Vent Sizing For Fire Emergencies

by Dr. Hans K. Fauske

Realistic sizing for fire emergencies for non-reactive systems requires information about the prevailing flow regime, i.e., is the system in question non-foamy or foamy in nature following incipient boiling and vaporization. This is especially the case for atmospheric storage tanks such as API Standard 650 tanks (3 oz. - 2.5 psig design pressure). Relevant experimental data simulating fire emergencies with non-foamy (tap water) and foamy (1000 ppm detergent in water) liquids (Fauske et al, 1986) clearly illustrate the difference in venting behavior (see Figure 1).

Non-Foamy Behavior

The venting requirement can be based upon all vapor venting consistent with the traditional approach (Crozier, 1985). The expected flow regime pattern is illustrated in Figure 1a, which results in a small liquid swell (typically less than 5%) due to the bubbles primarily forming and adhering close to the vertical walls (Fauske et al., 1986). The minimum free-board height, h (m), below which two-phase venting can be expected (Figure 1a) is given by (Epstein et al., 1989)

$$h = \left(\frac{\dot{Q}}{2 \pi U_E} \right)^{1/2} \tag{1}$$

U_E (m s^{-1}) is the Kutateladze (1972) entrainment velocity given by

$$U_E = 3 \left[\frac{\sigma g \rho_l}{\rho_v^2} \right]^{1/4} \tag{2}$$

where σ (kg s^{-2}) is the liquid surface tension, g (9.8 m s^{-2}) is the gravitational constant, ρ_l (kg m^{-3}) is the liquid density and ρ_v (kg m^{-3}) is the vapor density.

$\dot{Q}$ (m^3 s^{-1}) is the volumetric vapor source resulting from the fire exposure and is given by

$$\dot{Q} = \frac{Q_F}{\lambda \rho_v} \tag{3}$$

where Q_F (J s^{-1}) is the total fire heat input rate (surface area x fire heat flux - see Crozier, 1985), and λ (J kg^{-1}) is the latent heat of vaporization. $\dot{Q}$ can also be represented in terms of the equivalent liquid volumetric heating rate, $\dot{T}$ (K s^{-1}), as follows

$$\dot{Q} = \frac{V \rho_l c \dot{T}}{\lambda \rho_v} \tag{4}$$

where V (m^3) is the volume of liquid, and c (J kg^{-1} K^{-1}) is the liquid specific heat. Considering vapor venting, the required vent area, A (m^2) is given by

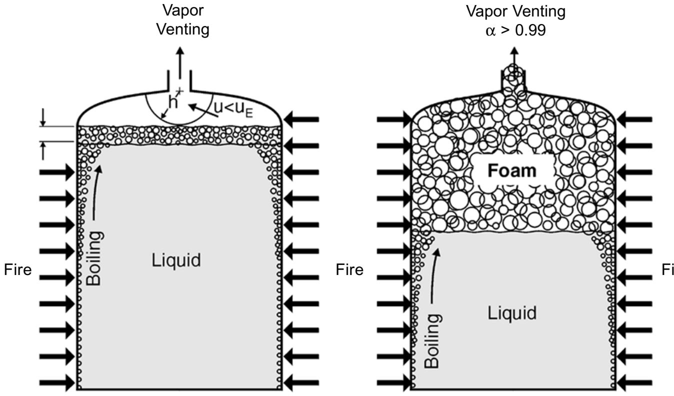
$$A = \frac{\dot{Q}}{C_D \; 0.61 \, (P / \rho_v)^{1/2}} \tag{5}$$

$$A = \frac{\dot{Q}}{C_D \, (2 \Delta P / \rho_v)^{1/2}} \tag{6}$$

for critical and highly subcritical flow conditions, respectively, where C_D is the appropriate discharge coefficient, P (Pa) is the venting pressure, and ΔP (Pa) is the overpressure.

Vent area requirements predicted from Eqs. 5 and 6 are compared to available large-scale non-foamy data in Table 1. The atmospheric water data were obtained with open sharp entrance short vent ducts, i.e., the appropriate value of $C_D = 0.61$. The noted good agreement is consistent with a free board value of less than 5% which accommodates both the liquid swell and the absence of liquid entrainment according to Eq. 1.

We note that for the propane trial listed in Table 1 (US DOT, 1984), Eq. 5 predicts a somewhat larger vent area requirement. This is consistent with the noted overpressure, ΔP = 40 psi, since according to Eq. 5 the product of A • P is essentially constant. Correcting for the noted overpressure, the experiment value becomes ($4.15 \cdot 10^{-5}$) (324/285) = $4.73 \cdot 10^{-5}$ m^{-1} which compares to the estimated value of $4.80 \cdot 10^{-5}$ m^{-1}. It is also of interest to note that the listed propane trial, despite the presence of adequate pressure relief, experienced a catastrophic failure, i.e., a so-called BLEVE.



a) Non-Foamy Behavior b) Foamy Behavior

Figure 1 Illustration of Non-Foamy and Foamy Venting Behaviors for Fire Emergencies

The occurrence of BLEVEs with tanks filled with pressure-liquefied gas (PLG) mostly involve fire impingement ranging from partial or complete fire engulfment to local jet or torch fires. The fire exposure leads to high wall temperatures above the liquid level and material weakening. Catastrophic tank failure may result even though the relief valve is open and venting vapor at a rapid rate. The sudden release and explosive evaporation of a superheated liquid can lead to severe consequences. If tanks can largely empty before they can fail, BLEVEs are eliminated and the outcome will be much less hazardous.

Timely removal of PLG can be facilitated by installing a "dip-tube" relief system in addition to the traditional vapor relief system (see Figure 2). The latter system controls the pressure by providing adequate vapor venting while the dip-tube design provides rapid liquid removal which can largely empty the tank before reaching the rupture condition. Considerations given to inherent temperature stratification (i.e., subcooled liquid conditions), and time to failure in connection with both fire engulfment and torch fire, indicate that installing a liquid removal system of similar size to the vapor relief system, will largely empty the tanks before failure can occur, i.e., prevent most BLEVEs.

Foamy Behavior

In contrast to the non-foamy behavior, for foamy systems such as exemplified by the foamy water trial listed in Table 1, a very high void fraction ($\alpha > .99$) regime continues to enter the vent line until the vessel is nearly empty, i.e., a freeboard volume free of liquid is only established after a large fraction of the liquid has vented (Figure 1b). The implication of this behavior leads to a larger vent area but also largely eliminates the potential for a BLEVE, as the walls continue to be wetted until most of the liquid has been vented. As for the increased vent area requirement, we note that the proposed DIERS methodology considering bubbly flow behavior (Fisher and Forrest, 1994) grossly overpredicts the requirement by an order of magnitude as illustrated in Table 1. Replacing the vapor density ρ_v in Eq. 6 with the two-phase density $\rho_l(1 - \alpha) + \rho_v \alpha$ and setting $\alpha = 0.99$, a reasonable safe vent area is estimated as shown in Table 1. Matching the experimental vent area with the measured overpressure of 0.4 psi results in $\alpha = 0.995$. Given the high value of the foam void fraction, a similar approach can be used for critical flow conditions, with $\rho_l(1 - \alpha) + \rho_g \alpha$ replacing ρ_v in Eq. 5 with $\alpha = 0.99$. Additional experiments to confirm the general use of this approach appear warranted. An easy method to determine the prevailing flow regime for actual fire emergency condition is provided by the Flow Regime Detector, which is offered as an option with the Advanced Reactive System Screening Tool (ARSST).

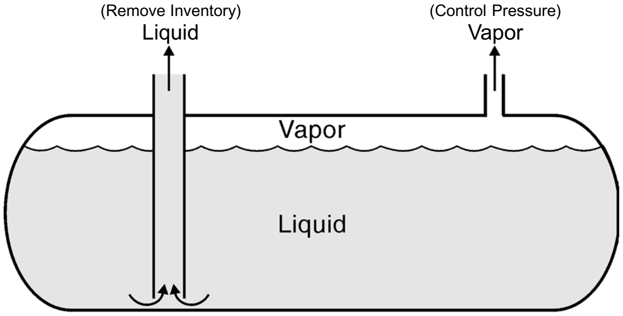


Figure 2 Illustration of Combined Liquid and Vapor Venting Resulting in Prevention of BLEVEs

System	$(A/V)_{exp.}$ m^{-1}	P psia	ΔP psi	$\dot{T}$ °C min^{-1}	$(A/V)_{predictions}$, m^{-1}	
					Foamy	Vapor Venting
Water, 0.312 m^3 Non-Foamy	$1.62 \cdot 10^{-3}$	14.7	~0.7	2.5	--	$1.68 \cdot 10^{-3}$ (Eq. 6)
Water, 0.312 m^3 Foamy	$6.48 \cdot 10^{-3}$	14.7	~0.4	2.5	$(5.83 \cdot 10^{-2})^*$ $8.86 \cdot 10^{-3}$	--
Propane, 122 m^3 Non-Foamy	$4.15 \cdot 10^{-5}$	285	40	3.36	--	$4.80 \cdot 10^{-5}$ (Eq. 5)

*DIERS Methodology, Fisher and Forrest, 1994

Table 1 Fire Simulation Experiments and Model Predictions

References

Crozier, R. A., 1985, "Sizing Relief Valves for Fire Emergencies," Chem. Eng. Magazine, McGraw Hill, p. 49, October 28 issue.

Epstein, M., Fauske, H. K. and Hauser, G. M., 1989, "The Onset of Two-Phase Venting via Entrainment in Liquid-Filled Storage Vessels Exposed to Fire," J. Loss Prev. Process Ind., Vol. 2 (1), 45, 1989.

Fauske, H. K., Epstein, M., Grolmes, M. A. and Leung, J. C., 1986, "Emergency Relief Vent Sizing for Fire Emergencies Involving Liquid-Filled Atmospheric Storage Vessels," Plant/Operations Progress, Vol. 5 (4), 205, 1986.

Fisher, H. G. and Forrest, H. S., 1994, "Protection of Storage Tanks From Two-Phase Flow Due to Fire Exposure," Paper Presented at the AIChE 1994 Summer National Mtg., August 15, 1994.

Kutateladze, S. S., 1972, "Elements of the Hydrodynamics of Gas-Liquid Systems," Fluid Mechanics - Soviet Research, Vol. 1, 29, 1972.

US DOT, 1984, Final Report FRA-OR&R75-32.