Relief Requirement for Gas Thermal Expansion

Saeid Rahimi

Revised on 04-Jun-2014[1]

Introduction

The first step in designing a pressure-relieving system is to specify all possible causes of overpressure which are applicable to different equipment. API 521 introduces the various emergency cases and general guidelines for calculating relief rate. While liquid thermal expansion is widely recognized as a cause of overpressure, gas thermal expansion is rarely taken as credible cause of overpressure. This is may be due to lack of guidelines in existing standards or common impression that gas thermal expansion has negligible contribution to overpressure. As a general practice for liquid thermal expansion, thermal relief valve (TRV) is normally provided for any equipment operating full of liquid that can be blocked-in between inlet and outlet valves, where sufficient heat may be applied to the fluid to increase the pressure above the equipment design pressure. The relief requirement of a vessel under fire containing only gas (unwetted vessel) has been developed by API 521 and other references. This paper will present cases where gas thermal expansion is caused by heat sources other than external fire such as process hot stream, solar radiation and ambient temperature variation.

Gas Expansion Fundamentals

Gas thermal expansion occurs in all equipment and piping with the following conditions:

- Line or equipment is isolated for operational / emergency purposes and
- There is a source of heat with temperature higher than operating temperature of gas.

For the described system, the relief valve is needed if:

- The pressure raise as a result of temperature increase exceeds the design pressure of system and
- There is no other type of overpressure protection device on the system, no provision to prevent gas tight blockage such as locked open (LO) valve, leaking check valve or venting procedure before closing isolation valves. Refer to “What You Should Know about Liquid Thermal Expansion” for more information.

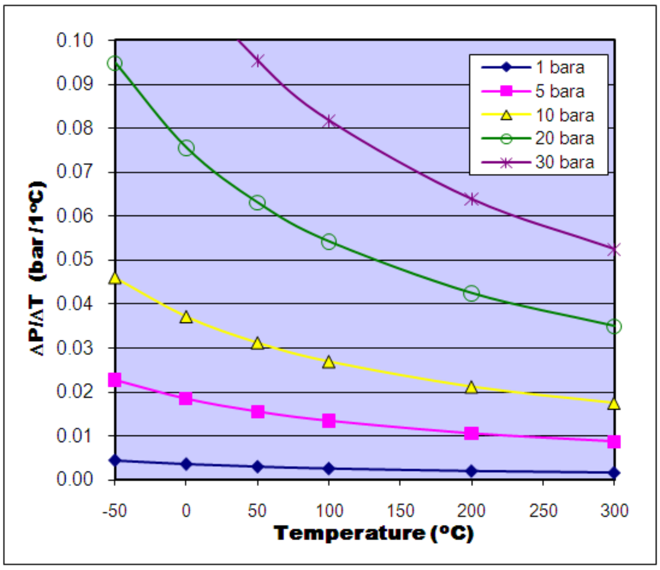

Figure 1a- Gas expansion for low to medium pressure

Figure 1 shows the pressure rise of blocked air based on the results of SRK equation of state (EOS) for different pressures and temperatures. As shown in figure 1, the blocked-in gas pressure rise due to temperature changes ($\Delta P/\Delta T$), is not significant in low to medium pressure applications. However, for high pressure gases it can reach 2 bar/°C. The values given in Figure 1 may be used to estimate the potential pressure rise for other gases (similar to air) but for gas mixtures with wide composition range, using EOS is recommended.

According to above figures, gas thermal expansion can be a credible cause of overpressure in the following systems:

1. Systems with high operating pressure where $\Delta P/\Delta T$ is significant. It means that even small temperature change may cause catastrophic failure of piping or equipment containing dense gas. For example, the pressure of 300 bar air cylinder stored in room temperature of 23°C will increase 1.3 bar per each degree centigrade, as shown in figure 1b. Therefore, failure of air conditioning system increases the room temperature to 40°C, cylinder pressure can reach 322 bar, subsequently. Another example is high pressure pipeline with possibility of blockage and exposure to sun radiation.

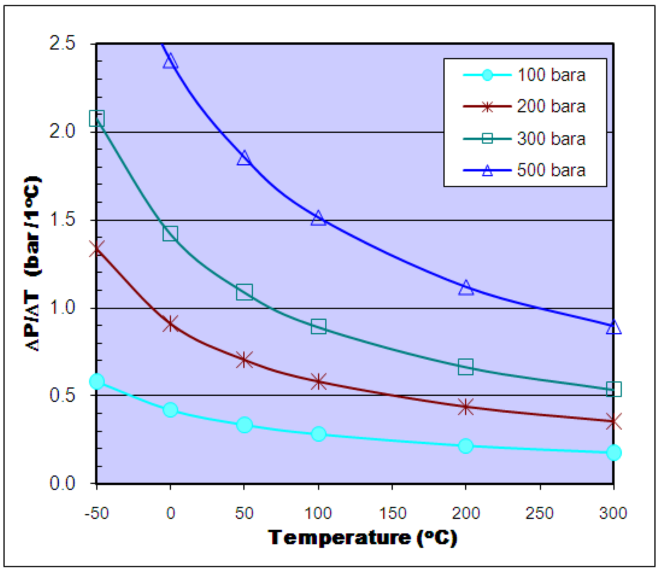

Figure 1b- Gas expansion for medium to high pressure

---

[1] First issued on 11-Oct-2011 in www.chemwork.org

2. System with high differential temperature between heat source and blocked gas. For 20 bar cold fuel gas which is superheated in a gas-gas heat exchanger using hot flue gas at 400°C, if fuel gas (cold side) is blocked, it can reach the hot gas operating temperature. Although the gas expansion is small at 20 bar, the high differential temperature can easily increase the blocked gas to pressure beyond the design pressure.

Relief Rate Calculation

There is no common approach for gas thermal expansion relief study that is applicable to all systems. What is common among different systems is that pressure can be maintained at a safe level if the excess mass is released from system. Writing a mass balance for blocked gas gives the required relief rate:

$$W(t) = \frac{-dm(t)}{dt} \qquad (1)$$

Assuming:

- Since the gas composition does not change during relief, gas molecular weight is constant. Hence, m (t) = MW n(t)
- Enough heat is supplied to keep the blocked gas at relieving pressure during relief. Therefore pressure is independent of time ($P = P_R$)
- $n = PV/R\bar{T}$ predicts gas thermodynamic behavior where $\bar{T} = zT$.

Equation (1) could be rewritten as:

$$W(t) = \frac{-P_R\,V\,MW}{R}\,\frac{d(1/\bar{T})}{dt} \qquad (2)$$

Rearranging above equation results in equation (3), which can be solved if the temperature variation with time is known.

$$W(t) = \frac{P_R\,V\,MW}{R\bar{T}^2}\,\frac{d\bar{T}}{dt} \qquad (3)$$

- **Initial Checking**

Equipment design pressure is one of the most appropriate safeguard against gas thermal expansion over-pressurization. Hence, before starting the relief rate calculation, it should be checked at which temperature the design pressure will be reached using equation (4):

$$\frac{P_D - P_N}{T - T_{N,ave}} = \text{Figure 1 value at } P_N \;\&\; T_{N,ave} \qquad (4)$$

A simplified form of ideal gas law, $T = T_{N,ave}\,P_D / P_N$ considering its limitations and applications can also be used.

Heat Transfer Background

Ignoring the effect of heat radiation, overall heat transfer coefficient for tube side of heat exchanger is calculated from the following relation.

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{\frac{k_w}{\Delta x}\left(\frac{A_w}{A_i}\right)} + \frac{1}{h_o\left(\frac{A_o}{A_i}\right)}$$

From heat transfer point of view, the main difference between operating and blocked-in condition is that heat transfer mechanism inside the tube changes from force convection to free convection. The following assumption is applicable to blocked-in condition:

$$h_i \ll \frac{k_w}{\Delta x} \ll h_o$$

Substituting (2) in equation (1) gives $U \approx h_i$.

There are many correlations for calculating free convection heat transfer coefficient, h_i, inside enclosed space. The following relation[5] can be used for estimating this parameter when $6 \times 10^6 < Gr\,Pr < 10^8$.

$$Nu = 0.104\,Gr^{0.305}\,Pr^{0.389}$$

Where,

$$Gr = \frac{g\,\beta\,(T_S - T)\,D^3}{\upsilon^2} \qquad Pr = \frac{\mu\,C_p}{k}$$

$$Nu = \frac{h_i\,D}{k} \qquad \upsilon = \frac{\mu}{\rho}$$

If the calculated temperature, T, is higher than temperature of heat source, no pressure safety valve is needed. In other words, the pressure of blocked gas does not reach relieving pressure even if its temperature increases from initial temperature to heat source temperature. If not, there is a potential for the blocked gas pressure to exceed the design pressure. The calculated temperature is the temperature where relief valve opens for the first time (the initial relieving temperature).

- **Relief Rate Calculation**

The following section introduces a very simple procedure to define the blocked gas temperature as a function of time and solve equation (3) for a gas-gas heat exchanger using numerical solution. This method may result in 10 to 20% overdesign on flow (required area) which is acceptable compared to the overdesign associated with relief valve selection procedure (selecting relief valve among standard orifices).

1. Assume constant temperature intervals, ΔT, between initial relieving temperature and heat source temperature and calculate T(t+Δt).

$$T(t+\Delta t)=T(t)+\Delta T \tag{5}$$

2. Calculate the average heat transfer rate between heat source and trapped gas by following equation.

$$Q(t)=U(t)\,A\,\left(T_S-T(t)\right) \tag{6}$$

3. Calculate the heat required to increase the temperature of trapped gas from T(t) to T(t+Δt) by using equation (7). Below equation ignores part of the heat that is consumed by gas container (heat exchanger metal).

$$q(t)=n(t)\,MW\,C_p(t)\left[T(t+\Delta t)-T(t)\right] \tag{7}$$

4. Calculate the time required to increase the temperature of trapped gas from T(t) to T(t+Δt) using below equation.

$$\Delta t=\frac{q(t)}{Q(t)} \tag{8}$$

5. Calculate relief rate using equation (9)

$$W(t)=\frac{P_R\,V\,MW}{R\,\overline{T}(t)^2}\,\frac{\left(\overline{T}(t+\Delta t)-\overline{T}(t)\right)}{\Delta t} \tag{9}$$

6. Calculate new number of trapped gas moles using equation (10) for next stage of calculation. Go to step 1.

$$n(t+\Delta t)=n(t)-W(t)\,\Delta t \tag{10}$$

Case Study

Natural gas with the conditions and composition specified in Table 1 is superheated from 100°C to 150°C in a gas-gas heat exchanger using 400°C HP steam. The heat exchanger tube inside diameter, total heat transfer area and total tube volume are 1in, 100m^2 and 1.5 m^3 respectively.

NOMENCLATURE	
A	Heat exchanger surface area, m^2
Cp	Gas heat capacity, kJ/kg K
D	Tube diameter, m
g	Gas constant, 9.81m/s^2
Gr	Grashof number, dimensionless
h	Heat transfer coefficient, J/s m^2 K
k	Thermal conductivity, J/s m K
m	Mass of trapped gas, kg
MW	Gas molecular weight, kg/kgmol
n	Mole of trapped gas, kgmol
Nu	Nusselt number, dimensionless
P	Pressure, bara
P_r	Prandtl number, dimensionless
Q	Total heat transfer rate, J/sec
q	Heat content of trapped gas, J
R	Gas constant, 8314 bara m^3/kgmol K
Ra	Rayleigh number, dimensionless
T_S	Heat source temperature, K
T	Blocked gas temperature, K
t	Time, sec
U	Overall heat transfer Coefficient, J/s m^2 K
V	Trapped gas volume, m^3
W	Relief rate, kg/hr
z	Gas compressibility factor
β	Cubical expansion coefficient, 1/K
μ	Dynamic Viscosity, Centipoises (Cp)
ν	Kinematic viscosity, m/s^2
Δx	Wall thickness, m
ρ	Density, kg/m^3

SUBSCRIPTS	
i	inside
o	outside
ave	Average
w	wall
N	Normal operation condition
D	Design condition
R	Relieving condition

Initial Checking: According to Figure 1a, pressure rise of trapped gas at an average temperature of 125 °C and 10 barg is 0.0289 bar/°C. Therefore, the minimum heat source temperature to increase the blocked gas pressure from operating to design pressure is:

$$\frac{P_D-P_N}{T-125°C}=0.0289\text{bar}/°C$$

Then:

$$T=\frac{12\ -\ 10}{0.0289}+125=194.2\ ^{o}C$$

Since the temperature of HP steam is higher than 194.2°C, therefore it will over-pressurize the cold side and relief valve is required for thermal gas expansion if the system is blocked-in.

Relief Rate Calculation: Considering relieving pressure of 13.2 barg, initial relieving temperature will be 235.7°C. Simulation software was used to obtain the physical properties of the gas at each temperature interval and the relief rate was calculated (Table 2).

Table 1- Gas Condition and Composition

Parameter		Value
Methane	(mole %)	0.84
Ethane	(mole %)	0.08
Propane	(mole %)	0.04
I-butane	(mole %)	0.02
N-butane	(mole %)	0.02
MW		19.97
P_N	(barg)	10
P_D	(barg)	12

Table 2 – Relief Rate Calculation

T (°C)	Cp* (kJ/kgK)	μ* (cP)	ρ* (kg/m^3)	k* (J/s m K)	z* (--)	Gr (--)	Pr (--)	Nu (--)	U (J/sm^2K)	Q (J/s)	m (kg)	q (J)	Δt (s)	W (kg/hr)
235.7	2.84	1.75E-02	6.74	6.42E-02	0.995	7.32E+06	0.775	11.7	30.0	493205	10.10	470582	0.95	1267.9
252.1	2.90	1.79E-02	6.53	6.70E-02	0.996	5.71E+06	0.776	10.8	29.1	429724	9.78	464857	1.08	1047.8
268.5	2.96	1.83E-02	6.32	6.98E-02	0.997	4.42E+06	0.777	10.0	28.0	368505	9.47	462289	1.25	853.5
285.0	3.02	1.87E-02	6.13	7.27E-02	0.998	3.38E+06	0.778	9.2	26.9	309314	9.17	454386	1.47	682.0
301.4	3.08	1.91E-02	5.95	7.56E-02	0.998	2.54E+06	0.779	8.5	25.7	253048	8.90	449576	1.78	531.4
317.8	3.14	1.95E-02	5.78	7.86E-02	0.999	1.87E+06	0.780	7.7	24.3	199593	8.64	447697	2.24	399.7
334.3	3.20	1.99E-02	5.62	8.15E-02	0.999	1.32E+06	0.781	7.0	22.7	149015	8.40	440545	2.96	285.4
350.7	3.26	2.03E-02	5.47	8.45E-02	1.000	8.82E+05	0.782	6.1	20.8	102460	8.17	436291	4.26	187.6
367.1	3.32	2.06E-02	5.33	8.75E-02	1.000	5.25E+05	0.782	5.2	18.4	60452	7.95	434803	7.19	105.8
383.6	3.37	2.10E-02	5.19	9.06E-02	1.001	2.34E+05	0.783	4.1	14.9	24373	7.74	428127	17.6	41.1
400.0	3.43	2.14E-02	5.07	9.36E-02	1.001	0.00E+00	0.783	0.0	0.0	0	7.54	---	∞	0.0

* Input from simulation software

In this particular example, the following points were observed:

- As the blocked gas temperature increases, the differential temperature decreases. This results in reduction of the overall heat transfer coefficient and subsequently relief rate.
- The maximum relief load takes place at the first interval when heat transfer rate is high.
- The time between two subsequent PSV opening (Δt) is initially so short that it can be assumed as continuous relieving. PSV will chatter as trapped gas temperature approaches heat source temperature.
- Unlike liquid thermal expansion where ¾" x 1" TRV will normally be sufficient, preliminary PSV sizing showed that a 1½" x 2" PSV with F designation would be needed for this case.
- When the gas temperature reaches 194.2°C the relief valve will open for the first time. If the heat transfer rate is high the relief valve will remain open otherwise it will close until pressure built-up is sufficient to reopen the relief valve again.

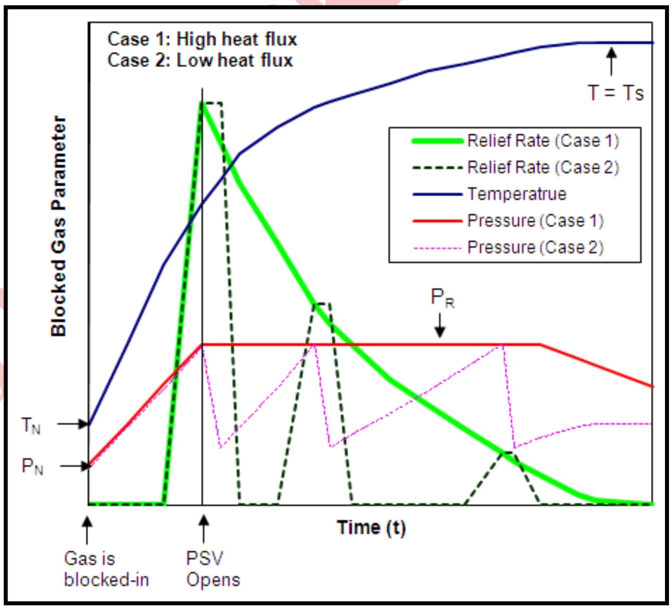

Figure 2 – Typical trend of blocked gas parameters

The typical trends of blocked gas major parameters for this case are depicted in Figure 2 (Case 1). In case of low heat flux, relief valve opens and closes repeatedly to release the excess pressure, as shown in Figure 2 with dotted line (Case 2).

Conclusion

Gas thermal expansion can cause system over-pressurization in particular conditions that were discussed. Ignoring this case may result in mechanical failure of system. A ¾ "x 1" TRV recommended by API-521 may not be sufficient for this case hence the relief rate has to be calculated according to system dimension and heat transfer rate from heat source to the blocked-in gas and adequate PSV size needs to be utilized. In absence of any standard addressing this case, different systems should be reviewed on case by case basis.

Contact

Please visit www.linkedin.com/groups/Chemwork-3822450 should you have any comment, question or feedback or feel free to contact S.Rahimi@gmail.com.