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Impact of Explosion Isolation Measures on the Reduced Explosion Overpressure in Vented Vessels

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Explosion isolation systems are protective systems designed to prevent an explosion pressure wave and a flame or only a flame from propagating via connecting pipes or ducts into other parts of apparatus or plant areas (EN 15089:2009, EN16447:2014).

During tests as part of the EU type examination of such systems, it was noticed for the first time that increased reduced explosion overpressures can occur in connected explosion-vented vessels due to a retroactive effect on the explosion process. The current dimensioning rules for explosion venting according to the harmonised European standard EN 14491:2012 does not consider such effects, which may result in a dangerous inappropriate design of explosion vented vessels in particular cases. Especially large process vessels of limited mechanical strength like e.g. filter houses which are as a rule protected by explosion venting, can be at risk.

A research project was launched in order to better understand the observed phenomena and with the aim of identifying the influencing parameters so that these effects can be taken into account in the design of the system. The results of these investigations made it possible to formulate a hypothesis which explains the observed phenomena and which served as the basis for the development of numerical value equations which can be used to estimate the increase in the reduced explosion overpressures due to the influence of the isolation device.

* 1. Introduction

The well-established and widely used explosion protection measure “explosion isolation” is often combined with enclosures protected by explosion venting. The venting areas are dimensioned according to EN 14491 and ensure that the reduced explosion overpressure does not exceed the intended strength of the enclosure. For explosion isolation systems the standard EN 15089 is decisive, for explosion isolation flap valves there is a separate standard, EN 16447. Explosion isolation systems are designed to prevent an explosion pressure wave and a flame or only a flame propagating via connecting pipes or ducts into other parts of the plant. As both explosion venting systems and explosion isolation systems fall within the scope of Directive 2014/34/EU, they must be type tested and certified by notified bodies before being distributed on the European market. Tests with explosion isolation systems in combination with vented vessels showed that the reduced explosion overpressure in the enclosure can reach significantly higher values than could be expected with an adequate design of the venting. If this observed phenomenon occurs in practice, the strength of the supposedly protected enclosures could be exceeded, which may result in a considerable risk to personnel and equipment. Knowledge about the phenomenon had to be gained and the influencing parameters needed to be extracted to consider the possible higher reduced explosion overpressure already while designing the plant.

* 1. Experimental investigations

In a research project a large amount of data was collected in hundred large scale explosion tests with four different vessels and two different explosion isolation systems.

The principal experimental set up included a vented explosion vessel with connected pipes and an explosion isolation device (EID) at the end of the pipe. Over all tests the pipe cross section and the dust concentration were constant parameters. To identify the variables with the greatest influence on the observed phenomenon, multiple aspects were varied. Two different passive explosion isolation systems with different operating principles were used: An explosion isolation flap valve and an axially operating explosion isolation valve. Four different vessel volumes of 1 m³, 5 m³, 9.6 m³ and 26 m³ with three different geometric ratios L/D (1.0, 1.5, 1.8) allowed, among others, to change the position of the connected pipe relative to the ignition location in the centre of the vessel and the venting area at the top of it. The isolation devices were installed in distances of 3 m, 4.5 m, 6 m and, for one test series, of 10 m. The use of three different so-called “organic dusts” made it possible to observe different explosion behaviours. Furthermore, the influence of the level of the reduced explosion overpressure in the vessel was also taken into account.

For each configuration, refence tests were executed with the vented vessel (without connected pipe). The reduced explosion overpressures determined in these preliminary tests were averaged for the respective configuration. This resulted in a reference value pred,0 for each tested configuration, which was used to standardise the maximum reduced explosion overpressures pi,max measured in the main tests with installed duct and EID. This quotient, which describes the maximum pressure increase due to the retroactive effects, was called the pressure piling factor PPF

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| --- | --- |
|  | (1) |

This newly introduced dimensionless parameter describes very clearly and vividly the influence of variations in the test parameters on the retroactive effects as a multiple of the reduced explosion overpressure expected for the same installation, but without pipework and EID.

* 1. Identification and evaluation of influencing parameters

In the course of the investigations, a large amount of data was generated, which was viewed and analysed in order to identify the relevant influencing parameters.

* + 1. Influence of vessel volume and installation distance

As the pipe cross-section was kept constant in all tests, the ratio of vessel volume to pipe cross-sectional area VB/AR changed linearly with the variation in vessel volume. The results show a dependence of the pi,max on the ratio VB/AR. In tests with the 26 m³ vessel, only a slightly higher pi,max than the pred,0 could be determined, if at all. In contrast, the pi,max for the 1 m³ vessel reached 4.6 times the reference value. The increase in pressure due to the retroactive effect was a factor of 3.0 for the 5 m³ vessel and approximately a factor of 2 for the 9.6 m³ vessel. Tests were carried out with the latter by varying the position of the pipe in relation to the ignition location and the position of the venting area. These parameter variations also had a considerable influence on the resulting maximum reduced explosion overpressure. An influence of the installation distance of the isolation device could not be derived from the data.

* + 1. Influence of the explosion characteristics of the dusts

Since the dusts have different explosion characteristics, it could be assumed that the phenomenon occurring or the extent of the effect observed could vary depending on the dust used. Therefore, the tests were executed with three so called ‘organic dusts’ (corn starch and wheat flour) with different KSt-values and minimum ignition energies MIE. The analysis of the measurement data showed that the resulting different maximum reduced explosion overpressure has no influence, but the combustion rate does. Considering all the tests, the tendence emerged that the lower the KSt-value resp. the higher the MIE, the stronger the retroactive effect. This was particularly evident in tests with the 1 m³ vessel: For the lowest KSt-value of 8∙106 Pa∙m∙s-1, the highest PPF of all tests was determined at 4.6. In tests with dust B (KSt = 12.5∙106 Pa∙m∙s-1), the factor was 2.8 and with dust A (KSt = 23∙106 Pa∙m∙s-1) even only 1.8.

Table 1: Selected explosion characteristics of the test dusts and PPF with the 1 m³ test vessel

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Test dust  | MinimumignitionenergyMIE [10-3 J] | MinimumignitiontemperatureMIT [°C] | LowerExplosionLimitLEL [g∙m-3] | Dust specificcharacteristicvalueKSt [106 Pa∙m∙s-1] | PressurePiling Factor1 m³ vesselPPF [1] |
| A | 3 < MIE < 10 | 350…380 | 60…125 | 22.5…24 | 1.8 |
| B | 30 < MIE < 100 | 360 | 60 | 12.5 | 2.8 |
| C | 300 < MIE < 1000 | 400…460 | 125 | 7…8 | 4.6 |

* + 1. Influence of the explosion isolation type

Two different passive explosion isolation systems were used for the tests: One system similar to an explosion isolation flap valve and a rotationally symmetrical, axially operating explosion isolation valve. Possible differences between the devices with regard to the retroactive effect could not be reproducibly determined. The similar closing times of the systems indicated that the influence of the isolation principle is marginal for the cases considered. Additionally, the large variance of large-scale tests made the differentiation of any effects of asymmetry during the closing process unreliable.

* + 1. Influence of the ignition location and vessel geometry

While in most tests the explosion was ignited in the centre of the vessel, in a series of tests with the 5 m³ explosion vessel the ignition location was also moved close to the pipe inlet. If an explosion starts here, the flame enters the pipe earlier. It therefore reaches the isolation device faster and at an earlier stage of the pressure increase in the vessel due to the explosion than when ignition occurs in the centre of the vessel. The evaluation of the results showed that the additional pressure increase due to the retroactive effects was lower with this configuration than with ignition in the centre of the vessel.

An influence of the vessel geometry could not be detected in the range of L/D of 1.0 and 1.5. For vessels with an L/D > 1.5, however, the geometry appears to be relevant and the pipe position must be taken into account. Higher pi,max were found for elongated vessels where the pipe is far away from the venting area.

* 1. Analysis and hypothesis

The following hypothesis was developed on the basis of the test results: The expansion flow driven by the explosion propagates through the pipe and the initially open explosion isolation device. As the pressure increases at the position of the EID, it closes and the flow is stopped abruptly and forced to reverse. This induces oscillations, differences in density and temperature across the pipe cross-section, shear flow, flame instabilities and a highly turbulent flow state in the pipe, thus intensifying the continuous reaction of the dust/air-mixture in the pipe. Due to the return flow into the vessel the reacting mixture enters the current explosion in the vessel and enhances the ongoing explosion.



Figure 1: Hypothesis on the development of increased reduced explosion overpressures in the connected vented vessel due to the closing of an explosion isolation device (EID)

The principle of isolating as such remains unchanged for every explosion, so that there is always a retroactive effect on the explosion in the vessel, although this does not always have to be accompanied by an increase in pressure. The pressure increase varies depending on various influencing variables. In particular, the explosion characteristics of the dust, the positioning of the venting area and the pipework in relation to each other in combination with the L/D ratio of the vessel and the ratio of vessel volume to pipework diameter were identified as the predominant variables in this respect. Their influence can be characterised as follows:

The pressure increase due to retroactive effects of explosion isolation devices on the reduced explosion overpressure in vented vessels is clearly dependent on

* the combustion velocity resp. the KSt value of the dust. For dusts with a high combustion rate (high KSt value) and a low MIE, a considerably faster conversion of the combustible material takes place. This results in less combustible material being available both in the pipework and in the vessel when the EID closes. In this case, the fuelling of the turbulence may have an intensifying effect, but since the explosion in the vessel is already relatively far developed when the return flow arrives, the effects on the reduced explosion overpressure in the vessel are barely visible.
* the ratio of vessel volume to pipe volume VB/AR. If the reaction chamber ‘pipework volume’ is small compared to the vessel volume, a reverse flow will only affect a small proportion of the much larger reaction chamber ‘vessel’ and the remixing of unburnt dust and hot combustion gases will also have less of an effect than if a duct of a comparatively large volume is combined with a small vessel.
* the positioning of the venting area relative to the position of the pipe at which the EID is installed, taking into account the vessel geometry. In elongated vessels, the flame propagation speed and thus also the reaction rate is accelerated. An increase in turbulence at a maximum distance from the vent will therefore have a more significant effect than in cubic vessels or in scenarios where the venting area is located close to the pipe.

The VB/AR ratio and the reactivity of the (organic) dust were identified as the dominant influencing variables. PPF increases exponentially as the VB/AR ratio decreases, the KSt value determines the level of the PPF.

* 1. Developing of a numerical value equation for worst-case estimation

For all organic dusts with explosion characteristics in the range of the dusts used in the underlying studies, it can be assumed that under optimum conditions, i.e. at the dust concentration at which the KSt was determined, no pressure increase is to be expected from a ratio of VB/AR ≥ 350 ‘m’ that exceeds the normal range of variation in the course of an explosion. In this context, ‘normal range’ refers to the range of reproducibility of the reduced explosion overpressure of ± 20 % - an empirical value from the practical testing of systems and devices developed for explosion protection.

At the present time, an analytical physical description has not yet been achieved. However, the investigations provide a valuable database for further theoretical work, in particular with the use of numerical simulation. But even at this stage, important findings can already be extracted that enable a worst-case assessment. Worst-case estimation because the investigations were carried out in the range of optimum concentrations for dust explosions and with an approximately homogeneous dust distribution in the volume, a condition that will not necessarily always occur in practical applications, indeed rather rarely or not at all. This is presumably also the reason why the phenomenon of retroactive effects has not yet been focussed on and provides a certain degree of safety.

Even at low dust concentrations, the described effects can occur when closing the EID, however, the devices and systems are also designed for the maximum values of the explosion characteristics under optimum conditions, as the principle of worst-case consideration is always applied in constructive explosion protection. Against this background, the criteria and tools described below have been developed to ensure that the safety-critical strengths of the devices and system components are not exceeded when they are complied with. They can be applied to all products that are comparable in design to the isolation devices used. The extent to which they can also be applied to extinguishing barriers or quench valves and similar designs has not yet been investigated.

* + 1. Assessment of the pressure increase due to the retroactive effects of an explosion isolation device

Two numerical equations with the influencing variables KSt, VB/AR and L/D as parameters were developed for the conservative estimation of the maximum pressure increase caused by the retroactive effects of an EID on the reduced explosion overpressure in the connected vented vessel. The curves described by these equations form envelope curves around the maximum values of PPF measured in this research project. The equations are based on the test conditions described.

For vessels with L⁄D ≤ 1.5, no dependency on the pipework position needs to be considered. The following applies:

 (2)

For longer vessels with L⁄D > 1.5, this must be taken into account if the pipework is located at a position away from the explosion vent. Then the following applies:

 (3)

The equations only apply to organic dusts with a KSt value within the investigated range:

7∙106 Pa∙m∙s-1 ≤ KSt ≤ 23∙106 Pa∙m∙s-1

The KSt value to be entered is the one used for the design of the explosion venting of the connected vessel.

* + 1. Estimation of the smallest non-critical vessel volume

Based on the maximum PPF determined in the KSt range under consideration, values above 1.2 times the reference value are unlikely for VB/AR ≥ 400 ‘m’. With this assumption, a ‘smallest non-critical vessel volume’ VB,unkrit can be defined as the smallest volume for which, in combination with a given pipe diameter, no critical pressure increase is to be expected due to the retroactive effect of an isolation device.



Figure 2: Estimation of the ‘non-critical vessel volume’ of an installation consisting of an vented vessel, pipework and explosion isolation device

For combinations of pipe diameters and vessel volumes, no pressure increase due to the reaction of a passive explosion isolation system of the analysed design must be taken into account in the design if the following applies:

An estimation of VB,unkrit can be achieved by transforming the numerical value equation (2) and resolving to VB. With the conditions

and

VB,unkrit can be represented as a ‘function’ of the KSt value of the dust and with the diameter of the pipe DR as array parameter. The result is

 (4)

with

Figure 2 visualises the result of such an estimation taking common pipe diameters as an example.

* 1. Conclusions

In an extensive research project, a causal relationship was ascertained between the acting of a passive explosion isolation system and the resulting higher than expected reduced explosion overpressure in a connected explosion vented vessel. Two main influencing parameters were identified, both of which are included in numerical value equations developed. They can be used to conservatively estimate the increase in the maximum reduced explosion overpressure in the explosion-vented vessel due to the retroactive effect of a passive isolation device (described by the pressure piling factor PPF) as a function of the geometry ratio VB/AR, the KSt value and the vessel L/D.

So far, only a phenomenological description of these retroactive effects has been achieved, but useful practical tools have already been developed. However, the long-term objective should in any case be to be able to describe the processes more ‘physically’ using the collected test data with the help of numerical simulation and, if necessary, further tests. Mapping the large number of influencing mechanisms in numerical models is, however, very complex and will certainly take some time.

Nomenclature

AR – pipe cross-sectional area, m2

EID – explosion isolation device

KSt – dust specific characteristic value, Pa∙m∙s-1

L/D – length to diameter ratio of a vessel, -

LEL – lower explosion limit, g∙m-3

MIE – minimum ignition energy, J

MIT – minimum ignition temperature, °C

pi,max – measured max. reduced explosion overpressure in the vented vessel with pipe and EID installed, Pa

pred,0 – maximum reduced explosion pressure in the vented vessel without pipe, averaged over a number of tests for a specific configuration, Pa

PPF – Pressure Piling Factor (ratio of pi,max to pred,0), -

VB – vessel volume, m3

VB,unkrit – smallest non-critical vessel volume, m3

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