NOVA

University of Newcastle Research Online

nova.newcastle.edu.au

Kundu, Sazal K.; Zanganeh, Jafar; Eschebach, Daniel; Mahinpey, Nader & Moghtaderi, Behdad. "Explosion characteristics of methane-air mixtures in a spherical vessel connected with a duct" Published in *Process Safety and Environmental Protection*, Vol. 111, Issue October p. 85-93, (2017).

Available from: <http://dx.doi.org/10.1016/j.psep.2017.06.014>

© 2017. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

Accessed from: <http://hdl.handle.net/1959.13/1352668>

Explosion Characteristics of Methane–Air Mixtures in a Spherical Vessel Connected with a Duct

Sazal K. Kundu^a, Jafar Zanganeh^{a,*}, Daniel Eschebach^a, Nader Mahinpey^b,

Behdad Moghtaderi^a

^aPriority Research Centre for Frontier Energy Technologies & Utilisation, Discipline of Chemical Engineering, School of Engineering, Faculty of Engineering & Built Environment, University of Newcastle, Callaghan, NSW 2308, Australia

^bDepartment of Chemical and Petroleum Engineering, Schulich School of Engineering, University of Calgary, Calgary, AB T2N 1N4, Canada

Abstract

With the aim of exploring explosion characteristics of methane–air explosive mixtures in a ducted vessel, a 20 litre spherical vessel connected with a 2813 mm long duct was employed. The experimental setup was comprised of a wafer check valve, which kept the methane-air mixture initially confined and opened at the time of explosion. The system introduced turbulence to the gas mixture during operation and pyrotechnic igniters were employed in the investigation. This approach assisted to obtain data that can be correlated with real world ducted explosion accidents where the explosion initiates in the presence of strong ignition energies and in turbulent states of methane-air mixtures. This study shows that the explosion severity can be very high in the turbulent field of methane-air mixture and in the presence of strong ignition energies. The pressure rise in the vessel and the flame speed along the length of the duct were found to be higher in the present study when compared to data obtained with quiescent mixtures of methane-air and low ignition energies. The impact of the duct length and pyrotechnic igniters' energy on reduced peak explosion pressure was characterised. The rate of pressure rise, a parameter linked to the burning rate, increased from the ducted to the vented configurations of the explosion test units.

Keywords: Ducted vessel, process industry, flammable gas, methane explosion, explosion pressure, rate of pressure rise

1. Introduction

In process industries, flammable gases and vapour may be present in vessels and storage tanks. These process units may contain feed material, product or fuel. In order to transport materials to and from these vessels and tanks, they need to be connected with pipelines (Kundu, 2010). With the advancement of control systems, these vessels and tanks are often connected with electrical sources and any naked electrical connection may become an ignition source in these systems (Chou et al., 2015). If there is any leak in the vessel/tank or pipeline, or any loose connection in the pipeline, oxygen may be present in the system. All of these conditions are capable of fulfilling the requirements for an explosion.

Pockets of methane gas are often present in coal mines. These mine areas may be connected with ducts or channels. In the presence of an ignition source, these areas may mimic an explosion model of a vessel connected to a duct. Several accidents in underground coal mines have been reported in the literature (Ajrash et al., 2016a, b; Kundu et al., 2016; Qin et al., 2016; Zhang and Ma, 2015) which have motivated researchers to understand the explosion characteristics of methane–air mixtures by employing explosion units of various geometries (Kundu et al., 2016). Therefore, understanding explosion characteristics in vessels with connected ducts is expected to provide important information in order to design proper safety measures in the process industries, including coal mines.

Ducts are often deliberately integrated with enclosed process units with the aim of reducing any potential damage caused by explosions of flammable substances (Foiles, 2004; Kasmani et al., 2013; NFPA-68, 2007; Russo and Di Benedetto, 2007), where the integrated duct is known as vent duct. The one end open duct usually reduces the severity of an explosion in the vessel by reducing the explosion pressure, and more importantly, discharging hot and toxic materials in a safe location if an explosion occurs.

When a flame propagates from a vessel to a duct, the properties of the flame are affected at the entrance of the duct (see Figure 1). The flame entering into the duct propagates in a constricted pattern where the flame is surrounded by cold unburned mixture. Downstream of the duct, the flame broadens covering the full cross-section of the duct (Iida et al., 1985).

Previous studies suggest that integrating a duct with a vessel increases pressure rise in the vessel during an explosion when compared to pressure rise in a simply vented vessel. In contrast, the pressure rise in a confined vessel is higher than in a vessel connected with a duct (NFPA-68, 2007). The modification of either a vented or confined vessel to ducted vessel introduces the severity of the explosion in the connected duct (Bouhard et al., 1991; Gardner et al., 1988; Kordylewski and Wach, 1986) and the findings are illustrated in Figure 1. While investigating the explosion characteristics of propane–air mixtures in a ducted vessel employing a duct of 200 mm length, 110 mm width and 70 mm depth, (Iida et al., 1985) found that a fully turbulent flame forms at three times the distance of the width of the duct ($x = 3b$), as illustrated in Figure 1. The evidence of a fully turbulent flame was confirmed by a schlieren image captured by Iida et al. and the image identified an intensive mixing of unburned fuel-air mixture and hot products from the combustion. The generated turbulence increases the burning rate, and for longer pipes a transition from deflagration to detonation can occur (Kosinski and Hoffmann, 2006; Ponizy et al., 2014; Russo and Di Benedetto, 2007). The mechanism of the generation of violent flames in a ducted vessel thus inspired a number of researchers to undertake explosion studies in ducted vessels with various flammable materials (Molkov, 1994; Russo and Di Benedetto, 2007; Tamanini and Valiulis, 1996).

As presented in Figure 1, the combustion products and the flame propagate from the vessel to the duct, and the pressure in the vessel reduces. The pressure profile thus obtained from the vessel, with respect to time, may be described as a reduced explosion pressure profile

(Barton, 2002). In the duct, the pressure rise, with respect to atmospheric pressure, occurs due to ongoing combustion of the discharged material from the vessel. The pressure profile thus developed in the duct as a function of time is termed the explosion pressure profile.

With the aim of exploring the characteristics of explosions in ducted vessels, several researchers employed propane–air mixtures (Bouhard et al., 1991; Ferrara et al., 2005; Iida et al., 1985; Kasmani et al., 2013; Ponizy et al., 2014; Willacy et al., 2007). Investigations were also carried out with acetone–air (Benedetto et al., 2008) and town gas–air (Kordylewski and Wach, 1986) mixtures (town gas is a gas mixture and includes mainly methane and hydrogen with smaller fractions of CO_2 and CO). Vessels of various geometries, such as cylindrical (Ferrara et al., 2008; Ponizy et al., 2014) and spherical (Kordylewski and Wach, 1988) shapes, were employed in prior research. The ducts utilised in the various studies mainly had circular cross-sections (Ferrara et al., 2008; Kasmani et al., 2013), but non–circular ducts were also employed (Iida et al., 1985).

While a number of studies were undertaken employing propane–air mixtures in ducted-vessels, only limited data is available in open literature for explosion studies with ducted vessels for methane–air mixtures. The previous examinations in confined vessels showed that spherical vessels with central ignition produced the highest explosion pressures. For vessels of other geometries and other ignition positions, the developed flame partially makes contact with the vessel wall and, as a consequence, due to heat loss the peak explosion pressure reduces (Bradley and Mitcheson, 1976, 1978; Garforth, 1976). However, in earlier explosion studies of methane–air mixtures with ducted vessels, cylindrical vessels were mainly employed (Ferrara et al., 2008; Kasmani et al., 2013). Therefore, investigations with non-cylindrical vessels connected with ducts will provide enhanced understanding of the explosion phenomena of methane–air mixtures in tunnels or chimneys that are present in

mines of mineral extraction and process industries. Process safety researchers and engineers will gain vital data in addressing explosion hazards in those industrial zones.

Pyrotechnic igniters were employed in the present investigation. The igniters with higher ignition energies are constructed with higher amounts of ignition powders and they produce higher flame areas once they get ignited. The overall burning rate increases with the increase of flame area (Lee and Guirao, 1982); therefore, explosion pressure increases with an increase of the ignition energy. For high energy pyrotechnic igniters, this effect diminishes because of the thermodynamic limit of explosion pressure.

With the aim of exploring the explosion characteristics of methane–air mixtures in a ducted vessel, a spherical vessel was employed in the present investigation. To the best of our knowledge, we are reporting the first explosion studies of methane–air mixtures employing a spherical vessel integrated with a duct. The effects of the ignition energy, the duct length and the concentration of methane were investigated. The variations of the rates of pressure rise in simply vented and ducted vessels, and the link of this explosion parameter with the burning rate, are explored and discussed.

2. Experimental

A 20 litre explosion sphere was employed in this investigation. The test vessel includes a closed circuit water cooling system. Piezoelectric pressure transducers (Kistler 701A) are mounted to measure the pressure during the explosion tests.

In order to achieve the goals of the present investigation, the 20 litre sphere was modified at its viewing port (see Figures 2 and 3). A duct, made of two parts, was connected with the vessel via a valve and a connector. The valve was a wafer check valve and was sourced from Process System Private Limited (Model number: FCVC–050). A rubber-coated flexible disc

acted as closure mechanism of the valve employed. The flexible disc assisted in closing the path while an underpressure was maintained in the sphere.

The lengths of the connector, valve, first and second section of the duct were 70, 203, 1000 and 1540 mm, respectively. This provides a total duct length of 2813 mm. The connector and both portions of the duct had an identical diameter of 42.72 mm, while the diameter of the valve was 50 mm. This variable diameter along the length of the duct enumerates an L/D value of 65.16.

The duct was equipped with five piezoresistive pressure transducers (model – ATM.ECO/Ex, manufacturer – STS Sensor Technik Sirmach AG, 0-10 bar) and five photodiode sensors (model – DET10A, manufacturer – Thorlabs, 200-1100 nm). Photodiode sensors were employed with viewing ports which narrowed down the viewing angle (the half angle was approximately 10°). This narrow sensing photodiode architecture of the explosion apparatus assisted in capturing light that mainly travels in a perpendicular direction from the duct axis. The employed photodiode sensors had a response time of 1 ns. The data acquisition system had a data collection capability at a rate of 10 MS s^{-1} .

The piezoresistive pressure transducers had a response time of 0.1 to 1 ms. The accuracy of the piezoresistive pressure transducers were $\pm 0.25\%$ of Full Span Value. The full span value of those pressure sensors were 10 barg. This provides the maximum tolerance value of ± 0.025 barg. These pressure sensors were calibrated introducing an elevated pressure in the ducted vessel where the open end of the duct was closed by a blind flange. The distance of the sensors from the sphere and their locations around the periphery of the duct are presented in Table 1.

The 20 litre sphere apparatus included a dust chamber. For this investigation, no dust was employed in this chamber; however, it was used in the gas introducing process. In order to introduce methane to the system, the sphere was evacuated to a desired underpressure (see Table 2), and then methane was introduced. When the pressure reached -60 kPag, the dust chamber was pressurised to 20 barg. In the next stage, the pressurised air in the dust chamber was released into the sphere via opening a fast acting valve. After 60 ms of the release of pressurised air into the sphere, the system's pressure equilibrated to atmospheric pressure (1 atm), the flexible disc of the check valve (mounted upside down to allow gravity assisted opening) opened just prior to the time the igniter was initiated. A small variation was found in the opening of the check valve and the tolerances of pressure and time values were 40 mbar and 1 ms respectively; this means that the check valve opened 1 ms to zero ms earlier than the initiation of igniter and at 973 to 1013 mbara pressure.

Pyrotechnic igniters of 1, 5 and 10 kJ (Simex Control) were employed in the investigations. The pressure rise values due to igniters were deducted in the reported explosion pressure data. The methane gas (Coregas) employed in the tests was of 99.95 % purity.

The pressure data from the explosion sphere was collected from the dynamic pressure transducers using ANKO Explosion Plotter (version 1.0.0.0) software. Pressure and light sensing data from the duct was collected from the photodiode sensors and pressure transducers using an ADLINK data acquisition system comprised of a PXI express chassis (PXES – 2590(G)), a data acquisition card (PXIe – 3975) and six digitizer cards (PXIe – 9816). The software employed in the data acquisition process was ANKO Dvmsoft (version 2.0.1.0).

3. Results and discussion

3.1. Reduced explosion pressure in the vessel

A number of factors affect the evolution of the reduced explosion pressure profile in a vessel connected to a duct. These factors include the vessel's volume, the diameter and length of the duct, the concentration of the flammable substance and the reactivity of the flammable material (Holbrow et al., 1996). Figure 4 illustrates the effect of the length of the duct on the reduced explosion pressure. These pressure profiles were developed by deducting the explosion pressure profiles of igniters from the experimentally obtained pressure profiles for methane-air mixtures from the ignition point (87 ms in the figure). The lowest reduced peak explosion pressure was observed when only the valve was used as duct (273 mm length of duct). This can be considered a vented-only explosion test. The reduced peak explosion pressure was observed to be higher in a ducted vessel than in a vented vessel.

The effect of ignition energy on the explosion pressure is presented in Table 3. The difference between the reduced peak explosion pressures of a 2813 mm duct and a 273 mm duct is significant for the investigation carried out at 1 kJ. This gap gradually diminished when the ignition energy increased to 10 kJ. The pyrotechnic igniters influence the explosion pressure mainly in two ways. They produce gas and this generation of gas elevates the total pressure during explosion. The reported reduced peak explosion pressure was calculated by deducting igniter's pressure rise as reported in the experimental section. The second way is the flame area they produce. For igniters of high ignition energies, higher flame areas are produced. The higher level of flame area from pyrotechnic igniters of higher energy, such as 10 kJ, decreased the difference of reduced peak explosion pressures when compared to ducted vessels of various duct lengths as presented in Table 3.

This investigation was designed in a way that the vessel to duct opening can be considered open at the time of explosion. This approach has provided an opportunity to investigate explosion parameters at zero static activation overpressure. Static activation overpressure is defined as the pressure to crack any membrane or disc that is often used in the explosion studies of ducted vessels (Bartknecht, 1981). For the purpose of the initial confinement of methane in the vessel, often a valve was employed instead of a membrane providing zero activation overpressure, but in some cases, a combination of a valve and a membrane was employed providing a positive value of static activation overpressure (Ferrara et al., 2008; Kasmani et al., 2013).

Methane-air mixture can be present in the turbulent state in real world scenarios. In addition, the presence of ignition sources can be diverse in reality. In the present study, the release of pressurised air from the dust chamber to the vessel introduced turbulence to the gas mixture while the application of pyrotechnic igniters mimicked the presence of a strong ignition source in an explosion event.

This approach to explosion tests has a significant impact on the obtained values of the explosion parameters. For instance, Ferrara et al. (2008) employed a 200 litre cylindrical vessel integrated with a 1 m long cylindrical duct of 162 mm diameter in the explosion study of methane-air mixtures. The L/D ratio for their setup was 6.17 which is very similar to the L/D ratio in this investigation with a 273 mm long duct ($L/D = 5.70$). However, the values of reduced peak explosion pressure were 1.20 barg in Ferrara's setup versus 4.32 barg in the present investigation; in both cases, the data were collected at the stoichiometric concentration. Factors that influenced the variation of explosion pressure data include the state of gaseous mixture and the type of igniters. In Ferrara's experiment, quiescent mixtures of methane and air with an electric spark were employed, while turbulent mixtures of methane and air with pyrotechnic igniters were employed in the present investigation. With the aim of exploring the dependence of the reduced peak explosion pressure on the concentration of methane for the ducted vessel geometry of interest, a detailed investigation was carried out at various concentrations of methane and various ignition energies (Figure 5).

The investigation was started with a methane concentration of 5 %, increased at a rate of 1.5 % in the successive tests, and terminated at 15.5 %. While the reduced peak pressure versus methane concentration profiles, obtained at various energies, are similar to peak explosion pressure versus methane concentration profiles of previous studies (Kundu et al., 2016), this figure provides experimental data of reduced peak explosion pressures at various methane concentrations for a ducted spherical vessel. At higher ignition energies the initial ignition flame area was higher which increased the burning rate of methane and consequently increased the maximum pressure for lean and rich mixtures of methane. The effect of ignition energies diminished as the concentration of methane approached the stoichiometric ratio, as illustrated in Figure 5.

3.2. Flame histories in the duct

Five photodiode sensors were used to understand the flame travel characteristics in the duct. As presented in Figure 6, all photodiode sensors detected light signals for the 6.5 % methane in air and this suggests that unburned gas was present, at least up to the fifth sensor. The closest sensor to the vessel, or the first sensor, recorded light for the longest continuous period of time (48 ms), indicating the flame was sustained for the longest period of time at the first sensor, as presented in Figure 6. The duration of the flame present in successive sensors gradually reduced to 36, 33, 25 and 21 ms, respectively. This was expected as at the location of the first sensor a higher amount of unburned gas is present and it faced the flame earlier than any other sensor.

Interestingly, the third sensor (1350 mm from the vessel exit) experienced the highest light intensity compared to any other sensor. This suggests that the maximum burning rate of gaseous mixture was in the vicinity of the third sensor. (Iida et al., 1985) found that the flame

in a rectangular duct becomes fully turbulent above thrice the width of the duct. In the present study, the employed duct was of circular cross-section and the thrice the diameter of the duct provides a length of 128 mm. While there was no sensor included at 128 mm of the duct or with the valve, the average flame speed estimated between the first and second photodiode sensors, as presented in the next section, clearly indicates a high level of Reynolds number and therefore the presence of turbulence at a distance of 350 mm from the vessel exit into the duct. The significant increase of light intensity from the first to the third photodiode sensor suggests that the level of combustion and hence turbulence increases up to 1350 mm. From the third photodiode sensor to the end of the duct, the burning rate is expected to drop according to the responses of the fourth and fifth photodiode sensors; however, the flammable molecules will still be burning and a significantly high turbulence level is expected to be maintained and this understanding is supported by the average flame speed data as presented in the next section.

3.3. Flame front propagation along the length of the duct

In the present investigation, the flame front propagation was observed to be dependent on the ignition energy. The first flame signal for the investigation of a stoichiometric methane–air mixture at 1 kJ was found at 103.4 ms since the software initiated the test process. This value was reduced to 94.2 ms and 92.2 ms when the ignition energy was increased to 5 and 10 kJ, respectively.

Figure 7 shows the average flame speed along the length of the duct, estimated based on the signals of two successive photodiode sensors. The estimated flame speed increased in general from the first calculated point to the end point. However, the values of the flame speeds at each flame front position were found to increase with an increase of the ignition energy.

The maximum flame speed estimated in the present study was 410 m s^{-1} . This value was the average flame speed between the second and third photodiode sensors and was obtained when an ignition energy of 10 kJ was employed. This flame speed corresponds to the deflagration state of an explosion, which is defined as a flame speed lower than the speed of sound. The speed of sound in combustion products is accounted for in this definition. As the temperature of the combustion products is much higher than the room temperature, the speed of sound in the explosion test unit is much higher than the speed of sound in air at room temperature (Kundu et al., 2016). The investigated explosion phenomena for the stoichiometric methane-air mixtures can therefore be characterised as deflagration.

While the presented data in Figure 7 was from the longest duct (2813 mm) employed in the experiment, flame speeds were also determined for a shorter duct (1273 mm). Flame speeds were found to be higher for the shorter duct length when compared to flame speed values for the longer duct. An average flame speed of 320 m s^{-1} was found for the shorter duct, which was determined using the signals from the first and second photodiodes for a stoichiometric methane-air mixture and an ignition energy of 10 kJ. The comparable value of flame speed for the longer duct was 290 m s^{-1} as presented in Figure 7.

The operation method (including the introduction of turbulence and the application of pyrotechnic igniters) in the investigation showed a significant difference of flame speed when compared to literature. Kasmani et al. (2013) reported a flame speed of 20 m s^{-1} from a methane-air explosion test (stoichiometric conditions) employing a cylindrical vessel of 200 litre volume connected with a 1.5 m long cylindrical duct of 162 mm diameter. While Kasmani et al. employed a combination of a gate valve and vent covers in most of their experiments, this data of Kasmani's work was collected in absence of a vent cover. This part of Kasmani's study is aligned with the present work in the context of operating experiments at zero activation overpressure. The L/D ratio in the case of Kasmani's experiment was lower

than that of the present investigation (9.3 versus 65.2). The lower value of the L/D ratio in Kasmani's experiment is expected to increase the flame speed. However, a significantly lower value of the flame speed was found in their experiment when compared to the present investigation. Numerically, flame speed was approximately 20 times higher in the present study when compared to Kasmani's experiment. The reason is: although both set of data were collected operating experiments at zero activation overpressure, there were still few differences in the experimental procedures. Kasmani et al. employed electric spark and quiescent mixtures of methane and air while pyrotechnic igniters and turbulent mixtures of methane-air were employed in the present study. The inclusion of turbulence and the application of strong igniters in the present study thus showed that the flame speed could be significantly higher than the scenario of quiescent mixture and low ignition energies.

3.4. Characterisation of explosion pressure along the length of the duct

Figure 8 shows the pressure–time profiles in five locations in the duct as a function of time. The steep pressure rises, observed in all five locations in the duct, provide an understanding of the burning rate and turbulence in the duct (Bouhard et al., 1991; Ferrara et al., 2008; Kordylewski and Wach, 1986, 1988; Molkov, 1994; Ponizy and Leyer, 1999). An increased burning rate of the flammable gas is expected, simultaneous with the steep pressure rise, which establishes an intense level of turbulence in the fluid stream. A relative gradual pressure decrease after reaching the peak pressure is representative of the venting characteristics observed along the length of the duct.

Table 4 shows the peak explosion pressures from each pressure transducer for the tests of stoichiometric methane–air mixtures as a function of the ignition energy. The recorded data shows that the variations of the peak explosion pressures from the first to the fifth pressure transducer were not significant. The peak explosion pressures were found to be dependent on the ignition energy. With an increase of ignition energy, the pressure transducers showed higher peak explosion pressures.

The first pressure transducer experienced the highest pressure in most of the experiments (Figure 9). In other experiments, the second sensor experienced the highest pressure, where the pressure difference between the first and second sensor was less than 0.1 bar. While conducting tests with stoichiometric methane–air mixtures employing igniters of variable energies, the highest values of peak explosion pressures were at the location of the first sensor, and the time to detect those peak explosion pressures were 109.7, 101.2 and 99.3 ms for ignition energies of 1, 5 and 10 kJ, respectively. Employing the obtained data, the estimated values of explosion times were 22.7, 14.2 and 12.3 ms. The definition of explosion time is the time interval to detect the peak explosion pressure where the time is counted from the ignition time (Razus et al., 2006). Heat loss in the form of conduction, convection and radiation increases in longer explosion times (Pekalski et al., 2005) and this provides an understanding of obtaining higher peak explosion pressure at higher ignition energies.

With the aim of exploring the pressure characteristics along the length of the duct for a particular moment, Figure 10 was constructed employing the pressure data of the various pressure transducers at 109.7 ms for 1 kJ, 101.2 ms for 5 kJ and 99.3 ms for 10 kJ tests. The pressure-distance profile at a particular moment clearly identifies the expected hazard levels along the length of the tube.

3.5. Rates of pressure rise in the vessel

The integration of a duct with a vessel impacts the rates of pressure rise in the vessel. This phenomenon is supported by Figure 11, which shows the rates of pressure rise in the vessel. These rates of pressure rises were constructed by deducting the rates of pressure rises of the igniters from the experimentally obtained rates of pressure rise for methane-air mixtures.

The highest rate of pressure rise was observed for a vented-only explosion (0.273 m length of duct). With the increased duct length, the rate of pressure rise was found to decrease.

Figure 12 illustrates the maximum rates of pressure rise or $(dP/dt)_{max}$ in the ducted vessel of 2.813 m duct length as a function of the methane concentration. This figure provides a new set of data for the ducted vessel geometry of interest. As described elsewhere, the generation of higher flame area increases the burning rate. This has been reflected in Figure 12 and the higher values of $(dP/dt)_{max}$ for a particular methane concentration were found for higher ignition energies applied.

3.6. Impacts of duct length on reduced peak explosion pressure

The impacts of the duct length on the reduced peak explosion pressure and maximum rate of pressure rise is presented in Table 5. (Ferrara et al., 2008) and (Kasmani et al., 2013) employed cylindrical vessels of the same geometry and the ducts they used were of the same diameter but of a different length.

The increase of the duct length from the investigation of (Ferrara et al., 2008) to (Kasmani et al., 2013) yielded an increase in the reduced peak explosion pressure. In an earlier study, Ferrara et al. stated that the flow resistance in a ducted vessel leads to elevated reduced peak explosion pressure when compared to a vented vessel (Ferrara et al., 2006). The level of the flow resistance will increase with the duct length and, therefore, a higher level of explosion pressure is expected in the vessel with an increase of the duct length. An increase of the reduced peak explosion pressure was also observed in the present study with an increase of the duct length, and is reported in Table 5.

4. Conclusion

Explosion studies of methane-air mixtures were carried out employing a spherical vessel integrated with a duct and the experimental outcome is aligned with the real world scenario of the presence of turbulent mixture of methane-air and strong ignition energies. This approach showed that the explosion severity can be much higher in the case of turbulent methane-air mixture and strong ignition energies than that of a quiescent mixture of methane-air and low ignition energies.

1. The pressure rise in the vessel was found to be much higher in the present work when compared to pressure rise data with quiescent mixture of methane-air and low ignition energies. The explosion severity in the context of explosion pressure or the destruction potential of the explosion is therefore much higher in the case of turbulent mixture of

methane-air and strong ignition energies than that of quiescent mixture of methane-air and low ignition energies.

2. Flame speed was found to be several magnitudes in the present study when compared to flame speed data with a quiescent mixture of methane-air and low ignition energies. In the case of a turbulent mixture of methane-air and strong ignition energies, the rate of flame spread is very high when compared to the case of a quiescent mixture of methane-air and low ignition energies.

Acknowledgement

This work was supported by the Department of Resources Energy and Tourism, Australia (grant number – G1201029) and ACA Low Emissions Technologies Ltd., Australia (grant number – G1400523).

References

- Ajrash, M.J., Zanganeh, J., Moghtaderi, B., 2016a. Experimental investigation of the minimum auto-ignition temperature (MAIT) of the coal dust layer in a hot and humid environment. *Fire Saf. J.* 82, 12-22.
- Ajrash, M.J., Zanganeh, J., Moghtaderi, B., 2016b. Methane-coal dust hybrid fuel explosion properties in a large scale cylindrical explosion chamber. *J. Loss Prev. Process Ind.* 40, 317-328.
- Bartknecht, W., 1981. Explosions: course, prevention, protection. Springer-Verlag, New York, USA.
- Barton, J., 2002. Dust Explosion Prevention and Protection: A Practical Guide. Institution of Chemical Engineers (IChemE), Warwickshire, UK.
- Benedetto, A.D., Russo, P., Salzano, E., 2008. The design of duct venting of gas explosions. *Process Saf. Prog.* 27, 164-172.
- Bouhard, F., Veyssiere, B., Leyer, J., Chaineaux, J., 1991. Explosion in a vented vessel connected to a duct. *Prog. Astronaut. Aeronaut.* 134, 85.
- Bradley, D., Mitcheson, A., 1976. Mathematical solutions for explosions in spherical vessels. *Combust. Flame* 26, 201-217.
- Bradley, D., Mitcheson, A., 1978. The venting of gaseous explosions in spherical vessels. I—Theory. *Combust. Flame* 32, 221-236.
- Chou, H. C., Yeh, C. T., Shu, C. M., 2015. Fire accident investigation of an explosion caused by static electricity in a propylene plant. *Process Saf. Environ. Protect.* 97, 116-121.
- Ferrara, G., Di Benedetto, A., Salzano, E., Russo, G., 2006. CFD analysis of gas explosions vented through relief pipes. *J. Hazard. Mater.* 137, 654-665.

- Ferrara, G., Di Benedetto, A., Willacy, S., Phylaktou, H., Andrews, G., Mkpadi, M., 2005. Duct-vented propane-air explosions with central and rear ignition. *Fire Saf. Sci.* 8, 1341-1352.
- Ferrara, G., Willacy, S., Phylaktou, H., Andrews, G., Di Benedetto, A., Salzano, E., Russo, G., 2008. Venting of gas explosion through relief ducts: Interaction between internal and external explosions. *J. Hazard. Mater.* 155, 358-368.
- Foiles, R., 2004. To vent or not to vent. *Chemical engineering* 111, 58.
- Gardner, B., Winter, R., Moore, M., 1988. Explosion development and deflagration-to-detonation transition in coal dust/air suspensions, *Symp. (Int.) Combust.* Elsevier, pp. 335-343.
- Garforth, A.M., 1976. Unburnt gas density measurement in a spherical combustion bomb by infinite-fringe laser interferometry. *Combust. Flame* 26, 343-352.
- Holbrow, P., Andrews, S., Lunn, G., 1996. Dust explosions in interconnected vented vessels. *J. Loss Prev. Process Ind.* 9, 91-103.
- Iida, N., Kawaguchi, O., Sato, G.T., 1985. Premixed flame propagating into a narrow channel at a high speed, part 1: flame behaviors in the channel. *Combust. Flame* 60, 245-255.
- Kasmani, R., Andrews, G., Phylaktou, H., 2013. Experimental study on vented gas explosion in a cylindrical vessel with a vent duct. *Process Saf. Environ. Protect.* 91, 245-252.
- Kordylewski, W., Wach, J., 1986. Influence of ducting on the explosion pressure. *Combust. Flame* 66, 77-79.
- Kordylewski, W., Wach, J., 1988. Influence of ducting on explosion pressure: small scale experiments. *Combust. Flame* 71, 51-61.
- Kosinski, P., Hoffmann, A.C., 2006. An investigation of the consequences of primary dust explosions in interconnected vessels. *J. Hazard. Mater.* 137, 752-761.

- Kundu, S., Zanganeh, J., Moghtaderi, B., 2016. A review on understanding explosions from methane–air mixture. *J. Loss Prev. Process Ind.* 40, 507-523.
- Kundu, S.K., 2010. Understanding and eliminating pressure fluctuations in an extended chlor-alkali plant due to the size detail of seal pots: A design correlation. *Process Saf. Environ. Protect.* 88, 91-96.
- Lawes, M., Ormsby, M., Sheppard, C., Woolley, R., 2005. Variation of turbulent burning rate of methane, methanol, and iso-octane air mixtures with equivalence ratio at elevated pressure. *Combust. Sci. and Tech.* 177, 1273-1289.
- Lee, J.H., Guirao, C.M., 1982. Pressure development in closed and vented vessels. *Plant/Operations Prog.* 1, 75-85.
- Molkov, V.V., 1994. Venting Of Deflagrations: Dynamics Of The Process In Systems With A Duct And Receiver. *Fire Saf. Sci.* 4, 1245-1254.
- NFPA-68, 2007. Standard on Explosion Protection by Deflagration Venting, National Fire Protection Association, Quincy, MA.
- Pekalski, A., Schildberg, H., Smallegange, P., Lemkowitz, S., Zevenbergen, J., Braithwaite, M., Pasman, H., 2005. Determination of the explosion behaviour of methane and propene in air or oxygen at standard and elevated conditions. *Process Saf. Environ. Protect.* 83, 421-429.
- Ponizy, B., Henneon, N., Claverie, A., Veyssiere, B., 2014. Detailed investigation of flame transmission from a vessel to a discharge duct. *Combust. Flame* 161, 1348-1364.
- Ponizy, B., Leyer, J., 1999. Flame dynamics in a vented vessel connected to a duct: 1. Mechanism of vessel-duct interaction. *Combust. Flame* 116, 259-271.
- Qin, B., Li, L., Ma, D., Lu, Y., Zhong, X., Jia, Y., 2016. Control technology for the avoidance of the simultaneous occurrence of a methane explosion and spontaneous coal

- combustion in a coal mine: A case study. *Process Saf. Environ. Protect.* 103, Part A, 203-211.
- Razus, D., Movileanu, C., Brinzea, V., Oancea, D., 2006. Explosion pressures of hydrocarbon–air mixtures in closed vessels. *J. Hazard. Mater.* 135, 58-65.
- Russo, P., Di Benedetto, A., 2007. Effects of a Duct on the Venting of Explosions—Critical Review. *Process Saf. Environ. Protect.* 85, 9-22.
- Tamanini, F., Valiulis, J.V., 1996. Improved guidelines for the sizing of vents in dust explosions. *J. Loss Prev. Process Ind.* 9, 105-118.
- Willacy, S., Phylaktou, H., Andrews, G., Ferrara, G., 2007. Stratified propane–air explosions in a duct vented geometry: effect of concentration, ignition and injection position. *Process Saf. Environ. Protect.* 85, 153-161.
- Zhang, Q., Ma, Q.J., 2015. Dynamic pressure induced by a methane–air explosion in a coal mine. *Process Saf. Environ. Protect.* 93, 233-239.

Figure 1: Illustration of the behaviour of a flame entering from a vessel to a duct (Iida et al., 1985).

Figure 2: Ducted vessel apparatus employed in the experimental investigations.

Figure 3: Experimental setup employed in the investigations: 1) 20 litre sphere, 2) connector, 3) valve, 4) first portion of the duct, 5) second portion of the duct, 6) photodiodes (open circles), 7) pressure transducers (closed markers), 8) flexible disc that closes when an underpressure is maintained in the explosion sphere and opens as soon as the vessel's pressure increased from underpressure to atmospheric pressure.

Figure 4: Pressure profile of the vessel as a function of time for a stoichiometric methane-air mixture when an ignition energy of 5 kJ was applied.

Figure 5: Effects of the methane concentration on the reduced peak explosion pressure of the vessel at various ignition energies for a ducted vessel with a duct length of 2813 mm.

Figure 6: Light intensity profiles at various locations of the duct as a function of time as recorded by photodiode sensors for a methane concentration of 6.5 % with an ignition energy of 5 kJ.

Figure 7: Flame speeds along the length of the duct ($L=2813$ mm) for a stoichiometric methane-air mixture.

Figure 8: Explosion pressure profiles at various locations in the duct as a function of time as recorded by the pressure transducers for stoichiometric methane–air mixtures applying an ignition energy of 5 kJ.

Figure 9: Effects of methane concentration on the peak explosion pressures at various locations in a duct of 2813 mm length when an ignition energy of 5 kJ was applied.

Figure 10: Explosion pressure profiles along the length of the duct at those moments when the duct experienced the maximum pressures – presented data was collected from the investigations with stoichiometric methane–air mixtures at various ignition energies.

Figure 11: Rates of pressure rise (dP/dt) in the vessel as a function of time for stoichiometric methane–air mixtures when an ignition energy of 5 kJ was applied.

Figure 12: Maximum rates of pressure rise $((dP/dt)_{\max})$ in the vessel as a function of methane concentration for a ducted vessel with a duct length of 2813 mm.

Table 1: Location of the sensors in the duct.

Sensor designation	Distance from the sphere (mm)	Pressure transducer	Photodiode sensor	Designation of angles
First	350	90°	270°
Second	850	90°	270°	
Third	1350	90°	270°	
Fourth	1850	90°	270°	
Fifth	2350	90°	270°	

Table 2: Operational conditions to inject methane into the sphere.

Concentration of methane (%)	Initial pressure (kPag)	Pressure after methane injection (kPag)
5.0	– 65.1	– 60
6.5	– 66.6	– 60
8.0	– 68.1	– 60
9.5	– 69.6	– 60
11.0	– 71.1	– 60
12.5	– 72.7	– 60
14.0	– 74.2	– 60
15.5	– 75.7	– 60

Table 3: Effects of ignition energy on reduced peak explosion pressures (in barg) in the vessel for stoichiometric methane–air mixtures at various configurations of the explosion unit.

Ignition energy	Vessel with 2813 mm duct	Vessel with 1273 mm duct	Vessel with 273 mm duct
1 kJ	4.58	4.41	4.07
5 kJ	4.67	4.53	4.32
10 kJ	4.72	4.68	4.60

Table 4: Effects of ignition energy on the peak explosion pressures (in barg) in a duct of 2813 mm length for stoichiometric methane–air mixtures.

Ignition energy	350 mm in duct	850 mm in duct	1350 mm in duct	1850 mm in duct	2350 mm in duct
1 kJ	3.28	3.21	2.93	2.95	2.91
5 kJ	3.41	3.40	3.03	3.02	2.94
10 kJ	3.82	3.78	3.32	3.30	3.22

Table 5: Comparison of the explosion characteristics of stoichiometric methane–air mixtures in ducted vessels.

Apparatus Description	L/D	Reduced peak explosion pressure (barg)	Reference
Cylindrical, central ignition, 200 litre vessel volume, 1000 mm long duct of 162 mm diameter	6.17	1.20	(Ferrara et al., 2008)
Cylindrical, central ignition, 200 litre vessel volume, 1500 mm long duct of 162 mm diameter	9.26	1.35	(Kasmani et al., 2013)
Spherical, central ignition, 20 litre vessel volume, 273 mm long duct of 42.72 mm diameter	5.70	4.32	This study (5 kJ)
Spherical, central ignition, 20 litre vessel volume, 1273 mm long duct of 42.72 mm diameter	29.11	4.53	This study (5 kJ)
Spherical, central ignition, 20 litre vessel volume, 2813 mm long duct of 42.72 mm diameter	65.16	4.67	This study (5 kJ)