Relief Rate Calculation; External Fire (Part 2)

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Introduction

One of the most important responsibilities of any process engineer is to ensure that plant will safely operate in the different emergency cases. One of the cases which lead to equipment overpressure is external fire. API-521, 4^{th} edition section 3.15, recommends the basic theory and formulas for calculating vapor rate generated during a fire due to liquid vaporization or gas expansion for wetted and un-wetted vessels, respectively.

In Part 1, a calculation procedure was presented to find weather a vessel is categorized as wetted or unwetted before beginning the relief rate calculation. This part reviews the different methods that are being used for relief rate calculation of wetted vessel in fire condition and introduces a new simple method for this purpose.

Relief Rate Calculation

For wetted vessels, fire relief load is equal to the rate of vapor generation due to heat input. This can be calculated through dividing the heat absorption rate by liquid latent heat.

$$W = \frac{Q}{\lambda} \qquad (1)$$

Where

$$Q = B\,F\,A^{0.82} \qquad (2)$$

There are some guidelines in API-521 section 3.15 for taking the effect of piping area and drainage facilities in calculating total heat (Q) absorbed by the vessel into account.

The accurate design of the pressure relief system capacity requires accurately estimating the gas and liquid phase properties at high temperature. The different methods for calculating fire relief load of wetted vessels and liquid latent heat as major parameters affecting the relief rate and the size of relief valve are reviewed in following paragraphs.

NOMENCLATURE	
$A_{orifice}$	Required effective discharge area of the valve
A	Wetted surface area of the vessel
B	Constant used in equation (2)
C	Coefficient in equation (3), a function of C_P/C_V (gas specific heat ratio)
D	Vessel diameter
E	Constant used in equation (6)
F	Environmental Factor, refer to Table 5 of API-521 section 3.15.2
H	Height of liquid inside the vessel
L	Vessel length
K_b	Capacity correction factor due to backpressure
K_d	Effective coefficient of discharge
M	Molecular weight
P_r	Relieving pressure
V_H	Vessel liquid hold up volume which is below the elevation of 25 ft (7.6m) from grade
V_T	Vessel total volume
T	Temperature
Q	Total heat absorption across wetted surface area
W	Relief rate
Z	Gas compressibility factor
λ	Latent heat of vaporization
ρ	density

1. Steady State Approach

This method basically uses the gas and liquid properties at initial boiling point of liquid (bubble point). For achieving this purpose, the first step is to simulate the liquid content of a particular vessel by defining one stream with the same composition at relieving pressure and vapor fraction of zero. This is to find the initial boiling point (saturation) temperature of liquid mixture (this temperature is also used as relieving temperature). The next step is to increase the stream temperature about 1-2°C above saturation temperature so that very small amount of vapor is generated (some references recommend increasing the temperature to get 3-5% vapor fraction).

The physical properties of gas and latent heat of residual liquid's at the slightly elevated temperature are used in equation (3) from section 4.3.2 of API-520 (7^{th} edition) to find the relief valve orifice size:

$$A_{Orifice} = \frac{W}{C\,K_d\,P_r\,K_b}\sqrt{\frac{T\,Z}{M}} \qquad (3)$$

When a computer simulator is not available, using a figure is a simple way to calculate latent heat. API PR-521, Appendix A, Figure A.1 shows the vapor pressure and latent heats of the pure single-component paraffin hydrocarbon liquids. This chart may be also used as an approximation for following hydrocarbon mixtures:

- Paraffin hydrocarbon mixtures composed of two components whose molecular weights vary no more than propane to butane and butane to pentane.
- Isomer hydrocarbons, aromatic or cyclic compounds, or paraffin hydrocarbon mixture of components that have slightly divergent molecular weight.

To estimate the latent heat of multi-component mixture that have a wide boiling range or widely divergent molecular weight, rigorous series of equilibrium calculations may be required so that the process simulation software might be used for this purpose. Refer to the method presented in article "Thermodynamic methods for pressure relief system design parameter," Fluid Phase Equilibria 241 (2006), pp. 41-50, Kwong W. Won, Arine R. Smith, Gerald A. Zeininger.

Calculating the relief rate and relief valve size based on gas and liquid properties at initial boiling point is simple and fast (which are the main interest of oil and gas contactors), but it may not be always conservative. This is because vapor and liquid composition and all process parameters change during fire, which affects the size of relief valve. Therefore there is no other way for accurately calculating the multi-component hydrocarbon systems fire relief rate other than dynamic simulation.

2. Dynamic Study

Dynamic simulation is undoubtedly the best methods for observing the behavior of system during fire. Building a dynamic model for fire is also relatively easy job which is possible by adding a vessel and some valves in Hysys or Unisim dynamic mode. Fire heat input also can be defined based on vessel wetted area using spreadsheet tool of simulation software. The only point is that considering the number of equipment where fire case is applicable and time required for making such model for each particular case, it may not be always feasible to perform fire relief study using this approach. Availability of dynamic licenses and people who are good at dynamic simulation can be other limiting factors.

3. Semi-Dynamic Approach

In this method, the physical properties of gas and liquid are obtained at 5 wt% vaporization intervals from simulation software and used in excel spreadsheet to find the maximum area required for relief valve during fire. The approach consists of a search for the point where the relief valve orifice area is maximized. The objective equation can be derived by substituting equations (1) and (2) into equation (3) which produces equation (4):

$$A_{Orifice} = \frac{B\,F\,A^{0.82}}{C\,K_d\,P_r\,K_b\,\lambda}\sqrt{\frac{T\,Z}{M}} \qquad (4)$$

Rewriting equation (4) produces:

$$A_{Orifice} = E\,\frac{A^{0.82}}{C\,\lambda}\sqrt{\frac{T\,Z}{M}} \qquad (5)$$

Where $E = \frac{B\,F}{K_d\,P_r\,K_b}$ (6)

Table 1 – Variation of Process Parameters During Fire

Parameter	Variation during fire	Effect on Orifice Area
Vessel wetted area	Decreasing	Direct
Gas temperature	Increasing	Direct
Gas compressibility factor	Decreasing	Direct
C (function of gas Cp/Cv)	Increasing	Reverse
Liquid latent heat	Decreasing	Reverse
Gas molecular weight	Increasing	Reverse

Performing this exercise needs the physical properties of liquid and gas phases and wetted area vs. time. Commercial software like Hysys produces the required physical properties (T, Z, M, Cp/Cv & λ). According to equation (4), the relation between process parameters and their effects on orifice area is shown in Table 1. The variation of process parameters specified in Table 1 is applicable to most hydrocarbon systems especially when major components are linear saturated hydrocarbons. A quick look at number of parameters, their variations and effects on orifice area makes you confident that it is quite impossible to predict the trend of $A_{orifice}$ curve without performing detail study for each system on case by case basis.

The wetted area of vessel can be also defined as a function of percent liquid vaporized or liquid hold up volume (V_H) by equations (7) and (8). For simplicity, the vessel cylindrical portion area can be assumed as wetted area (head cap area ignored).

For vertical vessel: $A = 4\,V_H / D$ (7)

For horizontal Vessel: $A = D\,L\,\text{Arccos}\,(1 - 2\frac{H}{D})$ (8)

Where $\frac{H}{D} = \frac{a + c\,x + e\,x^2 + g\,x^3 + i\,x^4}{1 + b\,x + d\,x^2 + f\,x^3 + h\,x^4}$ (9)

and $x = V_H / V_T$

Table 2 – Equation (9) Coefficients

a = 0.00153	b = 26.787
c = 3.299	d = -22.923
e = 24.353	f = -14.845
g = -36.999	h = 10.529
i = 9.892	

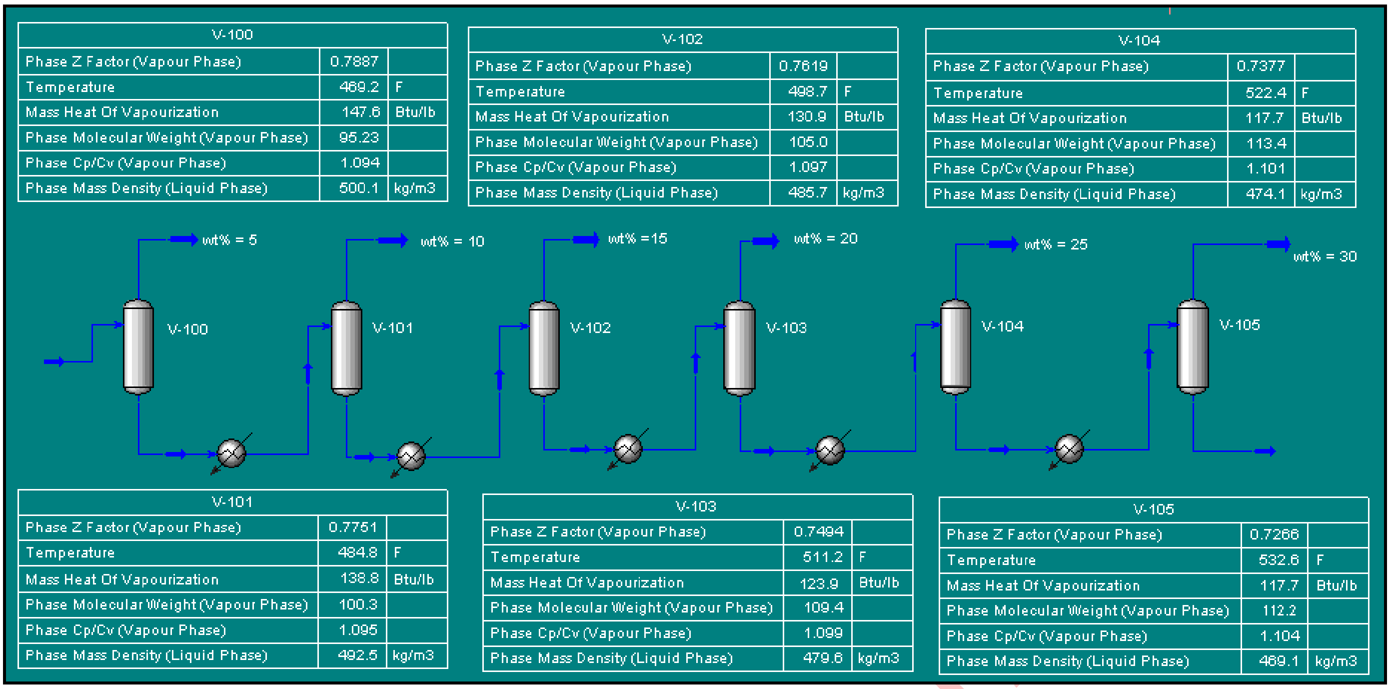

Figure 1 – Schematic representation of sequential flashing in Hysys

Case Study

To review the effect of different process parameters variations on the relief valve required area, semi dynamic approach is utilized for a vertical vessel in condition specified in Table 3.

As depicted in Figure 1, gas and liquid physical properties at each 5wt% interval are obtained and used in Excel spreadsheet (Table 4) to calculate require orifice area. The vessel is assumed to be vertical with elliptical heads. The wetted area is calculated by $A = \frac{4\,V_H}{D} + 1.305\,D$ (one head is exposed to fire).

The calculation result for base case has been plotted in Figure 4 where the maximum area required for relief valve is 0.1655 in^2 which corresponds to 20% liquid vaporization. Similar calculations have been done for the same system with different initial liquid content to see its effect on shape of curve and point at which relief valve required area is maximized. The results are shown in Figures 2, and 5.

Table 3- Base Case Condition & Composition

Composition		
C3	mole%	2.824
nC4	mole%	3.954
nC5	mole%	5.649
nC6	mole%	8.474
nC7	mole%	8.474
nC8	mole%	11.299
nC9	mole%	11.299
nC10	mole%	14.124
nC11	mole%	16.949
nC12	mole%	16.949
Condition		
Relieving Pressure	barg	12.0
Vessel Diameter	m	1.0
Vessel Height	m	3.0
Liquid Height	m	1.5

Table 4 – The calculation results for condition specified in Table 1

Vap wt%	**ρ* (kg/m^3)**	**V_H (m^3)**	**Mass (kg)**	**A (m^2)**	**Q (btu/h)**	**λ* (btu/lb)**	**W (lb/hr)**	**Z* (---)**	**T* (°F)**	**M* (---)**	**Cp/Cv* (---)**	**$A_{Orifice}$ (in^2)**
0	508.5	1.18	599	6.02	641812	157.6	4072	0.8025	451.6	89.8	1.094	0.1600
5	500.2	1.14	569	5.85	627669	147.7	4250	0.7888	469.1	95.2	1.094	0.1623
10	492.6	1.09	539	5.68	612424	138.8	4412	0.7751	484.8	100.3	1.095	0.1641
15	485.8	1.05	509	5.50	595999	131.0	4550	0.7621	498.6	105.0	1.097	0.1650
20	479.6	1.00	479	5.30	578555	124.0	4666	0.7495	511.1	109.3	1.099	0.1655
25	474.1	0.95	449	5.09	560028	117.8	4754	0.7378	522.3	113.3	1.101	0.1651
30	469.1	0.89	419	4.88	540580	112.2	4818	0.7267	532.6	117.0	1.104	0.1642
35	464.5	0.84	389	4.66	520288	107.1	4858	0.7163	541.9	120.5	1.107	0.1625
40	460.3	0.78	359	4.43	499158	102.5	4870	0.7063	550.6	123.7	1.110	0.1602

* Physical properties obtained from simulation software

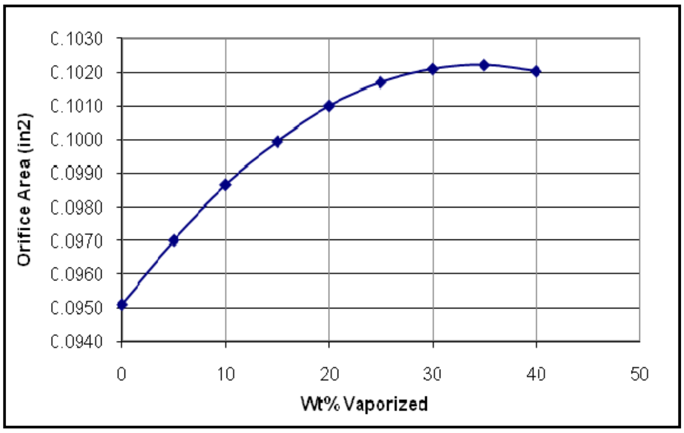

Figure 2 – Required area for 0.3 m of liquid level

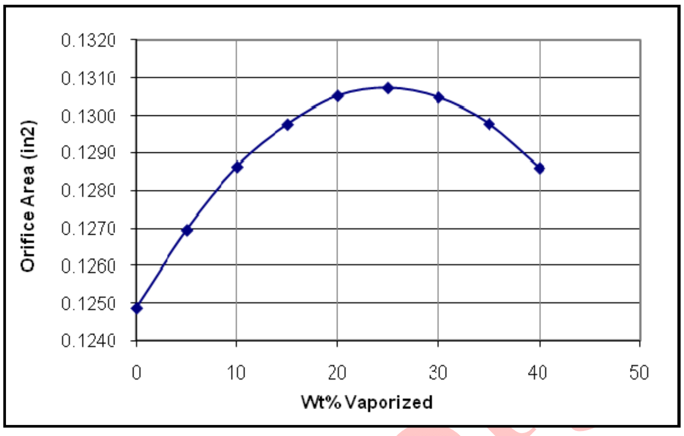

Figure 3 – Required area for 1.0 m of liquid level

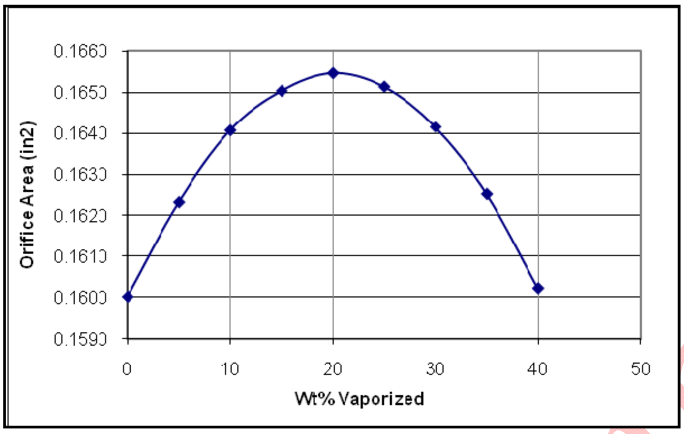

Figure 4 – Required area for 1.5 m of liquid level

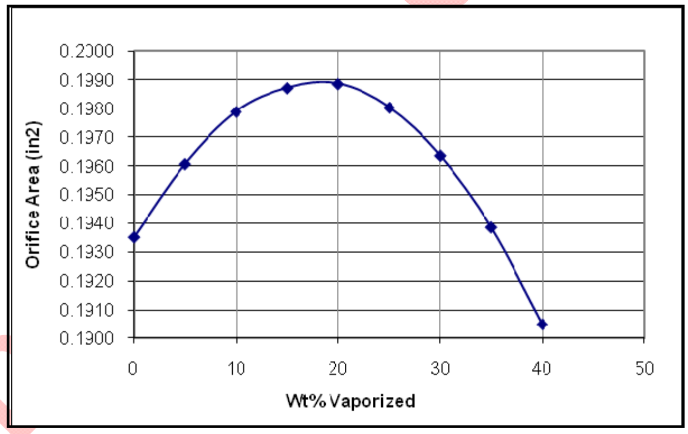

Figure 5 – Required area for 2.0 m of liquid level

Conclusion

The results of this particular example show that the graph of orifice area versus liquid percent vaporized (time) shows a peak. This peak usually happens at first 30% liquid vaporization range. The maximum relief valve required area (peak point) is not more than 5% higher than required orifice at initial condition (relief valve size based on 0% liquid vaporized – steady state approach).

In view of above and considering following facts, I believe conventional approach (using initial gas and liquid properties) is the most practical method for fire relief study.

- There are lots of uncertainties in fire relief rate calculation such as size of fire, distance to fire, fire heat flux rate, the effect of fire fighting and depressuring facilities and fire team action on reducing relief load and demand on relief valve.
- There are lots of overdesign factor such as piping area contingency, wetted area (vessel liquid level) overdesign, etc which covers this 5% difference.
- Fire is usually categorized as remote emergency.
- The selected relief valve orifice is usually much bigger than required one.
- The limitation of man hour and other resources which are required for rigorous calculation.

In other words, although rigorous methods gives realistic picture but the time needed for building this realistic picture and the benefits gained form it makes conventional method quite competitive and applied.

Contact

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