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Suppression of Flame Propagation in a Long Duct by Segregation with Inert Gases

Hui-Ning Yang, Yu-Jhen Lin, Chien-Ho Liu, Mo-Geng Chin, Cheng-Chieh Wang, Hsiao-Yun Tsai & Jenq-Renn Chen*

Department of Safety, Health and Environmental Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan
jrc@nkust.edu.tw

Ignition and explosion from accidental leaks of large amount of flammables into a long, underground trench may result in extensive damage and fatalities. Mitigation of such leak and explosion is difficult although not impossible. Typical explosion suppression measures such as water spray and inert powder cannot be readily applied owing to underground location. In this work, a concept of suppression the flame propagation instead of explosion overpressure was proposed via injecting inert gas into the underground duct to segregate the flammable gases and suppressing the flame propagation throughout the duct. Experimental studies were done with a small pipe with a diameter of 0.043 m and a large pipe with a diameter of 0.49 m. Tests were carried in an ignition section containing propylene/air mixture near stoichiometric concentration and generating a peak flame propagation speed of approximately 100 m/s. The ignition section is connected to a section filled with an inert gas, another section with flammable mixtures, and finally a sufficient long, ambient section to accommodate flame propagation. The critical length of the inert gas section required for successful suppression of flame from igniting the flammable section is found to be 0.3 m for CO_2 and 0.9 m for N_2 in the large pipe and 0.2 m for CO_2 and 0.3 m for N_2 in the small pipe. Finally, application of the results in responding to large-scale leak into underground duct is discussed.

1. Introduction

Large scale leak of flammables into a duct such as underground trench and its subsequent ignition and explosion may cause significant damage. Although such type of explosion was rare compared with unconfined vapor cloud explosion, the damages were far more severe as shown by the incidents in Guadalajara, Mexico in 1992 (Anderson and Morales, 1992), Qingdao, China in 2013 (Zhu et al., 2014), and more recently in Kaohsiung, Taiwan in 2014 (Yang et al., 2016). For the latter case, a total of 4.5 km of road surface was blow out causing extensive damage in lives and properties. The above three cases have a common source of leak: a corroded underground pipeline transporting flammable fluids. Another striking common feature is that the delay time between leak and ignition is considerably longer than unconfined vapor cloud explosion. Part of the reason is attributed to the fact that there were usually more ignition sources in an open space than the confined duct. Although the long delay time of ignition is part of the causes of extensive damage, it also opens an opportunity to mitigate or to prevent the explosion, provided that proper action can be taken.

Extensive work has been done on explosion suppression which focuses mainly on reduction of explosion intensity upon the ignition and explosion was initiated. For long duct filled with flammable gases or vapours, such suppression is possible but usually special devices are needed for injecting the suppressant. For underground trench lasted for several kilometres, the number of suppression device required can rendered the suppression impractical.

In this work, we explore the possibility of mitigating the explosion by suppressing the flame propagation with inert gas segregation. The idea is simple: by injecting non-flammable gases such as nitrogen or carbon dioxide into the duct at different section before the ignition, the flammable gases or vapours in the duct are segregated. Should ignition occurred in any section of the duct, flame will only propagate in that section but not other sections owing to the isolation by the inert gas plug. The explosion is thus limited to a few meters

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rather than a few kilometres. Similar ideas have been carried out Du et al. (2014) and Zhang et al. (2014) in a duct for the suppressions of the gasoline/air mixture explosion by non-premixed nitrogen. However, both sides of the duct were closed which prevent the outflow of the gases and resulted in an excessively long suppression section for a successful suppression. It is reported that failure of suppression was caused by insufficient dilution from the inert gas. For an open duct such as an underground trench, flame propagation resulted in overpressure, volume expansion and gas outflow. It is expected that the suppression mechanism will be different from those of closed ends.

In this work, the idea is explored by using a pipe comprising an ignition section, suppression section, flammable section with ignition at the closed end and flammable section at the open end. Critical length is determined for propylene/air mixture with a peak flame propagation speed of approximately 100 m/s. Implication of the results for responding to large scale leaks are discussed.

2. Experimental setups

A stainless-steel pipe with internal diameter of 0.043 m is used as the small-scale duct. The total pipe length is adjustable through assembling of different length of pipe by clamping flanges. Flame sensors and pressure sensors were installed on each section of pipe. The pressure sensors used were Kistler Type 211B quartz sensors with response time of 1 μs. The flame sensors used were high-speed silicon photodiodes from OSI Optoelectronics Type PIN-HR008 with spectral range from 350 nm to 1100 nm and response time of 0.6 ns. All sensor data were acquired by a Yokogawa DL850E data acquisition recorder at a rate of 5,000 Hz.

The whole pipe comprised of four sections depending on test configuration. The first section consists of a 3-m long ignition section with one end sealed with a blind flange and an inserted Nichrome wire igniter. The igniter provided a glowing ignition source with energy around 10 J which is sufficient to ignite flammable mixture but did not disturb the mixture. The first section was filled with propylene/air mixture. The second section was filled with an inert gas such as N_2 or CO_2 and the length was varied between 0.1 m to 6 m. The third section consisted of another 3-m long flammable section also filled with propylene/air mixture. The fourth section was an empty pipe open to ambient air with a length of 18 m which acted as a buffer section to avoid the outflow of flammable gas in the third section. All sections were separated by a thin polyethylene film.

Propylene with a purity of 99.5 % was used as the flammable gas. The flammable sections comprised of air from an air compressor and then propylene fed by pressure to a concentration around 4.5±0.15 %. The third section also filled with propylene/air mixture but at slightly higher concentrations of 5.3±0.1 % to prevent possible dilution from the inert section. Exact concentration was determined from a sampling and analysis by GC-TCD.

Although tests with small pipe offered easy operation and one-dimensional characteristics of flame propagation and suppression, actual flame propagation is multi-dimension in a large duct. To verify the results from small-scale tests, a large stainless-steel pipe with an internal diameter of 0.49 m is used as the duct. The whole pipe comprised of four sections. The first section consisted of a 0.6-m long ignition section and was filled with propylene/air mixture. The second section was filled with an inert gas such as nitrogen or carbon dioxide and the length was varied between 0.3 m to 0.9 m. The third section consisted of another flammable section with length varied between 0.3 to 3 m, also filled with propylene/air mixture. The fourth section was an empty pipe with a length of 9~12 m.

3. Results and discussion

3.1 General observation of flame propagation

The flame propagation in a duct with ignition at the closed end and open at the other end has been studied extensively in classical experiments by Guénoche (1964), and more recently by Jones and Thomas (1991) and Kerampran et al. (2000). The flame propagation behavior was quite complex and subjected to be affected by several factors such as flammable concentration, duct length, roughness, etc. The most notable feature is the oscillating flame propagation which was resulted from tube acoustics initially set in motion by the expansion due to ignition at the closed end.

To validate the current setup, several blank tests with the third section of flammable mixture replaced by an inert gas. The results were shown in Figure 1 in which it is clear that the flame from the 3-m flammable section may propagated deep into the inert gas section. The propagation distance for the flame from first section is however not affected by the length of the inert section as shown in Table 1 in which all flame propagation terminated at downstream distance of 4.8~6 m. Clearly, the flame propagation outside the flammable section is mainly caused by expansion and outflow from the burnt gases.

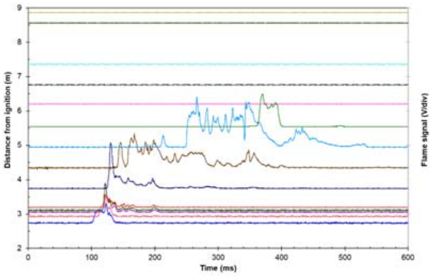

Figure 1: Typical results of flame propagation for a blank test, Test S10 in Table 1.

3.2 Results of Flame Propagation Suppression in a small duct

The full results of maximum flame sensor signal at different location of the pipe were summarized in Table 1. All tests with 6-m of inert section showed no ignition and flame in the third section. Subsequent tests with 0.6-m and 0.3-m of inert section also showed similar results. It is also interested to note that these tests with the third section filled with flammable mixture showed roughly the same flame propagation distance compared with the corresponding blank tests. Clearly, the flame propagated well into the third section with flammable mixture yet the flammable mixture was not ignited but instead pushed downstream.

Further tests, Test S12 and S13, with 0.1-m of inert section filled with nitrogen and carbon dioxide, respectively, failed to suppress the flame propagation and the flammable section was ignited in both cases. The flame sustained and created stronger flame further downstream. This is also evident from the comparison of overpressure measurement for Tests S10 and S12 in Figure 2(a). Overpressure measurement for both tests was roughly the same before 330 ms from ignition. After 330 ms, Test S12 showed slightly larger overpressure and the flame propagated to further downstream of 6.2 m and eventually all the flammable section in the downstream was ignited producing significant overpressure at 800 ms from ignition. Comparison of the flame signal and overpressure measurement for Tests S10 and S12 confirmed that the flammable section in Test 12 was ignited and the flame propagation suppression by 0.1 m inert section was failed.

Finally, Test S18 with 0.2-m of inert section filled with nitrogen showed clear flame in all downstream flame sensors as shown in Figure 2(b). However, two repeated tests, Test S19 and S20, with a 0.2-m inert section filled with carbon dioxide showed flame propagation up to less than 6 m as shown in Figure 2(c). The overpressure for Test S19 also diminished gradually while Test S18 showed similar overpressure until when the flammable section was ignited and generated significant overpressure. Therefore, the 0.2 m inert section is near the boundary of failed/successful suppression of flame propagation. The 0.3 m inert section is considered as the critical length for a successful suppression of flame propagation from a 3-m propylene ignition section.

The current, short suppression section is far smaller than the studies done by Du et al. (2014) which used a sealed pipe at both ends. The critical length of inert section is only 1/10 of the ignition section in the current work while the ratio was 1~4, depending on the fuel concentration in the ignition section, in the closed tube tests of Du et al. (2014). Zhang et al. (2014) performed similar tests but with a section for visualization of flame propagation. Analysis of photos of the flame front by Zhang et al. (2014) showed that the whole suppression process can be divided into three periods, inertia maintenance stage, suppression attenuation stage and diffusion extinguishment stage. They suggested that nitrogen molecule took away the energy of the high-energy radicals of the combustion reactions during the suppression process, resulting in the termination of the main reaction chains. Another factor that contributes to the discrepancy between the current results and those of Du et al. (2014) is the criterion of successful suppression. Du et al. (2014) required that flame sensors behind the suppression section did not detect any flame signal as the condition for successful suppression. This criterion will be ambiguous in the present cases with an open duct and gas outflow. In fact, the stringent requirement of no flame signal after inert section is only achievable with sufficient long inert section and sealed pipe.

Clearly, the mechanism of flame propagation suppression in the open duct is completely different from those of a sealed duct. For a sealed duct, the suppression is achieved through complete flame quench by the inert gas. For an open duct, the suppression is achieved through isolation during out flow and is thus called inertia isolation. Different inert gas did show slightly different results as 0.2 m section of CO_2 successfully suppressed the flame while 0.2 m section of N_2 failed. Such results are also in consistent with the fact that minimum oxygen concentration in CO_2 is larger than that of N_2 (Crowl and Louvar, 2011) and the fact that CO_2 gas a higher gas capacity to absorbed the heat of combustion in comparison with N_2 (Chen et al., 2009). To further validate the proposed mechanism, a separate test, Test S23 in Table 1, was performed with the inert gas replaced by air. The results showed almost identical and successful result of suppressing the flame propagation from the ignition section to the flammable section. The only notable difference between Test S23 and Tests S14~S17 is that flame propagation distance with air is larger than those with inert gas. The inert gas did contribute to the flame quench and thus giving smaller flame propagation distance.

Table 1: Summary of small-scale test results. The flame sensor locations were given based on the ignition end.

Test no.	Ignition section		Inert section		Flammable section		Buffer section	Total length	Maximum flame sensor signal													
	L (m)	Fuel (%)	L (m)	Inert gas	L (m)	Fuel (%)	L (m)	L (m)	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14
Flame sensor location from ignition									2.74	2.93	5.34	5.93	6.51	7.10	7.69	8.09	8.88	9.05	9.60	10.20	11.10	14.41
S1	3	4.32	6	N_2	0	-	18	27	0.04	0.05	0	0	0	0	0	0	0	0	0	0	0	0
S2	3	4.64	6	CO_2	0	-	18	27	0.07	0.05	0.06	0	0	0	0	0	0	0	0	0	0	0
S3	3	4.67	6	N_2	6	5.17	12	27	0.05	0.05	0.17	0.09	0	0	0	0	0	0	0	0	0	0
S4	3	4.55	6	CO_2	6	5.38	12	27	0.04	0.04	0	0	0	0	0	0	0	0	0	0	0	0
Flame sensor location from ignition									2.74	2.93	3.14	3.33	3.52	3.69	4.23	4.83	5.43	6.03	6.69	7.25	7.85	9.05
S5	3	4.78	0.6	N_2	0	-	23.4	27	0.04	0.04	0.09	0.22	0.25	0.21	0.16	0.13	0.14	0	0	0	0	0
S6	3	4.45	0.6	CO_2	0	-	23.4	27	0.03	0.04	0.06	0.09	0.13	0.11	0.11	0.11	0	0	0	0	0	0
S7	3	4.45	0.6	N_2	6	5.38	17.4	27	0.05	0.04	0.07	0.10	0.16	0.11	0.09	0.13	0.16	0.11	0	0	0	0
S8	3	5.04	0.6	CO_2	6	5.12	17.4	27	0.03	0.03	0.04	0.05	0.05	0.04	0.16	0.15	0.02	0	0	0	0	0
S9	3	4.47	0.6	CO_2	6	5.27	17.4	27	0.04	0.05	0.10	0.15	0.17	0.12	0.25	0.11	0.09	0	0	0	0	0
Flame sensor location from ignition									2.74	2.93	3.06	3.11	3.20	3.74	4.34	4.95	5.54	6.20	6.76	7.36	8.56	8.86
S10	3	4.54	0.1	N_2	0	-	24	27.1	0.06	0.06	0.09	0.08	0.04	0.13	0.10	0.15	0.10	0	0	0	0	0
S11	3	4.65	0.1	CO_2	0	-	24	27.1	0.06	0.06	0.11	0.10	0.04	0.08	0.11	0.17	0.11	0	0	0	0	0
S12	3	4.50	0.1	N_2	6	5.22	18	27.1	0.07	0.07	0.11	0.11	0.05	0.13	0.29	0.17	0.12	0.12	0.16	0.29	0.27	0.23
S13	3	4.38	0.1	CO_2	6	5.38	18	27.1	0.06	0.05	0.08	0.09	0.04	0.09	0.09	0.08	0.07	0.12	0.08	0.11	0.24	0.09
Flame sensor location from ignition									2.74	2.93	3.13	3.24	3.38	3.93	4.53	5.13	5.73	6.40	6.95	7.55	8.75	9.05
S14	3	4.68	0.3	N_2	0	-	24	27.3	0.10	0.15	0.24	0.26	0.10	0.18	0.25	0.27	0.17	0	0	0	0	0
S15	3	4.40	0.3	CO_2	0	-	24	27.3	0.05	0.05	0.05	0.12	0.04	0.07	0.08	0.07	0	0	0	0	0	0
S16	3	4.35	0.3	N_2	6	5.44	18	27.3	0.04	0.04	0.08	0.11	0.03	0.05	0.05	0.06	0	0	0	0	0	0
S17	3	4.47	0.3	CO_2	6	5.19	18	27.3	0.05	0.03	0.04	0.06	0.02	0.04	0.05	0.11	0	0	0	0	0	0
Flame sensor location from ignition									2.74	2.93	3.07	3.16	3.30	3.85	4.45	5.05	5.65	6.31	6.87	7.46	8.67	8.97
S18	3	4.27	0.2	N_2	6	5.13	18	27.2	0.04	0.05	0.07	0.08	0.02	0.03	0.06	0.06	0.07	0.07	0.07	0.10	0.07	0.08
S19	3	4.47	0.2	CO_2	6	5.26	18	27.2	0.05	0.05	0.08	0.10	0.04	0.09	0.11	0.13	0.07	0	0	0	0	0
S20	3	4.40	0.2	CO_2	6	5.33	18	27.2	0.04	0.04	0.07	0.06	0.03	0.06	0.08	0.10	0	0	0	0	0	0
Flame sensor location from ignition									2.74	2.93	3.17	3.28	3.48	4.03	4.63	5.23	5.83	6.49	7.04	7.64	8.84	9.14
S21	3	4.39	0.4	N_2	6	5.30	18	27.4	0.05	0.05	0.10	0.15	0.07	0.07	0.04	0.01	0	0	0	0	0	0
S22	3	4.58	0.4	CO_2	6	5.26	18	27.4	0.07	0.05	0.06	0.06	0.04	0.05	0.06	0.07	0	0	0	0	0	0
Flame sensor location from ignition									2.64	2.83	3.00	3.09	3.93	4.12	4.94	5.13	5.95	6.14	8.98	9.17	11.00	11.19
S23	3	4.67	0.3	Air	9	4.51	-	12.3	0.32	0.29	0.39	0.39	0.35	0.33	0.27	0.22	0.23	0.28	0	0	0	0

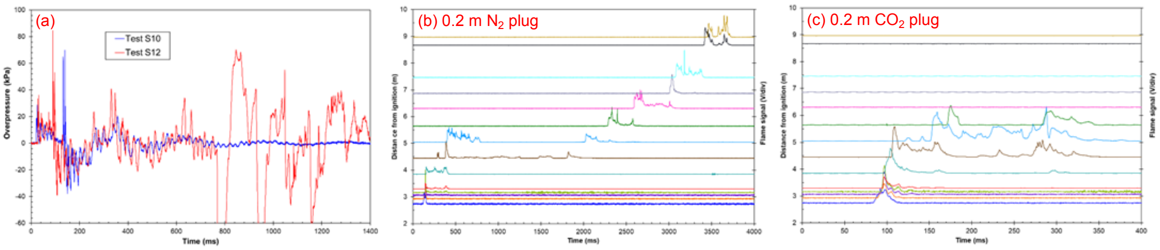

Figure 1: Results of failed and successful suppression test for (a) Tests S10 and S12, (b) Test S18 and (c) Test S19. The overpressure was measured at 8.75 m from ignition.

3.3 Results of Flame Propagation Suppression in a large duct

Although the above small-scale tests offered promising results for inertia isolation for suppressing flame propagation in a long duct, it is necessary to validate the results with a larger scale duct. In a large duct, the flame propagation is multi-dimensional in the axial and radial directions. The extra flame propagation may give complex turbulent flow, higher overpressure and non-uniform flame across the duct cross-sectional area. It is expected that the effectiveness of suppression by inert isolation will be deteriorated. The larger duct however offers the possibility of observing the flame propagation which was done with a high-speed camera with a rate of 2000 frame/s.

Table 2 shows the summary of large-scale tests results. Tests L1~L3 were done with a 3-m ignition section without a flammable section. The flame was initiated from the center of the closed end flange, propagating nearly hemi-spherically towards pipe wall as well outwards directions. Upon reaching pipe wall, the flames coalesced forming strong turbulent flame. It was clear that a 3-m ignition section produced a very strong flame and propelled out of the pipe. The calculated flame propagation speed reached about 300 m/s near the exit of the pipe. This is far larger than the corresponding small duct, e.g. Test S10 in Figure 1, with flame propagation speed of less than 100 m/s. Although it is still possible to suppress such a rapid flame, it would require a much longer duct that was not available. Thus, the ignition section was reduced to 0.6 m in the remaining tests.

Table 2: Summary of large-scale test results.

Test no.	Ignition section		Inert section		Flammable section		Buffer section	Total length	Maximum flame sensor signal																		
	L (m)	Fuel (%)	L (m)	Inert gas	L (m)	Fuel (%)	L (m)	L (m)	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15	f16	f17	f18	f19
Flame sensor location from ignition									0.5	2.9	4	5	6.5	7.1	8.5	10	11.5										
L1	3	4.69	3	Air	0	-	6	12	0.39	0.53	0.51	0.49	0.49	N/A	0.51	N/A	0.47										
L2	3	4.94	3	N_2	0	-	6	12	0.36	0.48	0.44	0.44	0.45	0.42	0.43	0.42	0.40										
L3	3	4.93	9	N_2	0	-	0	12	0.35	0.43	0.40	0.42	0.42	0.39	0.39	0.41	0.38										
Flame sensor location from ignition									0.07	N/A	0.97	1.60	2.69	3.50	4.40	5.50	6.50	7.00	8.00	8.60	9.27	10.00	10.26	11.50	12.01	12.50	13.40
L4	0.6	5.20	0.3	N_2	0	-	12.6	13.5	0.42	N/A	0.45	0.45	0.44	0.38	0.21	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
L5	0.6	5.96	0.3	N_2	0.6	6.98	12	13.5	0.39	N/A	0.46	0.43	0.35	0.42	0.44	0.43	0.40	0.39	0.36	0.33	0.28	0.23	0.17	0.12	0.04	0.06	0.06
Flame sensor location from ignition									0.07	0.67	1.43	1.60	2.69	3.50	4.40	5.50	6.50	7.00	8.00	8.60	9.27	10.00	10.26	11.50	12.01	12.50	13.40
L6	0.6	4.86	0.6	N_2	0.3	0.56	12	13.5	0.38	0.39	0.37	0.33	0.29	0.13	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
L7	0.6	4.87	0.6	N_2	0.3	6.05	12	13.5	0.43	0.42	0.41	0.42	0.34	0.35	0.19	0.09	0.07	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Flame sensor location from ignition									0.07	0.67	1.30	2.20	2.39	3.20	4.10	5.20	6.20	6.70	7.70	8.30	8.97	9.70	9.96	11.50	11.71	12.20	13.10
L8	0.6	4.93	0.6	N_2	3	5.80	9	13.2	0.35	0.29	0.31	0.30	0.32	0.31	0.31	0.29	0.31	0.31	0.29	0.32	0.34	0.31	0.36	0.36	0.35	0.33	0.09
L9	0.6	4.45	0.6	CO_2	3	3.59	9	13.2	0.39	0.36	0.39	0.38	0.37	0.36	0.33	0.27	0.20	0.13	0.05	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.10
L10	0.6	4.64	0.6	CO_2	3	5.67	9	13.2	0.33	0.32	0.26	0.22	0.20	0.07	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Flame sensor location from ignition									0.07	0.67	0.97	1.60	2.69	3.50	4.40	5.50	6.50	7.00	8.00	8.60	9.27	10.00	10.26	11.50	12.01	12.50	13.40
L11	0.6	4.97	0.3	CO_2	0.6	5.98	12	13.5	0.35	0.36	0.33	0.33	0.31	0.26	0.15	0.16	0.14	0.12	0.06	0.05	0.03	0.02	0.01	0.01	0.00	0.00	0.01
Flame sensor location from ignition									0.07	0.67	1.60	2.50	2.69	3.50	4.40	5.50	6.50	7.00	8.00	8.60	9.27	10.00	10.26	11.50	12.01	12.50	13.40
L12	0.6	4.99	0.9	N_2	3	5.94	9	13.5	0.35	0.34	0.34	0.26	0.27	0.17	0.08	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01

Figure 2 shows the results of Test L4, a blank test with a 0.6-m ignition section with no flammable section. The peak flame propagation was 95 m/s, comparable to the small-scale tests. One notable feature observed from the flame visualization and flame signals are the oscillatory flame in the duct. Such flame oscillation was also observed in small-scale tests. The oscillatory growing and decaying flame is in consistent with existing literatures such as Guénoche (1964) except that all previous literatures deal with a duct filled with flammable gas mixture for the whole length of duct. Comparing the flame visualization and flame signals with the recorded overpressure in the duct confirmed that the oscillatory flame as a result of oscillatory flow from flame propagation, volume expansion and overpressure generation. Before the flame was completely diminished, the expansion and outflow created subsequent vacuum which drawn downstream gas to back flow. The back flow created mixing in the ignition section and the remaining unburnt gases continued to burn. The cycle repeated until all the fuel in the ignition section was depleted.

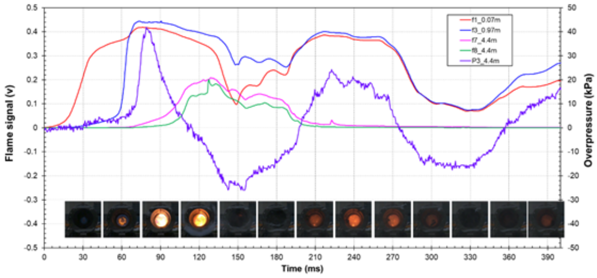

Figure 3: Results of flame visualization, flame signals and the recorded overpressure for Test L4.

An additional feature observed in Figure 3 is that the flame propagation was not uniform. Both flame sensors f7 and f8 located 4.4 m from the igniter but showed slight discrepancy in flame arrival time of 8.5 ms. The flame propagation speed calculated from nearby sensors is about 40 m/s. Therefore, the flame front spanned more than 0.34 m. It is expected that such a non-uniform flame front may easily penetrate a 0.3-m inert section and ignite the flammable section. The results as shown in Table 2 found that a 0.9-m nitrogen section gave a successful suppression as in Test L12 while a 0.6-m nitrogen section failed to suppress the flame and resulted in ignition in the flammable section as in Test L8.

Surprisingly, Test L10 and L11 showed that CO_2 successfully suppressed the flame propagation and prevented the ignition in the flammable section, with a 0.6-m and a 0.3-m inert section, respectively. Thus, the suppression by CO_2 is far more effective than that of nitrogen as the flame was not only isolated but also thermally quenched owing to the higher heat capacity of CO_2 (Chen et al., 2009).

In summary, the large-scale results do show that inertia isolation is possible although the effectiveness depends strongly on the non-uniformity of the flame front and speed of the flame propagation. The isolation suppression can be improved with the use of high heat capacity inert gas such as CO_2.

3.4 Implications for Responding Large Scale Leaks

The current study is limited to a fixed fuel concentration and some fixed lengths of ignition section giving a peak flame propagation speed of about 100 m/s. Certainly, the critical length for successful suppression in an open pipe may varied depending on the type of fuel, fuel concentration, the length of ignition section, and the peak flame propagation speed. Nevertheless, the short critical length required for suppression offer excellent opportunity for practical field application of suppression in large-scale flammable leak into a long duct.

In large-scale leaks of flammables into an underground duct such as the incidents described in Yang et al. (2016), the long trench was never sealed but was similar to the open duct as the current study. It is impossible to inert all the length of duct as the required inert gas can be excessive. To suppress the flame propagation, one simply need to inject the inert gas into the duct at fixed intervals. The best point of injection of inert gas will be the manhole to the underground trench. The length of the injected inert gas should be able to prevent the flame penetration from non-uniform flame propagation. In the present studies with a large duct of 0.49 m, the required length was found to be 0.9 m for N_2 and 0.3 m for CO_2. In actual field application with larger duct, the required inert length could be larger and appropriate safety factor should be applied. Injection of inert gas is however far easier than other explosion suppression methods such as water spray, water mist, dry power etc. All these suppression methods require continuing injection in order to maintain the effectiveness. Inert gas injection remained effective as long as the diffusion across the inert/fuel gas interface is insignificant.

4. Conclusions

Leak of flammables from a pipeline into a confined duct such as an underground trench has been a major safety issue across different countries. Upon ignition, flame and explosion propagated along the duct will create a significant impact to community and environment. The concept of suppressing flame propagation in a long duct was proposed via injecting an inert gas into the duct at multiple locations to act as inert gas sections which segregate the flammable mixture. The segregation limits the flame propagation to only one section without reaching nearby sections and thus prevents the successive ignition and flame propagation throughout the duct. The concept is demonstrated in a small duct and a large duct with peak flame propagation speed of 100 m/s. The critical length required for successful suppression of flame propagation is found to be 0.3 m for CO_2 and 0.9 m for N_2, which is considered practical in actual field response to leak of flammables into a long duct.

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