SIZING RUPTURE DISKS (RDs) FOR TWO-PHASE FLOW

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SUMMARY

An easy and accurate method for estimating two-phase flow through RDs is outlined. Given information about stagnation conditions the model can handle gas-liquid, vapor-liquid and hybrid flows including subcooled flashing flows. Examples are provided illustrating sizing of RDs for gas-liquid, vapor-liquid, hybrid and flashing flows. The examples illustrate the importance of considering two-phase flows when sizing rupture disks.

INTRODUCTION

RDs are extensively used for overpressure protection in the chemical process industries and sizing methods for all liquid and all gas flows are well established and easy to use (see Fike Metal Products catalog). In comparison, two-phase flow methods proposed over the years have been far more complex and difficult to use than the single-phase flow methods. Here we introduce an equally easy to use two-phase flow method with accuracy equal to or better than that provided by the more complex models (Fauske, 1998).

The RD size is obtained by assuring a balance between the required venting rate, W (kg/s) and the discharge rate

$$W = K_d \; A \; G \qquad (1)$$

where K_d (0.62) is the rupture disk flow coefficient given in the ASME Boiler and Pressure Vessel Code (1983), A (m^2) is the vent area, and G (kg/m^2-s) is the two-phase mass flux given by

$$G = \left[\frac{1-x_o}{G^2_{x_o=0}} + \frac{x_o}{G^2_{x_o=1.0}} \right]^{-1/2} \qquad (2)$$

where x_o is the stagnation gas and/or vapor quality.

GAS-LIQUID FLOWS

For two-compartment two-phase flows such as air-water flows, $G_{x_o=0}$ is determined

$$G_{x_o} = \sqrt{2\left(P_o - P_b\right)\rho_{\ell,o}} \qquad (3)$$

where P_o (Pa) is the stagnation pressure, P_b (Pa) is the back pressure, and $\rho_{\ell,o}$ (kg/m^3) is the liquid density. For critical flows $G_{x_o=1.0}$ is given by

$$G_{x_o=1.0} = P_o \left(\frac{M_w}{R \; T_o} \right)^{1/2} \left[k \left(\frac{2}{k+1} \right)^{(k+1)/(k-1)} \right]^{1/2} \qquad (4)$$

and for subcritical flows by

$$G_{x_o=1.0} = P_o \left(\frac{M_w}{R \; T_o} \right)^{1/2} \left\{ \left(\frac{2\,k}{k-1} \right) \left[\left(\frac{P_b}{P_o} \right)^{2/k} - \left(\frac{P_b}{P_o} \right)^{(k+1)/k} \right] \right\}^{1/2} \qquad (5)$$

where M_w is the molecular weight, R (8314 Pa-m^3/K-kg-mole) is the gas constant, and k is the isentropic coefficient (see Table 3, Fike Metal Products Catalog, for values of k).

VAPOR-LIQUID FLOWS

For one-component two-phase flows, such as steam-water flows, $G_{x_o=0}$ can be estimated from

$$G_{x_o=0} = \rho_{v,o} \; \lambda_o \left(T_o \; c_o \right)^{-1/2} \qquad (6)$$

where $\rho_{v,o}$ (kg/m^3) is the stagnation vapor density, λ_o (J/kg) is the latent heat of vaporization, T_o (K) is the stagnation temperature and c_o (J/kg-K) is the liquid specific heat. Similar to two-component two-phase flows $G_{x_o=1.0}$ is given either by Equation (4) or Equation (5).

HYBRID GAS-VAPOR-LIQUID FLOWS

For hybrid two-phase flows such as air-steam-water flows $G_{x_o=0}$ is determined from

$$G_{x_o=0} = \left[2\ P_{g,o}\ \rho_{\ell,o} + \lambda_o^2\ \rho_v^2 / T_o\ c_o\right]^{1/2} \qquad (7)$$

where $P_{g,o}$ (Pa) is the stagnation gas partial pressure and $G_{x_o=1.0}$ is again given by either Equation 4 or Equation 5 with the molecular weight M_w given by

$$M_w = M_{w,g}\left(P_{g,o} / P_o\right) + M_{w,v}\left(P_{v,o} / P_o\right) \qquad (8)$$

where $P_{v,o}$ (Pa) is the vapor pressure corresponding to the stagnation temperature T_o. The value of the isentropic coefficient k can be estimated in a similar manner.

ALL LIQUID FLASHING FLOWS

For all liquid initial conditions, Equation 2 reduces to $G = G_{x_o=0}$. In case of saturated inlet or stagnation conditions, G is determined from

$$G = \rho_{v,o}\ \lambda\left(T_o\ c_o\right)^{-1/2} \qquad (9)$$

and for subcooled inlet conditions the expression is the same as that for hybrid vapor-gas-liquid flows with $x_o = 0$

$$G = \left[2\ P_{g,o}\ \rho_{\ell,o} + \lambda_{v,o}^2 / T_o\ c_o\right]^{1/2} \qquad (10)$$

EXAMPLE 1 - SIZING FOR GAS-LIQUID FLOWS

What size rupture disk is required to relieve an air-water mixture under the following conditions:

W = 50 kg/s, x_o = 0.01, $P_o = 7 \bullet 10^5$ Pa,
$P_b = 10^5$ Pa, T_o = 300 K, and $\rho_{\ell,o} = 10^3$ kg/m^3.

$$G_{x_o=0} = \sqrt{2\left(7 \bullet 10^5\right)1000} = 3.46 \bullet 10^4\ kg / m^2 - s$$

+

$$G_{x_o=1.0} = 7 \bullet 10^5\left(\frac{29}{8314 \bullet 300}\right)^{1/2}\left[1.4\left(\frac{2}{1.4+1}\right)^{\frac{(1.4+1)}{(1.4-1)}}\right]^{1/2}$$
$$= 1.63 \bullet 10^3\ kg / m^2 - s$$

$$G = \left[\frac{0.99}{\left(3.46 \bullet 10^4\right)^2} + \frac{0.01}{\left(1.63 \bullet 10^3\right)^2}\right]^{-1/2}$$
$$= 1.48 \bullet 10^4\ kg / m^2 - s$$

$$A = 50 / \left(1.48 \bullet 10^4 \bullet 0.62\right)$$
$$= 5.44 \bullet 10^{-3} \quad or \quad 8.44\ in^2$$

Answer: 4 inch diameter rupture disk.

What size rupture disk is required to relieve only the gas portion of the above air-water mixture, all other conditions remaining the same.

$$A = \frac{W\ x_o}{K_d\ G_{x_o=1.0}} = \frac{50 \bullet 0.01}{0.62 \bullet 1.63 \bullet 10^3}$$
$$= 4.95 \bullet 10^{-4}\ m^2 \quad or \quad 0.77\ in^2$$

Answer: 1 inch diameter rupture disk, i.e., in case of no liquid entrainment the required rupture disk size is much smaller.

EXAMPLE 2 - SIZING FOR VAPOR-LIQUID FLOWS

What size rupture disk is required to relieve a vapor-liquid ethylene mixture under the following conditions:

W = 300 kg/s, x_o = 0.01, $P_o = 2 \bullet 10^6$ Pa,
$P_b = 10^5$ Pa, T_o = 245 K.
Other physical properties: $\rho_{v,o}$ = 38.5 kg/m^3,
$\lambda_o = 3.2 \bullet 10^5$ J/kg, c_o = 3050 J/kg-K, M_w = 28,
and k= 1.26.

$$G_{x_o=0} = 38.5 \bullet 3.2 \bullet 10^5 (245 \bullet 3050)^{-1/2}$$
$$= 1.43 \bullet 10^4\ kg / m^2 - s$$

+ Critical flow condition is used: $P_b/P_o = 0.143 <$ $P_c/P_o = \left(\frac{2}{K+1}\right)^{k/(k-1)}$ = 0.53, where P_c is the critical pressure.

$$G_{x_o=1.0} = 2 \bullet 10^6 \left(\frac{28}{8314 \bullet 245} \right)^{1/2} \left[1.26 \left(\frac{2}{1.26+1} \right)^{\frac{(1.26+1)}{(1.26-1)}} \right]^{1/2}$$

$$= 4.89 \bullet 10^3 \ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(1.43 \bullet 10^4\right)^2} + \frac{0.01}{\left(4.89 \bullet 10^3\right)^2} \right]^{-1/2}$$

$$= 1.38 \bullet 10^4 \ kg/m^2 - s$$

$$A = 300/(1.38 \bullet 10^4 \bullet 0.62)$$

$$= 3.51 \bullet 10^{-2} \ m^2 \quad or \quad 54.4 \ in^2$$

Answer: 10 inch diameter rupture disk.

What size rupture disk is required to relieve only the vapor portion of the above ethylene mixture, all other conditions remaining the same

$$A = (300 \bullet 0.01)(4.89 \bullet 10^3 \bullet 0.62)$$

$$= 9.90 \bullet 10^{-4} \ m^2 \quad or \quad 1.53 \ in^2$$

Answer: 1-1/2 inch diameter rupture disk, i.e., in case of no liquid entrainment the required rupture disk is much smaller.

EXAMPLE 3 - SIZING FOR GAS-VAPOR-LIQUID HYBRID FLOWS

What size rupture disk is required to relieve an air-steam-water mixture under the following conditions:

W = 100 kg/s, $x_o = 0.01$, $P_o = 10^6$ Pa, T = 443 K, $P_b = 10^5$ Pa.
Other physical properties: $P_{g,o} = 2.08 \bullet 10^5$ Pa, $\rho_{\ell,o} = 8.97 \bullet 10^2$ kg/m^3, $\rho_{v,o} = 4.12$ Kg/m^3, $\lambda_o = 2.05 \bullet 10^6$ J/kg-K, and $c_o = 4366$ J/kg-K.

$$G_{x_o=0} = \left[2 \bullet 2.08 \bullet 8.97 \bullet 10^2 + \frac{\left(2.05 \bullet 10^6\right)^2 \left(4.12\right)^2}{(443)(4366)} \right]^{1/2}$$

$$= 2.2 \bullet 10^4 \ kg/m^2 - s$$

$$M_w = 29\left(2.08 \bullet 10^5/10^6\right) + 18\left(7.92 \bullet 10^5/10^6\right)$$

$$= 20.29$$

$$k = 1.4\left(2.08 \bullet 10^5/10^6\right) + 1.324\left(7.92 \bullet 10^5/10^6\right)$$

$$= 1.34$$

$$G_{x_o=1.0} = 10^6 \left[(20.29/(8314)(443)\right]^{1/2} \left[1.34 \left(\frac{2}{1.34+1} \right)^{\frac{(1.34+1)}{(1.34-1)}} \right]^{1/2}$$

$$= 1.58 \bullet 10^3 \ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(2.02 \bullet 10^4\right)^2} + \frac{0.01}{\left(1.58 \bullet 10^3\right)^2} \right]^{-1/2}$$

$$= 1.25 \bullet 10^4 \ kg/m^2 - s$$

$$A = 100/(1.25 \bullet 10^4 \bullet 0.62)$$

$$= 1.29 \bullet 10^{-2} \ m^2 \quad or \quad 20.3 \ in^2$$

Answer: 6 inch diameter rupture disk.

What size rupture disk is required to relieve the above mixture in the absence of air, i.e., P_o is reduced to $P_{v,o} = 7.92 \bullet 10^5$ Pa with all other conditions remaining the same.

$$G_{x_o=0} = 4.12 \bullet 2.05 \bullet 10^6 \ (433 \bullet 4366)^{-1/2}$$

$$= 6.07 \bullet 10^3 \ kg/m^2 - s$$

$$G_{x_o=1.0} = 7.92 \bullet 10^5 \left(\frac{18}{8314 \bullet 443} \right)^{1/2} \left[1.324 \left(\frac{2}{1.324+1} \right)^{\frac{(1.324+1)}{(1.324-1)}} \right]^{1/2}$$

$$= 1.18 \bullet 10^3 \ kg/m^2 - s$$

$$G = \left[\frac{0.99}{\left(6.07 \bullet 10^3\right)^2} + \frac{0.01}{\left(1.18 \bullet 10^3\right)^2} \right]^{-1/2}$$

$$= 5.39 \bullet 10^3 \ kg/m^2 - s$$

$$A = 100/\left(5.39 \bullet 10^3 \bullet 0.62\right)$$

$$= 2.99 \bullet 10^{-2} \ m^2 \quad or \quad 46.35 \ in^2$$

Answer: 8 inch diameter rupture disk, i.e., in absence of air the required rupture disk diameter is significantly increased.

EXAMPLE 4 - SIZING FOR SUBCOOLED FLASHING FLOWS

What size rupture disk is required to relieve subcooled flashing water under the following conditions:

W = 100 kg/s, $P_o = 10^6$ Pa, $T_o = 443$ K,

$P_b = 10^5$ Pa.
Other physical properties: $P_{v,o} = 7.92 \bullet 10^5$ Pa, $P_{g,o} = 2.08 \bullet 10^5$ Pa, $\rho_{\ell,o} = 8.97 \bullet 10^2$ kg/m^3, $\rho_{v,o} = 4.12$ kg/m^3, $\lambda_o = 2.05 \bullet 10^6$ J/kg-K, and $c_o = 4366$ J/kg-K.

$$G = \left[2 \bullet 2.08 \bullet 10^5 \bullet 8.97 \bullet 10^2 + \frac{\left(2.05 \bullet 10^6\right)^2 \left(4.12\right)^2}{\left(433\right)\left(4366\right)} \right]^{1/2}$$

$$= 2.02 \bullet 10^4 \; kg/m^2 - s$$

$$A = 100/(2.02 \bullet 10^4 \bullet 0.62)$$
$$= 7.98 \bullet 10^{-3} \; m^2 \quad or \quad 12.37 \; in^2$$

Answer: 4 inch diameter rupture disk.

What size rupture disk is required if the water is saturated, i.e., T_o = 453 K ($\rho_{\ell,o} = 8.97 \bullet 10^2$ kg/m^3, $\rho_{v,o} = 5.16$ kg/m^3, $\lambda_o = 2.02 \bullet 10^6$ J/kg, $c_o = 4403$ J/kg-K).

$$G = 5.16 \bullet 2.02 \bullet 10^6 \,(4403 \bullet 453)^{-1/2}$$
$$= 7.38 \bullet 10^3 \bullet 0.62)$$

$$A = 100/(7.38 \bullet 10^3 \bullet 0.62)$$
$$= 2.19 \bullet 10^{-2} \; m^2 \quad or \quad 33.87 \; in^2$$

Answer: 8 inch diameter rupture disk, i.e., in absence of subcooling the required rupture disk diameter is significantly increased.

REFERENCES

ASME Boiler and Pressure Vessel Code, 1983, Section VIII, Div. 1, ASME, NY.

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