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An Overview of Design and Validation of Explosion Vents

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Abstract:

Industrial plants that operate under high pressure and temperature conditions are often subjected to hazards that may harm the equipment or the overall system and lead to explosions and leakages, which ultimately result in capital and financial losses while also posing safety risks to workers. The problem of occurrence of excessive pressures is overcome with the help of explosion venting technology. The term 'rupture disc' is synonymous with explosion vent. The pressure is alleviated by controlled release of fluids or gases through these discs when they burst. This research paper provides a comprehensive overview of eminent research articles on explosion venting technology. The key focus has been on understanding design principles, finite element analysis, and validation of results through testing. The study offers solutions on improving the performance and responsiveness of rupture discs, by recommending use of right material under right operating conditions. The findings will be of particular interest to process design engineers, professionals working in chemical, oil and gas industries, educators and engineering students, who are seeking a generalized overview of the design and testing process of rupture discs.

Keywords —**Explosion vents, Rupture discs, Design of Rupture Discs, FEA on Rupture Discs.**

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I. INTRODUCTION

Process environments with elevated temperature are pressure levels are common in chemical industries. Rapid advancements in industrial technology have given rise to pressure safety devices that can counter hazards which pose a threat to the machinery and jeopardize the safety of the workers. Explosion vents are a reliable and widely-used pressure safety mechanism. These guard against the high internal pressures brought on by explosions or unregulated process parameters in buildings, pressure vessels, or equipment. They are also known as rupture panels. These panels have another application, that is, to act as protective diaphragms that maintain a constant storage pressure inside a vessel.

The vent acts as a weak spot in the enclosure during a deflagration, i.e., the rapid movement of flames, offering a specially designed passage for flames and fluids with rising pressures to escape. These vents are made to release pressure as soon as their burst/opening/rated pressure is exceeded. They come in a range of sizes and shapes.

Typically, an explosion vent consists of scored metal sheets and a frame that keeps the diaphragm in place. The scores are provided for a more regulated rupture situation. A variety of shapes and sizes of explosive vents, including domed, square, rectangular, and circular shapes, are available. Their exact cutting patterns allow them to rupture at certain over-pressures.

A rupture disc is also a certain type of explosion vent. Hence, throughout this paper, the term 'rupture disc' is used synonymously with 'explosion vent'. A rupture or burst disc is a thin metallic plate or sheet designed to fail at a given pressure. These are non-reusable or non-reclosing devices [1]. To safeguard the equipment, it can be utilised alone or in combination with a pressure safety valve. If there is a large and sudden rise in pressure, the safety valve cannot respond quickly and fails to open. In this case, the rupture disc acts as a reliable backup system to relieve the pressure. Hence, these devices provide rapid response to changes in system pressure and ensure quick pressure relief when needed.

They are often used in combination with a holder that clamps them and holds them in place. The pressure at which the disc opens is known as its burst pressure. Several tests are conducted on a rupture disc and the resulting values of their burst pressures are averaged to determine the marked burst pressure for that disc. The desired burst pressure may lie above or below the marked burst pressure, depending on the manufacturing design range [2].

Pressure relief valves are costly and have complicated operating mechanism and they are unable to relieve pressure within milliseconds. The ideal solution to this problem is the use of rupture discs, which are both economically and operationally effective than pressure relief valves [3]. Once the disc ruptures, it can easily be replaced with a new one. The rupture disc should have a low factor of safety, approximately equal to zero, so that it bursts quickly.

This paper explores the operational requirements, design principles, theoretical concepts and empirical evidence shared in major researches published on rupture discs.

II. WHEN TO SELECT RUPTURE DISCS?

Process engineers must be provided with a useful guide for designing pressure relief systems [4]. The initial stages of design for these systems involves addressing key areas prone to damage due to high pressures and identification of the form of safety mechanism that can provide damage insulation to these key areas. Engineers must ascertain the drawbacks and merits of using either bursting discs or safety valves or a combination of both for various use cases. After determining the requirement and location of relief devices as well as the sources of excess pressures in the plant, the engineer must decide on the type of relief device to be used. In case of a rapid rise in the pressure, such as a shock wave, rupture discs should be preferred over safety valves. They can also be used when the manufacturing of safety valves is difficult in unusual use cases (for e.g., diameter of relief being too large or too small). They are useful in case the working fluid is toxic, corrosive, or expensive. They cannot be used where processes cannot be halted (for replacement of the disc). Authors also advise that a reverse acting disc should be used when the margin between the operating pressure and the bursting pressure is low. Reverse acting disc guarantees a longer service life. However, it should not be used in case the excess pressure is caused by expansion of liquid. For a better understanding of all these requirements, a visual approach, i.e., a flow chart, should be preferred for evaluation of all alternative designs and arriving at the best solution.

III. INFLUENCE OF GEOMETRICAL FEATURES ON THE BURST PRESSURE

For an efficient design, it is important to understand the rationale behind the selection of specific design parameters so that the operating as well as the failure condition is satisfied. The examination of the structural deformation and failure of a thin domed-scored metallic rupture disc was done [5]. The disc was supposed to withstand the storage pressure in a rocket silo and rupture under impulsive loading. From the study, we understand the progression of failure in the disc. It was evident that the equivalent stress and strain a) increase with respect to the applied pressure at centre of the disc in the scored location, and b) reduce with respect to increasing r/R ratio (where r is the radial distance of any point under consideration and R is the radius of the disc). Since the disc has high stiffness with lower diameter-to-thickness ratio (<100), which gives high burst pressure and burst time, an appropriate value of diameter-to-thickness ratio must be chosen for it to burst at the required pressure in less time. Also, as the number of scores increases beyond 10, the failure may not be initiated and propagated in all the scores.

The influence of geometrical features on the burst pressure is an important aspect of designing a rupture disc. A handful of papers have estimated the relationships between geometrical parameters and the burst pressure. The effect of depth of grooves and the radius of curvature of a rupture disc on its opening time and shock formation distance was examined [6]. Smaller radii of curvature results in shorter disc opening time (burst time). This was because of the linear relationship between the burst time and the radius of curvature. The grooved disc has a shorter opening time than the non-grooved disc. Moreover, the burst pressure increases with increase in the disc thickness and this effect is more pronounced in the case of higher groove thickness-to-plate thickness ratios [7]. Other researchers had also arrived at the same conclusion [8].

Plates with greater thickness experience more unstable tearing propagation, leading to asymmetric deformed shapes upon failure. Such asymmetry is undesirable for safety device applications. The groove depth-to-plate thickness ratio must be equal to or more than 0.4 so that the failure develops in the scored region of the plate [9]. The localization of stresses and progression of failure in the scored region is important as it prevents fragmentation. Shorter radii of curvature are likely to show bursting along the petals, than larger radii of curvature [7].

In case the pressure fluctuations are large, the disc may fail (as a result of fatigue loading) at a pressure lower than the design pressure, as suggested in a study [10]. In addition, the bursting pressure is proportional to the ratio of the thickness of the disc to its diameter. It was also found that the burst pressure decreases as the bulge diameter increases [8]. This fact is also highlighted in another study [11].

Design of a suitable disc majorly depends upon its operating conditions. For instance, a scored forward acting disc is applicable where operating pressures can reach up to 80% of the marked burst pressure, since they are made thicker than other tension loaded discs for enhanced service life [11]. They tend to prevent fatigue and creep in the material of the disc even during loadings of up to 85% of the marked burst pressure.

During the hydroforming process on a rupture disc, it was found that the arch height of the disc can either be controlled by having optimum values of loading rate or by controlling the friction coefficient between the disc and its holder [12]. This is done so as to maintain a low thinning ratio, which is the percentage change in thickness of the top part of the disc after hydroforming. A higher thinning ratio causes the disc to burst before the expected bursting pressure is reached.

IV. DESIGN FORMULAE

The relation between the burst pressure of a disc without grooves and the ultimate tensile strength for its material was defined [13] -

$$P_b = \frac{2\,\Delta\,\sigma_{us}}{R}$$

Where,

P_b= Burst Pressure of disc in kg/cm^2
Δ = Thickness of disc in mm
σ_{us} = Ultimate tensile strength of the material in kg/cm^2
R = Radius of curvature of disc in mm

We can determine the radius of curvature of the disc, using the formula given below –

$$R = \frac{D}{4}\sqrt{\frac{1+\frac{\delta}{100}}{\sqrt{1+\frac{\delta}{100}}-1}}$$

Where,

D = Diameter of the disc in mm
δ = Elongation for the material in %

Similar formulae can be found in other papers as well. For instance, while studying the characteristics of grooving process on a rupture disc made of 316L-grade stainless steel, the disc thickness was calculated with the formula given below [14] –

$$t = \frac{P_b\,k\,d_o}{UTS}$$

Where,

t = Plate thickness in mm
P_b= Burst Pressure of disc in N/mm^2
k is a factor

d_o is the Effective Discharge Diameter
UTS means Ultimate Tensile Strength of the material in N/mm^2

The equations help us to understand the dependence of the burst pressure on various aspects, such as the disc thickness, diameter, and the type of material.

V. MATERIAL CONSIDERATIONS

It is important to understand the desirable properties of materials suitable for rupture discs. The material should have low strength, good creep resistance, and must be available as a thin sheet [10]. Some of the suitable materials for this application are aluminium, nickel, copper, brass, and silver. Other articles mention some common materials such as titanium, stainless steel 316, and plastic [15].

During analysis, the material exhibits a non-linear behaviour [16]. Also, different materials may exhibit different failure characteristics. For example, both discs made of Stainless Steel 304, having low strength and high ductility, and ABS-C Carbon Steel, having medium strength and ductility, fail at the centre. Whereas an A-533-B disc, having high strength and low ductility, fails at the periphery [17].

Quality of the material is another significant consideration. Satisfactory quality provides better fatigue resistance which is expected of a rupture disc with good service life. It was found that high sulphur content, grain impurities, and strip-shaped inclusions are the major reasons behind fatigue fraction in an Inconel 600 alloy disc. Grain impurities also reduce the ductility of the material [18].

VI. FINITE ELEMENT ANALYSIS ON RUPTURE DISCS

The behaviour of the disc using Finite Element Analysis (FEA) to determine its deformation and failure response was examined [5]. Under constant internal pressure, the von-Mises stresses are mostly concentrated along the scores and the maximum stress is developed at the centre of the disc. This stress must be below the initial yield strength of the material to satisfy the storage pressure requirement. Under impulsive loading on the concave side of the disc, the maximum strain occurs at its centre. The failure initiated at the centre of the disc in the score location is propagated along the score until the outer periphery of the metallic disc. Beyond a certain loading rate the burst pressure and time of burst are shown to have no variation with respect to applied pressure.

In order to understand how temperature impacts the ultimate burst pressure of rupture discs, an FEA study on a 316L austenitic stainless steel rupture disc to obtain the distribution of plastic deformation was conducted [19]. The results from the study showed that the ultimate burst pressure gradually decreased with increase in temperature. Strain hardening is observed through fracture morphologies when the temperature rises. However, the material also determines the extent to which the temperature may affect the burst pressure.

A comparison between experimental results and the values obtained through FEA for a flat rupture disc was attempted [16]. We understand the brief methodology for the simulation on the rupture disc through this process. Both material nonlinearity and geometric nonlinearity are observed. With strain hardening, the ability of the rupture disc to withstand pressure increases as it deflects. Hence, non-flat shapes are more robust and capable of withstanding higher pressures.

Simulation of the working environment for the disc becomes relatively simple with FEA. The time required for initiation of stress corrosion cracking (SCC) for an Alloy 600 rupture disc working in a primary water environment was found [20]. Growth of the crack leads to leakage or rupture in the disc along the edges of the dome. The applied stress is found to vary for different discs due to variation in their thicknesses. Also, as the disc thickness increases, the stress value decreases. This is followed by a decrease in the height of the dome. Hence, it is established that the thickness of the disc dictates the time for SCC. Thicker discs can operate for longer time periods before SCC initiates.

Different approaches to stress analysis can be used for determining the strength of pressure relief devices. For instance, different specimens can be analysed using linearization of elastic FEA stresses, Large Strain Large Displacement Elastic-Plastic FEA (LSLD EP FEA), and Small Strain Small

Displacement Elastic-Perfectly Plastic FEA (SSSD EPP FEA) [17]. Ratio of measured burst pressure of the disc to its calculated burst pressure (failure margin) is found to be largest for linearized elastic FEA, followed by SSSD EPP and LSLD EP. A large failure margin in case of linearized elastic FEA highlights the fact that it also accounts for secondary stresses concentrated at the edges which include some extra bending force. Whereas SSSD EPP only considers the main stresses that cause the failure.

The character of the mesh also influences the accuracy of the solution. A comparison of tetrahedral meshes with hexahedral meshes reveals that the former have more stiffness than the latter, and hence generate comparatively smaller values of stress [21]. The hexahedral meshes are generally more accurate than tetrahedral meshes [22].

A specific burst criterion can be set during FEA, which helps in finding the design parameters of grooved thin-plate rupture discs that allow it to burst at the expected pressure and temperature. The researchers define an "explosion" condition, which occurs when the local primary membrane equivalent stress at the location of the grooves exceeds the maximum allowable stress for the material [23]. From the analysis, only those models that undergo explosion are desirable.

Accuracy in the FEA is also an important concern. Most of the experimental results agree with those obtained from FEA [9, 16, 20]. FEA is also able to predict grooving depths during manufacturing with an error range less than 20 percent [14]. However, accurate results are obtained at the cost of time and computational resources. To manage this problem, one must find the signs of instability in the solution where a small increase in pressure causes very large deflections and longer convergence times. This often indicates that the structure is on the verge of failure. The pressure at which such a condition occurs is assumed to be the burst pressure for the disc [17].

VII. EXPERIMENTATION ON RUPTURE DISCS

Experimentation on rupture discs is often carried out using a large set of discs, made of different materials. This simply increases the reliability of the results. For instance, the maximum bursting pressure for a set of 100 rupture discs made of aluminium, stainless steel, nickel can be determined [24]. The maximum burst pressure is obtained with the help of the mean squared deviation of discs' calculated bursting pressure from actual bursting pressure. It was found that by increasing the value of n, the difference between the calculated maximum bursting pressure and actual maximum bursting pressure reduces. Another study also experimented with different disc specimens for validation of FEA results, and found a good agreement with small percentage errors [9].

The bulge forming process is examined under dynamic as well as static loading. The researchers may base their approach on plastic membrane theory and force equilibrium equations. How rupture disc materials behave under the bulge process is important to understand. It is observed that at the same bulge pressure, a higher pressure rise rate results in a smaller bulge height and effective strain [25]. Moreover, as the height during bulge forming increases, the thickness of the disc at its top decreases [8]. The percentage change in thickness of the top part of the disc after bulge forming is known as the thinning ratio. This thinning ratio decreases linearly with decreasing loading rate [12].

The experimentation phase must also expand upon the failure mechanism of the disc. A study showed that some discs failed in shear at the boundary while others showed radial failure [26]. On a careful examination of the premature bursting of an Inconel 600 alloy disc [18], its failure was found to be caused by a fatigue fracture instead of corrosion. The cracks were said to have propagated quickly due to the presence of impurities in grains found in the alloy which can weaken the grain boundary and lead to reduced ductility. The possible modes of failures must be inspected, such as large permanent deflections without any material rupture, tensile rupture, and shear failure at supports [27]. From the study we understand that the plate tearing takes place at the boundary on account of strain concentration due to plate bending. Rapid plate tearing may not allow plate deformation to develop fully in regions adjacent to the plate boundary.

VIII. CONCLUSION

After reviewing previous research, it is evident that geometrical features, type and quality of the material, effects of the hydroforming process, and the operating conditions play an important role in determining the burst pressure of the rupture disc, which is the most important characteristic that indicates its performance. Different simulation methods for rupture discs exist to capture the non-linear behaviour of the material. Also, adequate samples must be experimentally tested to improve reliability of results as well as examine different causes and modes of failure.

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