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An easy method to design gas/vapor relief system with rupture disk

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A R T I C L E I N F O

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A B S T R A C T

Tank discharge gas/vapor flow problems are frequently encountered in both practice and design. To perform this type of design calculation, the first step is to identify whether the flow is choked or not through a trial-and-error solution of an equation for adiabatic flow with friction from a reservoir through a pipe. Developing a direct method without any trial-and-error to identify a choking condition would be helpful for expediting the flow calculations. This paper presents an easy and quick method to identify the choking of gas flow for an emergency relief system consisting of a rupture disk and vent piping. This greatly simplifies the design calculations. The proposed method for validating the venting adequacy of existing ERS circumvents the iteration calculation and the use of Lapple charts. Three case studies for the design of vent piping for rupture disks support the proposed method.

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1. Introduction

Emergency Relief Systems (ERS) are installed to protect process vessels from the catastrophic effects of excessive overpressure and subsequent rupture. An Emergency Relief System can be thought of as being composed of three different elements: pressure source (reservoir), relief device, and vent line. The pressure source can be a reactor, a pipe needing to be protected, or any other equipment or process vessel. Rupture disks and safety valves are the primary relief devices by which pressurized vessels and pipelines are protected against intolerable overpressures. The safety valve is a reclosing pressure relief device that will reclose once the protected-system pressure is lower than the set pressure of the valve, minus the "blowdown" of the valve. The blowdown of a safety valve is the difference between the set pressure and the closing pressure of a safety valve, expressed as a percentage of the set pressure. The rupture disk is a non-reclosing pressure relief device actuated by the differential pressure between the inlet and outlet sides of the disk, and it is designed to function by bursting.

The methods for designing gas/vapor emergency relief system have been well established and used in industrial practice (API standard 520, 2008; API standard 521, 2008; Kern, 1975; Cox and Weirick, 1980; Kandell, 1981; Van Boskirk, 1982; Friedel and Schmidt, 1993; Westman, 1997, 1998). The design of a safety valve is more complicated than a rupture disk because the calculations for the inlet and outlet piping of a safety valve usually have to be done separately. The current code requires the un-recoverable pressure loss of the inlet piping of a pressure relief valve to be less than 3% of the set pressure to avoid rapid cyclic opening and closing of the valve, commonly known as "chattering". This can reduce the flow capacity of the valve and can result in damage to the valve and the inlet piping. The discharge piping system should be designed so that the "back pressure" caused by flow through the piping does not reduce the intended capacity of the system.

The design for a rupture disk system is much easier than that of a safety valve. Generally, one does not need to separately consider the piping before and after a rupture disk, and a rupture disk can be treated as a pipe fitting with a flow resistance obtained from the manufacturer or using a value of 2.4 according to Section UG131 of the ASME Boiler and Pressure Vessel Code (BPVC). Also, the calculated relieving capacity is to be multiplied by a factor of 0.9 or less to allow for any uncertainties according to Section UG127 of the ASME BPVC.

To find the discharge rate from a pressure source requires a trial-and error-solution for equations that relate adiabatic flow to friction-caused pressure drop. The well-known Lapple charts (Lapple, 1943) (later corrected by Levenspiel (Levenspiel, 1977) in 1977) are usually used for a quick graphical solution. However, to perform this type of design calculation, the first step is to determine if the flow is choked. That is, to determine if the flow changes from subsonic to sonic at some point in the piping. Choked flow is a limiting condition which occurs when the mass flow rate will not

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increase with a further decrease in the downstream pressure environment while upstream pressure is fixed. For a fluid flow with a constant pipe diameter, the choke can only occur at the pipe exit if the Mach number at inlet of pipe is subsonic. The gas flow may be supersonic for a short distance downstream of fittings, e.g., orifices and contractions of the cross-sectional pipe area, where the gas can be highly accelerated. At the end of this distance the change from supersonic to subsonic flow occurs due to a single shock or a series of oblique or normal shocks. For simplicity, these are assumed to occur immediately behind the fitting, i.e. before entering the following pipe component, and the extra pressure loss in the supersonic velocity region is superimposed on the losses due to the fitting.

Developing a direct "analytic" method to identify a choking condition would be helpful for expediting design calculations. This paper presents an easy and quick method to determine whether or not choking of gas flow would occur for ERS containing a rupture disk. The proposed method for validating the venting adequacy of existing ERS circumvents the iteration calculations and the use of Lapple charts. Three case studies for the design of vent piping for rupture-disk systems support the proposed method.

2. Design of a gas/vapor relief system

A schematic for a pressure relief system with a rupture disk and a constant pipe diameter is shown in Fig. 1. The properties of the protected tank/vessel and its contents – like the Maximum Allowable Working Pressure (MAWP) and the gas/vapor temperature – under emergency conditions are known. The designer needs to calculate the downstream "state" variables – pressure, temperature, density, and velocity (Mach number) – at the inlet and outlet of each pipe section.

Generally, it is assumed that the flow initially is steady and one-dimensional, and the vent line system is assumed to be adiabatic, with no heat losses from the gas/vapor stream. An adiabatic flow can be either frictional or frictionless. A reversible adiabatic flow (without friction loss) is called as an isentropic flow. Also, the gas/vapor is treated as a perfect gas, such that the ideal gas law applies. The four variables of pressure, temperature, density, and velocity (Mach number) at any location in the pipe can be solved by four equations of continuity (mass balance), momentum balance, energy balance, and equation of state at any known boundary conditions. Such solutions (White, 2001) are shown in Table 1, where the stagnation value (subscript o) is used as the reference condition for isentropic flow while the critical value under sonic condition (Mach number = 1, denoted by asterisks, whether or not it is actually reached in the pipe exit) is used as reference condition for adiabatic flow with friction. The stagnation state has a macroscopic flow velocity of zero, which can be an actual state in a reactor, or a hypothetical state in frictional flow where a state is isentropically transformed to a stagnation state. Mass flux can be calculated

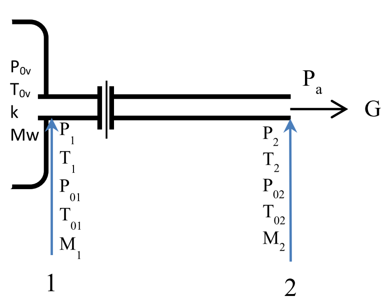

Fig. 1. Schematic of pressure relief system with rupture disk.

through Eq. (8a) at any location in the venting line for any given Mach number. Eq. (8b) is the critical mass flux under the condition of assuming choked flow at the exit from a pipe frictionless flow.

Eq. (4) can be used to establish the relationship between the pressures at points 1 and 2:

$$\frac{P_2}{P_1} = \frac{M_1}{M_2}\cdot\left[\frac{2+(k-1)M_1^2}{2+(k-1)M_2^2}\right]^{\frac{1}{2}} \tag{9}$$

Usually, fluid flow from the protected vessel to inlet of the ERS is treated as isentropic flow but with 0.5 velocity head loss. Therefore, $P_{o1} = P_{ov}$, $T_{o1} = T_{ov}$. Then the pressure ratio is given by:

$$\eta_2 = \frac{P_2}{P_{ov}} = \frac{P_2}{P_{o1}} = \frac{P_2}{P_1}\frac{P_1}{P_{o1}} \tag{10}$$

Substituting Eq. (1) and Eq. (9) into Eq. (10):

$$\eta_2 = \frac{M_1}{M_2}\cdot\sqrt{\frac{1}{\left(1+\frac{k-1}{2}M_2^2\right)\left(1+\frac{k-1}{2}M_1^2\right)^{\frac{k+1}{k-1}}}} \tag{11}$$

If flow at the exit from the ERS (location 2 in Fig. 1) is choked, then $M_2 = 1$. Eq. (11) becomes:

$$\left(1+\frac{k-1}{2}M_1^2\right)^{\frac{k+1}{k-1}} = \frac{2}{k+1}\frac{M_1^2}{\eta_2^2} \tag{12}$$

The Taylor series expansion of $(1+x)^n$ is:

$$(1+x)^n = 1 + nx + \frac{1}{2}n(n-1)x^2 + \cdots \tag{13}$$

Applying the first three members of this expansion to the left side of Eq. (12) gives:

$$\left(1+\frac{k-1}{2}M_1^2\right)^{\frac{k+1}{k-1}} \approx 1 + \frac{k+1}{2}M_1^2 + \frac{k+1}{4}M_1^4 \tag{14}$$

Thus, Eq. (12) becomes:

$$M_1^4 + 2\left[1-\left(\frac{2}{k+1}\cdot\frac{1}{\eta_2}\right)^2\right]M_1^2 + \frac{4}{k+1} = 0 \tag{15}$$

Solving Eq. (15) to obtain the Mach number at location 1,

$$M_1 = \sqrt{\left(\frac{2}{k+1}\cdot\frac{1}{\eta_2}\right)^2 - 1 - \sqrt{\left[1-\left(\frac{2}{k+1}\cdot\frac{1}{\eta_2}\right)^2\right]^2 - \frac{4}{k+1}}} \tag{16}$$

However, M_1 can also be solved through Eq. (7) if the total friction resistance coefficient of both the pipe internal surface and fittings is known, from (Cox and Weirick, 1980):

$$N = 4f\frac{L}{d} + \sum K_i \tag{17}$$

Fig. 2 shows the comparison of M_1 from the theoretical solution from Eq. (7) and the simplified analytical solution from Eq. (16). For a total friction resistance larger than 0.5, which is the case for most practical application – because the vessel exit velocity head loss is 0.5 – the relative error of comparing the theoretical solution to the simplified solution is less than 0.5% with the k value of 1.4. The relative error of M_1 from the theoretical solution from Eq. (7) and the simplified analytical solution from Eq. (16) varies from 0.2% to

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Table 1
Equations for calculating the state variables and Mach numbers along the relief line for gas/vapor relief.

	Isentropic process	Adiabatic process with friction
Pressure	$\frac{P_o}{P}=\left(1+\frac{k-1}{2}M^2\right)^{\frac{k}{k-1}}$ (1)	$\frac{P}{P^*}=\frac{1}{M}\left[\frac{k+1}{2+(k-1)M^2}\right]^{\frac{1}{2}}$ (4)
Temperature	$\frac{T_o}{T}=1+\frac{k-1}{2}M^2$ (2)	$\frac{T}{T^*}=\frac{k+1}{2+(k-1)M^2}$ (5)
Density	$\frac{\rho_o}{\rho}=\left(1+\frac{k-1}{2}M^2\right)^{\frac{1}{k-1}}$ (3)	$\frac{\rho}{\rho^*}=\frac{1}{M}\left[\frac{2+(k-1)M^2}{k+1}\right]^{\frac{1}{2}}$ (6)
Mach number relationship		$kN=\frac{1}{M_1^2}-\frac{1}{M_2^2}+\frac{k+1}{2}ln\left[\frac{2+(k-1)M_2^2}{2+(k-1)M_1^2}\cdot\frac{M_1^2}{M_2^2}\right]$ (7)
Mass flux	$G=\rho u=\frac{PMw}{RT}M\sqrt{\frac{kRT}{Mw}}=PM\sqrt{\frac{kMw}{RT}}=P_oM\sqrt{\frac{kMw}{RT_o}}\left(1+\frac{k-1}{2}M^2\right)^{-\frac{k+1}{k-1}}$ (8a)	
	$G_c=P_{ov}\sqrt{\frac{kMw}{RT_{ov}}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$ (choked frictionless flow) (8b)	

0.8% for the k value from 1.9 to 1.000001 for a total friction resistance of 0.5. A larger error would result only if N could be less than 0.5. The largest error is 13.6% with N = 0 for isentropic flow.

Theoretical solution of Eq. (7) is based on the perfect gas law. Process conditions such as vessel pressure, k, and fluid viscosity would not impact the M_1 solution from Eq. (16) as well as its comparison to theoretical solution by Eq. (7), only if the perfect gas law can be applied.

However, if the solution from Eq. (16) is set as an estimation of M_1, then M_{1e} would be given by:

$$M_{1e}=\sqrt{\left(\frac{2}{k+1}\cdot\frac{1}{\eta_2}\right)^2-1-\sqrt{\left[1-\left(\frac{2}{k+1}\cdot\frac{1}{\eta_2}\right)^2\right]^2-\frac{4}{k+1}}} \quad (16a)$$

and

$$M_1=M_{1e}+M_{1e}^{14.8} \quad (18)$$

Eq. (18) is established by regressing the relative error with the M_{1e}. The relative error of comparing the theoretical solution to the solution from Eq. (18) is less than 2% for any resistance coefficient, N, as shown in Fig. 3.

To make Equation (16) be solvable, the following inequality has to be satisfied

$$\left[1-\left(\frac{2}{k+1}\cdot\frac{1}{\eta_2}\right)^2\right]^2-\frac{4}{k+1}\geq 0 \quad (19)$$

which gives

$$\eta_2\leq\frac{2}{k+1}\cdot\left(1+\frac{2}{\sqrt{k+1}}\right)^{-\frac{1}{2}} \quad (20)$$

If

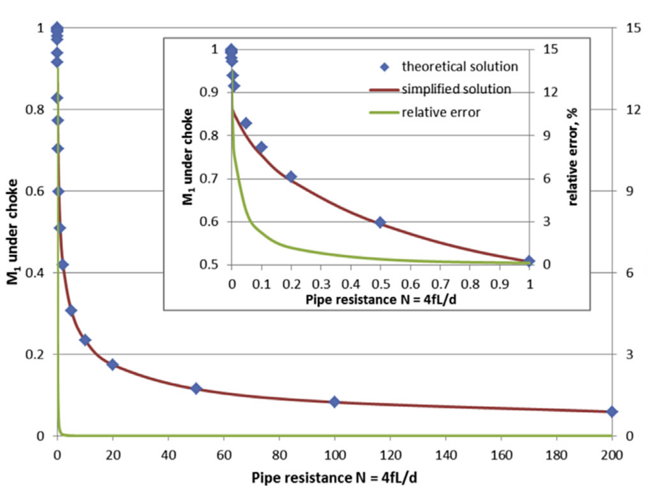

Fig. 2. A comparison of values of M_1 from the theoretical solution of Eq. (7) and the simplified analytical solution of Eq. (16) with exit choked ($M_2 = 1$) (k = 1.4).

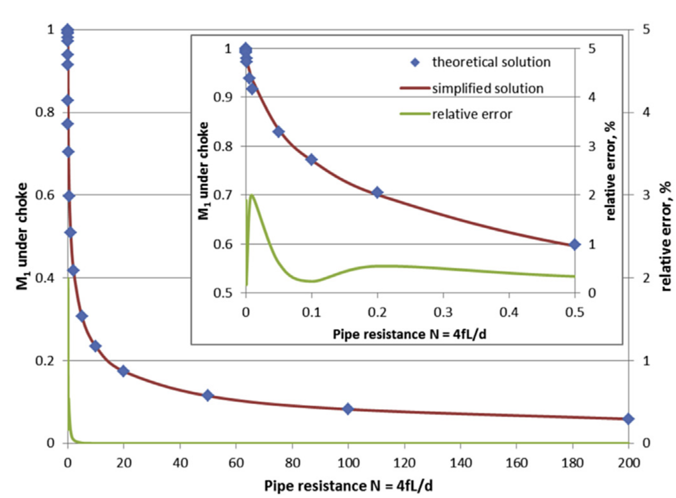

Fig. 3. A comparison of values of M_1 from the theoretical solution of Eq. (7) and the simplified analytical solution of Eq. (18) with exit choked ($M_2 = 1$) (k = 1.4).

$$\eta_2 > \frac{2}{k+1}\cdot\left(1+\frac{2}{\sqrt{k+1}}\right)^{-\frac{1}{2}} \tag{21}$$

then the ERS line exit is not choked.

3. An easy way to identify a choked condition at the exit

Based on the above discussion, an easy way to determine if a choked condition exists at the exit from an ERS is the following proposed procedure:

(1) Calculate $\eta_2 = \frac{P_a}{P_{ov}}$,
(2) If $\eta_2 > \frac{2}{k+1}\cdot\left(1+\frac{2}{\sqrt{k+1}}\right)^{-\frac{1}{2}}$, ERS line exit is not choked; otherwise, continue with the following procedures,
(3) Calculate M_1 from Eq. (16),
(4) Calculate $f(M_1)$ from the following equation (rearranged from Eq. (7) with $M_2 = 1$)

$$f(M_1) = \left(\frac{1}{M_1^2}-1\right) + \frac{k+1}{2} ln\left[\frac{(k+1)M_1^2}{2+(k-1)M_1^2}\right] - kN \tag{22}$$

if $f(M_1) \geq 0$, ERS line exit is choked. Otherwise, the ERS is not choked at the exit.

Two type of ERS design work are mostly required in the engineering practice. One is for capacity evaluation. The other is for validating adequacy of the existing ERS.

For capacity evaluation, the above proposed procedures (1) to (4) can be used to identify if the ERS line exit is choked or not. If ERS venting line exit is choked, η_2 is not known. M_1 has to be solved from Eq. (7) with $M_2 = 1$. If ERS line exit is not choked, $\eta_2 = \frac{P_a}{P_{0v}}$ is known. Eq. (7) and Eq. (11) have to be solved simultaneously to get M_1 and M_2. With known Mach number of location 1 and 2 as shown in Fig. 1, all state variables of pressure, temperature, and density at location 1 and 2 can be calculated from Equations (1)–(6). Then the mass flux in the ERS can be calculated from Eq. (8a).

For validating adequacy of the existing ERS, the required mass flow rate, accordingly, the required mass flux, G_r, is known. The above proposed procedures (1) to (4) can be used to identify if the ERS line exit is choked or not. If ERS venting line exit is choked with $M_2 = 1$, dividing Eq. (8a) by Eq. (8b)

$$\frac{G_r}{G_c} = \frac{P_2\sqrt{\frac{kMw}{RT_2}}}{P_{ov}\sqrt{\frac{kMw}{RT_{ov}}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} = \frac{P_2\sqrt{\frac{kMw}{RT_{ov}}\cdot\frac{k+1}{2}}}{P_{ov}\sqrt{\frac{kMw}{RT_{ov}}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} = \frac{P_2}{P_{ov}}\left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} \tag{23}$$

From Eq. (23), the required $\eta_2 = \eta_2^*$,

$$\eta_2^* = \frac{G_r}{G_c}\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{24}$$

Table 2
Design parameters for capacity evaluation of rupture disk.

Molecule weight, kg/kmol	20
MAWP, barg	6.90
Relieving pressure, bara	8.60
Relieving temperature, °C	93.33
Total resistance, N	4.04
Atmospheric pressure P_a, bara	1.01
k	1.4

With the calculated η_2 from Eq. (24), the required M_1 can be calculated through Eq. (16). With known M_1 and M_2, the resistance coefficient N_r for the required mass flux can be calculated through Eq. (7). If N_r is larger than the total flow resistance of the existing venting line, the existing ERS system is adequate. Otherwise, the existing venting system is not adequate, therefore, has to be modified to reduce flow resistance by reducing the length of venting line, and/or enlarging the pipe/rupture disk size, and/or making flow as straight as possible, and/or reducing number of pipe fittings, etc.

If ERS venting line exit is not choked, M_1 can be calculated in the same way as above from Eq. (24) and Eq. (16) because η_2^* can be calculated from Eq. (24) (however, the actual $\eta_2 = \frac{P_a}{P_{0v}}$). The M_2 can also be directly solved with known $P_2 = P_a$ through applying Eq. (8a) to location 2,

$$G_r = P_2M_2\sqrt{\frac{kMw}{RT_2}} = P_aM_2\sqrt{\frac{kMw}{RT_{ov}}\left(1+\frac{k-1}{2}M_2^2\right)} \tag{25}$$

Then M_2 is

$$M_2 = \sqrt{\frac{-1+\sqrt{1+2(k-1)\frac{G_r^2}{P_2^2}\cdot\frac{RT_{ov}}{kMw}}}{k-1}} \tag{26}$$

In the same way as above, with known M_1 and M_2, the resistance coefficient N_r for the required mass flux can be calculated through Eq. (7). If N_r is larger than the total flow resistance of the existing venting line, the existing ERS system is adequate.

In this way, the iteration calculation and the use of Lapple charts to solve Eq. (7) is circumvented, and the validation of adequacy of ERS is quite straightforward.

The following three case studies are using the proposed strategy to evaluate the design of ERS with rupture disk.

Case study 1. Capacity evaluation

The Annex E of API 520 (8th Edition) gives an example of capacity evaluation of rupture disk and piping system of 100% vapor flow with constant pipe diameter. The given design parameters shows in Table 2.

Using the proposed method as above,

$$\eta_2 = \frac{1.01}{8.60} = 0.118,$$

$$M_1 = \sqrt{\left(\frac{2}{1.4+1}\cdot\frac{1}{0.118}\right)^2 - 1 - \sqrt{\left[1-\left(\frac{2}{1.4+1}\cdot\frac{1}{0.118}\right)^2\right]^2 - \frac{4}{1.4+1}}} = 0.130$$

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Table 3
The calculated results for capacity evaluation of rupture disk.

Location	0	1	2
Pressure P, bara	8.60	7.97	2.44
Stagnation pressure P_o, bara	8.60	8.60	4.61
Temperature T, °C	93.33	85.46	32.25
Stagnation temperature T_o, °C	93.33	93.33	93.33
Mach number: M	0	0.33	1
Velocity u, m/s	0	151.32	421.59
Density ρ, kg/m^3	5.64	5.34	1.92
Mass flux G, kg/m^{2}s		808.64	808.64
Mass flow rate W, kg/s		3.47	3.47

$$f(M_1) = \left(\frac{1}{0.130^2} - 1\right) + \frac{1.4+1}{2} ln\left[\frac{(1.4+1)\times 0.130^2}{2+(1.4-1)\times 0.130^2}\right] - 1.4 \times 4.04 = 53.1 > 0.$$

Then, that the exit of pipe flow to atmosphere is choked can be immediately confirmed without any detailed calculations of trial and error. Therefore, $M_2 = 1$. The actual Mach number of location 1 can be calculated from Eq. (7). The calculated results show in Table 3. The calculated approximate mass flow rate from the Crane chart as shown in Annex E of API 520 (8th Edition) is 3.62 kg/s, which is about 4% larger than the result in Table 3.

$$M_1 = \sqrt{\left(\frac{2}{1.06+1}\cdot\frac{1}{0.233}\right)^2 - 1 - \sqrt{\left[1-\left(\frac{2}{1.06+1}\cdot\frac{1}{0.233}\right)^2\right]^2 - \frac{4}{1.06+1}}} = 0.244$$

Case study 2. Validation of venting adequacy for Neopentyl Glycol relief with exit choked

Neopentyl glycol is pumped to a 45.4 m^3 vessel with a MAWP of 2.76 barg and heated up to 200 °C for other use. The fill ratio is 0.85. A 0.0762 m diameter rupture disk with a burst pressure of 1.03 barg is installed on the top of vessel. An inlet pipe with length of 0.305 m is connected to a rupture disk with an outlet pipe length of 9.14 m including two 90° elbows to atmosphere. All pipes and rupture disk have the same internal diameter. The question is whether the current emergency relief venting configuration is adequate or not under scenario of external fire with complete vapor disengagement. The design parameters are given in Table 4.

With the condition provided above, the total resistance including vessel entrance, the pipe line, and rupture disk is calculated to be 6.86. The specific heat ratio, k, of neopentyl glycol is 1.06. Under external fire case, the following parameters can be calculated:

Table 4
Design parameters for neopentyl glycol relief (Case study 2).

Molecule weight, kg/kmol	104.15
Relieving pressure, Bara	4.35
Boling temperature at relieving pressure, °C	259.4
Total resistance, N	6.86
Vessel Volume: m^3	45.42
fill ratio	0.85
filled volume, m^3	38.61
filled height, m	4.31
wetted area, m^2	54.68
insulation factor (NFPA 30)	0.3
Q, kW (NFPA 30)	647.66
Latent heat at 259.4 °C, kJ/kg	520.12
required mass flowrate, kg/s	1.25
Critical mass flux, G_c, kg/m^{2}s	1307.60

The relieving pressure: 1.21*MAWP +1.01 = 4.35 Bara.

The relieving temperature: 259.35 °C from Antoine equation of neopentyl glycol (Yaws, 2004).

Then $\eta_2 = \frac{1.01}{4.35} = 0.233$,

$$f(M_1) = \left(\frac{1}{0.244^2} - 1\right) + \frac{1.06+1}{2} ln\left[\frac{(1.06+1)\times 0.244^2}{2+(1.06-1)\times 0.244^2}\right] - 1.06 \times 6.86 = 5.68 > 0.$$

Then, following the strategy proposed in this paper, that the pipe flow outlet to atmosphere is choked can be immediately confirmed without any detailed calculations of trial and error. Therefore, $M_2 = 1$. Then

$$\eta_2 = \frac{G_r}{G_c}\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \frac{273.05/0.9}{1307.60}\left(\frac{2}{1.06+1}\right)^{\frac{1.06}{1.06-1}} = 0.138$$

Here that the required mass flux is divided by a coefficient of 0.9 is to comply with UG127 of ASME BPVC.

$$M_1 = \sqrt{\left(\frac{2}{1.06+1}\cdot\frac{1}{0.138}\right)^2 - 1 - \sqrt{\left[1-\left(\frac{2}{1.06+1}\cdot\frac{1}{0.138}\right)^2\right]^2 - \frac{4}{1.06+1}}} = 0.141$$

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Table 5
The calculated results for neopentyl glycol relief with a 0.0762 m rupture disk installed.

Location	0	1	2
Pressure P, bara	4.35	4.14	1.25
Stagnation pressure P_o, bara	4.35	4.35	2.11
Temperature T, °C	259.35	257.86	243.84
Stagnation temperature T_o, °C	259.35	259.35	259.35
Mach number: M	0	0.31	1
Velocity u, m/s	0	64.85	209.16
Density ρ, kg/m^3	10.23	9.76	3.03
Mass flux G, kg/m^{2}s		633.25	633.25
Mass flow rate W, kg/s		2.60	2.60
required mass flux, G_r, kg/m^{2}s	273.05		
required mass flowrate, kg/s	1.25		

$$N_r = \frac{1}{k}\left(\frac{1}{M_1^2} - 1\right) + \frac{k+1}{2k} ln\left[\frac{(k+1)M_1^2}{2+(k-1)M_1^2}\right] = \frac{1}{1.06}\left(\frac{1}{0.141^2} - 1\right) + \frac{1.06+1}{2\times 1.06} ln\left[\frac{(1.06+1)0.141^2}{2+(1.06-1)0.141^2}\right] = 42.6$$

The N_r is larger than 6.86 of the actual flow resistance. Therefore, the existing ERS is adequate.

The actual Mach number and state variables of location 1 and 2 can be also calculated from Equation (1) through (7). The calculated results are shown in Table 5. The calculated mass flow rate, 2.60 kg/s, is larger than the required mass flowrate of 1.25 kg/s. Therefore, that the existing ERS is adequate is also confirmed by capacity evaluation.

Instead, if a 0.0508 m diameter rupture disk is installed (the actual flow resistance is 8.16 in this case), that the pipe flow outlet to atmosphere is choked can be also immediately confirmed following the preceding procedure. Therefore, $M_2 = 1$. Then

$$\eta_2 = \frac{G_r}{G_c}\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \frac{614.37/0.9}{1307.60}\left(\frac{2}{1.06+1}\right)^{\frac{1.06}{1.06-1}} = 0.310$$

$$M_1 = \sqrt{\left(\frac{2}{1.06+1}\cdot\frac{1}{0.310}\right)^2 - 1 - \sqrt{\left[1-\left(\frac{2}{1.06+1}\cdot\frac{1}{0.310}\right)^2\right]^2 - \frac{4}{1.06+1}}} = 0.333$$

$$N_r = \frac{1}{k}\left(\frac{1}{M_1^2} - 1\right) + \frac{k+1}{2k} ln\left[\frac{(k+1)M_1^2}{2+(k-1)M_1^2}\right] = \frac{1}{1.06}\left(\frac{1}{0.333^2} - 1\right) + \frac{1.06+1}{2\times 1.06} ln\left[\frac{(1.06+1)\times 0.333^2}{2+(1.06-1)\times 0.333^2}\right] = 5.47$$

The N_r is less than 8.16 of the actual flow resistance. Therefore, the existing ERS is not adequate.

The actual Mach number and state variables of location 1 and 2 can be also calculated from Equations (1) through (7). The calculated results are shown in Table 6. The calculated mass flow rate, 1.09 kg/s, is less than the required mass flowrate of 1.25 kg/s. Therefore, that the existing ERS is not adequate is also confirmed by capacity evaluation.

Table 6
The calculated results for neopentyl glycol relief with a 0.0508 m rupture disk installed.

Location	0	1	2
Pressure P, bara	4.35	4.16	1.18
Stagnation pressure P_o, bara	4.35	4.35	1.98
Temperature T, °C	259.35	258.05	243.84
Stagnation temperature T_o, °C	259.35	259.35	259.35
Mach number: M	0	0.29	1
Velocity u, m/s	0	60.70	209.16
Density ρ, kg/m^3	10.23	9.82	2.85
Mass flux G, kg/m^{2}s		596.19	596.19
Mass flow rate W, kg/s		1.09	1.09
required mass flux, G_r, kg/m^{2}s	614.37		
required mass flowrate, kg/s	1.25		

Table 7
Design parameters for neopentyl glycol relief (Case study 3).

Molecule weight, kg/kmol	104.15
Relieving pressure, Bara	2.27
Boling temperature at relieving pressure, °C	235.6
Total resistance, N	6.86
Vessel Volume: m^3	45.42
fill ratio	0.85
filled volume, m^3	38.61
filled height, m	4.31
wetted area, m^2	54.68
insulation factor (NFPA 30)	0.3
Q, kW (NFPA 30)	647.66
Latent heat at 235.6 °C, kJ/kg	559.02
required mass flowrate, kg/s	1.16
Critical mass flux, G_c, kg/m^{2}s	696.42

Case study 3. Validation of venting adequacy for Neopentyl Glycol relief with exit not choked

The same vessel configuration as the Case study 2 is discussed here. However, MAWP of the vessel is 1.03 barg. A 0.0762 m diameter rupture disk with a burst pressure of 0.5 barg is installed on the top of vessel. An inlet pipe with length of 0.305 m is connected to a rupture disk with an outlet pipe length of 9.14 m including two 90° elbows to atmosphere. All pipes and rupture disk have the same internal diameter. The question is whether the current emergency relief venting configuration is adequate or not under scenario of external fire with complete vapor disengagement. The design parameters are given in Table 7.

With the condition provided above, the total resistance including vessel entrance, the pipe line, and rupture disk is calculated to be 6.86. Under external fire case, the following parameters can be calculated:

The relieving pressure: 1.21*MAWP +1.01 = 2.27 Bara.

The relieving temperature: 235.64 °C from Antoine equation of neopentyl glycol (Yaws, 2004).

Then $\eta_2 = \frac{1.01}{2.27} = 0.447$,

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$$M_1=\sqrt{\left(\frac{2}{1.06+1}\cdot\frac{1}{0.447}\right)^2-1-\sqrt{\left[1-\left(\frac{2}{1.06+1}\cdot\frac{1}{0.447}\right)^2\right]^2-\frac{4}{1.06+1}}}=0.521$$

$$f(M_1)=\left(\frac{1}{0.521^2}-1\right)+\frac{1.06+1}{2}ln\left[\frac{(1.06+1)\times0.521^2}{2+(1.06-1)\times0.521^2}\right]-1.06\times6.86=-5.91<0.$$

Then, following the strategy proposed in this paper, that the pipe flow outlet to atmosphere is not choked can be immediately confirmed without any detailed calculations of trial and error. Therefore, $M_2<1$. Then

$$\eta_2^*=\frac{G_r}{G_c}\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}=\frac{254.05/0.9}{696.79}\left(\frac{2}{1.06+1}\right)^{\frac{1.06}{1.06-1}}=0.240$$

$$M_1=\sqrt{\left(\frac{2}{1.06+1}\cdot\frac{1}{0.240}\right)^2-1-\sqrt{\left[1-\left(\frac{2}{1.06+1}\cdot\frac{1}{0.240}\right)^2\right]^2-\frac{4}{1.06+1}}}=0.252$$

M_2 can be calculated from Eq. (26),

$$M_2=\sqrt{\frac{-1+\sqrt{1+2(1.06-1)\frac{254.05^2}{101325^2}\cdot\frac{8.314\times508.79}{1.06\times0.104}}}{1.06-1}}=0.543$$

$$N_r=\frac{1}{k}\left(\frac{1}{M_1^2}-\frac{1}{M_2^2}\right)+\frac{k+1}{2k}ln\left[\frac{2+(k-1)M_2^2}{2+(k-1)M_1^2}\cdot\frac{M_1^2}{M_2^2}\right]$$

$$=\frac{1}{1.06}\left(\frac{1}{0.252^2}-\frac{1}{0.543^2}\right)+\frac{1.06+1}{2\times1.06}ln\left[\frac{2+(1.06-1)0.543^2}{2+(1.06-1)0.252^2}\times\frac{0.252^2}{0.543^2}\right]=10.16$$

The N_r is larger than 6.86 of the actual flow resistance. Therefore, the existing ERS is adequate.

The actual Mach number and state variables of location 1 and 2 can be also calculated from Equations (1) through (7). The calculated results are shown in Table 8. The calculated mass flow rate, 1.35 kg/s, is larger than the required mass flowrate of 1.16 kg/s. Therefore, that the existing ERS is adequate is also confirmed by capacity evaluation.

Instead, if a 0.0635 m diameter rupture disk is installed (the actual flow resistance is 7.42 in this case), that the pipe flow outlet to atmosphere is not choked can be also immediately confirmed following the preceding procedure. Therefore, $M_2<1$. Then

$$\eta_2^*=\frac{G_r}{G_c}\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}=\frac{365.84/0.9}{696.79}\left(\frac{2}{1.06+1}\right)^{\frac{1.06}{1.06-1}}=0.346$$

$$M_1=\sqrt{\left(\frac{2}{1.06+1}\cdot\frac{1}{0.346}\right)^2-1-\sqrt{\left[1-\left(\frac{2}{1.06+1}\cdot\frac{1}{0.346}\right)^2\right]^2-\frac{4}{1.06+1}}}=0.378$$

Here that the required mass flux is divided by a coefficient of 0.9 is to comply with UG127 of ASME BPVC.

M_2 can be calculated from Eq. (26),

$$M_2=\sqrt{\frac{-1+\sqrt{1+2(1.06-1)\frac{365.84^2}{101325^2}\cdot\frac{8.314\times508.79}{1.06\times0.104}}}{1.06-1}}=0.778$$

Table 8
The calculated results for neopentyl glycol relief with a 0.0762 m rupture disk installed.

Location	0	1	2
Pressure P, bara	2.27	2.16	1.01
Stagnation pressure P_o, bara	2.27	2.27	1.25
Temperature T, °C	235.64	234.30	229.64
Stagnation temperature T_o, °C	235.64	235.64	235.64
Mach number: M	0	0.30	0.63
Velocity u, m/s	0	61.57	130.11
Density ρ, kg/m^3	5.58	5.33	2.52
Mass flux G, kg/m^{2}s		328.64	328.64
Mass flow rate W, kg/s		1.35	1.35
required mass flux, G_r, kg/m^{2}s	254.05		
required mass flowrate, kg/s	1.16		

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Table 9
The calculated results for neopentyl glycol relief with a 0.0635 m rupture disk installed.

Location	0	1	2
Pressure P, bara	2.27	2.17	1.01
Stagnation pressure P_o, bara	2.27	2.27	1.24
Temperature T, °C	235.64	234.38	229.97
Stagnation temperature T_o, °C	235.64	235.64	235.64
Mach number: M	0	0.29	0.61
Velocity u, m/s	0	59.65	126.47
Density ρ, kg/m^3	5.58	5.35	2.52
Mass flux G, kg/m^{2}s		319.23	319.23
Mass flow rate W, kg/s		0.91	0.91
required mass flux, G_r, kg/m^{2}s	365.84		
required mass flowrate, kg/s	1.16		

$$N_r = \frac{1}{k}\left(\frac{1}{M_1^2} - \frac{1}{M_2^2}\right) + \frac{k+1}{2k} ln\left[\frac{2+(k-1)M_2^2}{2+(k-1)M_1^2}\cdot\frac{M_1^2}{M_2^2}\right]$$

$$= \frac{1}{1.06}\left(\frac{1}{0.378\ ^2} - \frac{1}{0.778^2}\right) + \frac{1.06+1}{2\times 1.06} ln\left[\frac{2+(1.06-1)0.778^2}{2+(1.06-1)0.378^2}\times\frac{0.378^2}{0.778^2}\right] = 3.66$$

The N_r is less than 7.42 of the actual flow resistance. Therefore, the existing ERS is not adequate.

The actual Mach number and state variables of location 1 and 2 can be also calculated from Equations (1) through (7). The calculated results are shown in Table 9. The calculated mass flow rate, 0.91 kg/s, is less than the required mass flowrate of 1.16 kg/s. Therefore, that the existing ERS is not adequate is also confirmed by capacity evaluation.

4. Conclusion

This paper proposes an easy and quick method to identify whether the venting line exit of the ERS with rupture disk is choked or not. The relative error comparing to theoretical solution for this method is less than 0.5% for any practical application. For capacity evaluation of ERS, solving the adiabatic flow with friction is necessary to get Mach number and state variables at any location of venting line. For validating the adequacy of ERS, a quick and straightforward method is proposed. This method circumvents solving adiabatic flow with friction. Three case studies are presented to support the proposed method.

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Nomenclature

d	Pipe internal diameter, m
f	Fanning friction factor, dimensionless
k	Specific heat ratio, dimensionless
K	Resistance coefficient of pipe fitting, dimensionless
L	Pipe length, m
M	Mach number, dimensionless
Mw	Molecular weight, kg/kmol
N	Pipe resistance coefficient, dimensionless
P	Pressure, bara
T	Temperature, K
η	Pressure ratio, dimensionless
ρ	Density, kg/m^3

Subscripts

0,1,2	Location of relief line
a	Ambient conditions
c	Critical condition
e	Estimation
o	Stagnation condition
r	Required

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