The Basis of API Correlation for Fire Relief of Unwetted Vessels

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Introduction

Many of us have utilized API-521 equation for calculating external fire relief rate of unwetted (gas filled) vessels.

$$W = 0.1406 \sqrt{PM} \; \frac{A \, \Delta T^{5/4}}{T^{1.1506}}$$

The same standard states that derivations of this equation is based on the physical propeties of air and the perfect gas low. The derivations assume that the vessel is uninsulated and has no mass, that the vessel wall temperature dose not reach rupture-stress temperature, and that there is no change in fluid temperature.

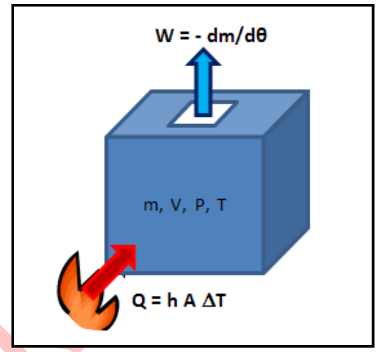

Figure 1 – System element

This notes reviews the equation derivaion to investigate the effect of above assumptions on its validity and aplicibility for different systems.

Equation Derivation

Writing mass balance for element shown in Figure 1 will result in: $-dm = W \, d\theta$

$$where\ m = \rho V = \frac{PM}{RT} V \qquad then \qquad \frac{VMP}{R} \frac{dT}{T^2} = W \, d\theta \qquad and\ finally \qquad \frac{dT}{d\theta} = W \frac{R \, T^2}{VMP} \qquad (1)$$

Assumption 0: Although API does not mention about it but the basis of mass balance is that vessel pressure is maintained at constant value throughout the fire by releasing the mass from the system.

Writing energy balance for element shown in Figure 1 will result in: $Q = m \, C_p \frac{dT}{d\theta} = \rho \; V \, C_p \frac{dT}{d\theta}$

Assumption 1: vessel has no (metal) mass and heat input from fire is totally transferred to the gas inside the vessel.

$$Q = h \, A \, \Delta T \qquad where \qquad h = h' \Delta T^{\frac{1}{4}} \qquad h' = D \left(\frac{\rho^2 \, \beta \; C_p \; k^3}{\mu} \right)^{\frac{1}{4}} \qquad and\ \beta = {}^{1}/_{T} \;\; (for\ gases)$$

Refer to note "Fire Heat Flux to Un-wetted Vessel" for heat transfer equation background.

Assumption 2: vessel is not insulated and rate of heat transfer from fire is controlled by free convection inside the vessel.

$$Replacing\ above\ relations\ in\ energy\ \ balance\ equation\ gives \qquad \frac{dT}{d\theta} = \frac{h' \, A \, \Delta T^{5/4}}{\rho \, V \, C_p} \qquad (2)$$

Equations (1) and (2) can be solved to find reléif rate, W.

$$W \frac{R \, T^2}{VMP} = \frac{h' \, A \, \Delta T^{5/4}}{\rho \, V \, C_p}$$

$$W = \frac{h' \, A \, \Delta T^{5/4}}{\rho \, V \, C_p} \; \frac{VMP}{R \, T^2}$$

$$\rho = \frac{PM}{RT}$$

Assumption 3: perfect gas low describes the relation between vessel gas pressure and temperature.

$$W = \left(\frac{h'}{C_p\ M^{1/2}}\right)\frac{A\ M^{1/2}\Delta T^{5/4}}{T} \qquad (3)$$

In following paragraph, we will replace the term inside brackets with system parameters (pressure and temperature).

$$\left(\frac{h'}{C_p\ M^{1/2}}\right) = D\ \left(\frac{\rho^2\ \beta\ \ C_p\ k^3}{C_p^4\ \ M^2\mu}\right)^{1/4} = D\ \left[\rho^2\mu^2\ \frac{\beta}{M^2}\left(\frac{k^3}{C_p^3\ \mu^3}\right)\right]^{1/4}$$

Since β, M and the ratio of $C_p\mu/k$ (Prandtle number) are independent of P and T, we may write:

$$\left(\frac{h'}{C_p\ M^{1/2}}\right) = D'\ (\rho^2\mu^2\ )^{1/4} = D'\ \left(\frac{P^2M^2}{R^2T^2}\mu^2\right)^{1/4}$$

Again M and R are independent of P and T.

$$\left(\frac{h'}{C_p\ M^{1/2}}\right) = D"\ \left(\frac{P^2\mu^2}{T^2}\right)^{1/4}$$

In above equation, μ can be replaced with T by using of regression technique to find a curve which fits to air viscosity data at different temperatures as shown in Table-1.

$$\left(\frac{1560}{460}\right)^n = \frac{0.001444}{0.000262}\ then\ (3.39)^n = 5.5$$

So n = 1.398 and

$$\left(\frac{h'}{C_p\ M^{1/2}}\right) = D"\ \left(\frac{P^2T^{1.398}}{T^2}\right)^{1/4} = D"\ \left(\frac{P^2}{T^{0.602}}\right)^{1/4}$$

Table 1- Air viscosity vs. temperature

T	µ	µ^2
460	0.016	0.000262
528	0.018	0.000323
660	0.021	0.000440
860	0.025	0.000625
1060	0.029	0.000840
1260	0.032	0.001050
1460	0.036	0.001295
1560	0.038	0.001444

Assumption 4: The regression of air viscosity versus temperature has been used for all gases.

D" value in above equation can be found by comparison made in Table 2 for different gases at same condition. According to this Table, the value of $\left(\frac{h'}{C_p\ M^{1/2}}\right)$ for air is greater than other gases whose properties are available in this table; and for many others, such as ammonia, nitrogen and oxygen whose properties were considered but not listed in the table. In view of this, the resultant D" will be overdesign if it is calculated based on air properties.

$$0.209 = D"\ \left(\frac{14.7^2}{528^{0.602}}\right)^{1/4} \rightarrow D" = 0.1406$$

Therefore

$$\left(\frac{h'}{C_p\ M^{1/2}}\right) = 0.1406\ \left(\frac{P^2}{T^{0.602}}\right)^{1/4} \qquad (4)$$

Assumption 5: Properties of Air at constant pressure and temperature (14.7psia and 528ºR) have been used for all other gases.

Table 2 – Value of *h'* for representative gases (All properties are at 14.7 psia and 528ºR)

Gas	k	C_p	μ	M	$\frac{M^2\, C_p\, k^3}{\mu}$	$\left(\frac{M^2\, C_p\, k^3}{\mu}\right)^{1/4}$	h'	$\frac{h'}{C_p\, M^{1/2}}$
Air	0.0161	0.24	0.018	29	0.0468	0.465	0.270	0.209
Hydrogen	0.1075	3.50	0.009	2	1.9324	1.181	0.685	0.138
Acetone	0.0065	0.34	0.0077	58	0.0408	0.448	0.260	0.100
Acetylene	0.0124	0.43	0.0100	26	0.0554	0.485	0.281	0.128
Benzene	0.0062	0.26	0.0075	78	0.0502	0.472	0.273	0.135
Ethyl Alcohol	0.0089	0.40	0.0094	46	0.0634	0.501	0.290	0.107
Ethyl Ether	0.0088	0.46	0.0077	74	0.2220	0.687	0.398	0.100
Water	0.0110	0.48	0.0097	18	0.0213	0.382	0.221	0.108
Methane	0.0195	0.54	0.0112	16	0.0911	0.549	0.319	0.148
Ethane	0.0123	0.42	0.0094	30	0.0764	0.525	0.305	0.131
Pentane	0.0083	0.34	0.0063	72	0.1599	0.632	0.366	0.127
Carbon Dioxide	0.0109	0.21	0.0146	44	0.0360	0.436	0.252	0.181
Freon 113	0.0054	0.16	0.0103	187	0.0855	0.542	0.313	0.143

API correlation is finally obtained by replacing equation (4) into equation (3).

$$W = 0.1406\,\sqrt{PM}\;\frac{A\,\Delta T^{5/4}}{T^{1.1506}} \qquad (5)$$

Where P and T are relieving pressure and relieving temperature.

Assumption 6: Vessel wall temperature dose not reach rupture-stress temperature and there is no change in fluid temperature. According to this, $\Delta T = T_w - T$ where T_w is the maximum tolerable temperature of vessel wall before it ruptures and T is the releiving temperature which are constant during the fire.

Discussion

Assumption 0 is made to simply the derivation and solution of mass balance otherwise equation (1) becomes partial derivative equation as temperature and pressure are both functions of time. Assuming constant pressure, the transient time during which system pressure migrates from operating to relief valve set (or relieving) pressure is ignored and the study focuses on duration at which relief valve is in operation. API assumes that system will remain at relieving pressure which leads to higher flow rate according to equation (5).

Assumption 1 is conservative because in reality part of fire heat input is absorbed by metal. If vessel has no (metal) mass then heat input from fire is totally transferred to the gas inside the vessel.

Assumption 2 is also conservative because addition of insulation resistance to heat transfer calculation may reduce heat input to the vessel content. Vessel is not insulated and rate of heat transfer from fire is controlled by free convection inside the vessel.

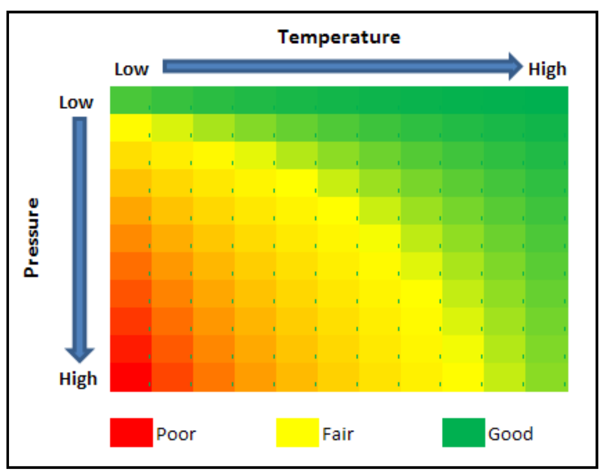

Figure 2 –The perfect gas low applicability

Since the effect of fireproofing insulation on fire heat input rate has been ignored in energy balance and cannot be easily entered into equation (5) then API recommends no credit for fireproofing insulation when determining fire relief requirements of gas filled vessels because, in most cases, a relatively small relief device is required even without a fire proofing credit.

Assumption 3 is about application of perfect gas low which has been used several times in the derivation process for density calculation. Figure 2 shows the validity of perfect gas law for a range of pressure and temperature. As shown in this figure, using this law will result in highest deviation from reality at high pressures and low temperatures. But the deviation caused by this law is not much compared to other assumptions made earlier.

Equation (5) can be reproduced in below form to show the effect of density calculation method on the final results accuracy.

$$W = 0.1406 \sqrt{R\rho}\ \frac{A\,\Delta T^{\frac{5}{4}}}{T^{0.6506}}$$

From above equation, the effect of using perfect gas is further reduced when square root of density is used in final equation.

Assumption 4 is quite valid and applicable to a wide range of gases with not a big error.

Assumption 5 (using air properties) can lead to relief rate up to double of other gases as shown in last column of Table 2.

Assumption 6 has been also made to simplify the corrolation and change it from a dynamic phenomana to simple applied equation which can be used by any user. Both of these assumptions are conservative because:

- Wall temperature increases during fire from initial temperature to rupture-stress temperature, therefore assuming wall temperature constantly at rupture-stress temperature will be conservative compared to reality. API recommends 1100F as a rupture-stress temperature of carbon steel. Obviously vessel wall temperature can exceed this temperature during fire but it seems logical to limit the T_w to this figure as there is no point in protecting a vessel which has already failed (with a relief valve sized for unreasonably high temperature).

- Gas temperature also keeps increasing during fire and heat transfer practically stops when gas reaches wall temperature. Assuming constant gas temperature throughout the fire results in higher differential temperature and higher heat input.

NOMENCLATURE	
A	Vessel surface area, ft2
Cp	Specific heat, Btu/lb R
D, D′, D″	Equation constant
h	Heat transfer coefficient, Btu/hr ft2 R
h′	Heat transfer constant
K	Gas thermal conductivity, Btu/hr ft R
m	Mass of vessel gas, lb
M	Gas molecular weight
P	Vessel pressure, psia
Q	Total heat transferred, Btu
R	Gas constant
T	Gas temperature, R
Tw	Wall temperature, R
V	Vessel gas volume,ft3
W	Venting rate, lb/hr
β	Thermal expansion coefficient, 1/R
θ	Time
μ	Gas viscosity, centipoises
ρ	Gas density, lb/ft3
Δ	Difference

Conclusion

There are lots of conservative assumptions made in derivation of API correlation for unwetted vessels fire relief rate. But most probably the most conservative one is assumption number 5 which can be optimized by calculating h′ and D″ through following relations for each individual system:

$$h' = \frac{0.27}{0.465}\left(\frac{M^2\ C_p\ k^3}{\mu}\right)^{\frac{1}{4}} \qquad (6)$$

$$D" = 0.67\left(\frac{h'}{C_p\ M^{1/2}}\right) \qquad (7)$$

(Note that all properties in equations 6 and 7 are at 14.7psia and 528ºR)

A customized version of API correlation is produced by replacing D" in below equation:

$$W = D" \sqrt{PM} \ \frac{A \, \Delta T^{5/4}}{T^{1.1506}} \qquad (8)$$

According to API ecommendation, relieving temperature (T) is usually calculated based on initial operating pressure, temperature and relieving pressure using perfect gas low. Using perfect gas low when system condition is in red zone of Figure 2 results in higher temperature than reality which ultimaty leads to underestimated releif load and relief valve size. Therfore, it would be more accurate if relieving temperature is calculated by using of SRK or PR equations of state.

Contact

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