In Out)	bar				
Rho*v² (In Out)	kg/m-s²				
Reynold's No.					
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Pressure Drop	bar/100-m				
Pipe Angle	°				
Elevation (In Out)	m				
Fittings					
45° Elbow (LR SR)	Qty				
90° Elbow (LR SR)	Qty				
180° Elbow (LR SR)	Qty				
Flanged Tee (Branch Run)	Qty				
Threaded Tee (Branch Run)	Qty				
Valve (Ball Gate)	Qty				
Valve (Globe Butterfly)	Qty				
Check Valve (Swing Lift)	Qty				
Control Valve CV	CV				
Additional K	K				
Crane X (K=X*ft)					
Additional Length	m				
Additional Drop	bar				
Inlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Entrance					
Outlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Exit					
Pressure Drops By Component					
Frictional	bar	0.001			
Static Head	bar	0.000			
Velocity Head	bar	0.000			
Static Pressure Drops					
Pipe	bar	0.000			
Fittings	bar	0.001			
Inlet Effect	bar	0.001			
Outlet Effect	bar	0.000			
Total	bar	0.002			

Sizing of a pressure relief valve PRV (high build-up back pressures)

HEXANE

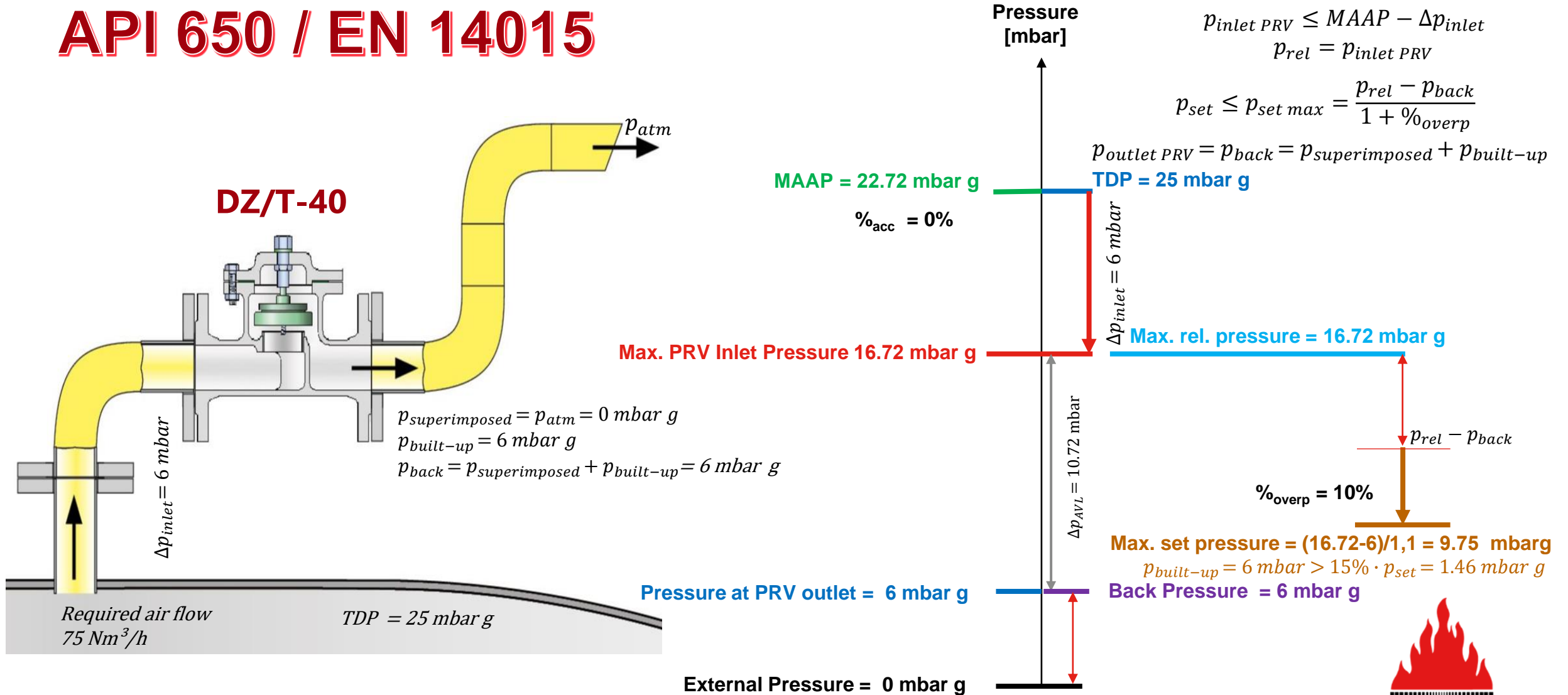
$$p_{built-up (gauge)} > 15\% \cdot p_{set (gauge)}$$

OR

$$\Delta p_{inlet} > 10\% \cdot p_{set (gauge)}$$

Approved for QuEST 3.0

API 650 / EN 14015

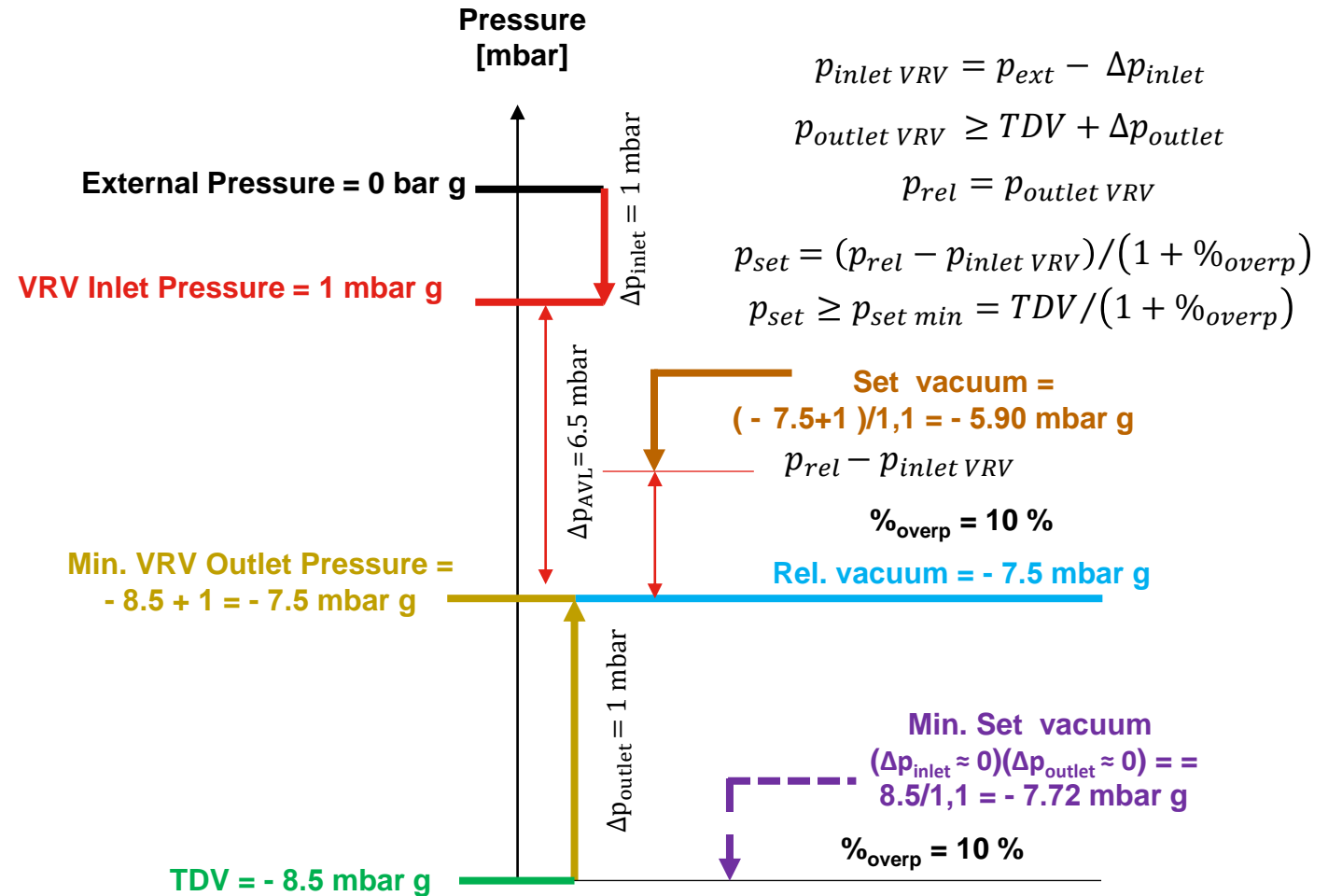
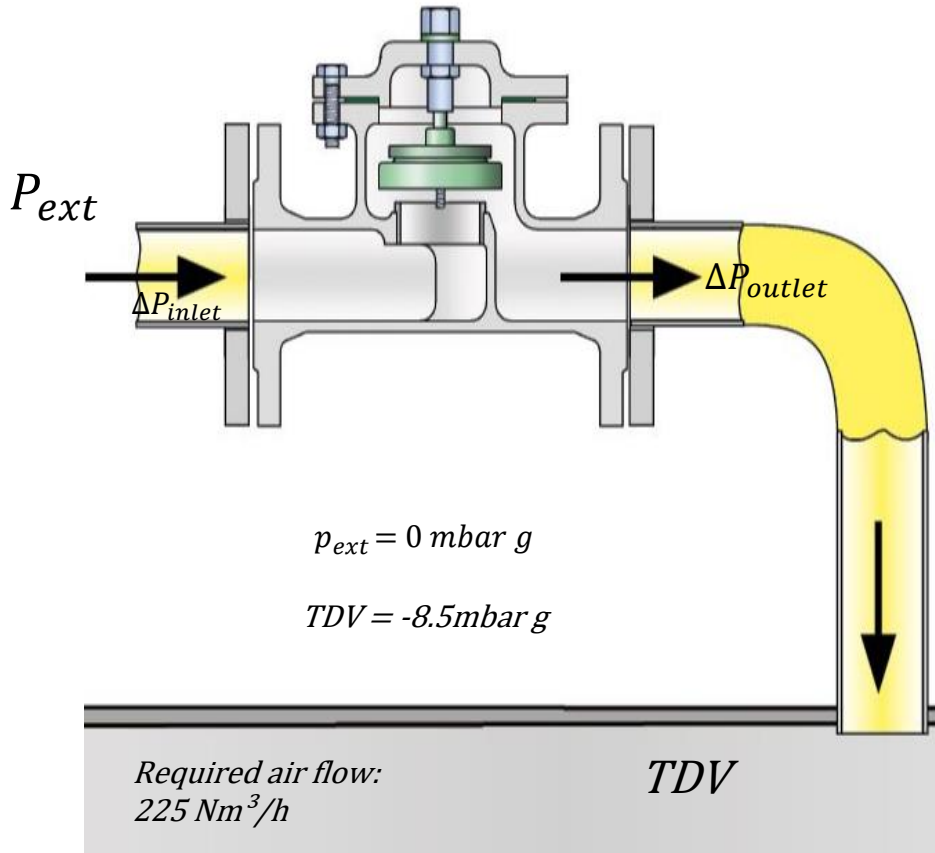


Sizing of a vacuum relief valve VRV

HEXANE

Approved for QuEST 3.0

DZ/T-100





Project		API 2000 - TFM			
Revision	0.0	Tank location	TARRAGONA		
Atmospheric pressure	1013.25	mbar-a	Tank label		
Quotation number		Tank number	HEXANE TANK		
Job number		Job number by Customer			
Editor	Mr. Joel Lopez	Date	08/08/2023		
Notes:					
Tank data					
Tank type	vertical, cylindrical	Height of elevation	0.0	m	
Tank height	10.0	m	Tank diameter	4.0	m
Tank volume	125.7	m³	Tank Wetted Surface area ATWS	114.9	m²
Tank design pressure	25.0	mbar-g	Tank design vacuum	-8.5	mbar-g
Max. filling rate	25.0	m³/h	Max. rate of liquid discharge	25.0	m³/h
Product data for normal breathing					
Product	Hexane				
Molar mass	-	Explosion Group	-		
C factor	6.50	Y factor	0.32		
Operating temperature	25.0	°C	Vapor pressure	> 5.0 kPa (0.73 psi)	
Notes					
Product data for emergency breathing					
Product	Hexane				
Molar mass	86.2	kg/kmol	Environmental factor	1.0	
Boiling point / bubble point	69.0	°C	Latent heat	335.0	KJ/kg
Notes					
Device data					
Max. relieving pressure acc. to	API 650 12th Ed. (EN 14015)	Burn rating	not burning proof		
Operating temperature	25.0	°C			



Venting calculation results			Outbreathing	Inbreathing
Normal venting capacity		m ³ /h	75	225
Load due to filling -in / out		m ³ /h	50	25
Thermal out- / inbreathing		m ³ /h	25	192
Uninsulated hot tanks (Vapor condensation)		m ³ /h	-	8.0
Emergency relief load		m ³ /h	16892	-
C factor	6.50		Y factor	0.32
Tank volume	125.7	m ³	Tank Wetted Surface area ATWS	114.9 m ²
Notes:				
Signatures and Stamps or Company logo:				

Loads are expressed in Air at Normal conditions (0.00 °C, 101.325 kPa-a)

Venting calculation results converted into PROTEGO® diagram conditions		Outbreathing	Inbreathing
Normal venting capacity	m ³ /h	82	245
Emergency relief load	m ³ /h	18369	-

Loads are expressed in Air at PROTEGO® diagram conditions (20°C, 1 bar)



Device selection / Basic data			
Device		DZ/T-40	DZ/T-100
Manufacturer		Braunschweiger Flammenfilter GmbH	Braunschweiger Flammenfilter GmbH
Type of device		In-line device	In-line device
Inlet flange	DN	40	100
Outlet flange	DN	40	100
Nominal width NG		-	-
Function		Pressure or Vacuum Relief Valve	Pressure or Vacuum Relief Valve
Set pressure P	mbar-g	9.75	-
Set pressure V	mbar-g	-	-5.9
Relieving pressure minus back pressure (P)	mbar	10.73	-
Relieving pressure minus inlet pressure (V)	mbar	-	-6.49
Adjusted set pressure (P)	mbar-g	9.75	-
Adjusted set pressure (V)	mbar-g	-	-5.9
Overpressure P / V	%	10.0 / -	- / 10.0
Capacity air at normal condition P	m³/h	81	-
Capacity air at normal condition V	m³/h	-	255
Back pressure	mbar-g	6.0	-
Inlet line pressure loss (P)	mbar	6.0	-
External pressure	mbar	-	0.0
Pressure loss to VRV inlet	mbar	-	1.0
Pressure loss between VRV outlet and tank	mbar	-	1.0
Capacity as per PROTEGO® Diagramm (P)	m³/h	88	-
Capacity as per PROTEGO® Diagramm (V)	m³/h	-	277
Number of required devices		1	1
Excess capacity air at normal condition P	%	8.92	-
Excess capacity air at normal condition V	%	-	13.7
<p>Notes: The pressure loss is considered. An additional inbreathing load is taken into account according to Fullarton calculation (see explanation Section 8.2)</p>			
<p>Signatures and Stamps or Company logo:</p>			

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



Device selection / Basic data			
Device		ER/V-500	
Manufacturer		Braunschweiger Flammenfilter GmbH	
Type of device		End-of-line device	
Inlet flange	DN	500	
Outlet flange	DN	-	
Nominal width NG		-	
Function		Pressure Relief Valve	
Set pressure P	mbar-g	22.72	
Relieving pressure minus back pressure (P)	mbar	25.0	
Adjusted set pressure (P)	mbar-g	22.72	
Overpressure P / V	%	10.0 / -	
Capacity air at normal condition P	m³/h	18102	
Back pressure		-	
Inlet line pressure loss (P)	mbar	0.0	
Capacity as per PROTEGO® Diagramm (P)	m³/h	19685	
Number of required devices		1	
Excess capacity air at normal condition P	%	7.65	
Notes:			
Signatures and Stamps or Company logo:			

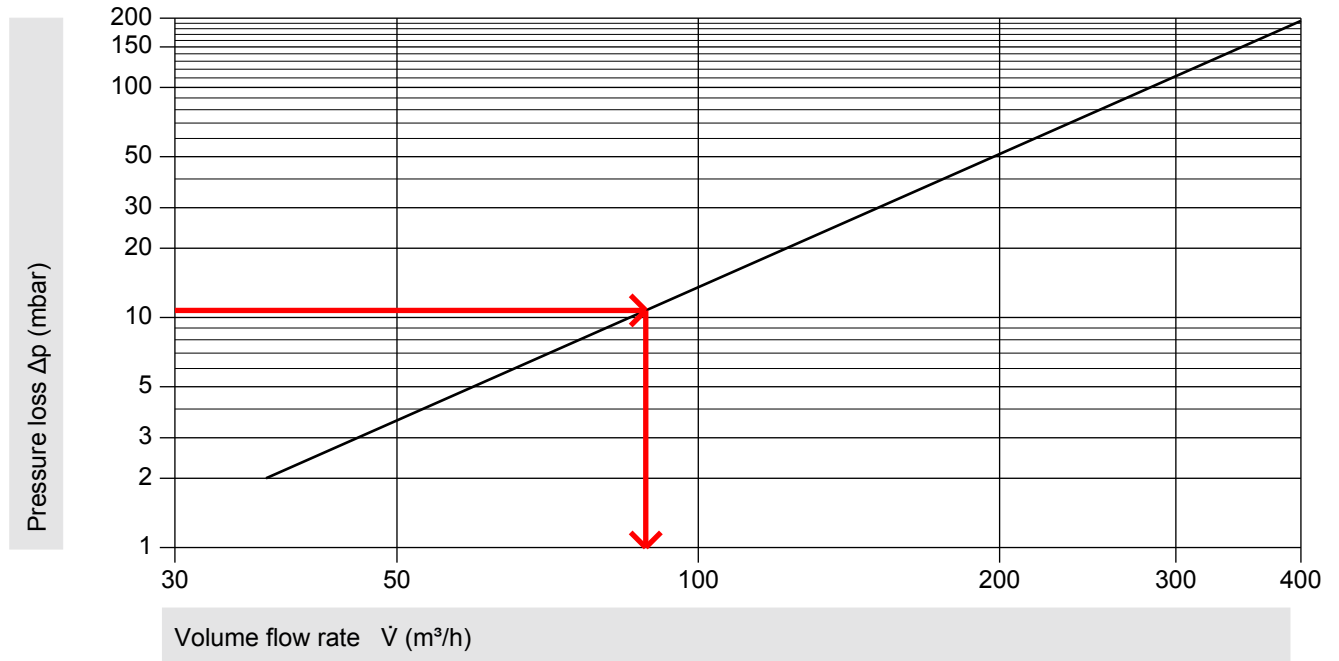
The required flow capacity for the emergency venting device is the difference between the emergency and the normal outbreathing requirement.

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



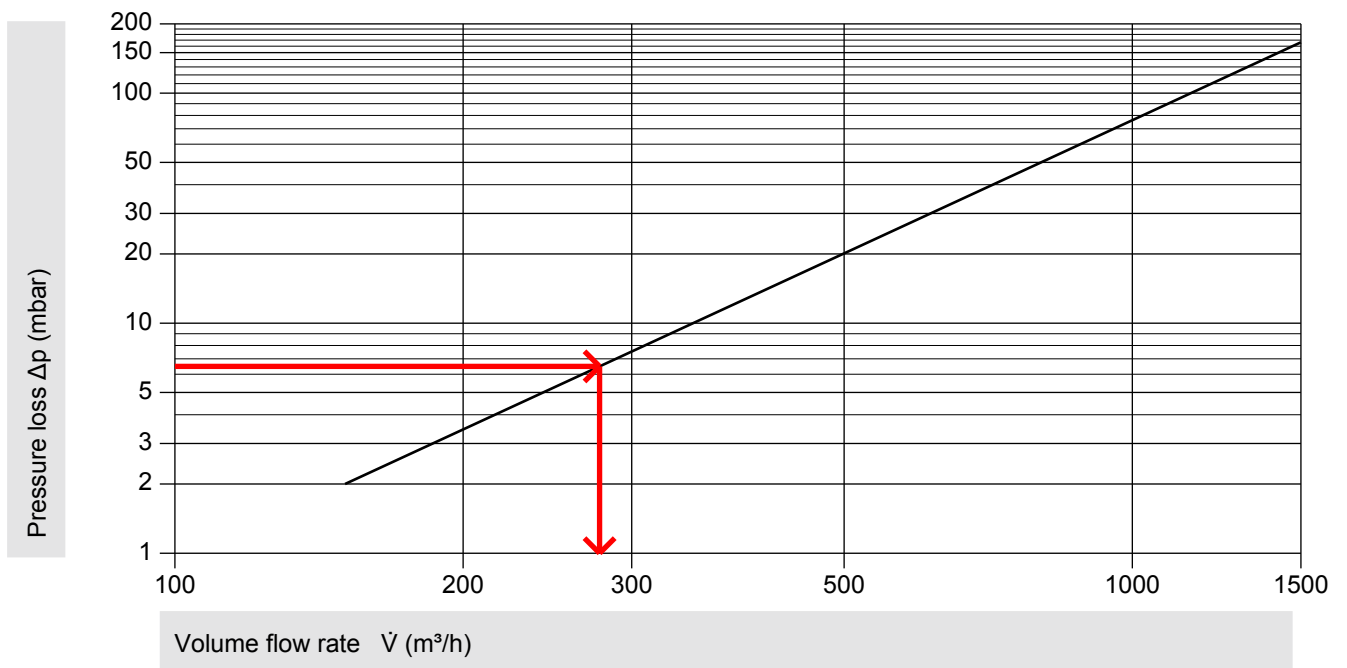
PROTEGO® capacity diagram

DZ/T-40, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

DZ/T-100, Vacuum

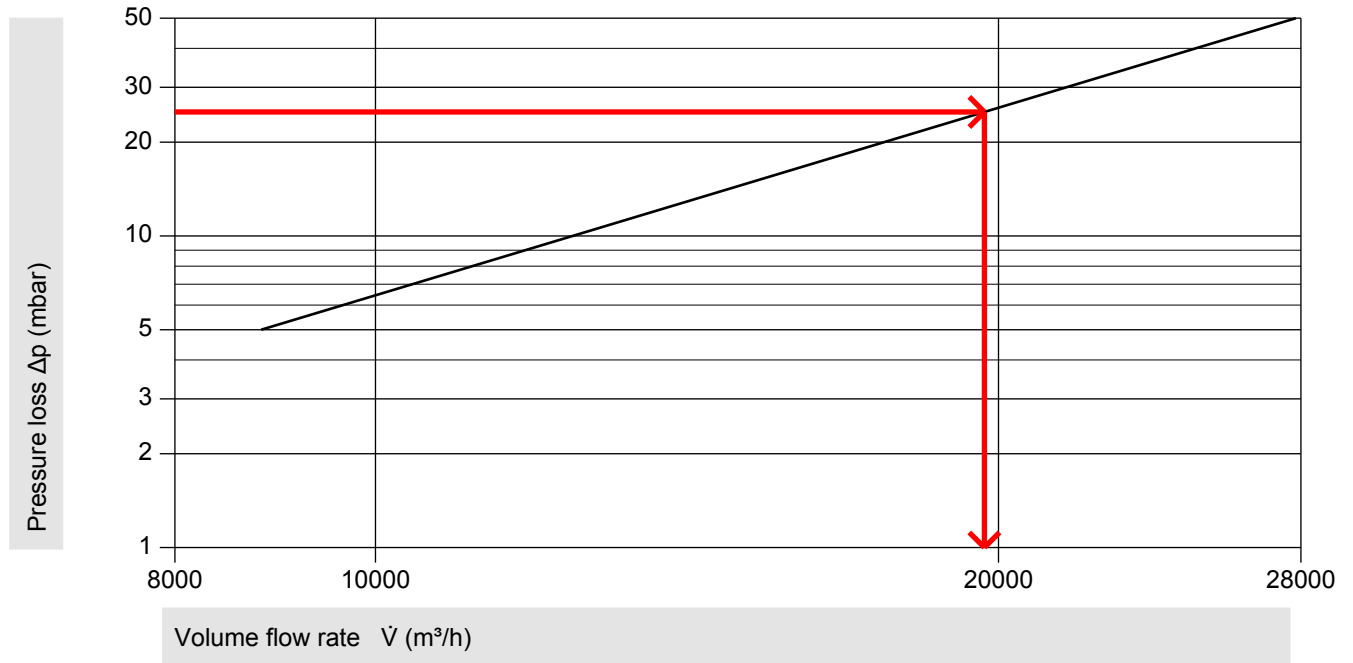


Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

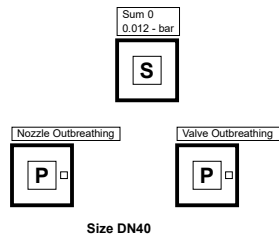


PROTEGO® capacity diagram

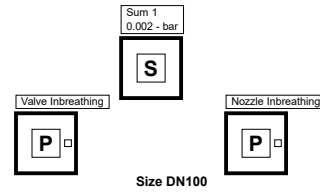
ER/V-500, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar



The required outbreathing flowrate (pump in + thermal effect) is 75 Nm³/h



The required inbreathing flowrate (API2000 > Fullarton; 217 > 214) is 217 Nm³/h.

Ethanol

Design Basis:

Upstream Valve:

- Pipeline = 2.5 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

Downstream Valve:

- Pipeline = 3 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

*For outbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

*For inbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Ethanol Case)

Contract: Ethanol Case
 Date: 8/10/2023

By:	Chk'd:	App'd:
JLG		

Engineer: _____
 Page 1 of 2

General										
Name	Valve Inbreathing		Nozzle Outbreathing		Nozzle Inbreathing		Valve Outbreathing		Sum 0	
Line No.										
Process Conditions										
Mass Flow	kg/hr	280.7		96.9		280.4		96.9		
Std. Volume Flow	Nm³/hr	217.0		75.0		217.0		75.0		
Viscosity	cP	0.019		0.019		0.019		0.019		
Temperature	°C	25.0		25.0		25.0		25.0		
Molecular Weight		29.0		29.0		29.0		29.0		
Compressibility		1.00		1.00		1.00		1.00		
Cp/Cv		1.40		1.41		1.40				
Inlet-Outlet Conditions										
Density (In Out)	kg/m³	1.187	1.186	1.191	1.184	1.186	1.185	1.191	1.184	
Velocity (In Out)	m/s	0.00	7.30	0.00	15.58	7.29	7.29	15.49	15.58	
% Critical Flow - (In Out)	%	0.00	2.50	0.00	5.33	2.49	2.49	5.29	5.33	
Mach Number - (In Out)		0.00	0.02	0.00	0.04	0.02	0.02			
Velocity Head (In Out)	bar	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	
Dynamic Pressure (In Out)	kPa_g	0.086	0.032	0.589	0.144	0.179	0.106	0.741	0.144	
Static Pressure (In Out)	kPa_g	0.086	0.000	0.589	0.000	0.147	0.075	0.598	0.000	
Details										
Design Factor - Frictional Only	%	120.00		120.00		120.00		120.00		
Connect Effect	bar	0.000		0.000		0.000		0.000		0.000
Pipe Data										
Size (Nominal Schedule)	mm	User		User		User		User		
Inside Diameter	mm	107.100		43.100		107.100		43.100		
Length	m	3.0		2.5		2.5		3.0		
Roughness	mm	0.07000		0.07000		0.07000		0.07000		
Friction Factor - (Moody Fully Turbulent)		0.02312	0.01775	0.02617	0.02218	0.02313	0.01775	0.02616	0.02218	
Density (In Out)	kg/m³	1.186	1.186	1.189	1.184	1.186	1.185	1.191	1.184	
Velocity (In Out)	m/s	7.30	7.30	15.52	15.58	7.29	7.29	15.49	15.58	
Velocity Head (In Out)	bar	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.001	
Rho*v² (In Out)	kg/m-s²	63.2	63.2	286.4	287.4	63.0	63.1	285.7	287.4	
Reynold's No.		48,797		41,676		48,730		41,851		
% Critical Flow - (In Out)	%	2.50	2.50	5.31	5.33	2.49	2.49	5.29	5.33	
Mach Number - (In Out)		0.02	0.02	0.04	0.04	0.02	0.02			
Pressure Drop	bar/100-m	0.008		0.105		0.008		0.105		
Pipe Angle	°	-7.66		9.21		-9.21		7.66		
Elevation (In Out)	m	10.8	10.4	10.0	10.4	10.4	10.0	10.4	10.8	
Fittings										
45° Elbow (LR SR)	Qty									
90° Elbow (LR SR)	Qty	2		2		2		2		
180° Elbow (LR SR)	Qty									
Flanged Tee (Branch Run)	Qty									
Threaded Tee (Branch Run)	Qty									
Valve (Ball Gate)	Qty									
Valve (Globe Butterfly)	Qty									
Check Valve (Swing Lift)	Qty									
Control Valve CV	CV									
Additional K	K					1.0		1.0		
Crane X (K=X*ft)										
Additional Length	m									
Additional Drop	bar									
Inlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Entrance		Flush (Sharp Edged)		Flush (Sharp Edged)		(none)		(none)		
Outlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Exit		(none)		(none)		(none)		(none)		
Pressure Drops By Component										
Frictional	bar	0.001		0.004		0.001		0.006		0.010
Static Head	bar	0.000		0.000		0.000		0.000		0.000
Velocity Head	bar	0.000		0.001		0.000		0.000		0.001
Static Pressure Drops										
Pipe	bar	0.000		0.003		0.000		0.003		0.006
Fittings	bar	0.000		0.001		0.001		0.003		0.004
Inlet Effect	bar	0.000		0.002		0.000		0.000		0.002
Outlet Effect	bar	0.000		0.000		0.000		0.000		0.000
Total	bar	0.001		0.006		0.001		0.006		0.012

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Ethanol Case)

Contract: Ethanol Case
 Date: 8/10/2023

By:	Chk'd:	App'd:
JLG		

Engineer: _____
 Page 2 of 2

General					
Name		Sum 1			
Line No.					
Process Conditions					
Mass Flow	kg/hr				
Std. Volume Flow	Nm³/hr				
Viscosity	cP				
Temperature	°C				
Molecular Weight					
Compressibility					
Cp/Cv					
Inlet-Outlet Conditions					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Velocity Head (In Out)	bar				
Dynamic Pressure (In Out)	kPa_g				
Static Pressure (In Out)	kPa_g				
Details					
Design Factor - Frictional Only	%				
Connect Effect	bar	0.000			
Pipe Data					
Size (Nominal Schedule)	mm				
Inside Diameter	mm				
Length	m				
Roughness	mm				
Friction Factor - (Moody Fully Turbulent)					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
Velocity Head (In Out)	bar				
Rho*v² (In Out)	kg/m-s²				
Reynold's No.					
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Pressure Drop	bar/100-m				
Pipe Angle	°				
Elevation (In Out)	m				
Fittings					
45° Elbow (LR SR)	Qty				
90° Elbow (LR SR)	Qty				
180° Elbow (LR SR)	Qty				
Flanged Tee (Branch Run)	Qty				
Threaded Tee (Branch Run)	Qty				
Valve (Ball Gate)	Qty				
Valve (Globe Butterfly)	Qty				
Check Valve (Swing Lift)	Qty				
Control Valve CV	CV				
Additional K	K				
Crane X (K=X*ft)					
Additional Length	m				
Additional Drop	bar				
Inlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Entrance					
Outlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Exit					
Pressure Drops By Component					
Frictional	bar	0.001			
Static Head	bar	0.000			
Velocity Head	bar	0.000			
Static Pressure Drops					
Pipe	bar	0.000			
Fittings	bar	0.001			
Inlet Effect	bar	0.000			
Outlet Effect	bar	0.000			
Total	bar	0.002			

Sizing of a pressure relief valve PRV (high build-up back pressures)

ETHANOL

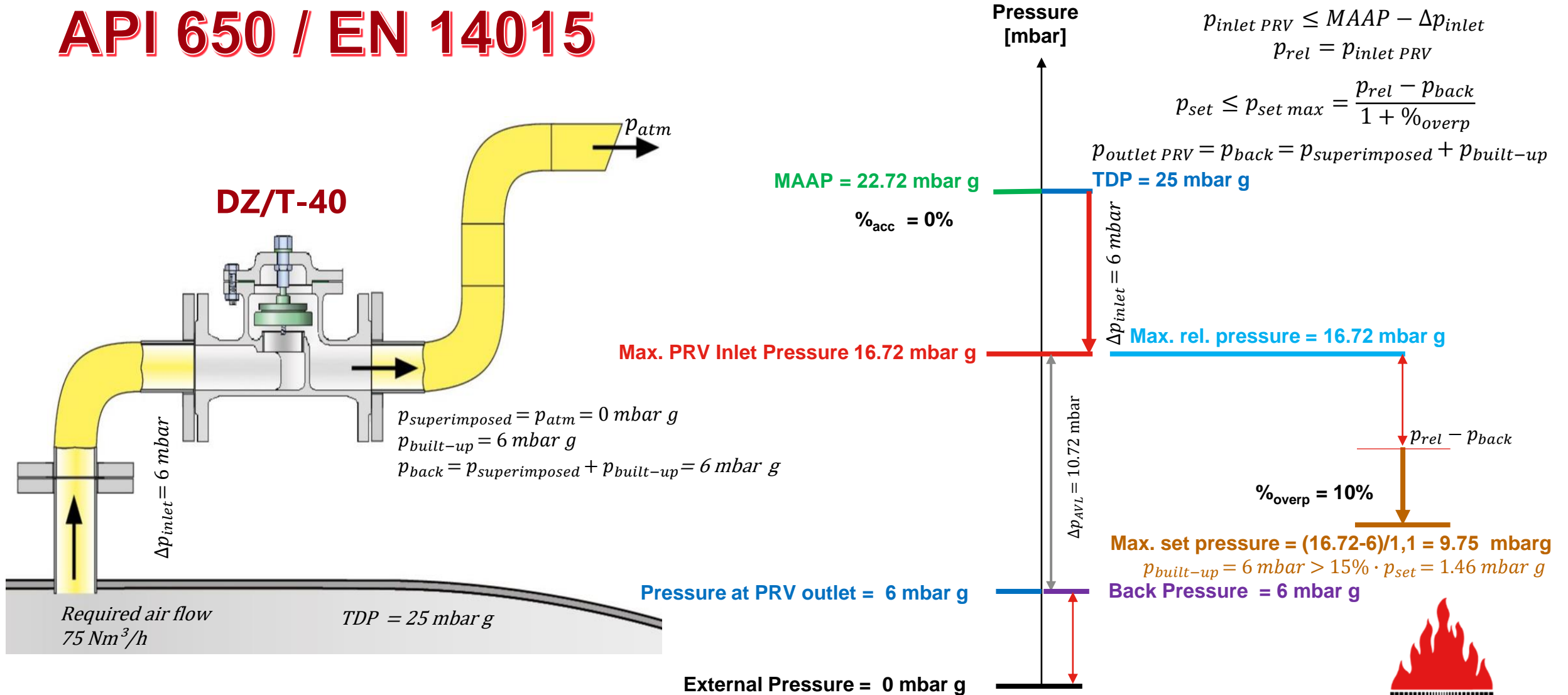
$$p_{built-up (gauge)} > 15\% \cdot p_{set (gauge)}$$

OR

$$\Delta p_{inlet} > 10\% \cdot p_{set (gauge)}$$

Approved for QuEST 3.0

API 650 / EN 14015

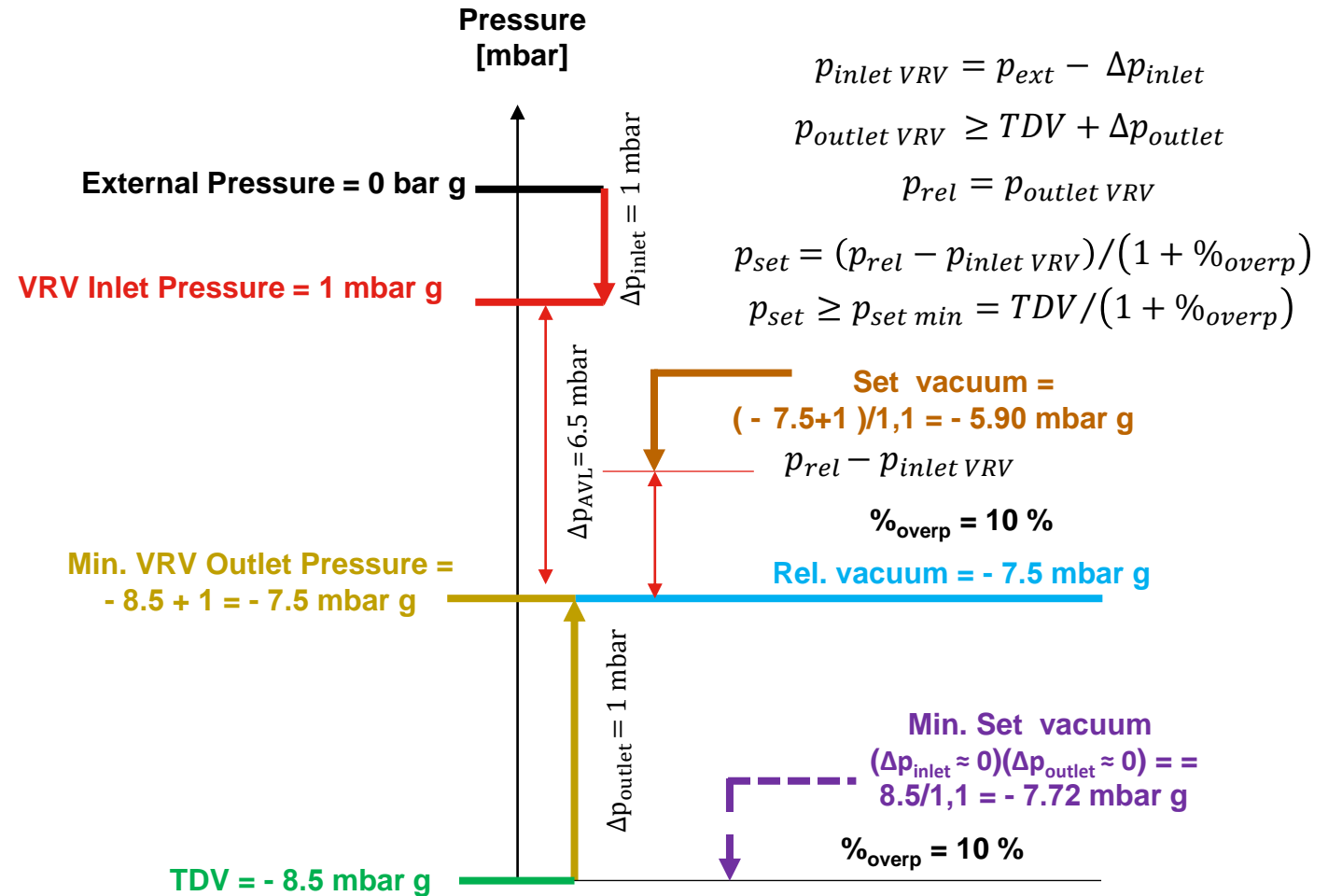
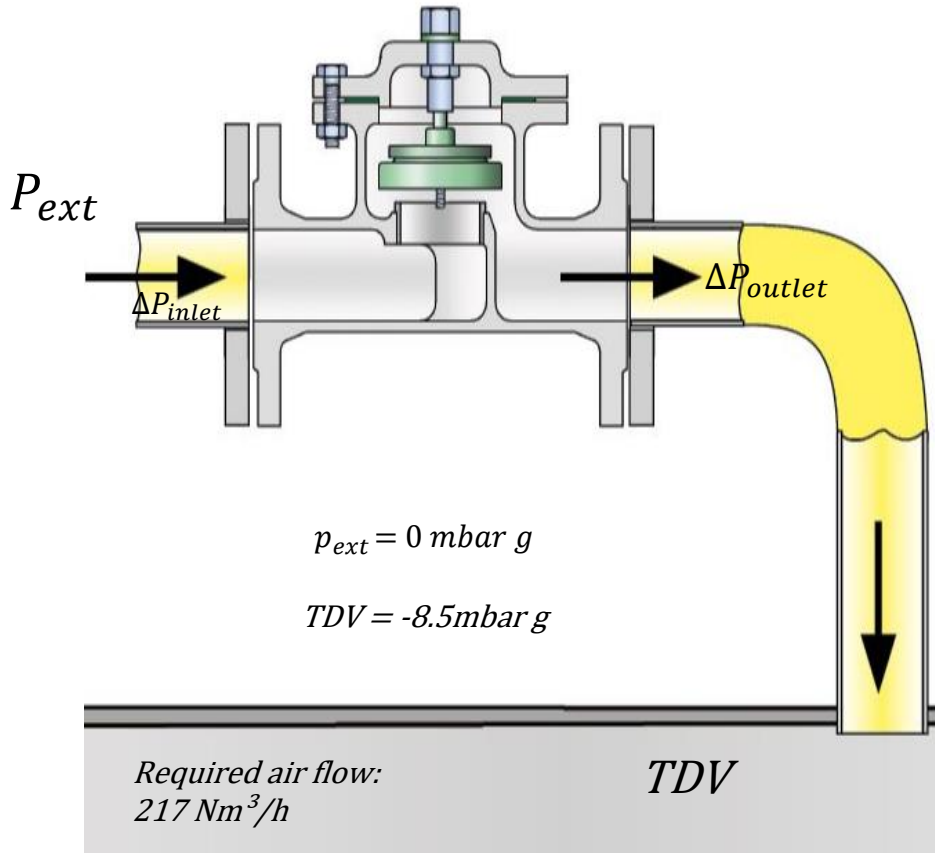


Sizing of a vacuum relief valve VRV

ETHANOL

Approved for QuEST 3.0

DZ/T-100





Project		API 2000 - TFM			
Revision	0.0	Tank location		TARRAGONA	
Atmospheric pressure	1013.25	mbar-a	Tank label		
Quotation number			Tank number		ETHANOL TANK
Job number			Job number by Customer		
Editor	Mr. Joel Lopez		Date		08/10/2023
Notes:					
Tank data					
Tank type	vertical, cylindrical		Height of elevation		0.0 m
Tank height	10.0	m	Tank diameter		4.0 m
Tank volume	125.7	m³	Tank Wetted Surface area ATWS		114.9 m²
Tank design pressure	25.0	mbar-g	Tank design vacuum		-8.5 mbar-g
Max. filling rate	25.0	m³/h	Max. rate of liquid discharge		25.0 m³/h
Product data for normal breathing					
Product	Ethanol				
Molar mass	-		Explosion Group		-
C factor	6.50		Y factor		0.32
Operating temperature	25.0	°C	Vapor pressure		> 5.0 kPa (0.73 psi)
Notes					
Product data for emergency breathing					
Product	Ethanol				
Molar mass	46.07	kg/kmol	Environmental factor		1.0
Boiling point / bubble point	78.17	°C	Latent heat		834.2 KJ/kg
Notes					
Device data					
Max. relieving pressure acc. to	API 650 12th Ed. (EN 14015)		Burn rating		not burning proof
Operating temperature	25.0	°C			



Venting calculation results			Outbreathing	Inbreathing
Normal venting capacity		m³/h	75	217
Load due to filling -in / out		m³/h	50	25
Thermal out- / inbreathing		m³/h	25	192
Emergency relief load		m³/h	9403	-
C factor	6.50	Y factor	0.32	
Tank volume	125.7	m³	Tank Wetted Surface area ATWS	114.9 m²
Notes:				
Signatures and Stamps or Company logo:				

Loads are expressed in Air at Normal conditions (0.00 °C, 101.325 kPa-a)

Venting calculation results converted into PROTEGO® diagram conditions			Outbreathing	Inbreathing
Normal venting capacity		m³/h	82	236
Emergency relief load		m³/h	10225	-

Loads are expressed in Air at PROTEGO® diagram conditions (20°C, 1 bar)



Device selection / Basic data			
Device		DZ/T-40	DZ/T-100
Manufacturer		Braunschweiger Flammenfilter GmbH	Braunschweiger Flammenfilter GmbH
Type of device		In-line device	In-line device
Inlet flange	DN	40	100
Outlet flange	DN	40	100
Nominal width NG		-	-
Function		Pressure or Vacuum Relief Valve	Pressure or Vacuum Relief Valve
Set pressure P	mbar-g	9.75	-
Set pressure V	mbar-g	-	-5.9
Relieving pressure minus back pressure (P)	mbar	10.73	-
Relieving pressure minus inlet pressure (V)	mbar	-	-6.49
Adjusted set pressure (P)	mbar-g	9.75	-
Adjusted set pressure (V)	mbar-g	-	-5.9
Overpressure P / V	%	10.0 / -	- / 10.0
Capacity air at normal condition P	m³/h	81	-
Capacity air at normal condition V	m³/h	-	255
Back pressure	mbar-g	6.0	-
Inlet line pressure loss (P)	mbar	6.0	-
External pressure	mbar	-	0.0
Pressure loss to VRV inlet	mbar	-	1.0
Pressure loss between VRV outlet and tank	mbar	-	1.0
Capacity as per PROTEGO® Diagramm (P)	m³/h	88	-
Capacity as per PROTEGO® Diagramm (V)	m³/h	-	277
Number of required devices		1	1
Excess capacity air at normal condition P	%	8.92	-
Excess capacity air at normal condition V	%	-	17.9
Notes: The pressure loss is considered. An additional load is considered according to Fullarton (see explanation Section 8.2)			
Signatures and Stamps or Company logo:			

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



Device selection / Basic data			
Device		ER/V-400	
Manufacturer		Braunschweiger Flammenfilter GmbH	
Type of device		End-of-line device	
Inlet flange	DN	400	
Outlet flange	DN	-	
Nominal width NG		-	
Function		Pressure Relief Valve	
Set pressure P	mbar-g	22.72	
Relieving pressure minus back pressure (P)	mbar	25.0	
Adjusted set pressure (P)	mbar-g	22.72	
Overpressure P / V	%	10.0 / -	
Capacity air at normal condition P	m³/h	11584	
Back pressure		-	
Inlet line pressure loss (P)	mbar	0.0	
Capacity as per PROTEGO® Diagramm (P)	m³/h	12597	
Number of required devices		1	
Excess capacity air at normal condition P	%	24.2	
Notes:			
Signatures and Stamps or Company logo:			

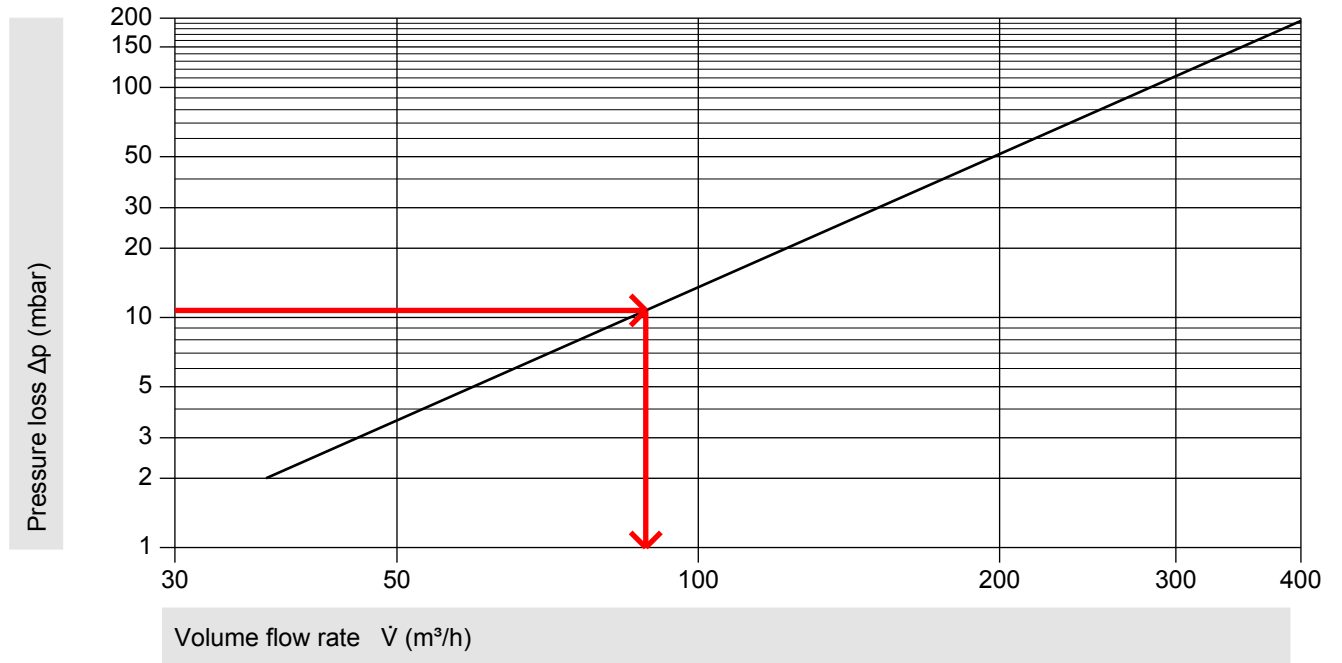
The required flow capacity for the emergency venting device is the difference between the emergency and the normal outbreathing requirement.

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



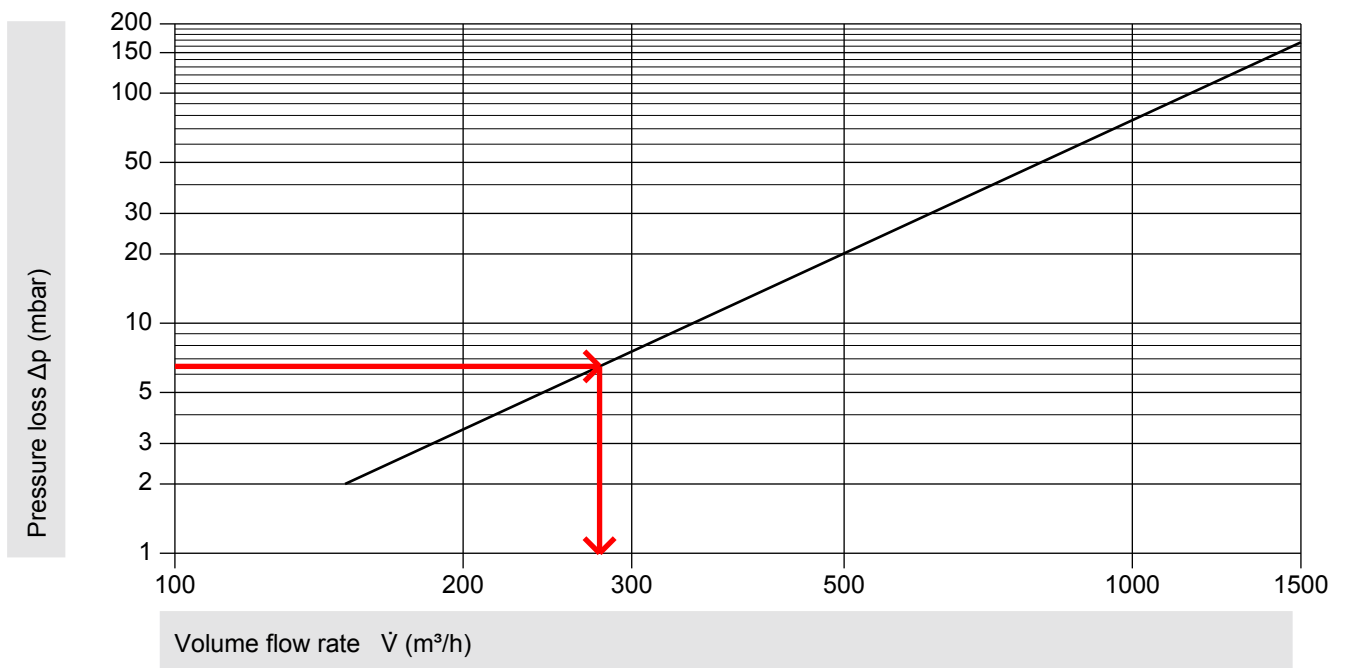
PROTEGO® capacity diagram

DZ/T-40, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

DZ/T-100, Vacuum

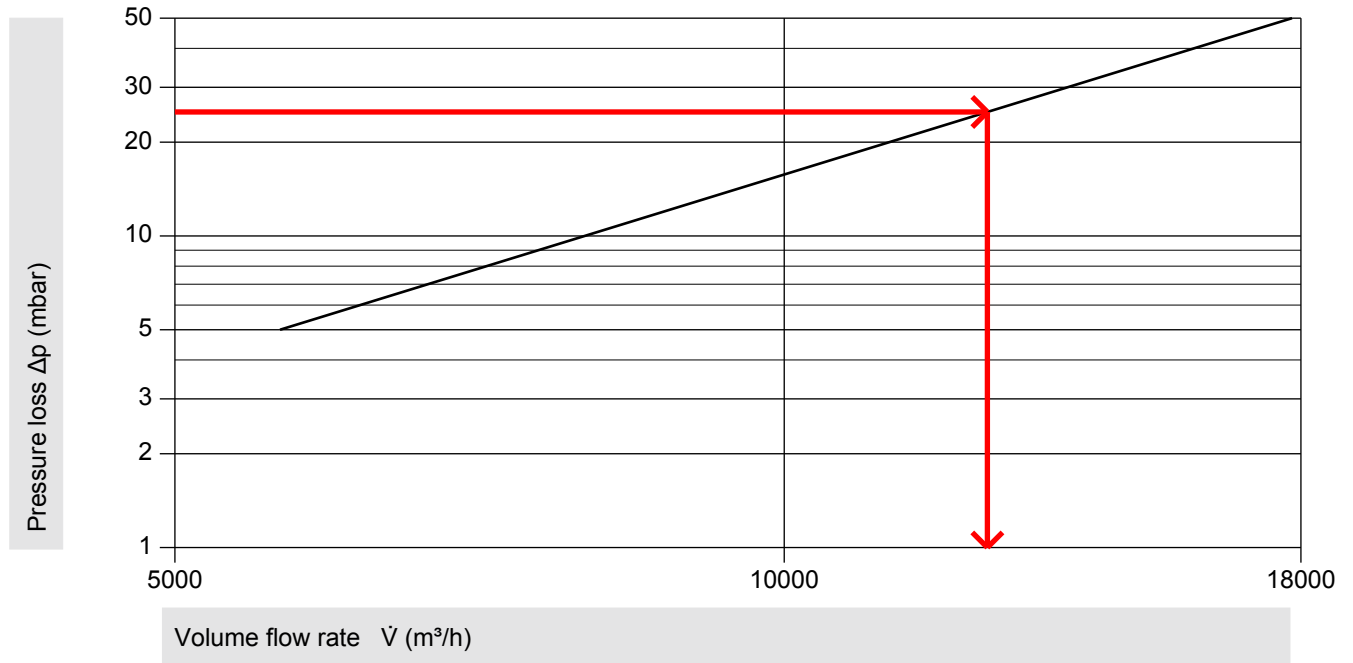


Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

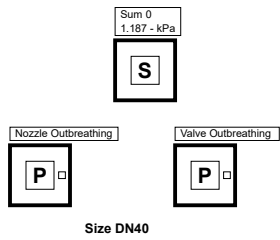


PROTEGO® capacity diagram

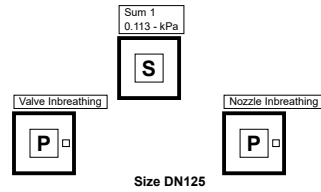
ER/V-400, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar



The required outbreathing flowrate (pump in + thermal effect) is 75 Nm³/h



The required inbreathing flowrate (API2000 < Fullarton; 217 < 290) is 290 Nm³/h.

Methanol

Design Basis:

Upstream Valve:

- Pipeline = 2.5 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

Downstream Valve:

- Pipeline = 3 m
- Absolute roughness = 0.07 mm
- Elbow 90° (Long x2)
- Flush sharp edged

*For outbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

*For inbreathing cases, an additional friction loss factor of K=1 at the outlet is taken into account, according to API520.
K=1 (Sudden expansion, exit loss)

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY
(Methanol Case)

Contract: Methanol Case
 Date: 8/10/2023
 By: _____ Chk'd: _____ App'd: _____
 Engineer: JLG
 Page 1 of 2

General										
Name		Valve Inbreathing		Nozzle Outbreathing		Nozzle Inbreathing		Valve Outbreathing		Sum 0
Line No.										
Process Conditions										
Mass Flow	kg/hr		375.2		96.9		374.7		96.9	
Std. Volume Flow	Nm³/hr		290.0		75.0		290.0		75.0	
Viscosity	cP		0.019		0.019		0.019		0.019	
Temperature	°C		25.0		25.0		25.0		25.0	
Molecular Weight			29.0		29.0		29.0		29.0	
Compressibility			1.00		1.00		1.00		1.00	
Cp/Cv			1.40		1.41		1.40			
Inlet-Outlet Conditions										
Density (In Out)	kg/m³	1.187	1.186	1.191	1.184	1.185	1.184	1.191	1.184	
Velocity (In Out)	m/s	0.00	6.45	0.00	15.58	6.45	6.45	15.49	15.58	
% Critical Flow - (In Out)	%	0.00	2.21	0.00	5.33	2.20	2.21	5.29	5.33	
Mach Number - (In Out)		0.00	0.02	0.00	0.04	0.02	0.02			
Velocity Head (In Out)	kPa	0.000	0.025	0.000	0.144	0.025	0.025	0.143	0.144	
Dynamic Pressure (In Out)	kPa_g	0.062	0.025	0.589	0.144	0.076	0.025	0.741	0.144	
Static Pressure (In Out)	kPa_g	0.062	0.000	0.589	0.000	0.052	0.000	0.598	0.000	
Details										
Design Factor - Frictional Only	%		120.00		120.00		120.00		120.00	
Connect Effect	kPa		0.000		0.000		0.000		0.000	0.000
Pipe Data										
Size (Nominal Schedule)	mm		User		User		User		User	
Inside Diameter	mm		131.700		43.100		131.700		43.100	
Length	m		3.0		2.5		2.5		3.0	
Roughness	mm		0.07000		0.07000		0.07000		0.07000	
Friction Factor - (Moody Fully Turbulent)		0.02244	0.01693	0.02617	0.02218	0.02245	0.01693	0.02616	0.02218	
Density (In Out)	kg/m³	1.186	1.186	1.189	1.184	1.185	1.184	1.191	1.184	
Velocity (In Out)	m/s	6.45	6.45	15.52	15.58	6.45	6.45	15.49	15.58	
Velocity Head (In Out)	kPa	0.025	0.025	0.143	0.144	0.025	0.025	0.143	0.144	
Rho*v² (In Out)	kg/m-s²	49.3	49.4	286.4	287.4	49.3	49.3	285.7	287.4	
Reynold's No.			53,032		41,676		52,959		41,851	
% Critical Flow - (In Out)	%	2.21	2.21	5.31	5.33	2.20	2.21	5.29	5.33	
Mach Number - (In Out)		0.02	0.02	0.04	0.04	0.02	0.02			
Pressure Drop	bar/100-m		0.005		0.105		0.005		0.105	
Pipe Angle	°		-7.66		9.21		-9.21		7.66	
Elevation (In Out)	m	10.8	10.4	10.0	10.4	10.4	10.0	10.4	10.8	
Fittings										
45° Elbow (LR SR)	Qty									
90° Elbow (LR SR)	Qty	2		2		2		2		
180° Elbow (LR SR)	Qty									
Flanged Tee (Branch Run)	Qty									
Threaded Tee (Branch Run)	Qty									
Valve (Ball Gate)	Qty									
Valve (Globe Butterfly)	Qty									
Check Valve (Swing Lift)	Qty									
Control Valve CV	CV									
Additional K	K						1.0		1.0	
Crane X (K=X*ft)										
Additional Length	m									
Additional Drop	kPa									
Inlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Entrance			Flush (Sharp Edged)		Flush (Sharp Edged)		(none)		(none)	
Outlet Effect										
R/E Inside Diameter	mm									
R/E Length (User Default)	mm									
Pipe Exit			(none)		(none)		(none)		(none)	
Pressure Drops By Component										
Frictional	kPa		0.042		0.440		0.056		0.592	1.032
Static Head	kPa		-0.005		0.005		-0.005		0.005	0.009
Velocity Head	kPa		0.025		0.144		0.000		0.002	0.146
Static Pressure Drops										
Pipe	kPa		0.010		0.267		0.008		0.318	0.585
Fittings	kPa		0.014		0.107		0.044		0.280	0.387
Inlet Effect	kPa		0.037		0.215		0.000		0.000	0.215
Outlet Effect	kPa		0.000		0.000		0.000		0.000	0.000
Total	kPa		0.062		0.589		0.052		0.598	1.187

Client: _____
 Plant: _____
 Site: _____
 Revision: _____

SUMMARY

(Methanol Case)

Contract: Methanol Case
 Date: 8/10/2023

By:	Chk'd:	App'd:
JLG		

Engineer: _____
 Page 2 of 2

General					
Name		Sum 1			
Line No.					
Process Conditions					
Mass Flow	kg/hr				
Std. Volume Flow	Nm³/hr				
Viscosity	cP				
Temperature	°C				
Molecular Weight					
Compressibility					
Cp/Cv					
Inlet-Outlet Conditions					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Velocity Head (In Out)	kPa				
Dynamic Pressure (In Out)	kPa_g				
Static Pressure (In Out)	kPa_g				
Details					
Design Factor - Frictional Only	%				
Connect Effect	kPa	0.000			
Pipe Data					
Size (Nominal Schedule)	mm				
Inside Diameter	mm				
Length	m				
Roughness	mm				
Friction Factor - (Moody Fully Turbulent)					
Density (In Out)	kg/m³				
Velocity (In Out)	m/s				
Velocity Head (In Out)	kPa				
Rho*v² (In Out)	kg/m-s²				
Reynold's No.					
% Critical Flow - (In Out)	%				
Mach Number - (In Out)					
Pressure Drop	bar/100-m				
Pipe Angle	°				
Elevation (In Out)	m				
Fittings					
45° Elbow (LR SR)	Qty				
90° Elbow (LR SR)	Qty				
180° Elbow (LR SR)	Qty				
Flanged Tee (Branch Run)	Qty				
Threaded Tee (Branch Run)	Qty				
Valve (Ball Gate)	Qty				
Valve (Globe Butterfly)	Qty				
Check Valve (Swing Lift)	Qty				
Control Valve CV	CV				
Additional K	K				
Crane X (K=X*ft)					
Additional Length	m				
Additional Drop	kPa				
Inlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Entrance					
Outlet Effect					
R/E Inside Diameter	mm				
R/E Length (User Default)	mm				
Pipe Exit					
Pressure Drops By Component					
Frictional	kPa	0.098			
Static Head	kPa	-0.009			
Velocity Head	kPa	0.025			
Static Pressure Drops					
Pipe	kPa	0.018			
Fittings	kPa	0.058			
Inlet Effect	kPa	0.037			
Outlet Effect	kPa	0.000			
Total	kPa	0.113			

Sizing of a pressure relief valve PRV (high build-up back pressures)

METHANOL

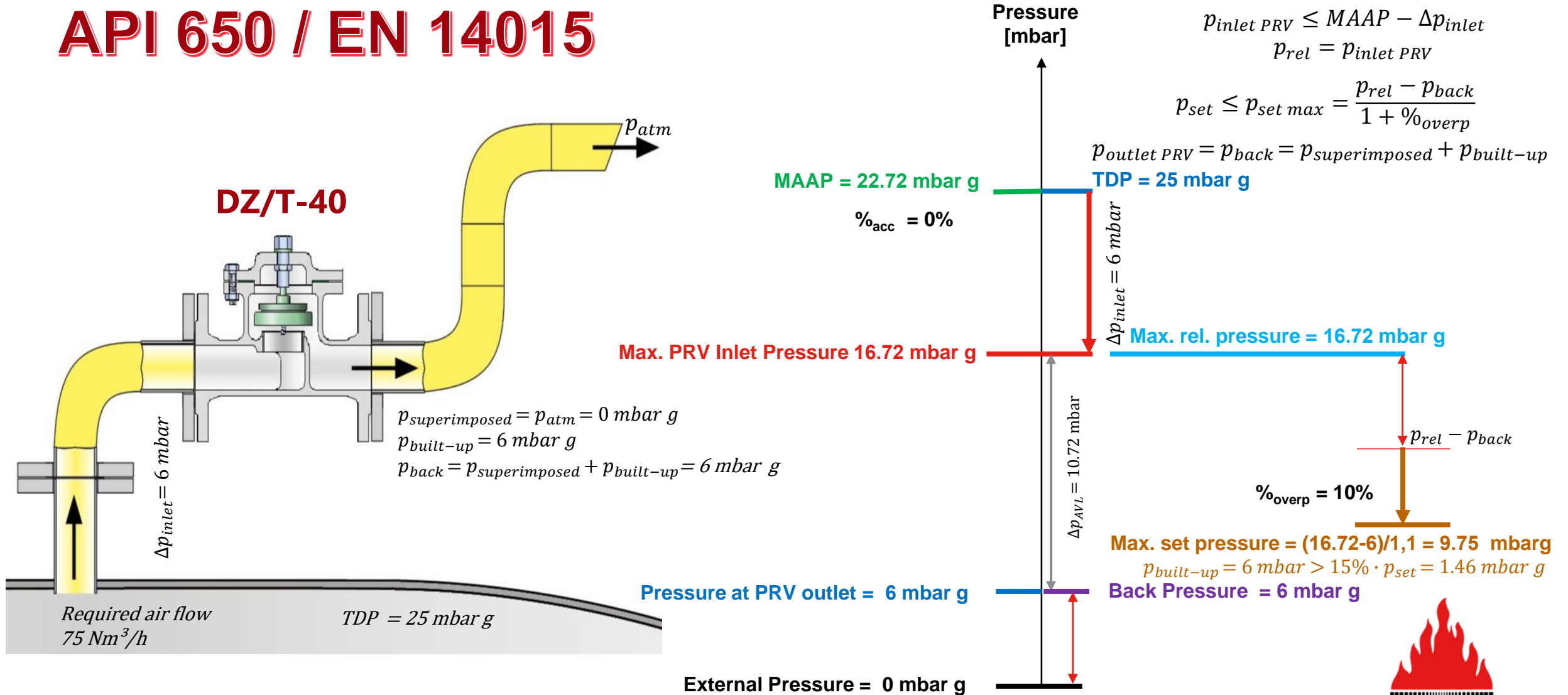
$$p_{built-up (gauge)} > 15\% \cdot p_{set (gauge)}$$

OR

$$\Delta p_{inlet} > 10\% \cdot p_{set (gauge)}$$

Approved for QuEST 3.0

API 650 / EN 14015

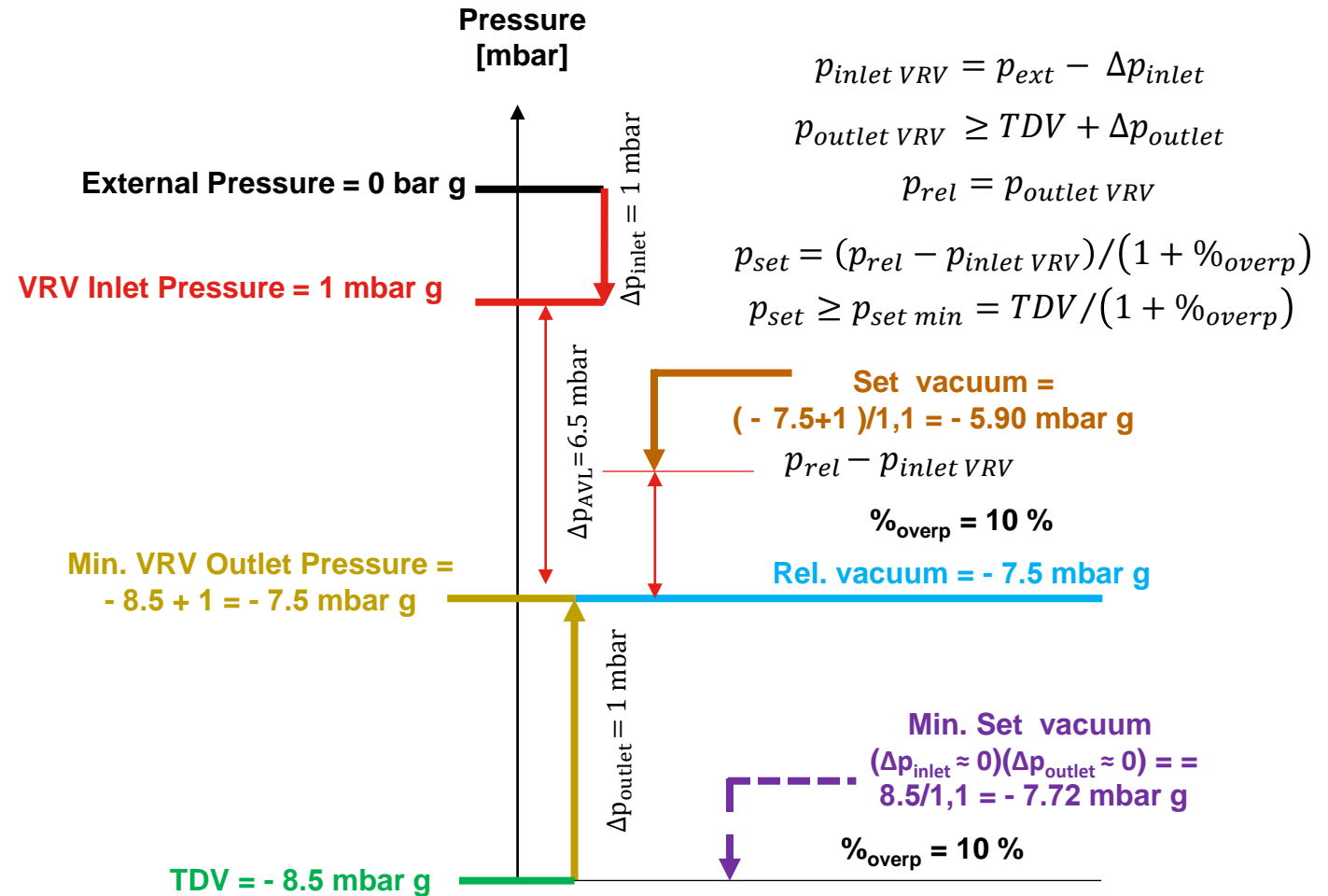
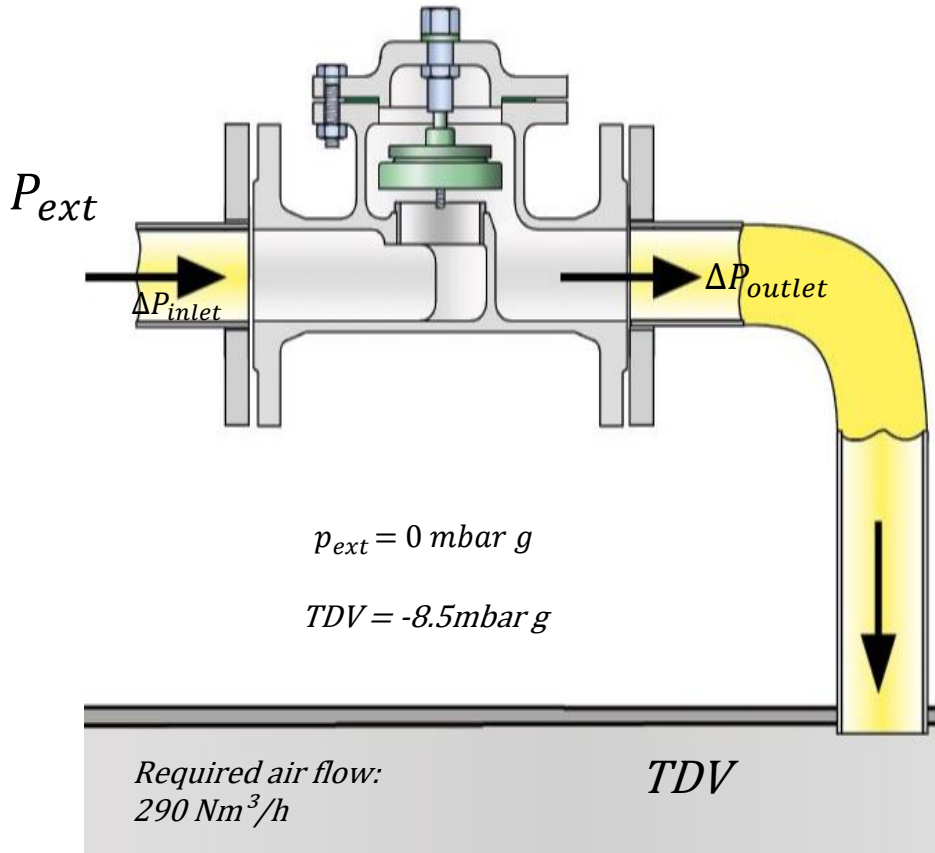


Sizing of a vacuum relief valve VRV

METHANOL

Approved for QuEST 3.0

DZ/T-125





Project		API 2000 - TFM			
Revision	0.0	Tank location		TARRAGONA	
Atmospheric pressure	1013.25	mbar-a	Tank label		
Quotation number			Tank number		METHANOL TANK
Job number			Job number by Customer		
Editor	Mr. Joel Lopez		Date		08/10/2023
Notes:					
Tank data					
Tank type	vertical, cylindrical		Height of elevation		0.0 m
Tank height	10.0	m	Tank diameter		4.0 m
Tank volume	125.7	m³	Tank Wetted Surface area ATWS		114.9 m²
Tank design pressure	25.0	mbar-g	Tank design vacuum		-8.5 mbar-g
Max. filling rate	25.0	m³/h	Max. rate of liquid discharge		25.0 m³/h
Product data for normal breathing					
Product	METHANOL				
Molar mass	-		Explosion Group		-
C factor	6.50		Y factor		0.32
Operating temperature	25.0	°C	Vapor pressure		> 5.0 kPa (0.73 psi)
Notes					
Product data for emergency breathing					
Product	METHANOL				
Molar mass	32.04	kg/kmol	Environmental factor		1.0
Boiling point / bubble point	64.5	°C	Latent heat		1100.0 KJ/kg
Notes					
Device data					
Max. relieving pressure acc. to	API 650 12th Ed. (EN 14015)		Burn rating		not burning proof
Operating temperature	25.0	°C			



Venting calculation results			Outbreathing	Inbreathing
Normal venting capacity		m ³ /h	75	290
Load due to filling -in / out		m ³ /h	50	25
Thermal out- / inbreathing		m ³ /h	25	192
Uninsulated hot tanks (Vapor condensation)		m ³ /h	-	73.0
Emergency relief load		m ³ /h	8383	-
C factor	6.50		Y factor	0.32
Tank volume	125.7	m ³	Tank Wetted Surface area ATWS	114.9 m ²
Notes:				
Signatures and Stamps or Company logo:				

Loads are expressed in Air at Normal conditions (0.00 °C, 101.325 kPa-a)

Venting calculation results converted into PROTEGO® diagram conditions		Outbreathing	Inbreathing
Normal venting capacity	m ³ /h	82	315
Emergency relief load	m ³ /h	9116	-

Loads are expressed in Air at PROTEGO® diagram conditions (20°C, 1 bar)



Device selection / Basic data			
Device		DZ/T-40	DZ/T-125
Manufacturer		Braunschweiger Flammenfilter GmbH	Braunschweiger Flammenfilter GmbH
Type of device		In-line device	In-line device
Inlet flange	DN	40	125
Outlet flange	DN	40	125
Nominal width NG		-	-
Function		Pressure or Vacuum Relief Valve	Pressure or Vacuum Relief Valve
Set pressure P	mbar-g	9.75	-
Set pressure V	mbar-g	-	-5.9
Relieving pressure minus back pressure (P)	mbar	10.73	-
Relieving pressure minus inlet pressure (V)	mbar	-	-6.49
Adjusted set pressure (P)	mbar-g	9.75	-
Adjusted set pressure (V)	mbar-g	-	-5.9
Overpressure P / V	%	10.0 / -	- / 10.0
Capacity air at normal condition P	m³/h	81	-
Capacity air at normal condition V	m³/h	-	408
Back pressure	mbar-g	6.0	-
Inlet line pressure loss (P)	mbar	6.0	-
External pressure	mbar	-	0.0
Pressure loss to VRV inlet	mbar	-	1.0
Pressure loss between VRV outlet and tank	mbar	-	1.0
Capacity as per PROTEGO® Diagramm (P)	m³/h	88	-
Capacity as per PROTEGO® Diagramm (V)	m³/h	-	444
Number of required devices		1	1
Excess capacity air at normal condition P	%	8.92	-
Excess capacity air at normal condition V	%	-	40.78
Notes: The pressure loss is considered. An additional inbreathing load is taken into account according to Fullarton calculation (see explanation in Section 8.2)			
Signatures and Stamps or Company logo:			

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



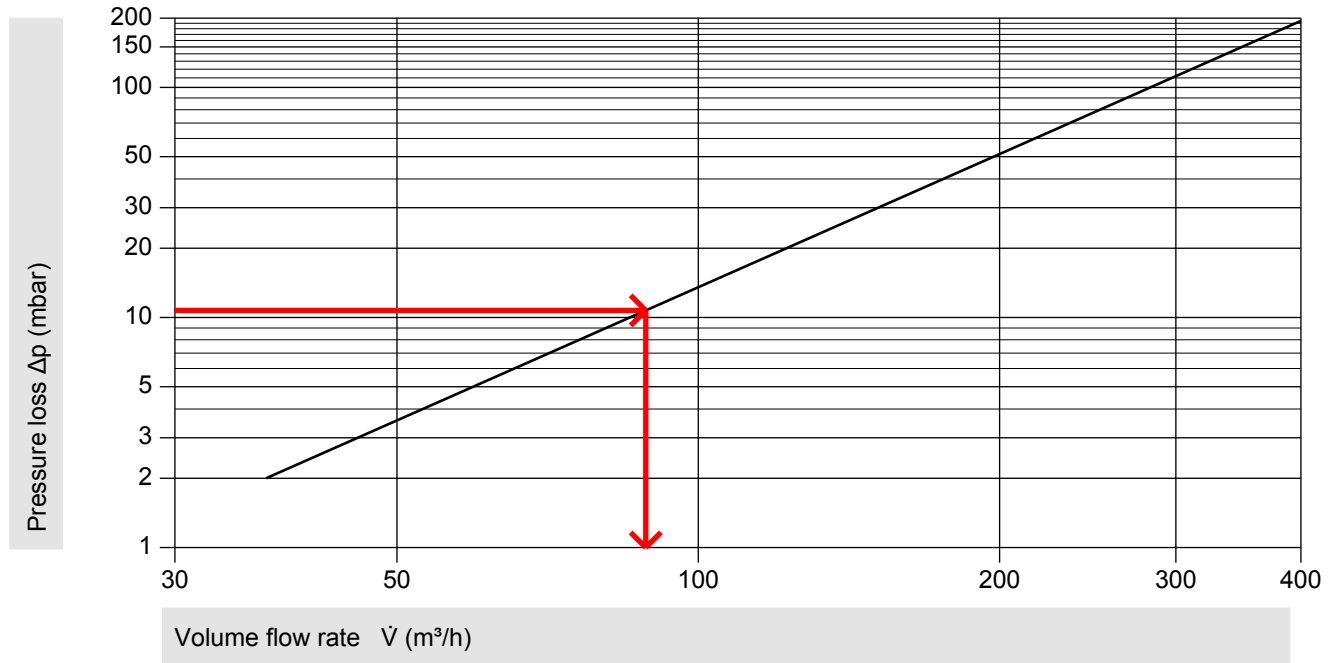
Device selection / Basic data			
Device		ER/V-350	
Manufacturer		Braunschweiger Flammenfilter GmbH	
Type of device		End-of-line device	
Inlet flange	DN	350	
Outlet flange	DN	-	
Nominal width NG		-	
Function		Pressure Relief Valve	
Set pressure P	mbar-g	22.72	
Relieving pressure minus back pressure (P)	mbar	25.0	
Adjusted set pressure (P)	mbar-g	22.72	
Overpressure P / V	%	10.0 / -	
Capacity air at normal condition P	m³/h	8870	
Back pressure		-	
Inlet line pressure loss (P)	mbar	0.0	
Capacity as per PROTEGO® Diagramm (P)	m³/h	9646	
Number of required devices		1	
Excess capacity air at normal condition P	%	5.83	
Notes:			
Signatures and Stamps or Company logo:			

Device flow capacity values are displayed as rounded down to the next lower unit. Excess capacity values are calculated with the actual device capacity. (P) Pressure (V) Vacuum. For built-up back pressures larger than 15% of set pressure please contact your PROTEGO sales representative



PROTEGO® capacity diagram

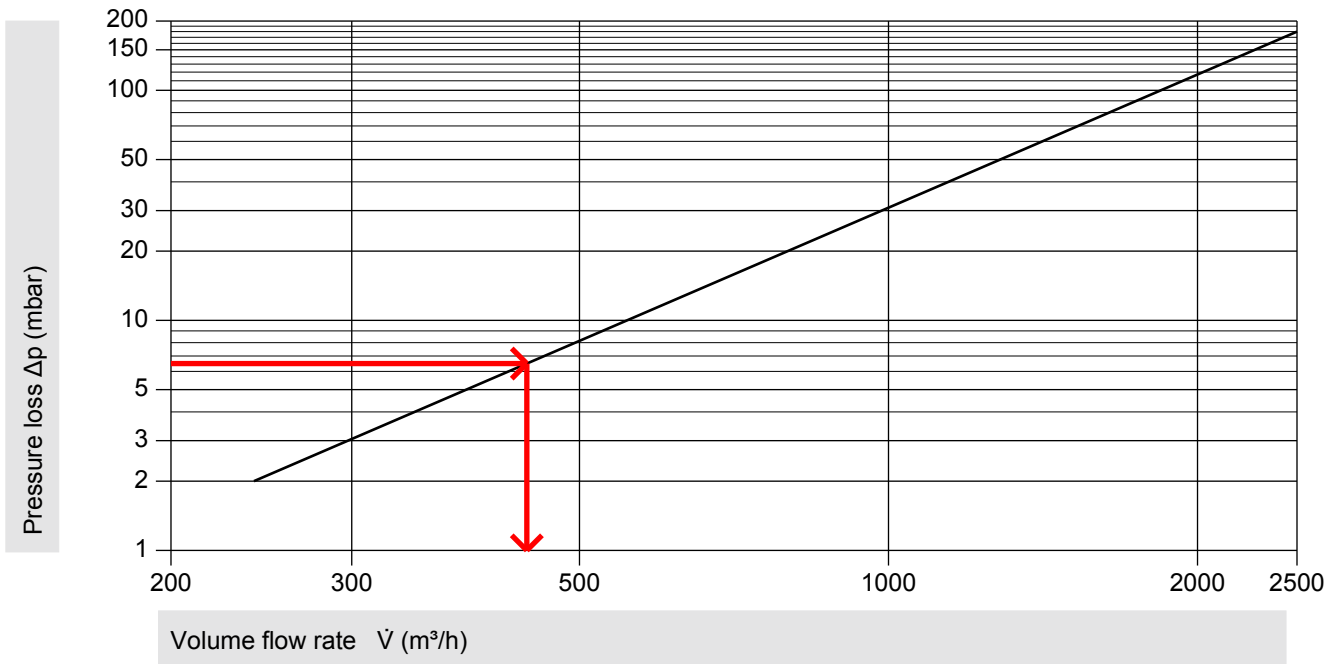
DZ/T-40, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar

PROTEGO® capacity diagram

DZ/T-125, Vacuum

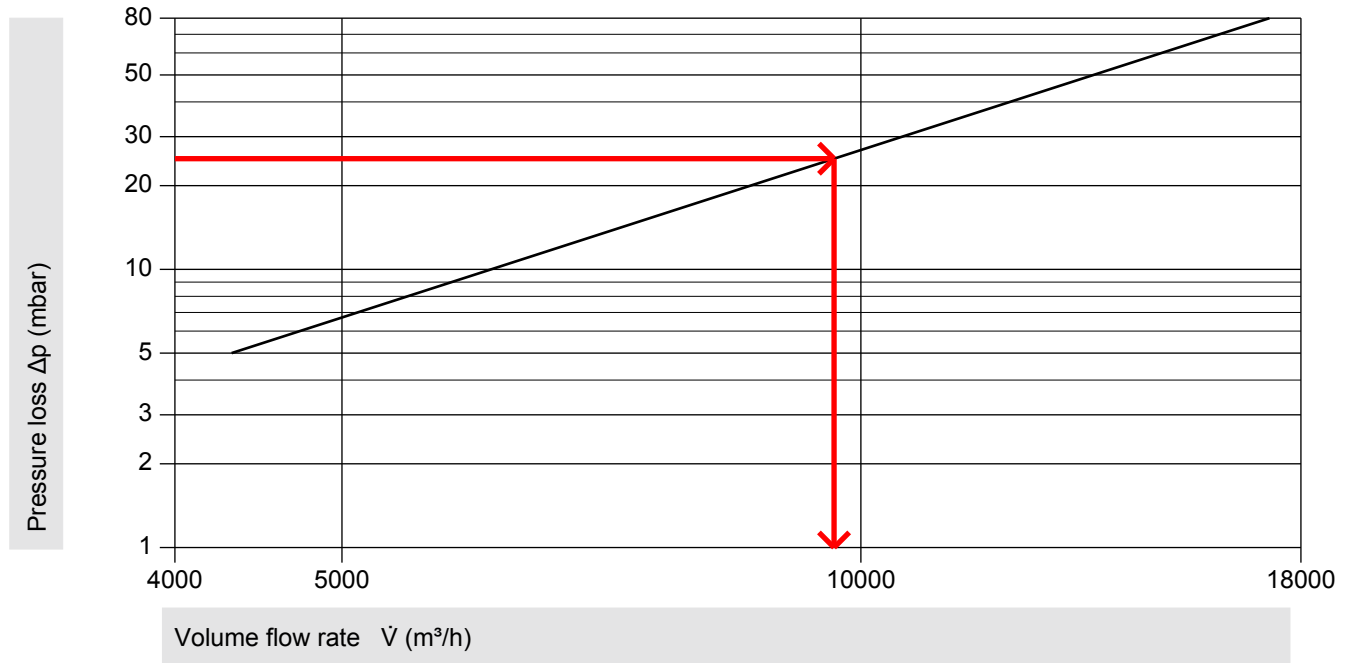


Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar



PROTEGO® capacity diagram

ER/V-350, Pressure



Capacity loads as per PROTEGO Diagrams refer to air as per ISO 6358 at 20°C, 1 bar