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Flame Deflagration In Side-on Vented Detonation Tubes: a Large Scale Study

Mohammed J. Ajrash Al-Zuraiji[a], Jafar Zanganeh[a]* and Behdad Moghtaderi[a]

[a]*The Frontier Energy Technologies Centre, Chemical Engineering,*
School of Engineering, Faculty of Engineering & Built Environment,
The University of Newcastle, Callaghan, NSW 2308, Australia

Abstract

Venting is often used in process industries to reduce the possibility of dangerous rises in pressure levels and the severity of explosions. To date, the effectiveness of side-on venting on methane flame deflagration in large scale operations has not been clearly addressed. This work explicitly investigates the influences of side-on venting on varied methane flame deflagration concentrations in a 30 m long Detonation Tube (DT).

Results corresponding to this study prove the existence of a significant correlation between the fire and explosion driving parameters such as pressure rise and flame propagation velocity with the vent location. It observed venting the explosion at distance between 6.5 m and 20.5 m from the ignition source resulted in reducing the explosion total pressure by about 33% to 56%. For methane concentration of 7.5% the dynamic and static pressures reduced by about 66% and 33%, respectively. The reduced pressure observed to decelerate the flame velocity by about 70%. Significant pressure rise and flame deflagration velocity reductions were observed in both upstream and downstream of the DT corresponding to the location of the vent. For high methane concentrations vacuum effect observed to drawback the flame into the vent and trigger the secondary pressure rise.

1. Introduction

The issue of flame deflagration is a matter of great safety concern in systems in industrial process and chemical plants. The pressure exerted on systems due to flame deflagration may reach up to 10 times the initial explosion pressure [1]. The flame deflagration acceleration could be reduced and/or stopped by relieving the pressure, also known as venting. Venting is a more reliable and less expensive method among the other passive flame mitigation systems [2–5].

The behaviour of flame deflagration in vented ducts has been investigated in the last few decades. The previous experimental work indicates that, in cases where long ducts are used for venting, the significant pressure increases at the duct, as compared to the pressure at the initial explosion in the vessel. In contrast, applying short ducts directed to the atmosphere increases the pressure reduction as compared to the pressure at the point of the explosion [6–9]. Later, it was discovered that in some cases of short duct venting, the pressure reduction in a vessel with a short duct may rise even more than the pressure without venting. This fact is attributed to a secondary explosion in the duct which reverses the pressure wave to the vessel [9–12].

Qi et al [13] posited an argument that the vent duct may enhance the flame velocity, especially at the stoichiometric concentration, also, the author reveal the oscillating pressure wave was more intense when the explosion vent cross-sectional area decreased [13]. Guo et al. [14] found a linear relationship between the pressure rise in the vessel with the bursting disk pressure of the vent. Cui et al [15] stated that increasing the length of venting duct results in an increase in the pressure at the end of the duct. Also, using vents with higher bursting pressure results in an increase in the explosion pressure. Bauwens et al. [16,17] stated that the explosion over pressure created in the venting of methane and propane explosions is also affected by the location and obstacles involved in addition to the bursting disk pressrue. Fakandu et al. [18] was in agreement with Bartknecht et al.[8] in consideration of a critical value for venting coefficient (K_v) of 9. Below this value, the redcution pressure could be determined from the static burst pressure. Ferrara et al. and Kasmani et al. [19–23] tried to give more information on the interaction between internal and external explosions. The most important outcome was that the violence of the external explosion highly depends on the gas velocity in the internal explosion and the velocity of the flame entering the venting duct. Consequently, since the ignition position was located in the rear of the vessel, the flame reached its highest velocity at the end of the duct and this increased the violence of the external explosion. These findings agreed with Alexiou et al.[24–26], where the later stated that the location of the single side vent has an important role in determining the reduction of the maximum pressure rise profile and the flame velocity [24–26]. Molkov et al. and Ponizy et al. [11,27,28] found that the burning rate of the flame significantly increases due to collision of the flame front with the outlet edge of the vent duct. This in turn results in a severe increase in the pressure, the pressure generated in some cases is much higher than the initial pressure rise of the vessel. Guo et al. [29] experimentally examined vessel venting by using a small cylindrical vessel linked with the vent. The results indicate that the venting area has no influence on flame velocity.Ajrash et al [2] experimentally evaluated the application of passive and active mitigation systems on a large scale detonation tube, Ajrash et al noticed that the flame velocity decreased after passing the vented section.

The literature review carried out shows a lack of information on large scale side-on venting of methane explosions in tubes. The objectives of this study include; i) examine the measure of pressure reduction associated with the venting, ii) investigate the influence of venting on the dynamic and static pressures; and iii) determine the impact of the vent location on the explosion characteristics and flame deflagration velocity. To achieve the broad objective of this study a comprehensive experimental investigation conducted on side-on vented detonation tube at the University of Newcastle.

2. Methodology and Technics

2.1 Experimental Setup

The detonation tube used in this study is made of mild steel and consists of eleven sections, as numbers in Figure 1 and 2. Each section is 3 m long and 0.5 m in diameter except sections 1, 6 and 10 are 2 m long. The pressure values the flame signals were detected via a set of pressure transducers and photodiodes mounted in the middle of each section, the response time for pressure transudes and photodiodes respectively is <1 ms and 1 ns, the data is damped to a PC at sample rate of 2000 sample/second.

The homogeneity of the methane air mixture was achieved by placing two circulation systems along the tube; the methane concentration error is about ±0.07%. Each circulation system consisted of a blower, four pneumatic valves, two methane monitors, a flame arrestor and a rotameter. For each circulation system there was a methane line connected to a methane cylinder via two pneumatic valves and a mass control flowmeter. The methane monitors were calibrated for each concentration by using a premix calibrated methane-nitrogen cylinders (see Figure 1).

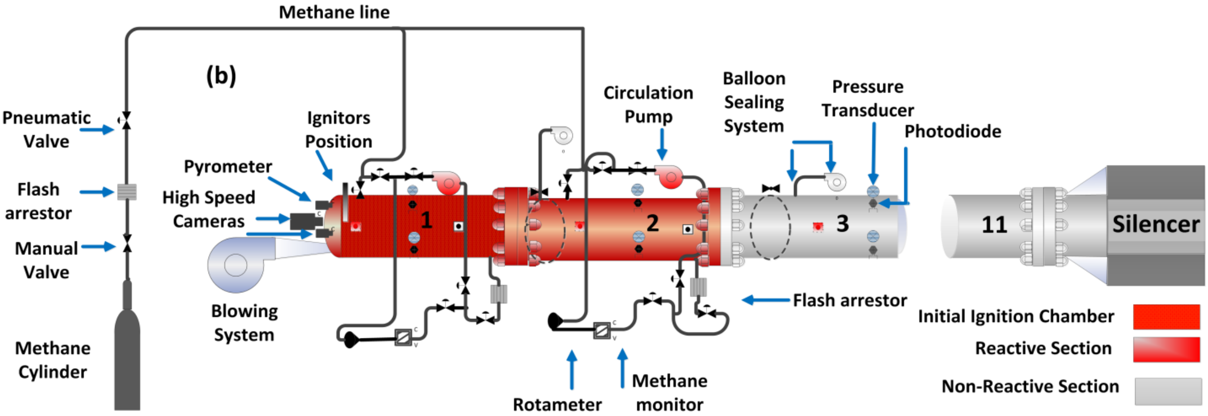

Figure 1: Detonation tube components

2.2 Configurations and venting duct

The ignition was initiated via a 50 mJ chemical ignitor. The methane-air mixture in the DT was ignited in two cases (see Figure 2). In both cases, the ignition chamber was fueled with a 9.5% methane concentration. The explosion and venting characteristics, pressure wave and flame velocities were investigated for four methane-air mixtures which were 1.25%, 2.5%, 5% and 7.5%.

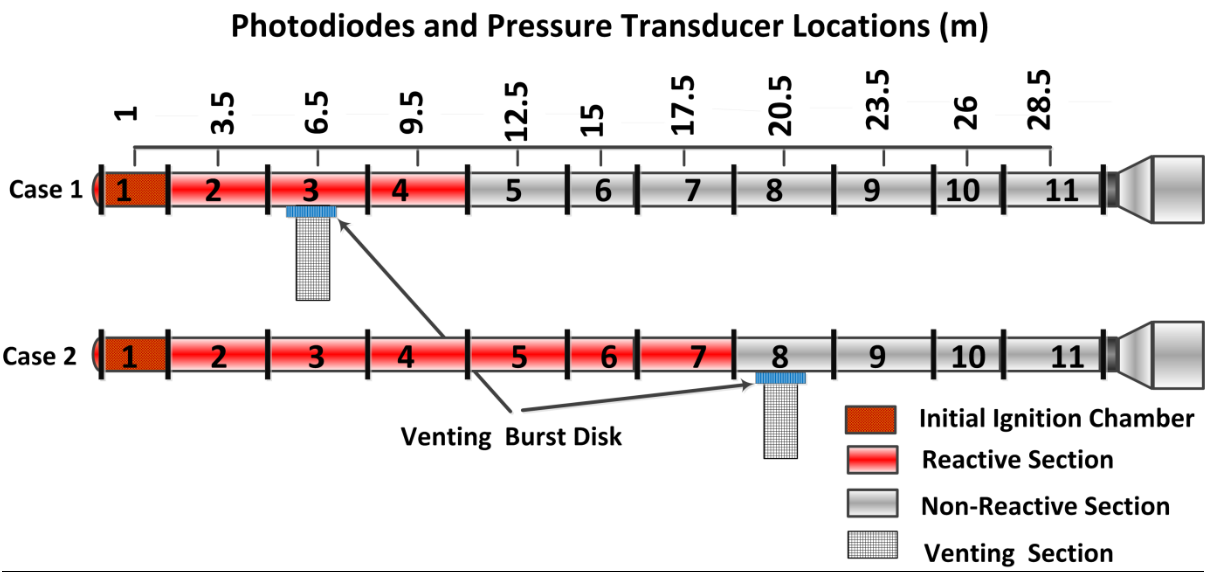

Figure 2: Venting configuration in the current experimental work

Figure 3: Venting duct

A bursting disk works as an interface between the tube surface and the venting duct. The bursting disk opens toward the venting duct when the static pressure exceeds 0.15 bar, for which the vent duct size was the same as the bursting disk (0.64 m × 0.32 m), and the duct was 2.2 m long. Two pressure transducers were mounted at 0.2 m and 2 m from the point of connection with the bursting disk (see Figure 3). The venting properties such as venting area (A_v), L/D of venting and the internal surface area of the tube before venting (A_s), and venting coefficient (K_v=$V^{(2/3)}$/A_v), V is the vessel volume, are summarised in Table 1.

Table 1: Venting properties

	Case 1	**Case 2**
Location	Section 3	Section 8
A_v (m^2)	0.2	0.2
A_s (m^2)	7.46	29.45
L/D	9	37
K_v	5.3	16.7

3. Results and Discussion

3.1 Influence of Venting on Static, Dynamic and Total Pressure

One of the most important knowledge gaps covered by the current work addresses the influence of the venting duct on the static, dynamic and total pressures at the end of the DT. These parameters are used to evaluate the influence and the performance of the vent ducting on the pressure dynamic. The static pressure was measured via three pressure transducers located at section 11 (28.5 m), and the dynamic pressure was measured via two pitot tubes penetrating section 11. The total pressure (stagnation pressure) is mathematically calculated from the summation of static and dynamic pressures [30,31]. It is important to mention that the results of venting are compared for the same conditions of the DT without venting [32–34]. This comparison provides clear evidence for researchers and industry to address the influence of venting on methane flame deflagration in large scale tubes. The results of the first configuration are shown in Figure 4. The first observation to be made from the results indicates that venting causes a significant reduction in the static, dynamic and consequently the total pressures; however, the reduction in the pressure varies depending on the methane concentration. Although 1.25% and 2.5% methane concentrations are below the lower flammable limit of methane, a slight increase in the dynamic pressure at the last section on the DT is expected [35]. The pressure waves for the 1.25% and 2.5% methane concentrations are mainly due to the initial explosion at section 1 (9.5% methane concentration). However, the results indicate that the presence of diluted methane concentrations, even below the lower flammability limit, enhances the flame travelling distance and enhances the products of combustion, resulting in increased pressure. The pressure wave of the initial ignition itself caused an increase in the static, dynamic and total pressures by about 0.2, 0.21 and 0.41 bar, respectively. The total pressure sightly increased by 0.41 to a range of 0.5 bar to 0.55 bar as 1.25% and 2.5% methane concentrations were introduced, respectively. The results reveal that the introduction of venting reduced the static and dynamic pressures by about 0.09 bar (decrease of 0.17 bar) and 0.13 bar (decrease of 0.19 bar) for the methane concentration ranges of 1.25% - 5%. The static and dynamic pressures were significantly reduced by about 0.29 bar and 1.2 bar for a 7.5% methane concentration.

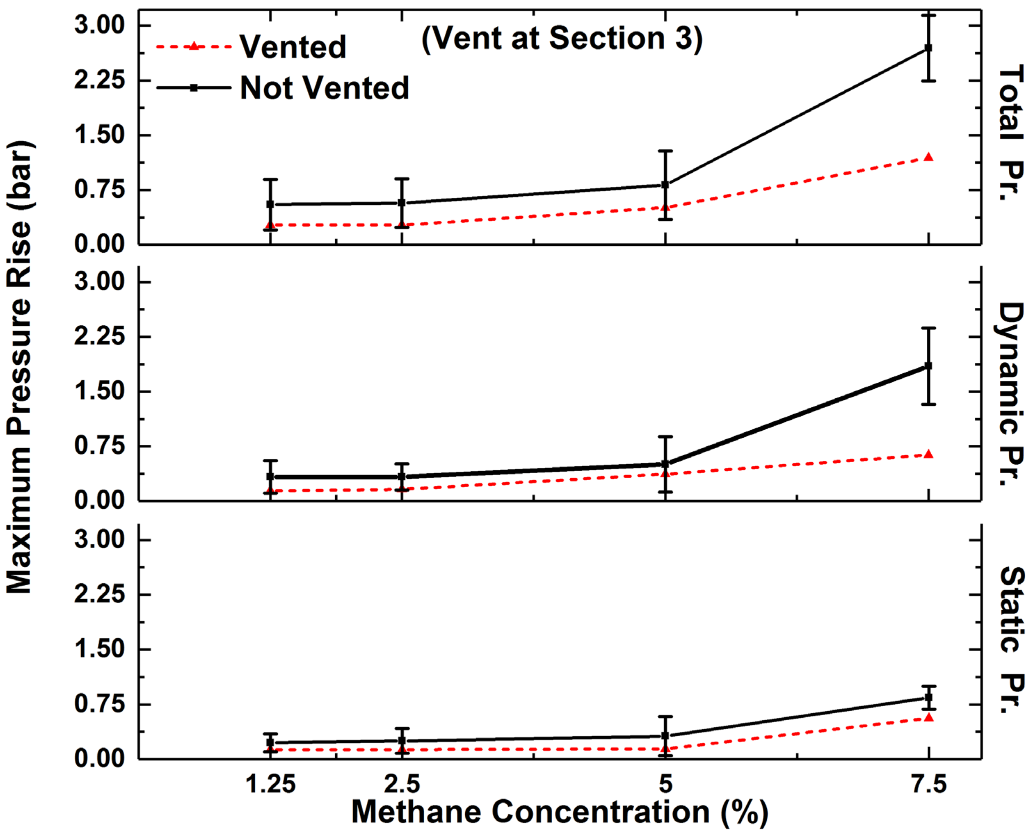

Figure 4: Static, dynamic and total pressure for vent location section 3

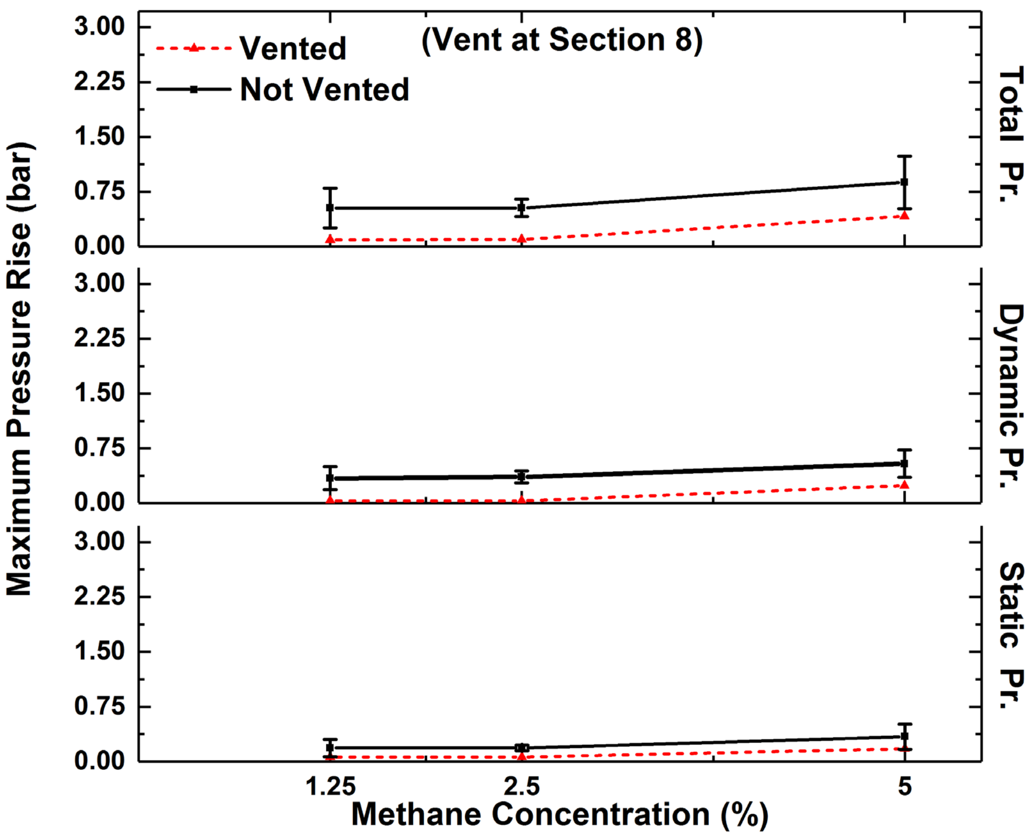

Figure 5: Static, dynamic and total pressure for vent location section 8

In the second venting case, only three methane concentrations were tested; 1.25%, 2.5% and 5%. The results (Figure 5) show that the static pressure reduction was more pronounced when the vent was located at section 3. This result is in good agreement with Rogowski et al. [36–38], closer venting location higher pressure reduction achieved. However, the reduction in dynamic pressure was more significant when the vent was located at section 8.

3.2 Influence of Venting On Pressure Wave Profile

This section illustrates the influence of the vent duct location on the pressure wave profile for a varied methane concentration.

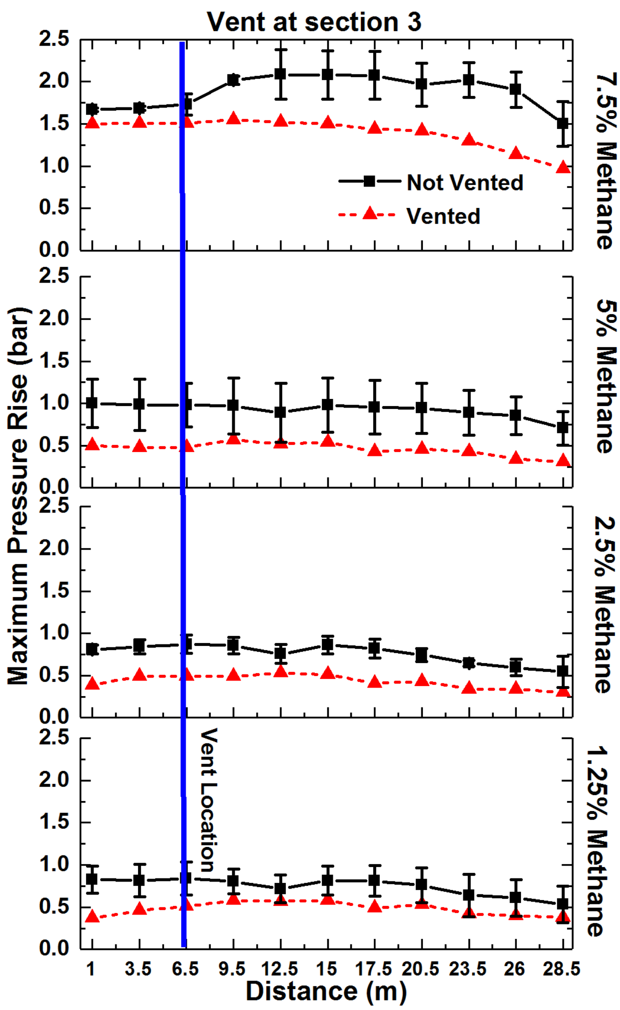

Figure 6: Pressure reduction for vent location on Section 3, where the vertical blue line represents the location of the vent

The pressure wave values of the vented (vent location at Section 3) and not vented DT experiments are shown in Figure 6. The first interesting outcome observed is that the venting not only limited to the downstream pressure of the DT corresponding to vent location(Sections

4 to 11) but also significantly influenced the upstream pressure of the DT corresponding to vent location (Sections 1 to 3). The reduction in pressure upstream could be explained by the venting of pressure compression ahead of the flame, eventually reducing the pressure value behind the flame. The results also indicate that the pressure reduction upstream was significantly reduced for low methane concentrations, where the gap between the pressure value with and without venting was in rang of 0.5 to 0.36 bar for 1.25%, 2.5% and 5% methane concentrations and 0.18 bar for a 7.5% methane concentration. At a 7.5% methane concentration, the typical flame deflagration without venting developed after reaching 9.5 m of distance, and the pressure rise increased to 2 bar, after the pressure wave had been travelling at about 1.67 bar (see Figure 6). When the venting duct was in place at Section 3, the vent prevented the pressure wave from developing and the pressure wave was travelling at about 1.65 bar. Also, the vent duct at high methane concentrations diminished the pressure wave earlier, where for a venting DT, the pressure wave values dropped 5.5 m earlier, as compared to a non-venting DT.

Figure 7 reveals the reduced pressure values of the vented DT when the vent was located at Section 3. The outcome clearly indicates two phases (before and after the vent location) of reduced pressure. In the first phase the impact of the venting duct was more pronounced for low methane concentrations than for high methane concentrations. This fact may be attributed to the relationship between the vent coefficient and the severity of the explosion. When the volumes of gas combustion products are low, a specific vent coefficient will be sufficient to release the over pressure. However, for high methane concentrations (up to stoichiometric concentrations), larger venting area required for better venting efficient. Directly after the flame reaches the vent duct, the products of the combustion are exerted and move away from the vent (weak point). At this point, the side-on pressure plays an important role in the reduction of the pressure wave values. The data reveals that there is a directly proportional relationship between increasing side-on pressure and the reduction of the pressure due to the venting. This fact is revealed in Figure 7 where the explosion of higher methane concentrations causes larger pressure reduction after the venting section.

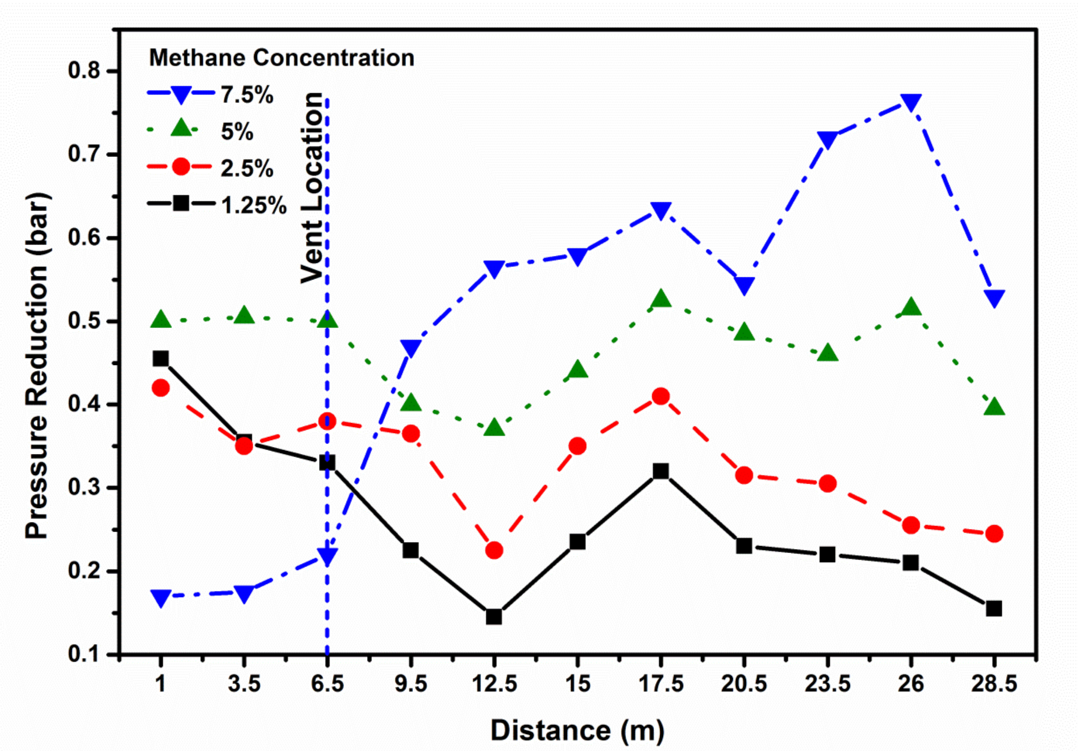

Figure 7: Reduction in pressure when the vent is located at Section 3

The pressure wave values of vented (vent located at Section 8) and not vented DTs are shown in Figure 8. The data shows a pronounced influence of venting on the upstream pressure wave values. The most significant drop in pressure wave values occurred before the vent location at distances of between 5.5 m and 8 m. This fact was observed for a venting of 5% methane concentration, where the pressure wave significantly decreased as compared to the unvented pressure wave. The pressure value was reduced by 29.8% while the pressure wave travelled from Section 4 to Section 8. However, the pressure reduction was only about 2.2% as compared to the unvented case for the same methane concentration. Similar behaviour was observed for methane concentrations of 1.25% and 2.5%, where the values of the pressure wave reduced by about 116% and 36.5% for vented DT's respectively, compared to 8.3% and 17% respectively for the unvented DTs. The influence of venting is less pronounced for the downstream section, where the pressure wave value was reduced by 29% and 11% respectively for 2.5% and 5% methane concentrations.

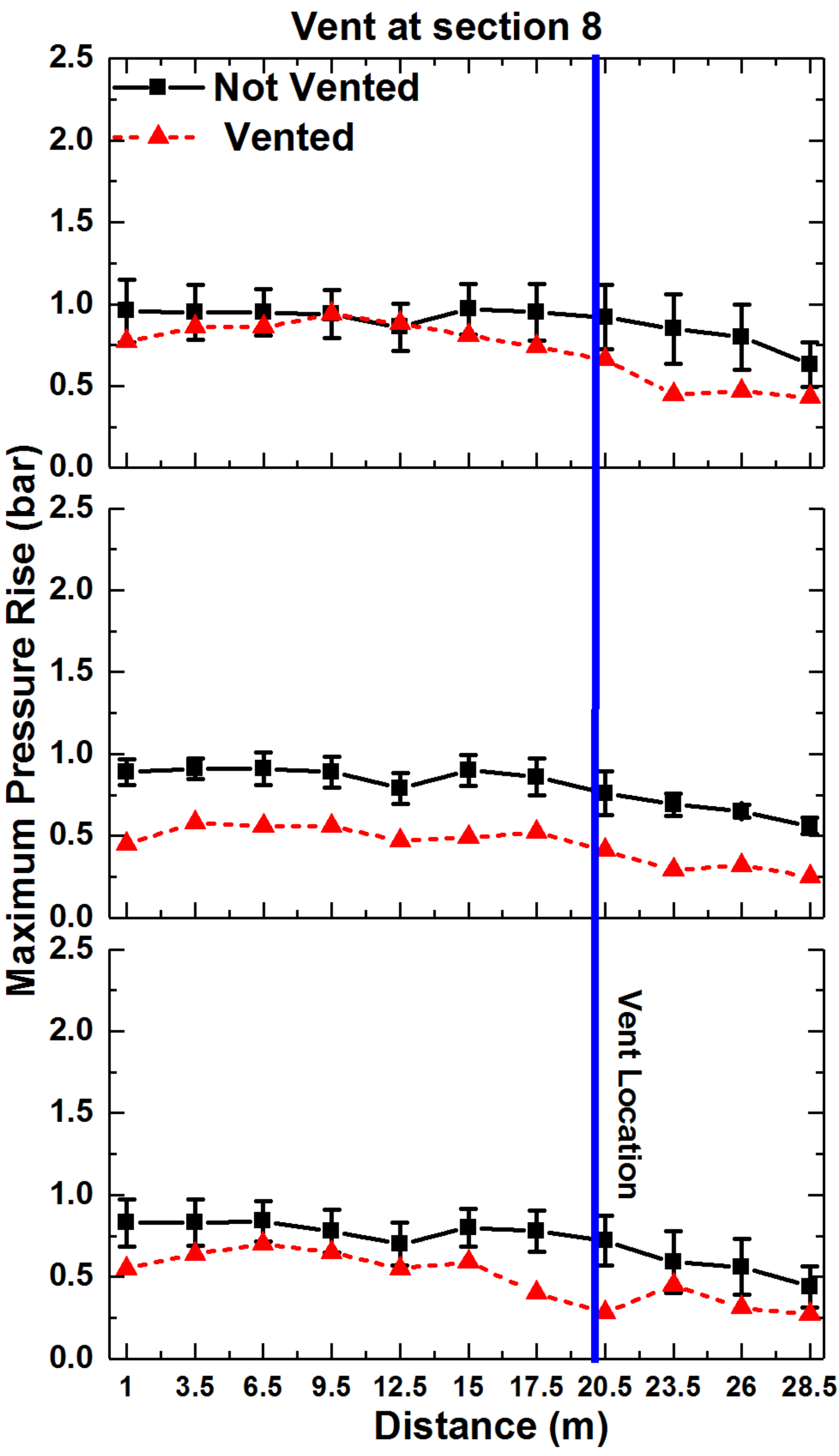

Figure 8: Pressure reduction when the vent is located at Section 8, the blue line representing the location of the vent

3.3 Influence of Venting Pressure Wave and Flame Velocity

One of the basic concepts of fire and explosion protection is addressing the pressure and flame velocity in the tubes. The challenge is that flame velocity accelerates as the L/D ratio is increased [39]. This section discusses the influences of venting on pressure and flame velocities along the DT. Figure 9 shows the influence of pressure wave and flame velocity for the vent located at Section 3. The velocity of both the pressure wave and the flame deflagration was calculated relatively to the location of initial ignition point, the time of pressure wave and the flame is considered true once the pressure rise reach to 0.3%, and photodiode signal reach to 0.05 V. This data, compared with the pressure wave and flame velocity of the same configuration without venting, shows a significant influence of the vent on the pressure wave and velocity. The pressure waves of the vented and unvented methane explosions were almost equal at Section 1. The pressure wave velocity for the vented methane, however, reduced the gap between the vented and unvented methane explosions, starting to increase almost in a liner relation with the distance. This outcome was true for all the methane concentrations. On the other hand, the reduction in pressure wave velocity was more significant for low methane concentrations (1.25% and 2.5%) rather than higher 5% and 7.5% methane concentrations.

Generally, the reduction in pressure wave velocity reached its maximum at the last section of the DT, where the deceleration of the pressure wave velocity was in the range of 48 $m.s^{-1}$ to 56 $m.s^{-1}$ at the end of the DT. The flame in the DT did not travel to the end of the DT as did the pressure wave, due to the consumption of fuel during the phase of the flame travelling in the non-reactive section, especially for low methane concentrations (i.e. below 5%) [40]. The influence of venting on the flame velocity at the upstream section was more obvious for low methane concentrations than for high methane concentrations (i.e. 7.5%); the reduction in flame velocity was about 24 $m.s^{-1}$ at Section 3 where there was only 1.25% of methane in the reactive section. The reduction in flame velocity, however, decreased as the methane concentration was increased, where the reduction in the flame velocity was in the rage of 8 to 10 $m.s^{-1}$ for 2.5% and 5% methane. The flame velocity for 7.5% did not show an influence on venting in either the upstream or the first section of the downstream, however, the flame velocity of the vented DT started varying from the flame velocity of the unvented 7.5% methane explosion at Section 5 (12.5 m) (see Figure 9**).**

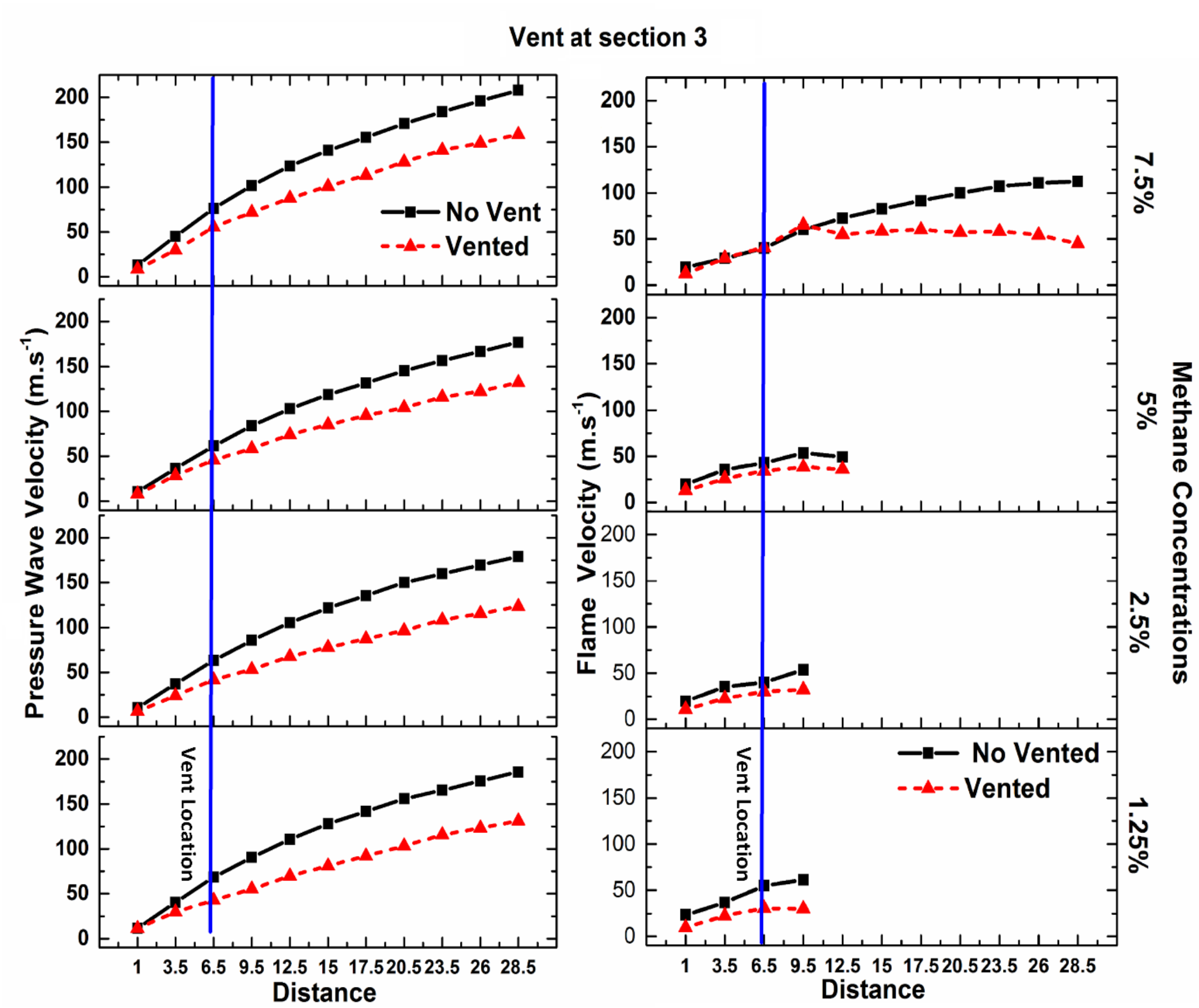

Figure 9: Pressure wave and flame velocity with and without vents, the blue line representing the location of the vent at Section 3

After Section 4, the reduction in flame velocity increased gradually until the end of the DT, and the maximum reduction of flame velocity was 68 $m.s^{-1}$. According to the current work matrix used for venting at Section 8, the flame does not reach Section 8 and was already diminished by Section 5. For this reason, the data of the flame velocity when the vent was located at Section 8 is not discussed here. Figure 10 shows the influence of the pressure wave when the vent was located at Section 8. This data, as compared with the pressure wave data of the same configuration without venting, shows that the reduction in pressure wave became more pronounced at 9.5 m when the vent was located at Section 8. However, the reduction was more pronounced at the first section when the vent was located at Section 3. This fact leads to the conclusion that the vent reduced the pressure wave velocity upstream up to 11 m from the location of the vent duct. The reduction in pressure wave velocity varied in the range of 25 $m.s^{-1}$ to 60 $m.s^{-1}$ for the methane concentration range of 1.25 % to 5% in the reactive section.

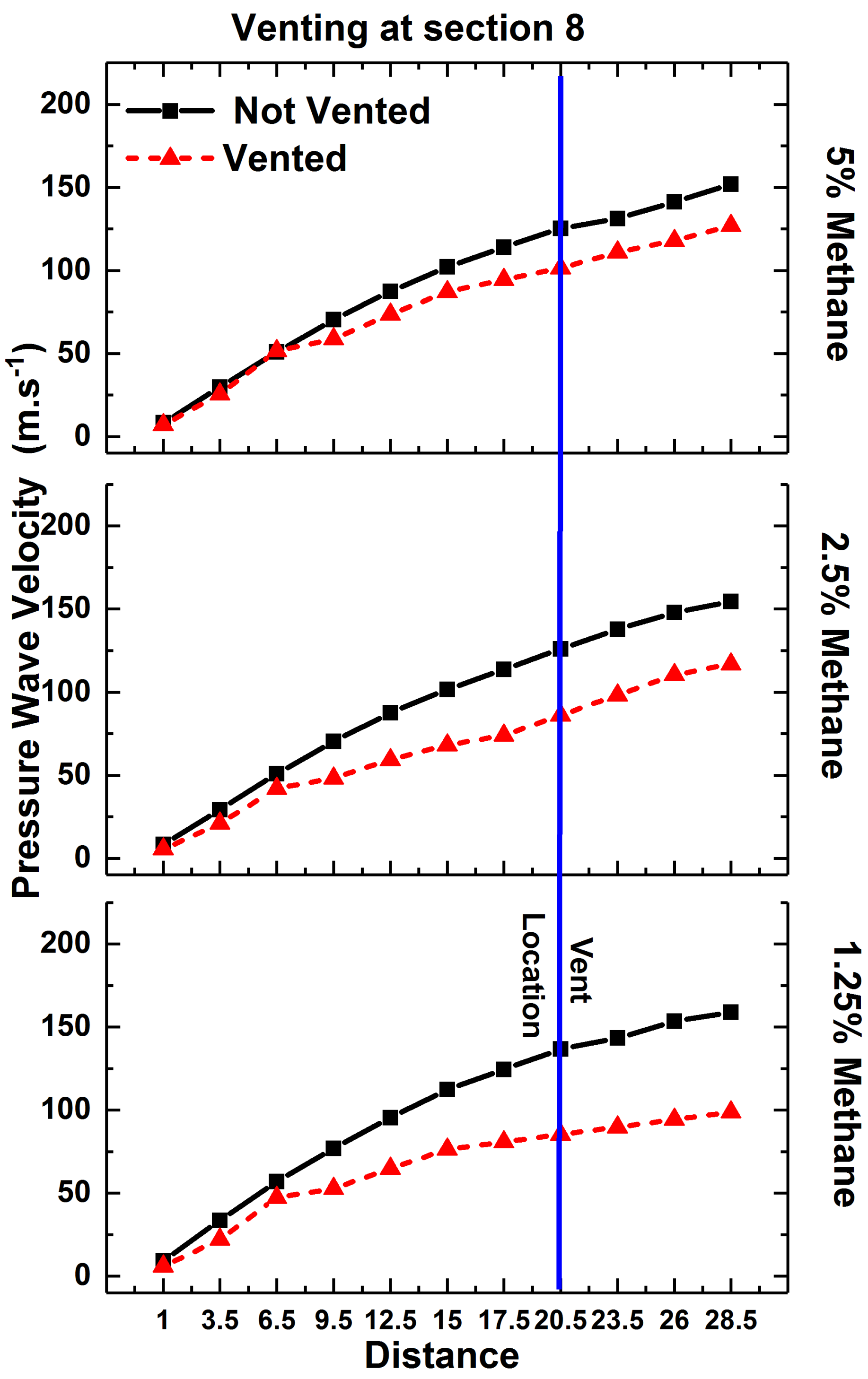

Figure 10: Pressure wave velocity reduction when the vent is located at Section 8, the blue line representing the location of the vent

3.4 Coherent Deflagration and Pressure Wave Characteristics in Venting Ducts

The extent of flame deflagration in venting ducts varies in accordance with the vent coefficient, vent length and intensity of the explosion. The hazards of flame and pressure rise in vent ducts are polarised into two aspects; deflagration detonation transition inside the vent and coherent deflagration that may form at the end edge of the vent and cause a reverse pressure flow [28,41]. The current experimental work investigated across a wide range of methane concentrations in addition to two locations for venting. The results show that the maximum pressure rise in the vent duct was significantly affected by both the location of the vent (either close to or far from the ignition source) and the methane concentration in the reactive section.

Table 2:Maximum pressure rise (bar) in the venting duct

Vent Location	Methane %	$P_{2\ \text{before vent}}$	$P_{3\ \text{after vent}}$	P_{v1}	P_{v2}
Section 3	**1.25**	0.45	0.5	0.55	0.54
	2.5	0.48	0.48	0.57	0.58
	5	0.47	0.47	0.57	0.59
	7.5	1.5	1.5	1.5	2.25
Section 8	**1.25**	0.39	0.27	0.34	0.26
	2.5	0.51	0.4	0.37	0.29
	5	0.73	0.65	0.36	0.3

Table 2 shows the maximum pressure rise in the vent duct and on the DT at the sensors nearest to the measured pressure, before venting and after venting. The pressure rise inside the vent, when the vent is located at Section 3, shows that the pressure before the venting ($P_{2\ \text{before vent}}$), is always showing a lower pressure value than does the first pressure transducer mounted in the venting duct (P_{v1}). The slight increase in the pressure at the venting duct is attributed to two main facts; the pressure wave due to the flame deflagration in the tube increases consistently as it travels from the ignition source, and once the flame enters the vent duct, the turbulence slightly increases and causes a slight increase in the maximum pressure rise. The increase in the pressure rise is about 0.1 bar. Also, it was found that the venting lowered the development of the pressure, whereas the levels of flame deflagration in the DT, for P_2 (before vent) and P_3 (after vent), were quite identical, especially for 2.5% and 5% methane concentrations (see Table 2).

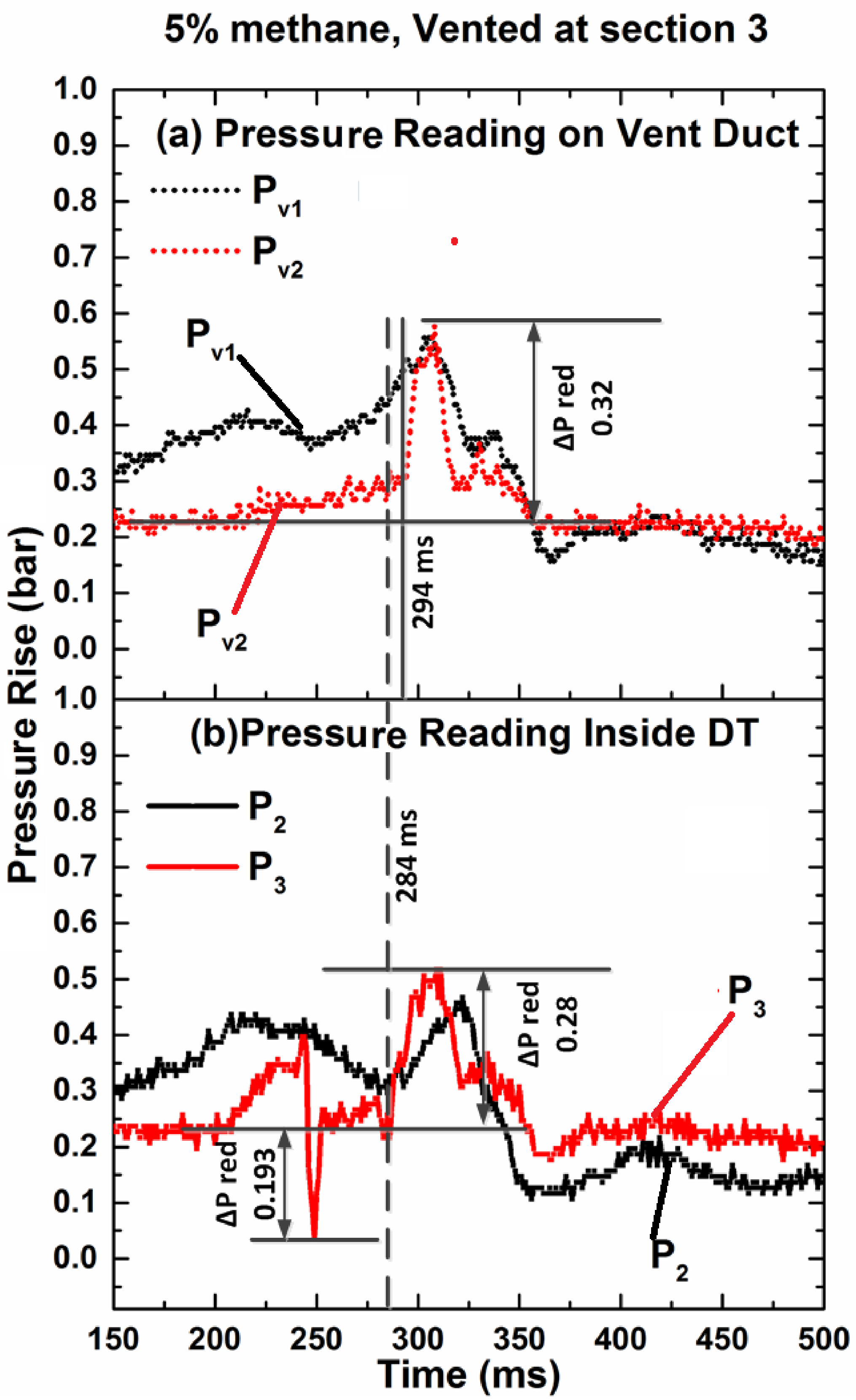

Figure 11: Pressure time profile for venting 5% methane

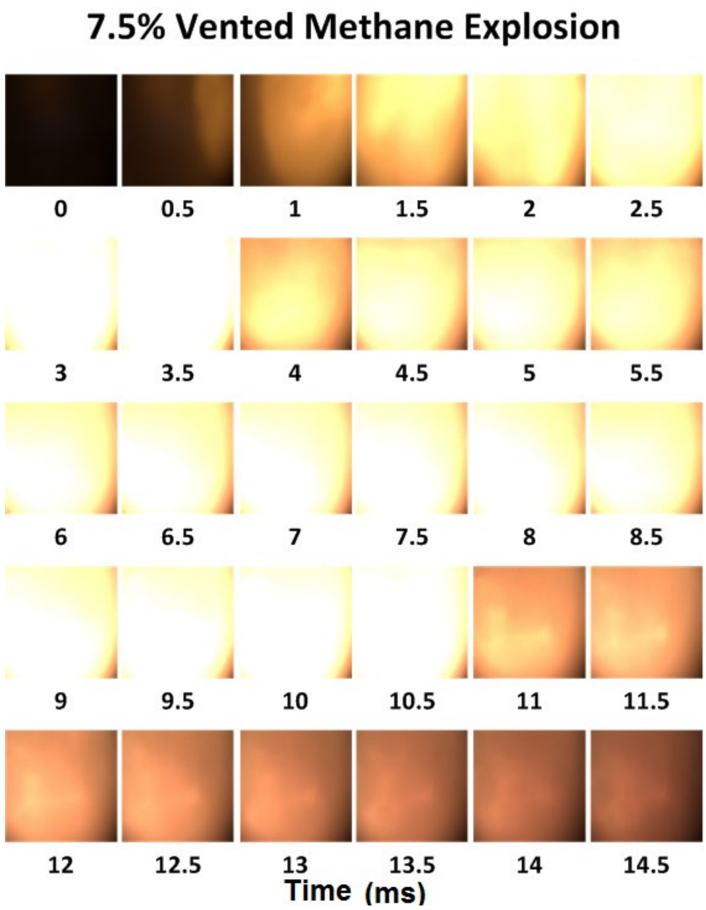

Figure 12: Frames of vented 7.5% methane deflagration

The pressure time profile for a 5% methane concentration venting is explicit in the Figure 11 deflagration. The behaviour of the pressure wave for a 5% methane deflagration represents a typical pressure venting without interaction with the flame, as seen in Figure 11 (b). Both P_2 and P_3 at about 240 ms (milliseconds), start to drop as functions of releasing part of the gas flow outwards through the vent. The pressure wave pattern similarity of both P_2 and P_{v1} is due to the fact that the P_{v1} is only 0.2 m away from the burst disk, and the disk fails to burst until it reaches 0.15 bar. The influence of venting is obvious at about 213 ms where the increase of the pressure starts to plateau and reduce. On the other hand, the P_3 and P_{v2} start to detect the pressure wave at about 204 ms and 224 ms respectively. Then P_3 significantly drops after about 40 ms, indicating a lack in pressure due to the gas venting. The pressure readings at P_{v1} and P_{v2} show a continual increase in the pressure. Up until 284 ms it is believed that the pressure rise is due to the compression wave in front of the flame. The data indicates that the flame crossed the P_3 and P_{v2} at about 284 ms and that caused a steep rise in pressure up to 0.51 and 0.56 respectively for P_3 and P_{v2}. The burned gas produced reached P_{v2} by 10 ms later than P_3, as the result of the fact that location P_{v2} is before P_3 by 1.25 m.

In the case of the flame travelling in the venting duct, a different profile will emerge. The best example is the methane deflagration for a 7.5% methane concentration with the vent located at Section 3 (see Figure 13). The pressure time profile reveals two distinct phenomena in the venting of a 7.5% methane concentration. The normal venting behaviour is continued until about 255 ms and 263 ms respectively for Figure 13(a) and Figure 13(b). The pressure profile shows a similarity with the 5% methane concentration venting at the normal venting behaviour, where the compressed wave in front of the flame vents outwards, and this is clearly shown by the reduction of P_3 at 240 ms. Then the flame crosses over P_3 at about 245 ms, causing an increase in the pressure up to 1.25 bar at 251 ms. At this stage the pressure wave crosses over the P_3. After a few milliseconds a relatively strong pressure rise emerges at the end of the duct, and causes a pressure build up in the DT, at which point it can be said that a coherent deflagration in the venting duct is formed.

The main observation to be made of this phenomenon is that when the flame reaches the second edge of the vent, the turbulence of the flame significantly increases. The burning rate of the front flame sharply develops due to the turbulence and the increase in the surface area, which produces a large amount of by-product, which eventually increases the pressure rise. This data is in good agreement with previous work related to coherent deflagration [9,28,42].

It is important to highlight that the previous investigations relating to coherent deflagration did not clarify or explicitly describe the behaviour of the flame, due to the inappropriate quality of the camera that was employed to capture the difference in flame behaviour between the flame deflagration and the coherent deflagration. This was due to the short time between them, which is only 10 ms in this work. Such a criticism is in good agreement with the literature review [41]. For this purpose, what is needed is a high speed camera (2000 $f.s^{-1}$) mounted in opposing directions located at the vent on Section 3, and focused on the centre of the DT. This would explicitly record the behaviour of the flame at the vent location. The frames captured for a vented 7.5% methane deflagration are shown in Figure 12. The frames reveal that the flame crossed the vent duct after 3 ms, and at 4 ms the flame in the duct separated from the flame in the tube. Then the phenomena of coherent deflagration formed at the end of the duct and the strong explosion caused the flame to travel back to the DT.

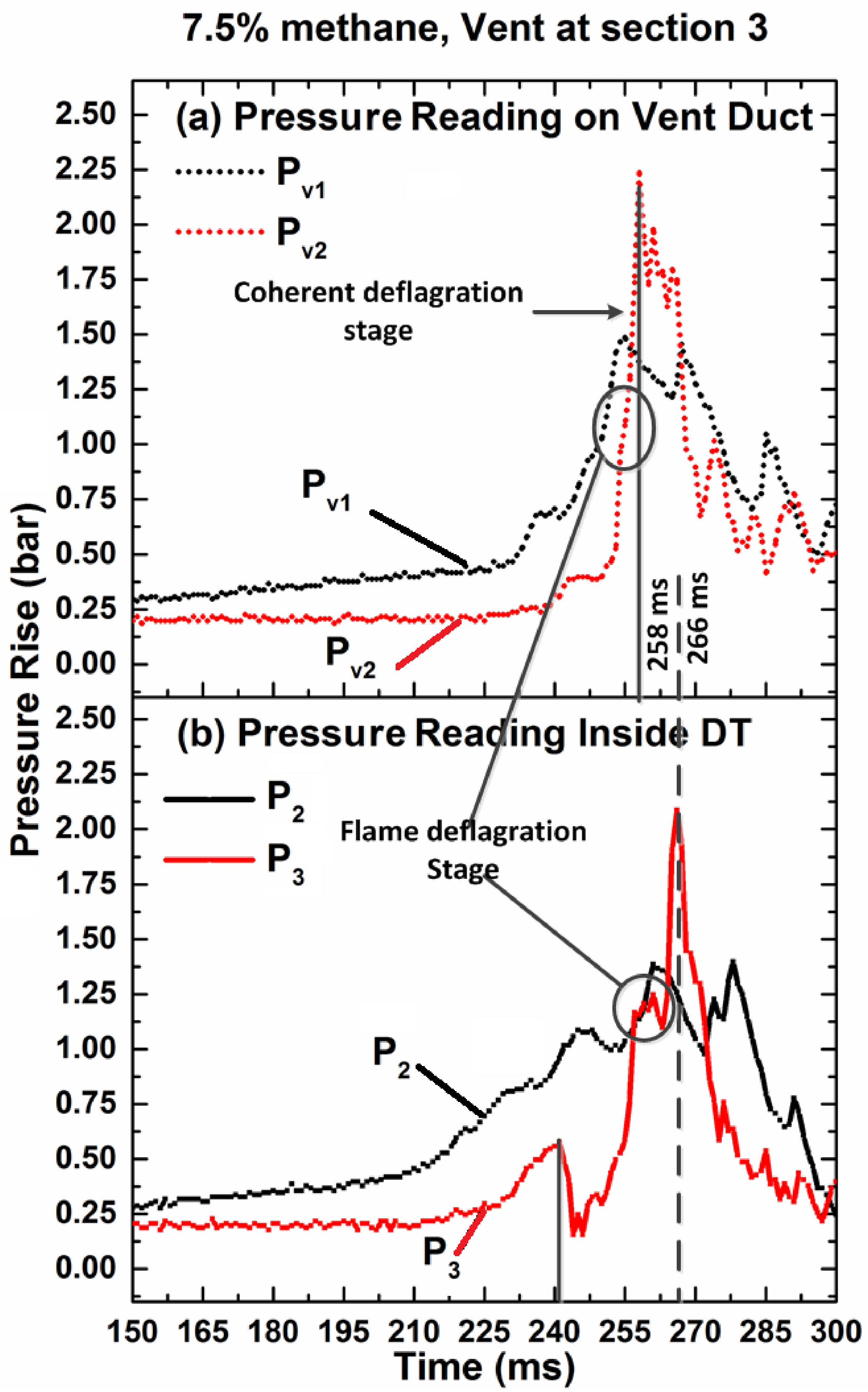

Figure 13: Pressure time profile for venting 7.5% methane

4. Conclusion

These experiments were performed by employing a large scale detonation tube to investigate the influence of venting on flame deflagration. Results for experimental work with venting located at Section 3 (6.5 m distance from ignition source) and Section 8 (20.5 m distance from ignition source) of the DT showed that the influence of the venting on reducing the flame deflagration velocity is significant both upstream as well as downstream from the non-vented DT. The static, dynamic and eventually total pressures at the last section of the DT were reduced. The total pressure reduction varied between 37% and 56% depending on the methane concentration, and the reduction in the dynamic pressure for a 7.5% methane concentration was significantly higher than the reduction in the dynamic pressure for a 5% methane concentration. The maximum pressure rise profiles indicated the importance of the location of the vent. The influence of the venting is obvious for the first 8 m up to the vent, where the maximum pressure rise starts to decline faster. The decelerations of the flame velocity as a result of venting have two distinct behaviours. For a methane concentration of 5% the flame velocity reduction was noticeable from the start of the flame's travelling until the flame started diminishing. However, for a 7.5% methane concentration, the flame velocity reduction was not noticeable until the flame crossed the vent. Then the flame decelerated dramatically faster while travelling to the end of the DT, where the flame reached the end of the DT with a velocity deceleration reaching to 67 $m.s^{-1}$.

Results for coherent deflagration were supported by a high speed camera to reveal the flame's behaviour between the DT and the vent duct. The visual observation revealed that the pressure rise in the DT and the venting duct during coherent deflagration was not only because of the pressure built up at the end of the venting duct, but also due to the flame reversing back from the venting duct to the detonation tube within only a few milliseconds.

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References

[1] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, Impact of suspended coal dusts on methane deflagration properties in a large-scale straight duct, J. Hazard. Mater. (2017) 334–342.

[2] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, Experimental Evaluation and Analysis of Methane Fire and Explosion Mitigation Using Isolation Valves Integrated with a Vent System, J. Hazard. Mater. (2017).

[3] M.A. Nettleton, C. Electricity, Pressure as a Function of Time and Distance in a Vented Vessel, 77 (1975) 65–77.

[4] B.E. Gelfand, S.M. Frolov, M.A. Nettleton, Gaseous detonations, Prog. Energy Combust. Sci. 17 (1991) 327–371.

[5] B. Wang, Z. Rao, Q. Xie, P. Wolański, G. Rarata, Brief review on passive and active methods for explosion and detonation suppression in tubes and galleries, J. Loss Prev. Process Ind. 49 (2017) 280–290.

[6] P. Russo, A. Di Benedetto, D.I. Benedetto, Effects of a duct on the venting of explosions-critical review, IChemE. 85 (2002) 9–22.

[7] V. Molkov, Venting of Deflagrations : Dynamics of the Process in Systems with a Duct and Receiver, in: Proc. Fourth Int. Symp. Fire Saf. Sci., 1994: pp. 1245–1254.

[8] W. Bartknecht, Dust Explosions: Course, Prevention, Protection, in: Springer-Verlag, Berlin., Pergamon, 1981: p. 251.

[9] D.P.J. Mccann, G.O. Thomas, D.H. Edwards, Gasdynamics of Vented Explosions Part I : Experimental Studies, 250 (1985) 233–250.

[10] W. Kordylewski, J. Wach, Influence of ducting on explosion pressure: Small scale experiments, Combust. Flame. 71 (1988) 51–61.

[11] B. Ponizy, J.C. Leyer, Flame Dynamics in a Vented Vessel Connected to a Duct : 1 . Mechanism of Vessel-Duct Interaction, Combust. Flame. 271 (1999) 259–271.

[12] E. Ural, A simplified method for predicting the effect of ducts connected to explosion vents, J. Loss Prev. Process Ind. 6 (1993) 3–10.

[13] S. Qi, Y. Du, S. Wang, Y. Zhou, G. Li, The effect of vent size and concentration in vented gasoline-air explosions, J. Loss Prev. Process Ind. (2016).

[14] J. Guo, C. Wang, Q. Li, D. Chen, Effect of the vent burst pressure on explosion venting of rich methane-air mixtures in a cylindrical vessel Ignition point 10-cm-long neck, J. Loss Prev. Process Ind. 40 (2016) 82–88.

[15] Y.Y. Cui, Z.R. Wang, L.S. Ma, Y.Y. Zhen, W. Sun, Influential factors of gas explosion venting in linked vessels, J. Loss Prev. Process Ind. 46 (2017) 108–114.

[16] C.R. Bauwens, J. Chaffee, S. Dorofeev, Effect of Ignition Location , Vent Size , and Obstacles on Vented Explosion Overpressures in Propane-Air Mixtures, Combust. Sci. Technol. 2202 (2016).

[17] J. Chao, C.R. Bauwens, S.B. Dorofeev, An analysis of peak overpressures in vented gaseous explosions, Proc. Combust. Inst. 33 (2011) 2367–2374.

[18] B. Fakandu, G.E. Andrews, H.N. Phylaktou, Vent burst pressure effects on vented gas explosion reduced pressure, J. Loss Prev. Process Ind. 36 (2015) 429–438.

[19] R. Kasmani, Vented gas explosions, University of Leeds, 2008.

[20] R.M. Kasmani, G.E. Andrews, H.N. Phylaktou, Experimental study on vented gas explosion in a cylindrical vessel with a vent duct, Process Saf. Environ. Prot. 91 (2012) 245–252.

[21] G. Ferrara, S.K. Willacy, H.N. Phylaktou, G.E. Andrews, Duct-vented Propane / Air Explosions with Central and Rear Ignition, (2005) 1341–1352.

[22] G. Ferrara, S.K. Willacy, H.N. Phylaktou, G.E. Andrews, A. Di Benedetto, E. Salzano, G. Russo, Venting of gas explosion through relief ducts : Interaction between internal and external explosions, J. Hazard. Mater. 155 (2008) 358–368.

[23] G. Ferrara, A. Di Benedetto, E. Salzano, G. Russo, CFD analysis of gas explosions vented through relief pipes, J. Loss Prev. Process Ind. 137 (2006) 654–665.

[24] Phylaktou, G.E. Andrews, Alexiou, A comparison between end-vented and side-vented gas explosions in large l / d vessels, Trans IChemE. 75 (1997) 9–13.

[25] A. Alexiou, G.E. Andrews, H. Phylaktou, C.L. Gardner, Side venting versus end venting for large L/D vessel explosives with and without an obstacle, in: Inst. Chem. Eng., 1997.

[26] Alexiou, G.E. Andrews, H. Phylaktou, Side-vented gas explosions in a long vessel :

the effect of vent position, 9 (1996) 351–356.

[27] V. Molkov, Venting of Deflagrations : the Dependence of Turbulence Factor on Enclosure Volume and Vent Ratio, in: Int. Assoc. Fire Saf. Sci., 1988.

[28] M. Vladimir, D. Makarov, The Nature of coherent Deflagration, in: Fifth Int. Symp. Hazards, Prev. Mitig. Ind. Explos., 2004: p. 10.

[29] J. Guo, C. Wang, X. Liu, Y. Chen, Explosion venting of rich hydrogen-air mixtures in a small cylindrical vessel with two symmetrical vents, Int. J. Hydrogen Energy. 42 (2017) 7644–7650.

[30] R. Eckhoff, Explosion hazards in the process industries, Elsevier, 2013.

[31] D. Bjerketvedt, J.R. Bakke, K. Van Wingerden, Gas explosion handbook, 1997.

[32] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, Deflagration of Premixed Methane-Air in a Large Scale Detonation Tube, Process Saf. Environ. Prot. 109 (2017) 374–386.

[33] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, Influences of the Initial Ignition Energy on Methane Explosion in a Flame Deflagration Tube, Energy & Fuels. (2017).

[34] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, The flame deflagration of hybrid methane coal dusts in a large-scale detonation tube (LSDT), Fuel. 194 (2017) 491–502.

[35] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, Effects of ignition energy on fire and explosion characteristics of dilute hybrid fuel in ventilation air methane, J. Loss Prev. Process Ind. 40 (2016) 207–216.

[36] Z.W. Rogowski, D.J.R. Rasbash, Relief of explosions in duct systems, (1960).

[37] Z.W. Rogowski, D.J.R. Rasbash, Relief of explosions in propane-air mixtures moving in a straight, (1963).

[38] D.J. Rasbash, Z.W.Rogowski, Gaseous Explosions in Vented Ducts, Combust. Flame. 84 (1960) 301–312.

[39] K.N. Palmer, Explosion protection of a dust extraction system, in: Proc. Symp. Chem. Process Hazards, 1974: pp. 211–222.

[40] M.J. Ajrash, J. Zanganeh, B. Moghtaderi, Methane-coal dust hybrid fuel explosion properties in a large scale cylindrical explosion chamber, J. Loss Prev. Process Ind. 40

(2016) 317–328.

[41] C. Catlin, Scale Effects on the External Combustion Caused by Venting of a Confined Explosion, 1 (1991).

[42] V. Molkov, D. Makarov, J. Puttock, The nature and large eddy simulation of coherent deflagrations in a vented enclosure-atmosphere system, J. Loss Prev. Process Ind. 19 (2006) 121–129.