Full Paper

Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201300010

Performance of Unconfined Detonable Fuel Aerosols of Different Height to Diameter Ratios

Allam Apparao*[a] and Chillarige Raghavendra Rao[b]

Abstract: Unconfined fuel aerosols known as fuel air explosives (FAE) are detonable in nature over a wide range of fuel concentrations in air. The fuel aerosols are formed by dispersing the fuel in air by explosive means and detonated using a suitable initiator charge leading to the generation of a high impulse blast. For weapon applications, the designers aim for higher lethal area for damaging soft targets. Theoretical estimations have shown that aerosols of lower height to diameter ratio (H/D) produce higher blast pressures at longer distances, thereby enhancing lethal area. However, there is no experimental data available in the open literature to validate the theoretical findings. In this study two approaches were followed to generate detonable aerosols of different H/D, viz.; use of different burster charge loadings for a given fuel container known as canister and fuel quantity and use of different size canisters for the same fuel quantity and burster charge loading. The aerosols formed by a given size of canister and 4.2 kg propylene oxide with different burster charge loadings having similar H/D values and blast performance. In the second approach, a canister with lower H/D containing 18.5 kg propylene oxide generated aerosols of lower H/D and higher blast performance at longer distances as compared to that of a canister with higher H/D with the same fuel quantity. The better canister fragmentation and fuel dispersion observed for the canister of lower H/D has been attributed to the better utilization of burster charge energy as evident from theoretical estimation of the time period for completion of the burster charge detonation and shock wave travel to canister wall. The experimentally observed initial velocity of fuel dispersion was found to be in well agreement with the theoretically estimated values. The results indicate tailorability of blast performance for a given quantity of fuel by choosing the canister H/D.

Keywords: Canister · Fragmentation · Propylene oxide · Aerosols · Detonation

1 Introduction

Unconfined fuel aerosols known as fuel air explosives (FAE) are detonable in nature over a wide range of fuel concentrations in air. The fuel aerosols are formed by dispersing the fuel in air by explosives. They are detonated using a suitable initiator charge leading to the generation of a high impulse blast. These aspects were studied by various research groups because of their industrial and military applications [1–7]. In this study, propylene oxide was selected as the fuel. It was filled in a cylindrical metallic container known as "canister" having 24 longitudinal equispaced serrations and a central coaxial burster tube for placing the explosive charge. The central burster charge, on detonation, broke open the canister along the serrations and dispersed the fuel in the air thereby forming the detonable aerosol. The delayed action of the secondary initiator charge placed in the aerosol, detonated the cloud and produced a high impulse blast. The performance of detonated aerosol was measured in terms of blast peak overpressures at different distances. For optimum blast generation, the fuel should undergo complete combustion in the detonation process. Thus, the formation and detonation of unconfined fuel aerosol is a two event complex phenomenon, which thereby requires a number of experiments for optimizing the performance parameters. The formation of aerosol depends on canister design and burster charge whereas the aerosol detonation depends on time delay, type, and quantity of initiator charge. Moreover, the performance of fuel aerosol is also dependent on the aerosol height to diameter ratio (H/D).

Sedgwick et al. [8] had estimated theoretically the blast performances of different fuel aerosols with various H/D values for a similar quantity of fuel (136 kg) and found that the generation of blast pressures is strongly dependent on aerosol H/D. The theoretical POP values indicate that the aerosols of lower H/D produces higher blast pressures at longer distances but decays faster as compared to that of

[a] *A. Apparao*
Allam Apparao
High Energy Materials Research Laboratory, DRDO
Sutarwadi, Pune 411 021, India
Fax: + 91-91-020-25912316
**e-mail: aar_hem@gmail.com*

[b] *C. R. Rao*
Chillarige Raghavendra Rao
ACRHEM, University of Hyderabad
Hyderabad 500 046, India

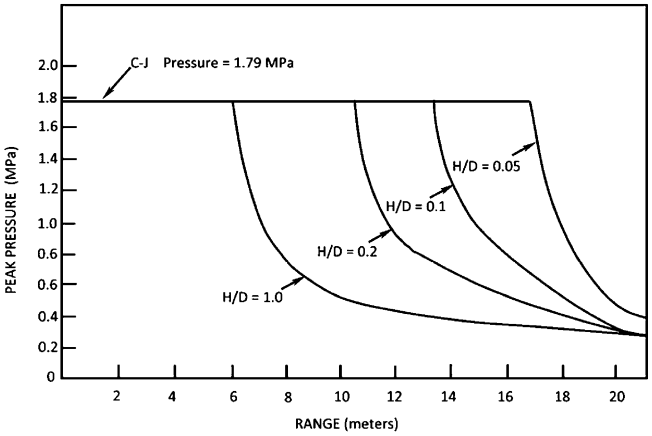

Figure 1. Estimated peak overpressure vs. distance for cylindrical aerosol of propylene oxide (136 kg) with different height to diameter ratios [8].

aerosols of higher H/D as shown in Figure 1. In military applications, the weapon designer is interested in getting higher blast pressures at longer distances so as to get more lethal area for damaging any specified soft targets. Hence, it is always preferable to have aerosols of lower H/D. However, the validation of these theoretical findings with experimental values has not been reported in the literature. It therefore, becomes necessary to study the formation of aerosols of different H/D values and evaluate their performances so that the system designer is able to choose suitable aerosol H/D for achieving the required damage criteria.

The parameters for fuel dispersion without ignition and aerosol formation were optimized separately [9]. In this study, attempts have been made to form aerosols of different H/D by following two approaches;

Approach 1: Use of different burster charge loadings (burster charge weight/surface area of canister) for a given size of canister and fuel quantity.

Approach 2: Use of canisters with different sizes but similar fuel quantities and burster charge loadings.

The formation of aerosols and their performances were experimentally determined and details are presented herein.

2 Experimental

2.1 Materials/Chemicals

Propylene oxide obtained from trade was used for the experiments due to wide range of explosive limits in air, high damage potential and high sensitivity to detonation [10]. Nitroguanidine (NQ) was used for the preparation of burster charge on account of low energetics and flashless nature [11]. RDX/wax (95/5) was used as initiator charge for detonability tests of the aerosols.

2.2 Preparation of Explosive Charges

The burster charges based on nitroguanidine were prepared by incremental filling method. Equal parts by weights of NQ powder were filled in burster tube and subjected to load after each addition so as to have a uniform loading density of 410 kg m^{-3}. RDX/Wax (95/5) pellets made with the help of hydraulic press (load-1500 kg) were used as initiators.

2.3 Design of Canister and Buster Tube

A canister made of mild steel having 24 equispaced longitudinal serrations and central coaxial burster tube was used for the experiments. Fuel was filled in the canister (Figure 2 and Figure 3) and the nitroguanidine based burster charge was kept inside the burster tube.

2.4 Formation of Aerosols and Detonation of 4.2 kg Propylene Oxide Fuel Using Different Burster Charge Loadings

Approach 1: a mild steel canister of 5 L capacity (ø = 180 × 225 × 1.6 mm) and burster tubes of different diameters were selected for the experiments. Aerosols were formed using NQ-based burster charge loadings varying from 0.2 to 1.0 kg cm^{-2} and were detonated after a preset time delay of 100 ms with the help of secondary initiator charge (100 g RDX/wax (95/5)). In these trials, the canister was placed on a MS stand of 2.0 m height whereas initiator charge was placed at 2.1 m height and 0.5 m away from the canister as shown in Figure 4. The events were record-

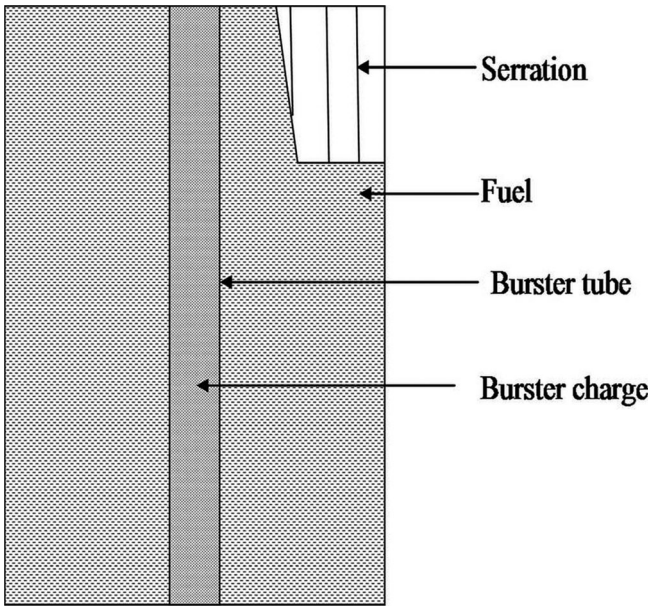

Figure 2. Canister with burster charge.

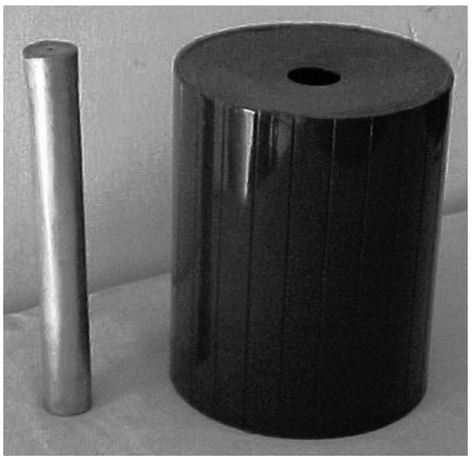

Figure 3. Canister and burster tube (fuel: 4.2 kg, dimension: ø = 180 × 225 × 1.6 mm).

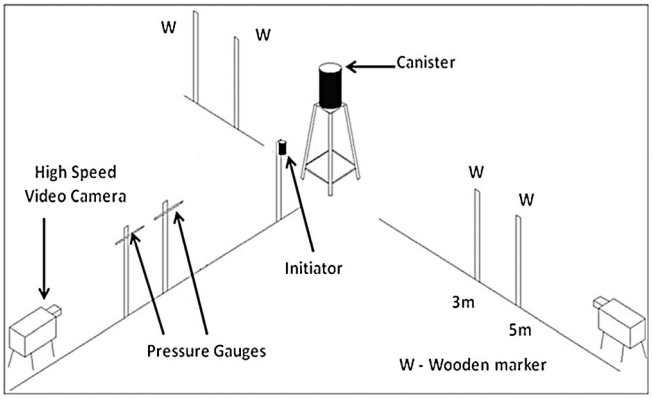

Figure 4. Experimental set-up for aerosol formation and detonation trials.

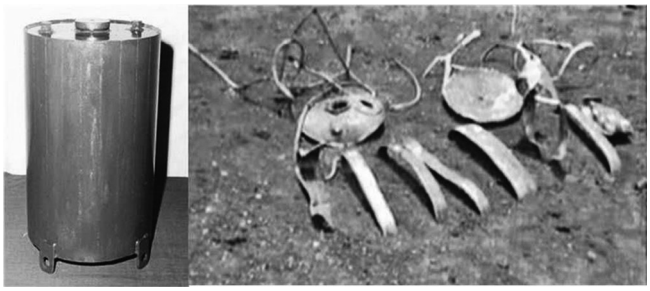

Figure 5. Canister with 1.5 H/D and the according fragmentation pattern (burster charge: 120 g NQ, burster charge loading: 0.33 kg m^{-2}).

ed using video cameras. Wooden markers were positioned on either side of the canister for measurement of aerosol dimensions at different time intervals using a video matrix system. The blast peak overpressures were measured using free field air blast transducers by placing at different distances from canister. The results of these trials are given in Table 1 and Table 2

Approach 2: Two types of MS canisters with a similar fuel capacity of 18.5 kg propylene oxide but with different H/D values were selected for studying the effect of canister H/D on aerosol H/D for a burster charge loading of about 0.3. The aerosol formation and detonation trials with both canisters were carried out using a similar experimental set-up as shown in Figure 4. In these trials, the canister was placed on a metallic stand of 2.0 m height and the initiator charge (200 g RDX/wax, 95/5) was kept at 2.2 m height and 1.0 m away from the canister. The aerosols were detonated after a time delay of 200 ms. Experimental details of the canisters along with the fragmentation patterns and aerosols formed are shown in Figure 5, Figure 6, Figure 7 and Figure 8. The results of the experiments are given in Table 3 and Table 4.

Table 1. Details of aerosols formed with different burster charge loadings for 4.2 kg propylene oxide. Canister: ø = 180 × 225 × 1.6 mm; burster charge: NQ.

Sl. No.	NQ [g]	Burster charge loading* [kg m^{-2}]	Aerosol dimensions		
			Diameter [m]	Height [m]	H/D
1	30	0.2	10.1	1.9	0.19
2	39	0.3	9.0	1.8	0.20
3	45	0.4	11.1	2.2	0.20
4	55	0.5	10.8	2.1	0.19
5	80	0.7	10.5	2.0	0.19
6	120	1.0	10.9	2.2	0.20

*Burster charge weight/surface area of canister.

Table 2. Blast performance of aerosols of 4.2 kg propylene oxide with different burster charge weight per unit surface area of canister. Canister dimension: ø = 180 × 225 × 1.6 mm; burster charge: NQ; initiator: 100 g RDX/wax (95/5); time delay: 100 ms.

Sl. No	NQ [g]	Burster charge loading* [kg m^{-2}]	Aerosol H/D	Blast peak overpressures [kPa]			
				5 m	7 m	9 m	11 m
1	39	0.3	0.20	113	67	40	40
2	55	0.4	0.19	98	63	55	41
3	80	0.7	0.19	97	71	49	45
4	120	1.0	0.20	136	64	41	34

*Burster charge weight/surface area of canister.

Table 3. Detailed data of aerosols of 18.5 kg propylene oxide.

Sl. no.	Canister			Burster charge [g]	Burster charge wt. per unit surface area of canister [kg m^{-2}]	Aerosol			Initial velocity of fuel dispersion [m s^{-1}]	
	Diameter [mm]	Height [mm]	H/D			Diameter [m]	Height [m]	H/D	Theoretical	Exptl.
1	275	415	1.50	120	0.33	19.4	2.05	0.10	143	125
2	220	650	2.95	143	0.32	13.3	2.50	0.19	140	103

Table 4. Blast performances of aerosols of 18.5 kg propylene oxide. Burster charge: NQ; initiator: 200 g RDX/wax (95/5); time delay: 200 ms.

Sl. no.	Canister H/D	Aerosol H/D	Blast peak over pressures [kPa]						
			5 m	6 m	7 m	8 m	9 m	10 m	11 m
1.	1.50	0.10	–	701.4	537.6	447.3	291.4	126.5	94.2
2	2.95	0.19	436.5	267.8	231.5	143.2	136.4	–	101.0

Figure 6. Canister with 2.95 H/D and the according fragmentation pattern (burster charge: 143 g NQ, burster charge loading: 0.32 kg m^{-2}).

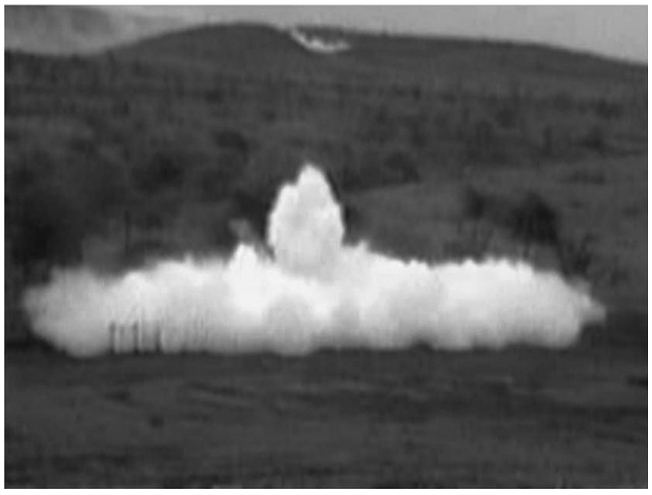

Figure 7. Aerosol formed for a canister with 1.5 H/D (fuel: 18.5 kg propylene oxide, burster charge: 120 g NQ, aerosol height: 2.05 m, diameter: 19.4 m, H/D: 0.10).

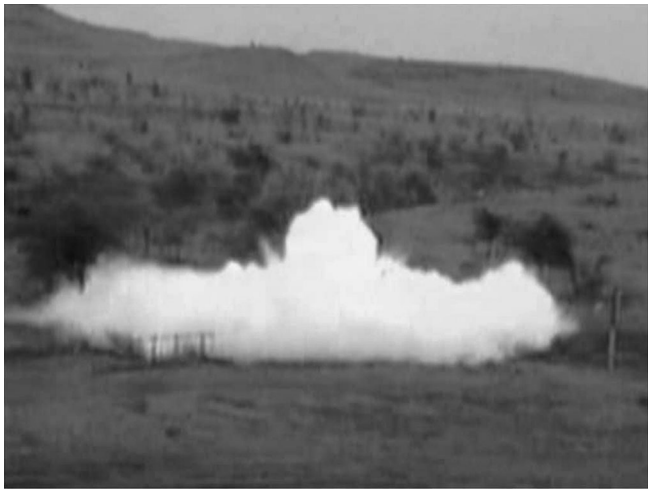

Figure 8. Aerosol formed for a canister with 2.95 H/D (Fuel: 18.5 kg propylene oxide, burster charge: 143 g NQ, aerosol height: 2.5 m, diameter: 13.3 m, H/D: 0.19).

3 Results and Discussion

3.1 Aerosols of 4.2 kg Propylene Oxide with Different Burster Charge Loadings

The results in Table 1 indicate that the aerosols formed with different burster charge loadings, viz.; 0.2, 0.3, 0.4, 0.5, 0.7 and 1.0, for 4.2 kg of propylene oxide do not have any significant change in the aerosol H/D as is also shown in Figure 9. It implies that the increase or decrease in burster charge quantity does not affect the aerosol size for a given canister and given quantity of fuel. It is also seen that the aerosols formed with burster charge quantities of 39, 55, 80 and 120 g have produced similar blast peak overpressures at each distance of 5, 7, 9 or 11 m as is evident from the results in Table 2. It is clear from the results that the detona-

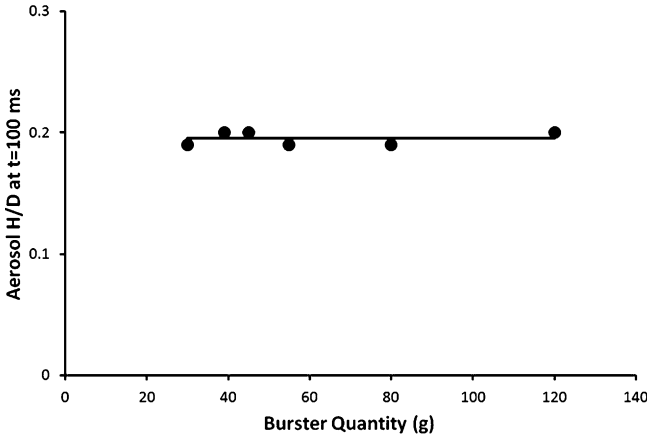

Figure 9. Effect of burster charge loading on aerosol H/D for 4.2 kg propylene oxide (canister dimension: 180×225×1.6 mm).

ble aerosols formed with different quantities of burster charge loadings have similar aerosol H/D values and produce similar blast performance for a given size of canister and fuel quantity.

3.2 Formation of Aerosols for Canisters with Different H/D Ratio

The fuel dispersion patterns for 18.5 kg of propylene oxide for canisters with H/D values of 1.5 and 2.95 are shown in Figure 10. The increase in radius of aerosol with time can be correlated with the forces acting on the fuel droplets as described by earlier researchers [6]. In the initial phase of dispersion, the explosive forces from the burster charge dominates resulting in the break-up of fuel into small droplets and accelerates them thereby causing rapid vaporization of the fuel droplets. Further, there will be a transition phase where the explosive forces on the fuel droplets are

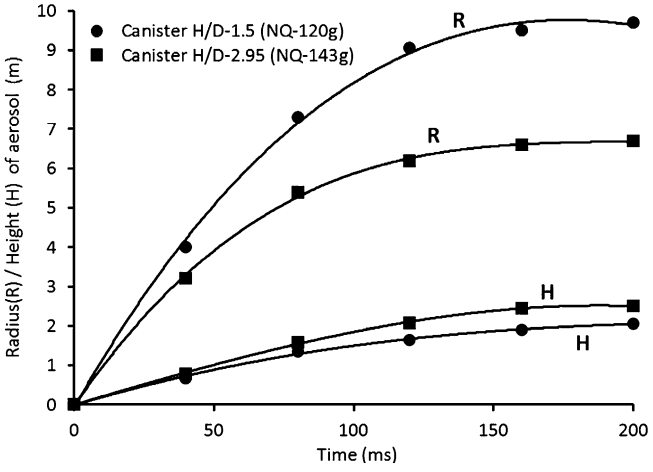

Figure 10. Fuel dispersion patterns of 18.5 kg propylene oxide for canisters with 1.5 and 2.95 H/D using similar NQ-based burster charge loadings.

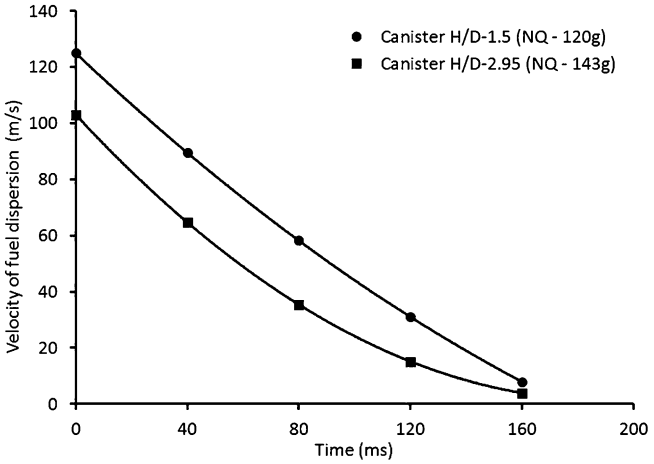

Figure 11. Dispersion velocities of 18.5 kg propylene oxide for canisters with 1.5 and 2.95 H/D using similar NQ-based burster charge loadings.

comparable with those of aerodynamic drag forces. In the final phase, the aerodynamic drag forces predominate resulting in deceleration of the fuel. A similar pattern is observed for the increase in height of aerosol with time. It can be seen from the results in Table 3 that the canister of lower H/D produced aerosol of lower H/D. Hence, the aerosol H/D is found to increase with the increase of canister H/D for 18.5 kg of propylene oxide.

The velocity of fuel dispersion (v)-time (t) data was generated for 18.5 kg propylene oxide using R-t data from Figure 11 by representing with polynomials and differentiating with respect to time. The v-t data is presented in Figure 11. The experimental values of initial velocities of fuel dispersion ($t=0$) for canisters with 1.5 and 2.95 H/D were found to be 125 and 103 $m\,s^{-1}$, respectively. The results indicate that the initial velocity of fuel dispersion is higher for the canister with lower H/D in spite of similar burster charge loadings for both canisters.

3.3 Theoretical Estimation of Initial Velocities of Fuel Dispersion for Canisters with Different H/D

Assuming that the behavior of propylene oxide is similar to that of water, the initial velocity of fuel dispersion due to burster charge detonation can be estimated by calculating the velocity of metallic plate of the canister by following the methods adopted in the case of underwater explosions and explosive working of metals [12,13]. The theoretical approach considers an infinite free metallic plate subjected to explosive loading through water medium. The explosive shock travels through the liquid column, impacts on plate and gets reflected resulting in motion of the plate in air. The initial velocity of fuel dispersion is correlated with the initial plate velocity. The plate velocity is given by Equation (1).

$$v_{plate} = [(2P_m)/(\rho_o c_o)]\ (\beta^{(1/(1-\beta))}),\ m\,s^{-1} \quad (1)$$

where ρ_o = density of water, 1000 kg m^{-3}; c_o = velocity of sound in water, 1500 m s^{-1}; $\beta = (\rho_o c_o\ \theta)/M$; θ = Time constant, s; $\theta = 10^{-4}(q)^{1/2}\ [r/(q)^{1/2}]^{0.45}$, s; M = mass of the plate, kg; P_m = underwater shock pressure, kPa and is given as $P_m = 72000[(q)^{1/2}/r]^{0.72}$, kPa; r = radius of canister, m; (0.137 m for a canister with 1.5 H/D and 0.110 m for a canister with 2.95 H/D); q = weight per unit length of burster explosive, kg m^{-1} (0.193 kg m^{-1} for a canister with 1.5 H/D and 0.147 kg m^{-1} for a canister with 2.95 H/D)

By using Equation (2), the plate velocities can be computed for both the canisters of 1.5 and 2.95 H/D with burster charges of 120 and 143 g of NQ respectively. The initial velocities of fuel dispersion represented by plate velocities are calculated to be 143 and 140 m s^{-1} for canisters of 1.5 and 2.95 H/D, respectively. It can be seen from Table 3 that the theoretical plate velocities are matching as expected because of the same burster charge loadings for both the canisters. However, the experimentally determined initial velocity of fuel dispersion for canister with 1.5 H/D (125 m s^{-1}) is very close to that of theoretical value (143 m s^{-1}). For canister with 2.95 H/D, large difference in theoretical and experimental values was observed. It can be presumed that the burster energy is not fully utilized for fragmentation and fuel dispersion for canister with 2.95 H/D.

3.4 Fragmentation Patterns of Canisters with Different H/D

The canister with 1.5 H/D fragmented into 11 to 14 pieces and the fragmentation was up to the full length of the serration (Figure 5). The canister with 2.96 H/D produced 6–8 fragments and each fragment was observed to have unseparated segments indicating that the segments were not completely fragmented up to the full length of serration but up to 35 to 70% of the total length (Figure 6). Hence, the fragmentation pattern for the canister with 1.5 H/D is found to be better as compared to that of the canister with 2.95 H/D for the same burster charge loading.

3.5 Blast Performances of Aerosols Formed with Canisters of Different H/D

The average blast peak over pressures measured at different distances for the aerosols of 18.5 kg propylene oxide formed with canisters of 1.5 and 2.95 H/D are shown in Table 4 and Figure 12. The results show that the aerosol of 0.1 H/D formed by canister with 1.5 H/D produced higher peak overpressures as compared to that of the aerosol with 0.19 H/D formed by canister with 2.95 H/D. From the blast profiles, it is also seen that the blast pressures of aerosol with 0.10 H/D decays faster as compared to that of aerosol with 0.19 H/D. These experimental observations confirm the theoretical findings of Sedgwick et al. [8] for 136 kg of propylene oxide aerosols with different H/D values

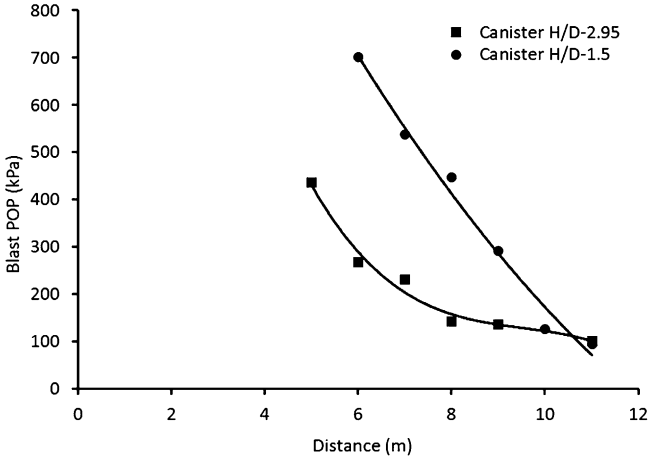

Figure 12. Blast performance of aerosols of 18.5 kg propylene oxide for canisters with 1.5 and 2.95 H/D.

(Figure 1). The results also indicate that the blast pressures can be tailored by varying canister H/D for the given quantity of fuel so as to achieve higher blast pressures at longer distances resulting in more lethal radius for a given soft target.

3.6 Theoretical Estimation of Time Durations for Burster Charge Detonation and Shock Wave Travel to Canister Wall

To understand the reasons for the differences observed in canister fragmentation, aerosol H/D and blast performance for the canisters with different H/D for the same burster charge loadings, time duration for completion of burster charge detonation (t_D) and time duration for the shock wave produced by burster charge to travel from center to canister wall (t_S) have been computed theoretically using Equation (2) and Equation (3).

$$t_D = L/VOD \quad (2)$$

L = length of burster charge, m; VOD = velocity of detonation of NQ (4350 m s^{-1});

$$t_S = r_c/U_s \quad (3)$$

r_c = Radius of canister, m (0.137 m for a canister with 1.5 H/D and 0.110 m for a canister with 2.95 H/D); U_s = Shock velocity at the canister wall, $U_s = a + b\ U_p$, m s^{-1} (a and b are constants where, $a = 1.647$ and $b = 1.921$ for water medium [11]). This results in Equation (4)

$$P_m = \rho_o U_s U_p,\ kPa \quad (4)$$

where U_p = Particle velocity, m s^{-1}; U_s = Shock velocity, m s^{-1}; The values of t_D and t_S were calculated using Equation (2) and Equation (3) respectively and presented in Table 5.

Table 5. Theoretically estimated time durations for completion of burster charge detonation and shock wave to reach canister wall. Fuel: 18.5 kg propylene oxide; burster charge: NQ (*VOD* = 4350 m s^{-1}).

Sl. No.	Height to diameter ratio of canister	Burster charge		Time duration	
		Length [mm]	Wt. [g]	t_D* [μs]	t_S** [μs]
1	1.50	409	120	94.0	75.0
2	2.95	644	143	148.0	60.0

*t_D – Time period for completion of burster charge detonation.** t_S – Travel Time for shock wave to reach the canister wall from burster charge.

The results indicate that the t_S and t_D for the canister with 1.5 H/D are similar (94 μs and 75 μs) and hence most of the burster energy from the burster charge is utilized for canister fragmentation and fuel dispersion. For the canister with 2.95 H/D, the value of t_D is higher than that of t_s (148 μs and 60 μs) indicating that the shock wave reaches the canister wall much earlier before the complete detonation of burster charge. Hence, it can be assumed that the complete energy of the burster charge is not available for canister fragmentation and fuel dispersion. This is in agreement with the results showing relatively poor fragmentation pattern and lower initial velocity of fuel dispersion for canister with 2.95 H/D as compared to that of canister with 1.5 H/D.

4 Conclusion

The following conclusions can be drawn from the above studies under given set of experimental conditions.

The detonable aerosols of 4.2 kg propylene oxide formed by a given size of canister with different burster charge loadings have similar H/D values and blast performance. It is not feasible to generate aerosols of different H/D increasing or decreasing the burster charge loading. Canisters with different H/D containing 18.5 kg propylene oxide can be used to generate aerosols of different H/D with different blast performance at longer distances. The canister with lower H/D utilized most of the burster charge energy and produced better canister fragmentation, fuel dispersion and blast performance. The initial velocities of fuel dispersion are in good agreement with the theoretically estimated velocities. The results indicate the tailorability of blast performance for a given quantity of fuel by choosing the canister H/D.

Acknowledgments

The authors are grateful to Director, HEMRL, Pune for his keen interest and encouragement during the course of this study. The support and help extended by Shri A. K. Vishwakarma, Dr. J. Saji and members of FAE Division and Inst. division of HEMRL and ACRHEM, UoH is also duly acknowledged.

References

[1] N. Eisenreich, H. Schneider, Possible Developments of Future Fuel Air Explosive Systems, *30th Int. Annual Conference of ICT, Karlsruhe*, Germany, June 29–July 2, **1999**, p. 107/1.
[2] D. C. Bull, M. A. McLeod, G. A. Mizner, Detonation of Unconfined Fuel Aerosols, in: *Gasdynamics of Detonations and Explosions, Progress in Astronautics and Aeronautics Series* (Eds.: J. R. Bowen, N. Manson, A. K. Oppenheim, R. I. Soloukhin), AIAA, New York, NY, USA, **1981**, p. 48.
[3] O. B. Kudryashova, B. I. Voroshtsov, E. G. Muravlev, I R. Akhmadeev, A. A. Pavlenko, S. S. Titov, Physicomathematical Modeling of Explosive Dispersion of Liquid and Powders, *Propellants Explos. Pyrotech.* **2011**, *36*, 524 – 529.
[4] Z. Qi, W. Kezhen, L. Aimin, W. Denggui, Q. Bin, Numerical Simulation on Dispersal Character of Fuel by Central HE, *Defence Sci. J.* **2007**, *57*, p. 425.
[5] M. Samirant, G. Smeets, Ch. Brass, H. Royer, L. R. Oudin, Dynamic Measurements in Combustible and Detonable Aerosols, *Propellants Explos. Pyrotech.* **1989**, *14*, 47 – 56.
[6] D. R. Gardner, *Near-Field Dispersal Modeling for Liquid Fuel-Air-Explosives*, Report No. SAND90–0686, Sandia National Laboratories, Albuquerque; NM, USA, **1990**.
[7] A. Apparao, Fuel Air Explosives, *Defence Sci. J.* **1987**, *37*, 23 – 28.
[8] R. T. Sedgwick, H. R. Kratz, Fuel Air Explosives: A Parametric Investigation, *10th Symposium on Explosives and Pyrotechnics*, San Francisco, CA, USA, February 14–16, **1979**, p. 33.1.
[9] A. Apparao, C. R. Rao, S. P. Tewari, Studies on Formation of Unconfined Detonable Vapour Cloud Using Explosive Means, *J. Hazard. Mater.* **2013**, *254*, 214–220.
[10] R. O. Kirk, T. John Dempsey, Propylene Oxide, in: *Kirk-Othmer Encyclopedia of Chemical Technology*, John Wiley & Sons, New York, NY, USA, **1980**, p. 246.
[11] W. E. Baker, P. A. Cox, P. S. Westine, J. J. Kulesz, R. A. Strehlow, *Explosion Hazards and Evaluation*, Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, **1983**, p. 110.
[12] R. H. Cole, *Underwater Explosions*, Princeton University Press, Princeton NJ, USA, **1948**, p. 87.
[13] P. W. Cooper, *Explosives Engineering*, VCH Publishers Inc., New York, **1996**, p. 189.

Received: January 25, 2013
Revised: July 25, 2013
Published online: September 19, 2013

