Sponsor: Defense Threat Reduction Agency – Joint Science and Technology Office (DTRA-JSTO)

Source Term Flow Rate Based on Container Wall Thickness

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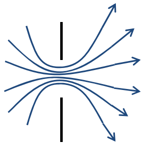
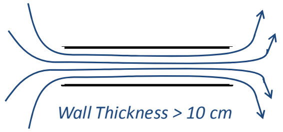
1. Current Saturated Liquid (Cl_2, NH_3, SO_2) Source Term Modeling Technique

- Container thickness
  - L = 0 cm
    - Straight – edged orifice
    - Bernoulli Equation applies

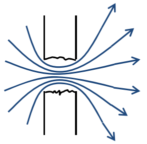
$$G(\frac{kg}{s\ m^2}) = C_D\sqrt{2g(P_{tank} - P_{amb})\rho_L}$$



  - L > 10 cm
    - Pipe flow
    - Fully developed two-phased flow applies (omega method)



  - 0 < L < 10 cm
    - The “in-between” region
    - What is the flow rate???



2. Common Container Wall Thicknesses

- Liquid chlorine rail tank car (105J500W)
  - 2.7 cm steel shell thickness
  - 5 cm ceramic insulation
  - 5 cm fiberglass insulation

~12.7 cm

- Industrial container
  - Accepted wall thickness equation
  - Assumptions
    - radius = height
    - corrosion allowance = 1 cm
    - joint efficiency = 1

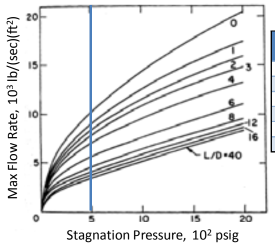
$$t = \frac{Pr_i}{S\,E_J - 0.6P} + C_C$$

t = wall thickness
P = pressure
r_i = radius
S = material strength
E_J = joint efficiency
C_c = corrosion allow.

Thickness (cm)	Volume (gallons)	Radius (in)	Pressure (PSI)	Tensile strength (PSI)
2.05	1000	42	110	11200
3.26	10000	90	110	11200
5.88	100000	194	110	11200

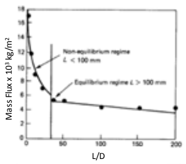
“Predicted Damage to a Chlorine Rail Tank Car from Selected Threat Weapons,” 2008.
The ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers, New York City, Section VIII.
Plant Design and Economics for Chemical Engineers, 4th edition. McGraw Hill. Peters and Timmerhaus. pp. 536. 1991.

3. Flow Rate of Flashing Saturated Liquid



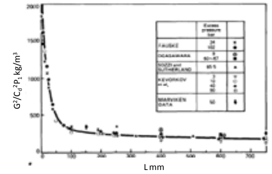
Tube Length (cm)	% of Bernoulli Flow		Length / Diameter
	34 bar	138 bar	
0	100	100	0
0.6	85	88	1
1.3	78	80	2
1.9	73	74	3
2.54	63	66	4
25	29	41	40

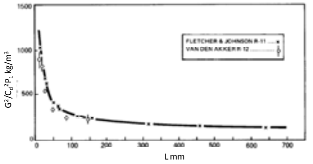
Fauske, H.K., “The Discharge of Saturated Water Through Tubes,” Chem. Eng. Prog. Symp. Series, Vol. 61, No. 59 (1965).



Critical Flow Experiments with Flashing Liquids

Source	Material	D (mm)	L/D	L (mm)	Pressure (bar)
Fauske	Water	6.35	~16	~100	34, 102
Ogasawara	Water	10.9, 32.9, 50.5			9, 60, 67
Sozzi and Sutherland	Water	12.7	~10	~127	65.6
Kevorkov et al.	Water	14, 25, 37.8			3, 10, 40, 90
Marviken	Water	500	> 0.33	> 166	50
Flinta	Water	35	~3	~100	
Uchida and Nariai	Water	4	~25	~100	
Fletcher	Freon-11	3.2	~33	~105	
Van Den Akker	Freon-12	4	~22	90	





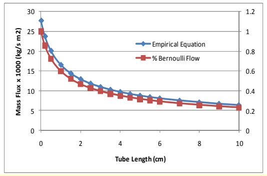
Fauske, H.K., 1985. Flashing flows or: some practical guidelines for emergency releases. Plant/Operations Prog. 4, 132-134.
Fletcher, B., 1984. Discharge of saturated liquids through pipes. J. Haz. Mat. 8, 377-380.

4. Zero’th Order Empirical Equation for Saturated Mass Flow Rate

$$G(kg/m^2) \approx \frac{h_{fg}}{V_{fg}}\left(\frac{1}{NTC}\right)^{1/2} \qquad N \approx \frac{h_{fg}^2}{2\Delta P\rho_l K^2 V_{fg}^2 TC} + 10L$$

G = mass flux
h_{fg} = heat of vaporization
V_{fg} = specific volume change
T = temperature
C = liquid heat capacity
ΔP = pressure drop
ρ_l = liquid density
K = discharge coefficient
L = tube length (0 – 10cm)

Theoretical Saturated Chlorine Flow Rate



5. Conclusions

- Industrial tanks have wall thicknesses ranging from 2- 8 cm
- Saturated liquid source terms are modeled with wall thicknesses
  - > 10 cm (Omega Method)
  - = 0 cm (Bernoulli Equation)
- **0 – 10 cm container wall thickness isn’t taken into account by any source term model**
- The error introduced by this omission is a flow rate that is off by **2 – 3 times** what experimental evidence shows
- In addition to bracketing saturated liquid source terms by using the Bernoulli equation and the Omega method, we recommend using the “fitted” equation demonstrated for containers with wall thicknesses < 10 cm