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Challenges in Sizing Rupture Disk Vent Line Systems Especially for Compressible Two-phase Flow

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In the chemical and petrochemical industry, vessels and pipes are protected against overpressure using safety relief devices, usually rupture disks (also called a bursting disc) or safety valves. In contrast to a safety valve, the opening of a bursting disk is a stochastic process leading to a certain range of flow areas, depending on the manufacturing process of the disc. In general, this area cannot be predicted to the last percent. It determines dominantly the overall pressure loss and, in case of critical flow, the mass flow rate to be discharged through a bursting disk vent line system. To date, tests to determine the rupture disk flow resistance factor are typically performed with low velocity, subcritical, almost incompressible flow with air, nitrogen and water. Test conditions are stationary flow despite the fact that the flow regime during emergency relief varies from liquid only, gas only, gas/liquid two-phase flow or even flashing liquids. Even though a rupture disk is used as a primary relief device, the rupture disk flow resistance coefficients are not precisely applicable for compressible gas, vapor liquid or multiphase service (Friedel & Kißner, 1988). For two-phase flow, there is neither a standardized test section, nor any reliable test results available. Consequently, there is also no precise model to size a rupture disk device in these cases (Schmidt & Claramunt, 2014). Additionally, for typical industrial rupture disk vent-line systems, significant errors can be made by applying current sizing methods (Schmidt, 2015). Over-dimensioning the rupture disk vent line system leads to unnecessary financial costs and may cause malfunction of the collecting systems downstream when the fluids discharged are more than the design limits. Under-dimensioning may lead to hazardous incidents with loss of human life and equipment. There is a strong need for experimental data and a reliably validated sizing method that is valid for single-phase compressible gas as well as for flashing and non-flashing two-phase flow.

1. Ideal and typical rupture disk vent line system

An ideal rupture disk vent line system has a rupture disk device installed directly on the equipment with a short or no inlet line, with a short discharge line and it discharges directly to the atmosphere (API, 2014); (Verband der TÜV e.V., 2006). A significant number of rupture disk devices are installed differently; with a vent line system, which has a long and complex inlet and outlet line. This happens because of restrictions arising from space, access and mountability amongst other reasons that vary depending on the local conditions. The complexity of a vent line varies subject to the installation scenario on a case-by-case basis. Further, discharge to the atmosphere is not always permitted by law. Therefore, a reasonable number of vent line systems discharge to a collecting system, a separator, quench or flare. In these cases, a vent line includes fittings such as elbows, tees or enlargements. As such, there is no typical rupture disk vent line system and the complexity varies in a substantial number of installations. The flow regime of the fluids being discharged also varies to a similar extent; from incompressible flow, to compressible flow which includes gas flow, two-phase flow or even flashing liquid flow. The fluids may also be single or multi-component fluids. Rupture disk devices are also used for viscous substances.

2. Sizing a rupture disk vent line system

Sizing a rupture disk vent line as a first step involves determining possible conditions at inlet and the mass to be discharged by: (A) undertaking a HAZOP study to identify the scenarios, (B) determine the worst case boundary conditions based on engineering calculations and (C) determination of the minimum flow rate to be

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discharged. The last step is the actual sizing of the rupture disk vent line system for the worst case scenario above (Schmidt & Claramunt, 2014). The designer has to answer these questions (a.) What size of rupture disk should be applied to discharge the predetermined minimum mass flow rate? (b.) What pressure loss is expected in the entire rupture disk vent line system? (c.) Will the pressure in the pressure vessel increase further taking note of the pressure losses in the vent-line? (d.) Do the collecting systems downstream have the design capacity larger than the mass flow rate to be discharged? (e.) Is the pressure vessel safe even for the worst-case scenario for the predetermined rupture disk vent line system?

2.1 The type of rupture disk device in the vent line

Rupture disks designs vary; there are significant constructive design differences. This means that the opening characteristics and flow conditions also vary depending on the rupture disk type. Small diameter and large diameter rupture disks are not geometrically similar and consequently have different flow characteristics even for rupture disks of the same type; as such scalability should be investigated. The sizing situation is further compounded by the fact that a rupture disk may not be sized separately as a black box; it must be sized in the context of the entire vent line system in which it is installed. Sizing a rupture disk vent line system reliably is a complex process.

2.2 Compressible fluid flow phenomena in pipes

Compressibility effects of gases are most evident in pipes as the velocity of fluid increases in the piping. This is especially the case for Mach number higher than 0.3. By definition the pressure drop in compressible fluids with ideal behavior is defined as in Table 1:

Table 1: Standard pipe pressure loss formulae

Pressure profile	Pressure gradient	Darcy friction factor
$p\{z\} = p_{in} + \int_0^z \frac{dp}{dz}\{z\} \cdot dz$	$\frac{dp}{dz}\{z\} = -\left[\frac{1+(\kappa_{in}-1)\cdot Ma\{z\}^2}{1-Ma\{z\}^2} \cdot \frac{\lambda_i \cdot \rho\{z\}}{2 \cdot D_{in}} \cdot w\{z\}^2\right]$	$\lambda_i = f\{\mathrm{Re}\{w_i, d_i, \upsilon_i\}, k_{pipe}, d_i\}$ Explicit approximation's, of Colebrook's equation e. g Chen
Equation (1)	Equation (2)	Equation (3)

What is the pressure gradient in this piping? What is pressure profile between the inlet and outlet? Using Fanno equations (Levenspiel, 1998) (Truckenbrodt, 2008) shows that the pressure gradient (dp/dz) is not constant. Therefore, the pressure profile, p(z) that is determined by integration of the pressure gradient (dp/dz) is not linear as seen in Figure 1: Pressure, Mach number and pressure gradient profile in pipe k = 70 µm, d_i=100 mm Figure 1. Note that the ratio of heat capacities κ is taken to be constant here, but it also varies with pressure.

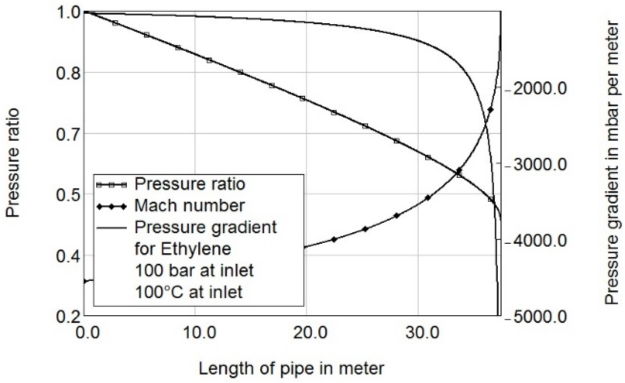

Figure 1: Pressure profile Mach number and pressure gradient in pipe k = 70 µm, d_i=100 mm (Mutegi, 2014)

This figure is computed for ethylene inlet pressure of 100 bar and 100°C assuming an inner pipe diameter of 100 mm and friction factor calculated according to Chen assuming pipe roughness of 70 µm and inlet pressure of 100 bar. This figure demonstrates that there is significant nonlinear behavior in pipe for compressible gas flow with Mach number of 0.3 at inlet. The pressure ratio ranges from 1.0 at inlet to about 0.54 while the Mach number increases from 0.3 to 1 ; the pressure gradient varies from about 1000 mbar/m to about 5000 mbar/m until a critical length of about 35 m where critical flow conditions are reached.

Depending on the type and location of a rupture disk device, also depending on the inlet Mach number and pressure and total pressure loss of the components upstream, the velocity of gas will increase and attain sonic speed (Ma = 1) as seen in Figure 1. While there is a general relationship representative of the relationship between the pressure drop and roughness in literature, it does not apply exactly for all plausible flow cases that occur in practice especially two-phase flow and flashing liquids flow (VDI-GVC, 2010). Determination of pressure drop in rough pipes has uncertainties. The following is true for compressible gas only flow through pipes: that, (i.) there is pressure drop in the piping, (ii.) that the velocity of fluid increases and the density decreases and (iii.) the Reynolds number increases due to the temperature dependency of the dynamic viscosity. The only constant parameters during relief after analyzing the pipe flow equations are geometric, such as the inner diameter (d_i) and the absolute roughness (k).

2.3 Choking area of a rupture disk in vent line system

The choking area in the vent line is not necessarily in the rupture disk device itself. Does an open rupture disk device cause a flow contraction or the so called Vena-Contracta? If so, when does this occur? This is relevant as the dischargeable mass flow rate of a compressible fluid through a rupture disk vent line system depends on the resistance of the piping geometry between the pressurized system and the first cross section where critical flow condition establishes (choking area). This chocking area limits the maximum flow rate through the whole system for prevailing inlet conditions. Any cross section where there is flow contraction or any diameter enlargement is potentially a choking area. Possible chocking areas are inlet, tees, bends, pipe enlargements, end of the relief line or at the rupture disk device itself (Schmidt, 2015). A rupture disk device is often modelled as an orifice plate. In real sense, it is not precisely so as an open device has an ear (the rest fragment) which protrudes into the piping contracting flow and causing pressure loss during relief (Figure 3). In addition, the rupture disk holder may cause pressure drop. In that case, the pressure drop attributed to the device also includes the pressure loss in the holder and the open rupture disk. The pressure profile may be like in Figure 4 when the disk holder behaves as a thick plate as presented. Other fittings have been investigated to much more detail especially for two-phase flow (Schmidt, 1992), (VDI-GVC, 2010). Observations from these studies indicate that the Vena-contracta phenomenon is real and there is need to study whether fluid flow in rupture disk vent line systems are subject to this phenomenon.

Figure 2: Closed and bursted rupture disk, Rembe GmbH, Brilon

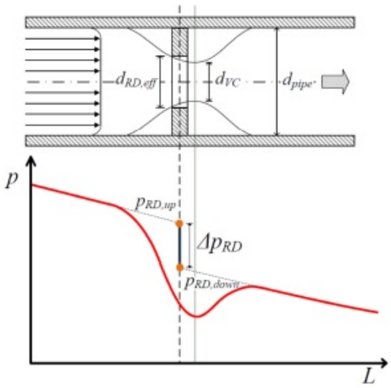

Figure 3: Fluid flow in across a rupture disk in a vent line (thin plate) (Schmidt & Claramunt, 2014)

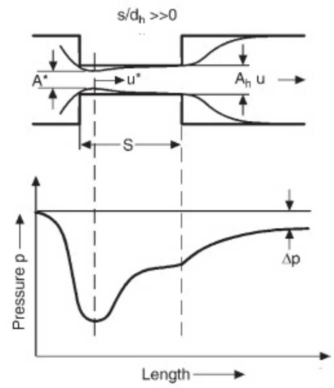

Figure 4: Fluid flow through a thick plate (image based on (VDI-GVC, 2010))

Compressibility effects make the determination of the pressure profile in the vent line complex – as they also depend on the flow regime. The gradient of the pressure profile upstream of a device is not the same as the one downstream for compressible flow (Figure 1). Figure 7 shows that the mass flow quality has an effect on when the Vena contracta phenomena occurs. Going by the initial calculations from models, the multi-critical flow phenomena (critical flow conditions at multiple locations) in a vent line has been observed as seen in Figure 9. There is a need to study this so as to better understand flow through a rupture disk device. This will be done experimentally in the context of a real rupture disk vent line system.

2.4 Minor loss coefficients of fittings in vent line for compressible flow

Minor loss coefficients of fittings are determined experimentally under ideal stationary almost incompressible flow conditions. The assumption is that the pressure profile is linear – this applies when the Mach-number (Ma) or the speed in the pipeline (w) is low such that the compressibility effects are taken to be negligible. In practice, this is not exactly always the case for gas flow during relief, where Mach number is higher than 0.3 and especially for two-phase flow and flashing liquids flow. Minor loss coefficients of fittings in pipes are determined under ideal almost incompressible stationary conditions with gas only (low velocities, with clean pipe). They are then used to size real vent lines where the flow conditions are dynamic and compressible during relief (with high velocities, rough piping with other fittings). Consider the method used for example to determine the rupture disk flow resistance factor which may be defined as follows analogous to the pipe drag coefficient:

$$K_R = \frac{\Delta p_{RD}}{\frac{\rho_{RD}}{2} \cdot w_{RD}^{\ 2}} = \frac{\Delta p_{RD}}{\frac{\rho_{RD}}{2}\left(\frac{q_m}{\rho_{RD}}\right)^2} = \lambda \cdot \frac{l_{eff,RD}}{d_{eff,RD}} \tag{4}$$

Where λ is the Darcy friction factor and the subscript eff, RD refers to the effective length and diameter of rupture disk device installed. The rupture disk flow resistance factor (K_R) is used to predict the pressure drop across a rupture disk device. It is a value that is experimentally determined and it is a value that most rupture disk device manufacturers certify. It is determined as described in the PTC 25 (ASME, 2014) test section under mostly incompressible test conditions – stationary flow, almost incompressible flow with clean pipe.

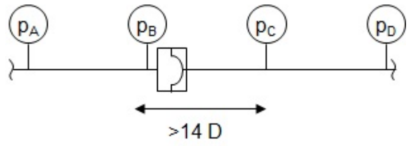

Figure 5 Rupture disk test section

The test section used has four pressure taps A, B, C and D. The first set of tests is run with only pipe while the second tests are run with rupture disk device installed between the pressure tap B and C. The length of pipe between these tap B and C pressure taps is at least 14D.

The total pipe resistance factor of the pipe segment ($K_{pipe,B\text{-}C}$) – without rupture disk installed – between pressure tap B and C is calculated as:

$$K_{pipe,B-C} = \lambda \cdot \frac{l_{B-C}}{d_i} \text{ , where } \lambda = f(\mathrm{Re}_D, k, d_i) \tag{5}$$

The Darcy friction factor (λ) is taken to be constant and is a function of the Reynolds number, Re, inner pipe roughness, k and the inner diameter of pipe, d_i. The total resistance factor of pipe (K) from inlet to pressure tap is then calculated from the measured pressure at the pressure tap assuming adiabatic, incompressible fluid flow in pipes (Fanno flow equations) (Levenspiel, 1998). It is from these calculated values of K that the total resistance factor of the pipe segment between pressure tap B and C ($K_{B\text{-}C}$) is calculated. The Rupture disk flow resistance factor is determined in the last step as the difference between the resistance factor of pipe segment between BC with rupture disk installed and without rupture disk.

$$K_R = K_{B-C} - K_{pipe,B-C} \tag{6}$$

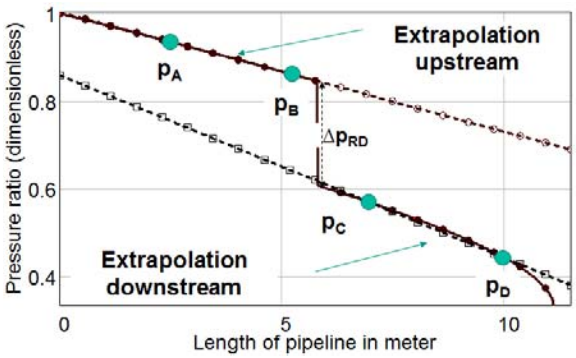

Figure 6 Computed pressure profile of a pipe extrapolated pressure profile upstream and downstream of a rupture disk device (Mutegi, 2014)

Depending on the inlet Mach number in the test section, the extrapolated pressure profile upstream and downstream do not have the same gradient – the pressure profile is NOT linear. The pressure drop across the rupture disk (Δp_{RD}) is therefore not uniquely defined and will change depending on where it is measured from. Looking at Equation (4), K_R will vary depending on where Δp_{RD} is measured and the nonlinear effects will increase as Mach number at inlet increases.

While determining the total pipe resistance factor $K_{pipe,B\text{-}C}$ without device installed, an assumption is made that the Darcy friction factor is constant. It is reasonably constant for the test case. Caution should be taken in practice while using the KR value determined under test conditions for all other possible relief cases where the Reynolds number and the absolute pipe roughness and medium differ significantly from test conditions. Beyond this, the Darcy friction factor used here is that of a clean pipe in contrast to most cases in practice where the vent line varies from the test conditions. While determining the total pipe resistance factor $K_{B\text{-}C}$ (between pressure tap B and tap C) with device installed, at least these two assumptions are made: That, (i.) the ratio of specific heats is constant and (ii.) the pipe resistance factor calculated under specific test conditions at inlet (low Mach number) is also comparable even for other conditions (high Mach number or two-phase flow. Beyond this, K_R put more in question for compressible two phase flow and flashing liquids flow where flow conditions vary most significantly from the test conditions (Schmidt, 2015). When it comes to safety related application of minor loss coefficients of other fittings in the vent line, there is need to investigate these factors to much more detail to ensure that they are applicable for cases in practice during relief, i.e. high Mach number at inlet and for two phase flow or even laminar viscous flow of polymer melts. Such studies have been done for other fittings in the vent line (Schmidt, 1992), (VDI-GVC, 2010) and the same should at least be done for the rupture disk devices.

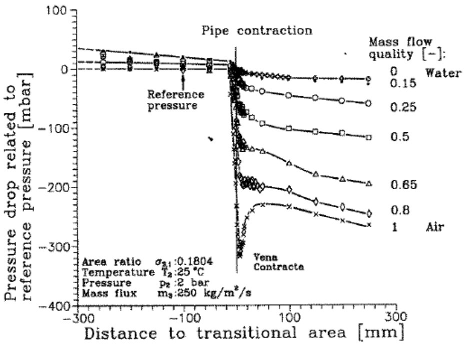

Figure 7: Static pressure profile in the centerline of a sudden pipe contraction measured in an air/water two-phase flow in a sudden pipe contraction (Schmidt & Claramunt, 2014)

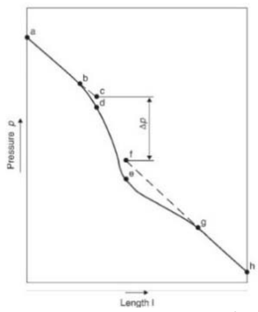

Figure 8 Δp in a 90° Bend (Image based on (VDI-GVC, 2010))

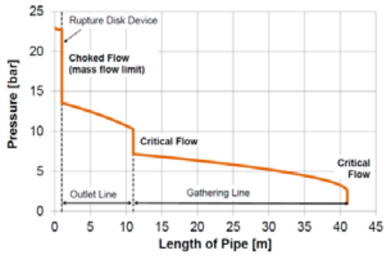

Figure 9: Pressure profile in a typical rupture disk vent-line system during relief of a two-phase steam/liquid flow (Schmidt & Claramunt, 2014)

3. Test facility for compressible flow in rupture disk vent line systems

CSE Center of Safety Excellence (CSE-Institut) in Pfinztal, Germany will construct a high pressure loop to investigate compressible flow in rupture disk vent line systems with test medium as air, nitrogen and water. This is being undertaken within the scope of the BurstDisk2Phase research program. The aim is to investigate the flow phenomena to detail for simple and real vent lines for compressible flow. Studies on flow phenomena such as vena-contracta, flow contraction in rupture disk devices, and pressure drop across rupture disk devices shall be undertaken. Real complex rupture disk vent line systems, with inlet and outlet line with other fittings will be considered to investigate critical flow, multi choking and pressure profile in vent line systems coupled with various piping fittings in horizontal and vertical flow. Scalability of flow phenomena observed in small and large diameter rupture disk devices will also be studied. Eventually the net flow area and the reproducibility for open rupture disk devices may be examined. The experimental results generated within the scope of this work will help fill the gap in research as presented and thereby deliver reliable experimental results for validating existing models. The capacity of the CSE HP-Loop test facility once complete is unique – as the facility will have capacity to even test large rupture disk vent line systems in the range of DN150. The test rig shall have a gas loop and water loop.

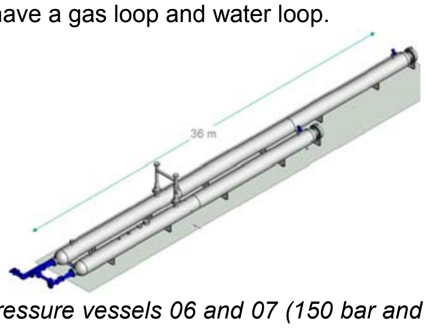

Figure 10 Pressure vessels 06 and 07 (150 bar and total volume of 67 m^3)

Figure 11 Venturi nozzle metering section

The gas loop shall operate on air and nitrogen. This gas loop has two vessels with a total volume of 67 m^3 with operating pressure of up to 150 bar amounting to about 12000 kg of nitrogen in full capacity. It also has other two pressure vessels (700 bar, 3 m^3 per vessel) and another three 3400 bar, 0.2 m^3 vessels for experiments at higher pressures. Flow measurement in the gas loop will be by using critical venturi nozzles and coriolis flow measurement techniques. The water loop will have a pump operated at pressures of up to 16 bar with a capacity of about 310 t/h. Two-phase loop shall be realized by coupling the gas and liquid loops.

4. Conclusion

While substantial and well thought out understanding of flow through rupture disk vent lines exists today, there is need to enhance this knowledge with a view to improving safety in technical plants especially for compressible fluid flow which is often the case during emergency relief. The matter at hand – sizing a safety relief device to prevent human loss, damage to environment and loss of property – needs to be done with utmost caution and understanding to reduce uncertainties and residual risks. In practice, sizing rupture disk devices is mostly complex in nature as the vent lines may only be sized reliably by taking the entire vent line system into consideration. This comes with uncertainties as presented as numerous assumptions have to be made when determining the mass flow rate through a vent line and the size of the rupture disk device by extension. Over dimensioning is one option taken today to mitigate high uncertainties. This is not always an option, as it comes with substantial cost effort and also puts the integrity of other systems downstream at risk. The characteristic numbers of rupture disk devices and the methods used to determine these numbers need be enhanced and harmonized to better capture the prevailing conditions in a vent line in practice especially for compressible flow. The current methods are not yet validated for piping systems typically encountered in industry. This is especially the case for two phase flow and flashing flow. Simplified models for engineering calculations are essential if they are validated reliably with experimental results. Today there are more than a dozen models in open literature and there are several commercially available Software tools to size rupture disk vent line systems. Sizing results differ by up to 200% depending on the model that is used to size the rupture disk device (Schmidt, 2015). A proper sizing model for bursting disks is indispensable. The HP-Loop will come in handy for improved models in generating the much needed suitable experimental data, deeper understanding and know-how. The BurstDisk2Phase research program at CSE Institute seeks to narrow this gap in research by capitalizing on concerted efforts between the technical plant operators, high quality rupture disk manufacturer, institutions of higher learning and a research team that is guided by experienced leaders with the core aim of promoting safety in technical plants of the future.

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