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Experimental Evaluation and Analysis of Methane Fire and Explosion Mitigation Using Isolation Valves Integrated with a Vent System

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Highlights

- Applying the passive isolation valve reduces the downstream peak pressure to approximately 0.42 bar.
- The passive mitigation valve stopped the flame but generated an oscillating pressure wave downstream.
- The active mitigation valve effectively isolates the flame without pressure detecting downstream.
- A reflected pressure wave significantly participates in deflagration mitigation upstream.

Abstract

There has been a surge of interest from the extractive industries in the application of mechanical means to the mitigation of flame deflagration. To verify the implementation and performance of passive and active mitigation protection, a comprehensive experimental investigation has been conducted on a large scale detonation tube, 30 m long and 0.5 m in diameter, with two mitigation valves (passive and active) and a burst panel venting system. The valves were used alternately to mitigate the flame deflagration of methane in concentrations ranging from 1.25% - 7.5%. The experimental work revealed that locating the passive mitigation valve at 22 m distance from the ignition source mitigates the flame by fully isolating the tube. However, closing the valve structure in the axial direction generated another pressure wave upstream, which was approximately the same value as for the original pressure wave upstream. In the case of the active mitigation system, the system perfectly isolated upstream from downstream with no further pressure wave generation. When the vent

was located at 6.5 m from the ignition source, the total pressure was reduced by 0.48 bar. Due to the counter flow of the reflected pressure wave the flame was extinguished at 12.5 m from the ignition source.

Key words: fire mitigation, flame deflagration, explosion vent, explosion isolation, detonation tube.

1. Introduction

The escalation of accidental fire is a major concern in the interconnected process industries. Unless the primary accidental fire is isolated or mitigated, another series of fires and explosions may be triggered, resulting in massive destruction as compared to the primary event [1,2]. The protection barriers for such fires should be designed in accordance with the requirements and the conditions of the expected hazards [2,3]. In cases where the barrier acts without external interference, it is referred to as passive mitigation (i.e. with a venting duct and a passive mitigation valve). Active mitigation refers to the situation where the barrier acts according to an external signal from a detector [3,4]. A further step required to ensure safer processes is applying and testing the barrier approach to a large scale setup for commercial purposes [5].

Extensive literature has previously considered explosion venting as a passive action to reduce the expected damage from the flame and pressure rise[6]. Much of the relevant literature focuses on the venting of a confined space, and the venting of a vessel interconnected to another vessel. In one particular study, the influence of venting on the maximum pressure rise was experimentally investigated based on a lab scale setups with explosion chambers varying from 20 L to 1000 L in capacity, the researchers agreed that applying venting technology significantly reduced the maximum pressure rise and the deflagration index [7–11]. The venting of pipes has also been highlighted by a number of researchers, who found that for side-on venting the maximum pressure rise may begin at the point of the venting duct and spread to the tube. This phenomena is known as coherent deflagration, where the flame turbulence significantly increases when the flame reaches the edge of the vent and causes a noticeable increase in the pressure, however, it has been found that the pressure declines quickly once the flame reaches beyond the second vent [12–14]. Other researchers have

concluded that the flame velocity is reduced only when the vent is located close to the ignition point [15,16]. In spite of the novel concept of the passive mitigation valve (PMV), the implications of these types of barriers require test verification for each of the application conditions, including variations in pipe diameters, locations of ignition points, fuel types and gas concentrations [17]. Literature shows an obvious lack of application testing for both the passive and active mitigation valves.

The current study mainly tested the application of passive and active mitigation barriers on the Ventilation Air Methane (VAM) capture duct. This included evaluating the performance of different scenarios of both passive mitigation barriers (Venting and PMV) and active mitigation barriers. The methane concentration is not expected to exceed 1.25% in standard operation conditions of the VAM capture duct; however, this concentration may increase under abnormal conditions. This work employed a wide range of methane concentrations, from 1.25% up to stoichiometric concentration, to include all possible fire and explosion scenarios. The new configuration is precisely designed based on intensive experimental work that has been carried out previously in a large scale straight tube facilitated at the University of Newcastle in Australia. The current study also provides insight into the influence of barriers on flame deflagration characteristics. Eventually, it delivered valid data for a number of scenarios with commercial purposes.

2. Methodology and Technique

A large vented deflagration tube (VDT) was established at the University of Newcastle (UoN), Australia to evaluate and examine the novel mitigation configurations of flame deflagration in tubes and tunnels. The 30 m (metre) tube (VDT) was vented at two locations. First the vent was located 6.5 m from the ignition source, and second, the vent was located 21 m from the ignition source. In both venting cases, two mitigation phenomena were examined; the pressure wave (PW) and flame deflagration. The pressure values were measured by thirty-three pressure transducers which were located radially around and along the DT at the rate of three pressure transducers per section. The pressure transducer measuring range was up to 60 bar, with an error of less than 0.25% and a response time of < 0.1 ms. The flame light emission intensities were detected by thirty-three semiconductors (photodiodes) which were mounted in the same configuration as the pressure transducers. The photodiodes had the following specifications: an active area of 0.8 mm^2 , a wavelength range of 200-1100 nm, a

rise time of 1 ns and a reverse bias voltage of 10 V, the maximum voltage output is about 10.2 V [18,19]. The venting duct cross sectional dimensions is 0.64 m height and 0.32 m width. The venting duct isolated from the tube by a burst panel where the burst pressure (relief pressure) for the panel was 0.15 bar. The burst panel was replaced with a new panel after each experiment. The total length of venting duct is 2.2 m and two pressure transducers mounted at a distance of 0.2 m 2 m from the edge of venting duct closer to the vent panel. The mitigation valve performances were examined at a number of methane concentrations in the reactive section (1.25% to 7.5%). It is important to mention that section number one was always fuelled with stoichiometric methane concentrations (9.5%).

2.1 Passive Mitigation Valve (PMV)

The concept of the PMV is considered one of the less complex approaches to mitigating flame deflagration in tubes. Application of the PMV for industry (for example, to a VAM shaft), however, needs performance verification to determine restrictions and side effects when the potential hazards are triggered [17]. The PMV is shown in Figure 1. The PMV integration with the VDT is shown in Figure 2. The PMV, located at section 9, is initially idle, without air flow and the closing device is held in the middle position. Air flows around the closing device in normal operation. In the case of an explosion, the pressure wave pushes the closing device against the device seal (see Figure 8). The valve remains locked in this state, preventing the spread of flames or pressure waves downstream. The device can be manually reset by manual handle levers on the sides of the spool piece.

2.2 Active Mitigation Valve (AMV)

Where AMVs are employed, it is desirable that neither the pressure wave (PW) nor the flame should be passed downstream. The AMV (see Figure 3) basically consists of three stages. First, upon explosion, the system detects the explosion via a dynamic pressure transducer and/or infrared light sensors, which are connected in parallel to the detection system. The detection of an increased signal response, according to pre-tuned background light and K_{st} values, provides an electronic signal which is processed at the control panel (stage 3). If an explosion is detected according to the settings in the control panel, the pre-charged 8 bar actuator, (an actuator on the high speed gate valve) seals the tube. The gate remains closed until it is reset by the control system. The system also includes a test open/close system to determine response times and possible defections in the plate.

AMV located on section 9 and its detectors were mounted on Section 2 providing 18 m distance between the AMV and its activation detector as shown in Figure 4.

The setting and the response time of the AMVs were adjusted at the control panel, then the AMV was activated. The VDT was then prepared for the test condition (i.e. methane concentration) via a control room located outside the VDT restricted area. Once the preparation was completed, the explosion in the VDT was initiated and the results were collected by a 100 kHz data acquisition system.

3. Results and Discussion

3.1 Maximum Pressure Rise (MPR)

The explosion pressure is a crucial factor in determining the design explosibility safety factor. The identification of flame deflagration hazards and violence is highly dependent on the MPR. The MPR of flame deflagration in open-ended tubes has relatively lower magnitudes than confined tubes and vessels have. This holds true, unless the flame deflagration develops to detonation or to a fast deflagration (such as a high MPR 40 times higher) which requires adequate L/D ratios, fuel concentrations and other properties [18–24]. Understanding the MPR of the flame deflagration not only reveals the pressure wave behaviour, but also assists in evaluating the performance of the PMV, AMV and venting technology. This section highlights the MPR at the vent duct and the MPR profile along the VDT. The MPR for varied concentrations of methane (1.25%, 2.5%, 5% and 7.5%) for PMV, AMV and vent only, are shown in Figure 5. The experimental error could be generated from the pressure transducer error ($\leq 0.25\%$), and the actual concentration of methane inside the tube where there was an allowance in range of 0-0.15%. These facts caused variation in the pressure reading in the range of 0.26 bar [25,26]. The primary results indicate that the MPR for venting configurations had significantly lower values before applying the PMV and AMV to the system. The MPR of AMV had the highest values as compared to the vent only or PMV, recording MPR's of 0.88 bar, 0.69 bar and 0.42 bar respectively for 7.5%, 5% and 2.5% methane concentrations.

The increase in MPR, as compared to the standard open-ended configuration, due to the PMV was significantly lower than it was for the AMV, and on some occasions was slightly higher than the MPR for the vent only setup. For instance, the MPR at a 5% methane concentration

recorded a MPR 0.22 bar higher when applying the PMV (see Figure 5). The MPR provides a clue for the increasing pressure due to application of the PMV and AMV. The variation of the

MPR during the phase of flame deflagration changed due to three main factors; the flame acceleration while it propagated along the tube, gases relieving via the venting duct, and the role of the mitigation valves. The MPR profile along the VDT for case 1 has been clarified in Figure 6. In each case a distinct pattern was observed. For venting only, the pressure profile fluctuated near the vent location then gradually diminished, and the total degradation of MPR in the pressure from the ignition section to 28.5 m distance was about 0.19 bar. This was mainly due to venting and loss in momentum while travelling. The MPR profile changed according to the mechanism of the action of the mitigation valves. When applying the PMV, the MPR had a pattern similar to the pattern for venting only, however the values of the MPR were higher.

The total degradation of MPR for the PMV was about 0.22 bar and the reduction in the pressure in this case was considerably lower than expected. Therefore, a comprehensive analysis was accomplished in the current study to detail the behaviours of the pressure wave and flame transport. The MPR noticeably increased just before the location of the AMV, then there was a steep drop in the MPR directly after the AMV. The peak in MPR reached the summit at 22.5 m, however the pressure began to increase from 3.5 m and the MPR significantly developed from the vent position and up to 22.5 m. Indeed, the pressure development at 22.5 m was a combination of the pressure wave and the reflected pressure wave, which is in good agreement with other research [27]. In this case, it is proposed that the increase in the pressure at locations after the vent is mainly dependent on the pressure reflection from the AMV and the pressure build up in the layer in front of the flame. This proposition will be discussed clearly by analysing the pressure time profiles of the tests later in this study. The AMV reduced the MPR by about 0.77 bar, and its summit was at about 1 bar at 22.5 m.

The MPR profile along the VDT for case 2 has been clarified in Figure 7. Relocating the vent duct to just before the mitigation valves influenced the pressure reflection and the pressure build up. It is important to note in this case that the PMV was permanently closed; the aim was to verify the effectiveness of the AMV and also to provide a clue for the case of the

closed end tube. The degradation of the MPR for the vent only setup was similar to that of case 2, except that the magnitude was less due to the potential release of methane in the early stages of flame deflagration. The MPR profile for the AMV case 2 does not match that of case 1. In case 2 the MPR fluctuated at the beginning then dropped until reaching the AMV.

The pressure peak is less noticeable before the AMV as most of the pressure was released through the vent duct before that point. In case 1 the MPR was about 0.58 bar higher than the MPR at the beginning of deflagration. However, for case 2 the MPR was lower than the MPR at the beginning of deflagration by about - 0.1 bar. The second difference was the location of the peak; in case 2 the location was 2 m earlier. The MPR after the AMV shows a good match with the closed PMV, which indicated the effectiveness of the AMV in sealing the pressure wave from heading upstream.

3.2 Pressure Wave (PW) Behaviour

The PW generated from the flame deflagration and/or explosion is a major hazard in the process industries. The hazardous PW not only accelerates flame deflagration, but also may initiate another explosion, pressure piling, inflicting damage, lifting the deposited combustible particles and making a favourable environment for dust explosions [28,29]. Venting flame deflagration has been found to reduce the magnitude of the PW as well as the severity of any explosion [30–33]. Blocking the path of a PW in a tube by a structure was found to increase the magnitude of the peak pressure, in addition to causing reflection of the pressure upstream [27].

This section, however, examines the PW behaviour of PMVs and AMVs integrated with the VDT. Figure 9 details a PW in the VDT when applying the PMV at a 5% methane concentration, case 1. The PW was analysed from four locations; at section 7 (17.5 m), at section 8 (20.5 m), before 1 m from the PMV blocking structure (22 m) and 1m after the PMV blocking structure (24.5 m). The PW at all predefined locations showed similarities to the first PW peak, where the PW rose slightly then diminished, due to a partial gas release from the vent at section 3. The single side venting reduced the PW amplitude, but not sufficiently to mitigate the PW, as seen at 17.5 m. The second peak was observed with a peak pressure of 0.29 bar (Figure 9). This was in good agreement with the literature; the PW for the PMV showed that the second peak doubled because the pressure increased upstream of the flame front [27].

While the flame reached the structure of the PMV, the burning rate decreased and produced a smaller amount of gas. This is clarified by the decrease in the second peak at 22.5 m by about 20%, as compared to the second peak at 20.5 m (1 m before the structure at 22.5m). The PW shows a reflected PW from the structure with a velocity of about 133 m.s^{-1} and only 10 ms separating the peak of the reflected PW from the deflagrated PW at 22.5 m (see Figure 9).

The PMV structure shut the air flow once enough dynamic pressure was delivered, blocking the path of the air. The mechanism for shutting the PMV is clarified in Figure 8. When the pressure wave velocity was greater than 20 m.s^{-1} , the structure moved toward the shutting state [5]. Accordingly, the PMV allowed a PW of less than 20 m.s^{-1} to pass from the upstream to the downstream of the PMV. During the phase of shutting the structure, a small amount of PW escaped downstream, around the valve edge, before the PMV was fully closed. The maximum pressure of 0.29 bar escaped from the PMV before being fully shut, with only a 34% reduction from the previous pressure at 22.5 m. In the downstream section (after 24.5 m), a pressure oscillation appeared after the PMV was fully shut in the shape of a saw tooth character. This feature is dominant for the explosions in one end open ducts [34–36]. However, it has not been observed in upstream locations due to the presence of venting, which dampens the oscillation. The first oscillation cycle pressure was in the range of 0.86 bar and the peak was 0.42 bar, which was only 0.02 bar below the reflected pressure. The magnitude of the peak pressure in the oscillation pressure cycle is mainly dependent on the escaped pressure wave and the timing of PMV shutting. A higher pressure escape caused higher negative pressure once the PMV structure closed, and eventually a higher peak pressure in the oscillation pressure. Figure 10 compares the PW behaviour for a 7.5% methane deflagration in VDT and AMV. The PW footage at 17.5 m for both cases had magnitudes and behaviour matching up for the first 312 ms. The PW magnitude slightly increased for the AMV as compared to the VDT, once the PW reached 21.25 m. As the PW travelled from 21.25 m to 22.5 m, the pressure gap significantly increased from 0.3 bar to 0.6 bar.

Two possible scenarios are connected to the continually increasing gap. The first is that the PW moves due to the combustion of products behind the front flame, causing a fluid compression ahead of the flame. The AMV structure blocked the path within only 65 ms after the PW was detected via dynamic pressure transducers at section 2, meaning the VDT had already closed before compression of the fluid ahead of the flame reached the location of the AMV. This action caused a more noticeable pressure build up ahead of the flame, which

caused decoupling between the pressure profiles of the AMV and the VDT (see Figure 10, 21.25 m and 22.5 m). This scenario is supported by Figure 10 for 21.25 m and 22.5 m, where the decoupling was noticeable before the PW peak after about 210-225 ms.

The second scenario that increased the pressure was the PW reflecting off the AMV structure. The constructive coupling of the reflected PW with the original PW produced a peak of 2.47 bar, which was about 1.01 bar higher than the original PW (see Figure 10, at 22.5 m). The reflected PW travelled backward at a velocity of 113 m.s^{-1} , diminishing at a rate of 20.3 bar.m^{-1} . The AMV effectively mitigated the PW, such that there was no noticeable trace of pressure change after the AMV (see Figure 10, at 24.5 m).

3.3 Flame Deflagration

In a straight smooth tube, the flame travelling profile interacts with the PW. The flame acceleration was intrinsically increased by the PW travelling in the same direction, increasing the temperature of unburnt gases and amplifying the flame front turbulence [37,38]. Accordingly, it is important to clarify the influence of the AMV on the upstream flame profile, the flame signal and the flame velocity. The flame signals for a 7.5% methane concentration deflagration in both VDT and AMV are shown in Figure 11. The venting process inevitably impacts on the flame profile as compared to a straight tube, as the venting process relieves both the pressure built up ahead of the flame and also the combustion products behind the flame [39]. These influences were obvious from the discontinuity of the flame signal, especially at points after the location of the vent (see Figure 11-b). The flame signal detected in the AMV configuration showed a distinct behaviour, as compared to the flame signal detected for the VDT configuration. The most important outcome was that the flame was completely extinguished after 12.5 m, however, in the case of VDT configuration the flame signal was detected even at 20.5 m. It is important to clarify that at 12.5 m there was a tiny flame signal of 0.03 V, which is not noticeable in Figure 11. The flame was extinguished near the 12.5 m mark, attributed mainly to the reflected PW from the AMV structure [40]. The extinguishing of the flame became more effective the earlier the vent was located. The gas between the vent point and the mitigation valve becomes compressed and flows towards the vent point, which opposes the direction of the flame.

This eventually restricts the flame from propagating towards the mitigation valve. The results also indicated that the flame signal before the vent was also affected by the earlier pressure

relief and the reflected pressure wave, seen in Figure 11 for a 1 m distance. In the VDT configuration the essential flame signal ended at about 300 ms, however, the AMV configuration flame signal ruptured and fluctuated until about 490 ms. The flame velocities of both the VDT and the AMV for 2.5%, 5% and 7.5% methane concentrations are displayed in Figure 12. The flame velocity was calculated according to the following equation

$$FlameVelocity = \frac{x}{t} \quad (1)$$

where t is the time at which the flame reached distance x from the ignition source.

The results reveal that the reflected PW for the AMV structure not only mitigated the flame earlier, but also reduced the flame velocity for all three of the methane concentrations (2.5%, 5% and 7.5%).

The flame velocity in this section was calculated from the time of the first rise in the flame signal corresponding to the time and distance of the initial ignition source. Up until the point of the vent location, the flame velocity was the same for both the VDT and AMV configurations of all the measured methane concentrations (see Figure 12). However, immediately after the vent location, the reduction of the flame velocity of the AMV configuration was noticeable as compared to the VDT configuration. The deceleration of the flame velocity was in the range of 4 m.s^{-1} to 18 m.s^{-1} .

4. Conclusion

This work examined three types of protective barriers which were venting, passive mitigation valve and active mitigation valve. The passive and active mitigation valves were verified alternatively with side-on venting of the detonation tube. A methane deflagration flame was used in the range of 2.5%-7.5% concentration. The results revealed that the maximum pressure rise developed at the upstream section for the active mitigation valve was always higher than it was for the passive mitigation valve, with a pressure difference of between 0.2 - 0.4 bar for methane concentrations of 1.2% - 5%. Also, the maximum pressure rise for the active mitigation valve was higher than for the vented detonation tube by 0.2 bar - 0.88 bar for methane concentrations in the range of 1.25% to 7.5%. For case 1 (vent duct located at section 3), the pressure profile when applying the AMV displayed a peak pressure which gradually increased from 0.51 bar until reaching the summit (1.08 bar) just before the AMV. However, for case 2 (vent duct located at section 8), the pressure rise profile shows the pressure slightly developed from 0.58 bar to 0.7 bar at 9.5 m distance, then the pressure rise

decreased to 0.45 bar and another peak appeared (0.57 bar) just before the AMV. The pressure profile shows that in spite of the fact that the passive mitigation valve is practicable for safer design [44], a pressure wave was generated downstream with pressure very close to the magnitude of the original pressure wave, due to the movement of the structure during the phase of shutting. However, in the case of the active mitigation valve, the data shows there was no trace of a pressure wave downstream of the AMV.

This indicates that applying the PMV totally isolates downstream from upstream, but it triggers additional hazards by generating a pressure wave downstream. Finally, it has been noted that the reflected pressures from the structure (for both PMV and AMV) mitigated the flame once it reached about 9.5 m distance from the ignition source.

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Figure 1: Passive Mitigation Valve

Figure 2: Configurations of Passive Mitigation Valve integrated with VDT

Figure 3: Active Mitigation Valve

Figure 4: Configurations of Active Mitigation Valves integrated with VDT

Figure 5: MPR for AMV, PMV and vent only setups for varied concentrations of methane (case 1)

Figure 6: MPR profile along the VDT with a 5% methane concentration (case 1) for vent only, PMV and AMV

Figure 7: MPR profile along the VDT for a 5% methane concentration (case 2) for Vent only, PMV and AMV setups

Figure 8: Mechanism of PMV operation

Figure 9: PW comparison generated in VDT with and without PMV

Figure 10: PW comparison generated in VDT with and without AMW

Figure 11: Flame signal comparison for a 7.5% methane deflagration for VDT and AMV

Figure 12: Flame velocity comparison between VDT and AMV

Table 1: Tests Matrix

Test No	Detonation tube Configuration	Targeted Methane Concentration (%)		Achieved Methane Concentration (%)	
		Initial ignition Section	Reactive Section	Initial ignition Section	Reactive Section
#1	VDT Case1	9.5	1.25	9.59	1.4
#2		9.5	2.5	9.57	2.6
#3		9.5	5	9.56	5.1
#4		9.5	7.5	9.44	7.65
#5	VDT Case2	9.5	1.25	9.57	1.15
#6		9.5	2.5	9.56	2.6
#7		9.5	5	9.46	5.11
#8	PMV Case1	9.5	1.25	9.64	1.29
#9		9.5	2.5	9.6	2.42
#10		9.5	2.5	9.45	2.6
#11		9.5	5	9.55	4.96
#12	PMV Case 2	9.5	1.25	9.72	1.3
#13		9.5	2.5	9.65	2.43
#14		9.5	5	9.5	5.11
#15		9.5	7.5	9.74	7.22
#16	AMV Case 1	9.5	1.25	9.58	1.3
#17		9.5	2.5	9.57	2.56
#18		9.5	2.5	9.72	2.42
#19		9.5	5	9.62	5.1
#20		9.5	7.5	9.7	7.36
#21	AMV Case2	9.5	1.25	9.66	1.29
#22		9.5	2.5	9.7	2.42
#23		9.5	5	9.74	4.96