Porous structures used as flameproof pressure relief elements a novel approach of flameless venting

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ABSTRACT
Here, a novel approach to flameless venting is presented, which offers the possibility of improving the design of flameproof enclosures without reducing any safety aspects. This approach is based on the integration of porous structures – such as traditional sintered metals or sintered metal fibers – into the enclosure walls acting as venting and flame-quenching elements. It is shown that proper use of these structures can enormously decrease the maximum explosion pressure while safely avoiding flame transmissions, even for a large number of consecutive internal explosions. However, the transmission of a gas explosion through porous structures is a transient and spatially inhomogeneous process that is strongly influenced by turbulence and chemical reactions. Especially the heating of the structures due to hot gas flow and heat conduction may lead to hot surfaces which can act as ignition sources. Hence, various porous structures were investigated: First of all, their ability to relieve pressure and their stability concerning the maximum explosion pressure were examined. Their ability to avoid flame transmissions was determined by performing a standardized test for the non-transmission of an internal explosion. And, finally, the temperature and flow characteristics of these porous structures were investigated, too. Significant differences in flow resistance and heat conduction leading to different pressure relief and flame transmission behaviors were identified, depending on the specifics of the structure. In particular, the internal structure of the examined porous media, which results from porosity and pore size distribution as well as from the shape of the solid phase (matrix), affects these characteristics.

INTRODUCTION
In chemical facilities and manifold other industrial areas, explosive atmospheres may occur. In these hazardous areas several explosion protection measures have to be taken in order to avoid any ignition of the explosive atmosphere induced by, e.g., electrical sparks, hot exhaust gases and flames or hot surfaces. All electrical and non-electrical equipment intended for use in hazardous areas, therefore, has to be specially designed according to the types of protection given in the international standard series IEC 60079-0 and the subsequent (IEC 2011) to avoid any initiation of an explosion. According to the safety concept of the type of protection “flameproof enclosure” (IEC 2007), potential ignition sources are enclosed by containments. If a combustible enters this kind of enclosure and is ignited, the enclosure must be robust enough to withstand the emerging explosion pressure without any ruptures or deformations. And, additionally, any flame transmission to the outer atmosphere due to escaping flames or hot exhaust gases definitely has to be avoided. To fulfill these requirements the construction of flameproof enclosures is related to the maximum explosion pressure of an internal explosion and all inevitable gaps are specially designed in shape, length and width so that any explosion has to be quenched properly within the gaps.

The risk assessment of flameproof enclosures in accordance with IEC 60079-1 (IEC 2007) includes experimental tests regarding the ability of the enclosure to withstand explosion pressure. When igniting explosive mixtures inside the enclosure, the reference pressure is determined as the highest value of the maximum pressure in several tests. The pressure build-up mainly depends on the initial pressure and temperature, the fuel type and its concentration and burning rate. Considering ambient pressure and temperature, the slightly rich mixtures used in these tests lead to typical reference pressure values in the range of 6 to 11 bar. However, in enclosures of complex geometry, precompression in a subdivision of the enclosure may occur prior to the flame arriving. Depending on the amount of this compression, pressure piling occurs which results in reference pressure values up to 35 bar (Singh 1984) or even higher. According to IEC 60079-1 (IEC 2007), such an enclosure has to withstand a static overpressure test of either a minimum of 1.5 times the reference pressure in routine overpressure testing or up to four times the reference pressure to avoid routine testing. Considering
these requirements for flameproof enclosures, the reduction of explosion pressure is worth pursuing.

Explosion venting has been an established protective measure for decades which is commonly used to prevent or to limit the structural damage of equipment or buildings from accidental high explosion pressures, by means of pressure relief through predetermined breaking points. Thus, the essential component of all venting devices is the closing element which provides the vent opening in case of an explosion. In general, venting devices are divided in devices with reusable elements and those with non-reusable elements. Whereas reusable elements like explosion doors are shut (automatically or manually) after the explosion, non-reusable elements such as bursting membranes need to be replaced by new ones after each incident. Regardless of the specific type used the opening of the venting device normally leads to a turbulent jet flame emerging from the venting device with high velocity. As it was shown that these flames escaping through the vent opening may attain considerable lengths (Hattwig et al. 2004), venting devices were combined with flame arresters. These so-called flameless venting devices (CEN 2011) are able to release explosion pressure and concurrently extinguish the flame (see, e.g., Chao and Dorofeev 2012). The passive devices acting as a flame arrester consist usually of various layers of stainless steel wire mesh. Other examples, which are installed behind the vent opening are described in EN 16009 (CEN 2011). Thus, if an explosion takes place inside the equipment, the expanding explosion is given relief through the vent opening at a certain value of overpressure and the subsequent flame, along with the burned and unburned discharge, enters the flame arrester element. The discharge will be retained in the device and the flame extinguishes within the wire mesh due to cooling. However, the use of these devices to extinguish flames from explosion vents also results in less efficient venting, increasing the reduced overpressure.

In this work, we present a methodology to expand the concept of flameless venting devices to the pressure relief of gas explosions inside flameproof enclosures. It is based on the integration of porous structures into the enclosure walls acting as both venting and flame arresting devices. So in this development the two functions “pressure relief” and “flame transmission avoidance” are integrated in one constructional element: the pressure relief element (PRE) made of porous structures. These structures have to fulfill several requirements. Firstly, to avoid flame transmissions safely, the porous structures must have a large internal surface to quench the flames and sufficiently cool down the hot gas flow (Mecke et al. 2008). Secondly, to withstand the thermal and pressure loads due to the internal explosion, they have to be strong enough (Hornig et al. 2010). Thirdly, the flow resistance of these structures should be as low as possible, improving their capability of relieving pressure (Mecke et al. 2007). Therefore, different porous structures were tested in accordance with IEC 60079-1 (IEC 2007). Firstly, their pressure relief capability was determined, which has already been published in more detail elsewhere (Hornig 2013). Moreover, the aim of this study was to examine the pressure relief elements made of porous structures with respect to flame transmission and thermal loads. The results clearly show that the proper use of these structures can enormously decrease the maximum explosion pressure inside the enclosure while safely avoiding flame transmissions, depending on the specifics of the structure.

**NOMENCLATURE**

- \( A \) = Area
- \( \text{PRE} \) = Pressure Relief Element(s)
- \( \Delta p \) = Overpressure
- \( SF \) = Sintered Fibers
- \( SM \) = Sintered Metal
- \( t \) = Time
- \( T \) = Surface Temperature of \( \text{PRE} \)

**Subscripts**

- \( \text{max} \) = Maximum
- \( \text{red} \) = Reduced
- \( V \) = Vent

**1 Experimental setup**

Within our investigations, three different porous structures as shown in figure 1 were examined regarding their applicability as pressure relief elements. Besides a traditional flame arrester made of crimped ribbon (Protego 2014) having a width of gap of 150 µm and a thickness of 10 mm, we focused our attention on two sintered porous structures. These were a typical sintered metal (Tridelta Siperm 2014), which is usually used for filtration applications in the field of chemical engineering, and sintered fiber structures (Fraunhofer IFAM 2014, Andersen 2002). While we investigated the sintered metal in one porosity (approx. 50 %) and one thickness (5 mm) only, the basic characteristics of the sintered fibers investigated cover the three porosities 60 %, 70 % and 80 % with a thickness of 5 mm and additionally, the combination of 70 % porosity and a thickness of 10 mm.

Figure 1: Test samples used, crimped ribbon (left) sintered metal (middle) and sintered fibers (right)
The scale of pressure and temperature loads depends, of course, on the volume and the internal structure of the enclosure. However, in order to compare and to classify these different porous structures systematically in terms of their pressure relief capability, flame quenching ability and temperature characteristics, all experimental tests were conducted using a basic experimental setup. Within the scope of the investigations described, a commercially available flameproof enclosure has been prepared in such a way that it is possible to insert as many test samples as possible into the enclosure walls. The enclosure is nearly cubic and has a volume of almost 2 L and openings for at the most 12 test samples. To easily integrate the porous structures to be tested into the enclosure walls and to enable fast modifications during test series, a special sample holder was developed. Figure 2 depicts this experimental setup showing a cross section of the 3-dimensional model of the enclosure with its openings to position the test samples, using the specially developed sample holder (pictured as an exploded view including one test sample).

All test series determining the explosion pressure within the enclosure and the outer surface temperature of the test samples have been conducted in accordance with IEC 60079-1 (IEC 2007). To characterize the dependence of pressure reduction and surface temperature on the size of the total vent area $A_V$, the number of inserted test samples, each having an active surface area acting as a vent area of about 315 mm$^2$, was gradually reduced from the maximum to the minimum while sealing the non-equipped openings. For every configuration investigated, a test series consisted of three explosion tests for each of the two given gas mixtures for reference pressure determination ((31 ± 1) vol. % hydrogen in air and (14 ± 1) vol. % acetylene in air) and of five explosion tests for each of the two given gas mixtures for thermal tests ((4.2 ± 0.1) vol. % propane in air and (7.5 ± 1.0) vol. % acetylene in air) according to IEC 60079-1. The ignition of the gas mixtures was always induced using the same spark plug inserted in the enclosure cover. The temporal evolution of overpressure $\Delta p(t)$ inside the enclosure was determined using a piezoelectric pressure sensor (Kistler, type 6031). And the surface temperatures of the porous structures were measured using a sheathed thermocouple type K (Rössel, type ALSTE-KB-0.5-50-3, class 1), a voltage amplifier (Analog Devices, type AD 595 AQ) and an oscilloscope (Yokogawa, type DL 1640).

It is important to mention that the usually used connection technique of bonding to realize the thermal connection between the element surface and the thermocouple causes an inhomogeneity on the element’s surface and in the pores below, because the glue infiltrates the element and thus, the pressure relief is affected. Hence, in order to perform measurements under reproducible conditions and to guarantee an enduring thermal connection between the element surface and the thermocouple – even during the high mechanical stress induced by the explosions – a special thermocouple holder was constructed. The following figure 3 shows two photographs of this special setup for surface temperature determination.

Figure 3: Experimental setup for surface temperature determination using a sheathed thermocouple fixed in a special holder

2 Results

This section summarizes the experimental findings of both the explosion pressure relief and the temperature experiments. To enhance its readability and facilitate its understanding, it is divided into two subsections regarding the experimental focus.

2.1 Pressure relief

To illustrate the experiments described figure 4 shows, as an example, four of the recorded overpressure evolutions inside the enclosure depending on both the sealing status of the enclosure and the gas mixture to be used for reference pressure determination. These curves illustrate impressively the potential of porous structures used as pressure relief elements. In comparison to the completely sealed enclosure, where maximum overpressures (gauge pressures) of almost 9 bar using acetylene ($C_2H_2$) and nearly 7 bar using hydrogen ($H_2$) arise, the integration of twelve PREs of porous structures into the enclosure walls leads to significantly lower maximum...
overpressures. As can be seen these are slightly more than 1 bar using acetylene and approximately 2 bar for hydrogen explosions.

In the following the arithmetic mean of the three determined maximum overpressures of the temporal overpressure evolutions for each structure, configuration and gas mixture tested is called reduced overpressure $\Delta p_{\text{red}}$. Figure 5 summarizes these reduced overpressures $\Delta p_{\text{red}}$ as a function of vent area $A_V$ for each structure examined using (14 ± 1) vol. % acetylene in air. The vent area $A_V$ corresponds to the number of pressure relief elements inserted during the experiments. As expected, the larger the vent area the better the pressure relief. However, as can be seen in figure 5 the reduced overpressure $\Delta p_{\text{red}}$ strongly depends on the type of porous structure and its flow characteristics: Elements of sintered metal provide, in all cases, the lowest pressure relief due to their low porosity. In contrast to this, the sintered fibers with a porosity of 80 % have only a low flow resistance leading to the strongest overpressure decrease. For more details considering pressure relief see (Hornig 2013).

2.2 Surface temperature

The following figure 6 shows in principle the temporal evolution of the surface temperature $T$ of a pressure relief element in relation to the emerging overpressure evolution $\Delta p(t)$ inside the enclosure (cf. figure 4). Immediately after the ignition at $t = 6$ s the pressure (blue) rises rapidly and the surface temperature of the pressure relief element (red) briefly increases due to the outflow of hot exhaust gas. At this time the heat transport is mainly caused by convection. After about 25 seconds following ignition a second temperature maximum of about 220 °C is visible which results from heat conduction. This global temperature maximum has to be considered as a possible ignition source.
### Table 1: Averaged maximum surface temperatures $T_{\text{max}}$ of different PREs consisting of sintered fibers (SF) and sintered metal (SM) with varying porosities (80 %, 70 %, 50 %) and thicknesses (in mm) depending on the number of inserted pressure relief elements (PRE) and the two gas mixtures for thermal tests propane ($\text{C}_3\text{H}_8$) and acetylene ($\text{C}_2\text{H}_2$)

<table>
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<tr>
<th>PRE</th>
<th>SF 80 % (5 mm)</th>
<th>SF 70 % (5 mm)</th>
<th>SF 70 % (10 mm)</th>
<th>SF 70 % (2 × 5 mm)</th>
<th>SM 50 % (5 mm)</th>
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<td>$\text{C}_3\text{H}_8$</td>
<td>$\text{C}_2\text{H}_2$</td>
<td>$\text{C}_3\text{H}_8$</td>
<td>$\text{C}_2\text{H}_2$</td>
<td>$\text{C}_3\text{H}_8$</td>
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</table>

Table 1 summarizes the respective average of the maximum surface temperatures of the different sintered structures depending on the number of PREs and the used gas mixtures. Fewer inserted elements result in higher surface temperatures for each structure. Considering the sintered fibers it can be seen that the surface temperature decreases with decreasing porosity and increasing element thickness, respectively, due to an increasing amount of metal. Regarding the pressure relief capability shown in figure 5 the sintered fiber structures with a porosity of 70 % (5 mm) are much better than sintered metal elements with only a porosity of approximately 50 %. However, their surface temperatures according to table 1 are very similar. This comparable thermal behavior of these two sintered structures is due to the anisotropic structure of the sintered fibers. The metal fibers forming the matrix of the fiber elements and having a length up to 10 mm and a diameter of about 100 µm are radially arranged. Thus, in comparison to the sintered metal which is nearly isotropic, heat conduction inside the sintered fiber elements perpendicular to the flow direction is promoted.

During both the pressure relief and the surface temperature experiments no explosion of the outer explosive gas mixture due to a pressure relief element’s hot surface was observed. Under the aggravated conditions during flame transmission tests in accordance with IEC 60079-1, however, several of those explosions were caused. Figure 7 shows a typical temporal evolution of the surface temperature $T$ of a pressure relief element during one of those flame transmission tests where the outer gas mixture was ignited. Initially, the temperature develops as described in figure 6, but at a time of $t \approx 12$ s the temperature suddenly increases. At this moment the explosive gas mixture outside the enclosure was ignited due to the hot surface of the pressure relief element. Therefore, with respect to explosion protection, the maximum surface temperature always has to be considered carefully to avoid any explosion.

**Figure 7: Temporal evolution of surface temperature $T$ of a PRE during a flame transmission test according to IEC 60079-1 where an ignition of the outer explosive gas mixture was caused due to the element’s hot surface**

**CONCLUSIONS**

Overall, this research work demonstrates the significant potential of the introduced novel approach to flameless venting based on porous structures. Due to the results obtained it is possible now to make qualifying statements about the fundamental applicability of porous structures...
and to recommend technical parameters for the use of such structures as explosion pressure relief elements to be used in flameproof enclosures.

By using porous structures as an integral part of flameproof enclosures acting as venting and flame quenching elements, it is possible to enormously reduce the explosion pressure inside these enclosures. These structures require a low flow resistance corresponding to high porosities by which they are capable of relieving the explosion pressure and venting the enclosure. At the same time any ignition of the outer atmosphere due to hot surfaces has to be avoided in any case by sufficient cooling. Especially sintered fiber structures made of high-temperature resistant materials are promising components to fulfill these contradictory requirements. Thus, this novel application of porous structures offers the possibility of improving the design of flameproof enclosures leading to slimmer and more customized enclosure constructions and smaller production costs.

REFERENCES


