7.4.8 Fire Case and Hydraulic (Thermal) Expansion acc. to API 521 and ISO 23251

This standard deals with the planning of safety requirements for pressure-relieving and depressurizing systems. It analyses the major causes for overpressure and gives some indicative values for the determination of the individual relieving rates in a variety of practical cases. It is fully introduced in the new standard[5] ISO 23251. Formulas in both standards are identical, except for the units. For the application of API 521 formulas the user must use the US units, which are reported on the third column of Table 7.4.8.1-1, while for the formulas in ISO 23251 the SI units, defined of the fourth column of the same table.

This section of ENGINEERING shows the equations for the sizing in case of

- ✓ Hydraulic Expansion (API 521 Par. 5.14, ISO 23251 Par. 5.14)
- ✓ External Fire Case (API 521 Par. 5.15, ISO 23251 Par 5.15)

Hydraulic expansion or Thermal expansion is the increase in the liquid volume due to an increment in temperature. Typically it occurs for liquids, which are trapped in vessels, pipes, heat exchangers and exposed to heat, for instance from electrical coils, ambient heat, fire, etc.

In the external fire case sizing API 521 distinguishes between *wetted* and *unwetted vessels* according to the following definitions and presents for each of them a sizing procedure.

A wetted vessel contains a liquid in equilibrium with its vapor or a gas. Wetted vessels contain temperated systems. In consequence of the heat transfer from the external fire a partial evaporation of the liquid occurs. In the calculation of the portion of vessel exposed to fire only that portion in contact with the liquid within a distance of 25 feet (in ISO 23251 7.6 m) above the fire source must be considered for sizing, see Table 7.4.8.3-1. If the exposure to fire leads to vapor generation from thermal cracking, alternate sizing methods may be appropriate.

An unwetted vessel is a vessel, which is either thermally insulated on the internal walls or filled with gases, vapors or a supercritical fluid. Unwetted vessels contain gassy systems. Vessels with separated liquid and vapor under normal conditions which become single-phase at relieving conditions belong here as well. However, vessels, whose walls become thermally insulated due to the deposition of coke or material from the contained fluids, are still considered wetted for fire sizing case however additional protection is required. In comparison to wetted vessels the thermal flow from the walls to the interior is low in unwetted vessels due to the large thermal resistance. In case of prolonged exposure of the outside surface to the fire source the temperature within the walls may be so high to cause thermal rupture of the vessel.

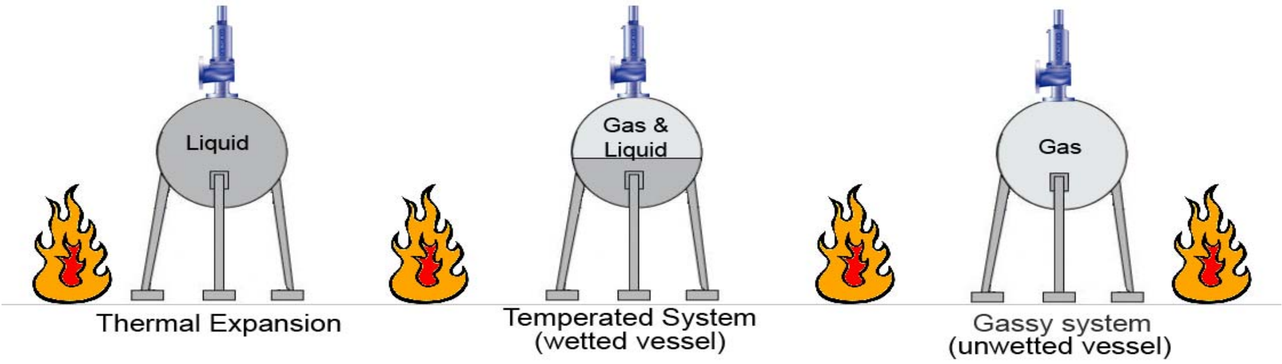

Figure: 7.4.8-1: Hydraulic (thermal) expansion and fire case

[5] ISO 23251 Petroleum and natural gas industries – Pressure relieving and depressuring systems, 2007

7.4.8.1 List of Symbols/Nomenclature

Symbol	Description	Units [US]	Units [SI]
A	Effective discharge area of the valve	[in²]	*
A'	Exposed surface area of the vessel	[ft²]	*
A_{ws}	Total wetted surface	[ft²]	[m²]
α_v	Cubical expansion coefficient of the liquid at the expected temperature	[1/°F]	[1/°C]
c	Specific heat capacity of the trapped liquid	[Btu/(lb °F)]	[J/(kg K)]
F	Environment factor	--	--
d	Relative density referred to water at 60°F (15.6°C)	--	--
h_{vl0}	Latent heat of vaporization	[Btu/lb]	[J/kg]
K_D	Coefficient of discharge	--	--
ϕ	Total heat transfer rate	[Btu/hr]	[W]
M	Molecular mass of the gas	[lb/lb_{mol}]	[kg/k_{mol}]
P_1	Upstream relieving absolute pressure	[psi]	*
Q	Total absorbed (input) heat to the wetted surface	[Btu/hr]	[W]
q	Volume flow rate at the flowing temperature	[gpm]	[m³/s]
q_m	Relief load / mass flow rate	[lb/hr]	*
T_1	Gas temperature at upstream relieving pressure	[°R]	*
T_w	Recommended max. vessel wall temperature	[°R]	*

Table 7.4.8.1-1 List of symbols for sizing acc. to API 521

* The sizing formulas in ISO 23251 are identical to those in API 521, which are expressed in US Units. Conversion factors to specified SI units have been not yet provided. The application of the formula using US units is therefore recommended.

7.4.8.2 Hydraulic Expansion (Thermal Expansion)

The mass flow rate for the sizing of the safety valve for a liquid vessel exposed to a heat source can be approximated by Eq. 7.4.8.2-1 (Eq. 7.4.8.2-2) for the case that the trapped liquid does not evaporate. However, the mass flow rates are usually so small that a safety valve sized NPS ¾ x NPS 1 (DN 20 x DN 25) should be sufficient acc. to API 521 Par. 5.14.2.

$$q = \frac{1}{500}\frac{\alpha_v \cdot \phi}{d \cdot c}$$ (API 521) *(Eq. 7.4.8.2-1)*

$$q = \frac{1}{1000}\frac{\alpha_v \cdot \phi}{d \cdot c}$$ (ISO 23251) *(Eq. 7.4.8.2-2)*

The cubical expansion coefficient of the liquid should be obtained from the process data; however, for water and hydrocarbon liquids at 60°F (15.6°C) some reference values are given in Table 7.4.8.2-1. However, more precise values should be obtained from process design data.

Gravity of liquid (°API)	α_v [1/°F]	α_v [1/°C]
3 – 34.9	0.0004	0.00072
35 – 50.9	0.0005	0.0009
51 – 63.9	0.0006	0.00108
64 – 78.9	0.0007	0.00126
79 – 88.9	0.0008	0.00144
89 – 93.9	0.00085	0.00153
94 – 100 and lighter	0.0009	0.00162
Water	0.0001	0.00018

Table 7.4.8.2-1 Value of cubical expansion coefficient for hydrocarbon liquids at 60°F in API 521

If the liquid is supposed to flash or form solids during the flow in the safety valve, the sizing procedure for two-phase flows in API RP 520 is recommended.

7.4.8.3 External Fire - Wetted Vessels

Class of vessels	Portion of liquid inventory	Remarks
Liquid-full, e.g. treaters	All up to the height of 25 ft (7.6 m)	
Surge or knockout drums, process vessels	Normal operating level up to the height of 25 ft (7.6 m)	
Fractionating columns	Normal level in bottom plus liquid hold-up from all trays dumped to the normal level in the column bottom; total wetted surface up to the height of 25 ft (7.6 m)	Level in reboiler is to be included if the reboiler is an integral part of the column
Working storage	Max. inventory level up to 25 ft (7.6 m), normally excluding the portions of the wetted area in contact with the foundations or the ground	For storage and process tanks, see API Standard 2000[6] or prEN 14015-1[7]
Spheres and spheroids	Up to the height of 25 ft or up to the max. horizontal diameter, whichever is greater	

Table 7.4.8.3-1 Portions of wetted surfaces to be considered

The amount of heat absorbed from a non-insulated vessel filled with a liquid depends at least on

- The type of fuel feeding the fire
- The degree of envelopment of the vessel with fire, which is a function of its size and shape
- The immediateness of firefighting measures and the possibility of drainage of flammable materials from the vessel

The total heat absorption Q for the wetted surface can be estimated by Eq. 7.4.8.3-1 in case of adequate drainage and prompt firefighting measures and by Eq. 7.4.8.3-2 in case of absent adequate drainage and/or firefighting measures.

	US units	SI units	
Drainage and firefighting measures	$Q=21000\ FA_{ws}^{0.82}$	$Q=43200\ FA_{ws}^{0.82}$	(Eq. 7.4.8.3-1)
Absent drainage and/or firefighting measures	$Q=34500\ FA_{ws}^{0.82}$	$Q=70900\ FA_{ws}^{0.82}$	(Eq. 7.4.8.3-2)

Adequate drainage of flammable fuels might be implemented with a strategic use of sewers and trenches as well as of the natural slope of the land. The values of the environment factor F for some types of installations are collected in Table 7.4.8.3-2. In case the conditions for Eq. 7.4.8.3-1 and 7.4.8.3-2 are not present, either higher values of the environment factor are assigned on the base of engineering judgment or some protection measures against fire exposure must be introduced to the plant. For water application facilities on bare vessels and depressurizing or emptying facilities insulation should withstand dislodgement by fire hose streams. Some example drainage criteria are given in API Standard 2510[8]

[6] API Standard 2000 Venting atmospheric and low pressure storage tanks : nonrefrigerated and refrigerated, 1998.

[7] prEN 14015-1: Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, metallic tanks for the storage of liquids at ambient temperature and above – Part 1: Steel tanks, 2000.

[8] API Standard 2510 Design and construction of liquefied petroleum gas installations (LPG), 2001

Type of Equipment		F
Bare vessel		1.0
Insulated vessel , with insulation conductance values for fire exposure conditions		
4 [Btu/(hr ft² °F)]	22.71 [W/ (m² K)]	0.3
2	11.36	0.15
1	5.68	0.075
0.67	3.80	0.05
0.5	2.84	0.0376
0.4	2.27	0.03
0.33	1.87	0.026
Water-application facilities, on bare vessel		1.0
Depressurizing and emptying facilities		1.0
Earth-covered storage		0.03
Below-grade storage		0.00

Table 7.4.8.3-2 Values of the environment factor F for various types of installations

Heat absorption equations in Eq. 7.4.8.3-1 and 7.4.8.3-2 are for process vessels and pressurized storage of liquefied gases. For other storage, whether on pressure vessels or vessels and tanks with a design pressure of 15 psig or less the recommended heat absorption rates in case of external fire exposure can be extracted from API Standard 2000. The wetted areas for pressurized vessels of different forms in respect of Table 7.4.8.3-1 are collected in Table 7.4.8.3-3. Some examples are described also graphically in Fig. 7.4.3.3-1. The symbols are conform to those in VALVESTAR®.

Class of vessels	Portion of liquid inventory and remarks
Sphere	$A_{wet} = \pi \cdot D \cdot F_{eff}$
Horizontal cylindrical vessel with flat ends	$A_{wet} = \beta \cdot D \cdot \left[L + \frac{D}{2} \right] - D \cdot \sin \beta \cdot \left[\frac{D}{2} - F_{eff} \right]$
Horizontal cylindrical vessel with spherical ends	$A_{wet} = \pi \cdot D \cdot \left[(L - D) \frac{\beta}{\pi} + F_{eff} \right]$
Vertical cylinder with flat ends ✓ Partially filled ($F < L$) ✓ Totally filled ($F = L$)	$A_{wet} = \pi \cdot D \cdot \left[\frac{D}{4} + F_{eff} \right]$ $A_{wet} = \pi \cdot D \cdot \left[\frac{D}{2} + F_{eff} \right]$
Vertical cylinder with spherical ends	$A_{wet} = \pi \cdot D \cdot F_{eff}$

Table 7.4.8.3-3 Calculation of the total wetted surface for some vessels.

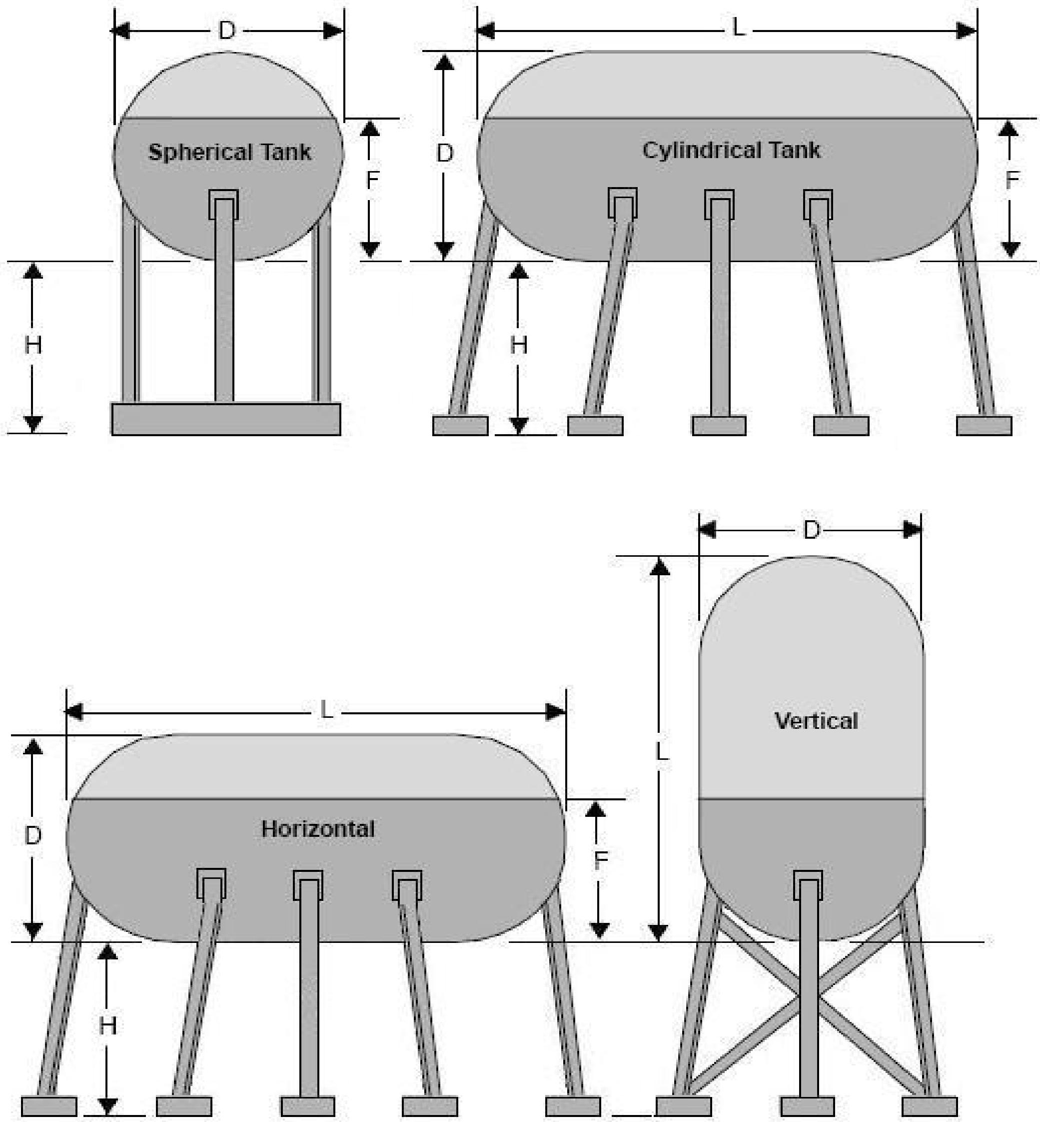

Figure 7.4.8.3-1 : Possible positions of wetted vessels, partially filled with liquids

The angle β in Table 7.4.8.3-3 is defined in Eq. 7.4.8.3-3

$$\beta = \cos^{-1}(1 - 2F/D) \quad \textit{(Eq. 7.4.8.3-3)}$$

and the height F_{eff} is the effective liquid level up to a max. distance of 25 feet away from the flame source, Eq. 7.4.8.3-4 (Eq. 7.4.8.3-5)

$$F_{eff} = \min(25 \ \ ft; F) - H \quad \text{(API 521)} \quad \textit{(Eq. 7.4.8.3-4)}$$

$$F_{eff} = \min(7.6 \ \ m; F) - H \quad \text{(ISO 23521)} \quad \textit{(Eq. 7.4.8.3-5)}$$

The mass flow rate to the safety valve is determined by Eq. 7.4.8.3-6, considering that all absorbed heat vaporizes the liquid

$$W = Q / h_{vl0} \quad \textit{(Eq. 7.4.8.3-6)}$$

7.4.8.4 External Fire - unwetted vessels

If the vessel is filled with a gas, a vapor or a supercritical medium, Eq. 7.4.8.4-1 may be used to find the safety valve discharge area

$$A = \frac{F'A'}{\sqrt{P_1}} \quad \textit{(Eq. 7.4.8.4-1)}$$

F' may be determined from Eq. 7.4.8.4-2 if the calculated value is less than 0.01, then a recommended minimum value equal to 0.01 must be taken. When the available information is not enough to use Eq. 7.4.8.3-8, then the environment factor can be assumed equal to 0.045. The recommended maximum vessel wall temperature T_w for the usual carbon steel plate materials is 1100°F (593°C). For plates made of alloys the wall temperature must be changed to a more adequate recommended max. value.

The constant C is given from Eq. 7.4.3-3.

$$F' = \frac{0.1406}{C \cdot K_d}\left[\frac{(T_w - T_1)^{1.25}}{T_1^{0.6506}}\right] \quad \textit{(Eq. 7.4.8.4-2)}$$

The relieving temperature T_1 is determined from Eq. 7.4.8.4-3 in function of the normal operating temperature and pressure, respectively T_n and $p_{n,}$ and of the relieving pressure

$$T_1 = T_n \frac{P_1}{P_n} \quad \textit{(Eq. 7.4.8.4-3)}$$

For plates made of alloys the gas mass flow rate can be calculated from Eq. 7.4.8.4-4

$$W = 0.1406\sqrt{M\ P_1}\left(A'\frac{(T_w - T_1)^{1.25}}{T_1^{1.1506}}\right) \quad \textit{(Eq. 7.4.8.4-4)}$$

The derivation of the formulas for unwetted vessels is based on the physical properties of air and ideal gas laws. Furthermore, they assume that the vessel is non-insulated and without its own mass, that the vessel wall temperature will not reach rupture under stress and that the fluid temperature does not change. All these assumptions should be checked if they are appropriate for the particular situation.

7.4.8.5 Consideration of Accumulated Pressure in Fire and Non-Fire Contingencies

The requirements on the accumulated pressure in API RP 520, sec. 3.5.2, page 39-40 propose different treatments for the cases of fire and non-fire contingencies.

In non-fire contingencies the accumulated pressure shall be limited to 110% of the maximum allowable working pressure (MAWP) in vessels that are protected by only one safety valve. If the MAWP lies between 15 and 30 psig, the allowable accumulation is fixed to 3 psi.
In vessels which are protected by more valves in non-fire contingencies, the accumulated pressure shall be limited to 116% of the maximum allowable working pressure (MAWP) or to 4 psi, if the MAWP lies between 15 and 30 psig. Typically the first safety valve is set at 100% of the MAWP and it is smaller than all other ones so to minimize the product loss. The additional valve is larger and it is sized in order to ensure the protection against the maximum required mass flow.

In fire contingencies the accumulated pressure shall be below 121% (= 10% above 110%) of the maximum allowable working pressure (MAWP), independently if the vessels are protected by one or more safety valves. Safety valves sized for the fire case may be also used in non-fire situations, provided that they satisfy the constrain on the accumulated pressure of 110% (one valve) and 116% (= 10% above 105%) (more valves) respectively.

Following the strategy of Table 7.4.8.5-1, which is extracted from the table on Page 39 in API RP 520, a safe sizing with a minimum product loss is possible. The supplemental valves are installed in case of an additional hazard, like fire case or other sources of external heat. Supplemental valves are in addition to devices for non-fire contingency.

	Single valve installation		Multiple valve installation	
Contingency	Max. set pressure [%]	Max. accumulated pressure [%]	Max. set pressure [%]	Max. accumulated pressure [%]
Non-fire contingency				
First valve	100	110	100	116
Additional valves	-	-	105	116
Fire contingency				
First valve	100	121	100	121
Additional valves	-	-	105	121
Supplemental valve	-	-	110	121

Table 7.4.8.5-1 Set pressure and accumulated pressure limits for safety valves