Article

Detonation velocity and pressure of the non-ideal explosive ANFO

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In order to obtain a better understanding of the non-ideal detonation characteristics of ANFO explosive (ammonium nitrate and fuel oil mixture), detonation velocity and pressure were measured in steel tubes simultaneously with ionization probes and piezo-resistive manganin gauges. Observed detonation velocity and peak pressure were compared with the theoretically predicted values obtained by the thermohydrodynamic CHEETAH code. Experimentally observed detonation parameters were determined as 60 to 72 % of the calculated detonation velocity and 42 to 58 % of the calculated detonation pressure. Furthermore the fraction reacted at the detonation front was estimated as 57 to 73 % of the calculated values for the ideal detonation.

KEYWORDS
Non-ideal detonation, Detonation velocity, Detonation pressure, ANFO, CHEETAH code

1. Introduction

Ammonium nitrate (abbreviated as AN, hereafter) and AN based explosives have been widely used as industrial explosives or energetic compositions such as ANFO, emulsion explosives or AN dynamite etc.. They are explosives known for its non-ideal detonation behaviour. This is shown, for example, by the detonation velocity which does not easily reach theoretically predicted values. Explosives behave non-ideally between the critical diameter (d_c) below which a steady detonation wave cannot be sustained, and the minimum diameter (d_m) above which the detonation is ideal. AN and AN based explosives are typical "non-ideal" explosive because they have large values for d_m and relatively small values for d_c. For most practical conditions they will never reach the ideal values as predicted by thermohydrodynamic theory[1].

It is the purpose of this investigation to obtain a better understanding of the non-ideal detonation behaviour of AN based explosives. In the previous papers we have reported the influence of the physical properties of AN on the detonation velocity of ANFO [2][3]. In this paper detonation velocity and pressure were measured in steel tubes simultaneously with ionization probes and piezo-resistive manganin gauges. Observed detonation velocity and pressure were compared with the theoretically predicted values calculated by the thermohydrodynamic CHEETAH code and non-ideal detonation behaviour was discussed.

2. Materials

The materials used in this study are listed in

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Table 1 Physical properties of AN used in this study.

Sample	Bulk density [kg/m^3]	Ave. particle diameter [mm]	Mode pore diameter [μm]	Total pore volume [cc/g]	Specific surf. area [cm^2/cm^3]
a	770	>1.40	9.1	0.167	19.1
b	790	1.10-1.18	7.6	0.136	26.3
c	820	<0.85	7.6	0.123	42.0

Table 1. Three kinds of AN were in a variety of 770 to 820 kg/m^3 in a bulk density and have the same physical properties but different only in particle diameter, which were obtained by sieving the same lot of AN. The purity of AN was more than 99% and the samples were treated with the anti-caking agent.

The mode pore diameter, the total pore volume were determined by the porosimeter with the mercury intrusion (pressurization) method with the assumption that the pore in the particle was cylindrical shape. In Table 1 the mode pore diameter is defined as the diameter which the relative frequency shows the maximum in the diameter vs. differential volume distribution. The specific surface area was calculated as the ratio of the surface area of the AN particle against the volume of the particle, and it neglects the surface area and volume of the pore in the AN particle.

In all tests ANFO composition were stoichiometric, i.e. 6 wt.% of No.2 fuel oil (commercially available gas oil for diesel engine) and 94 wt.% of AN. ANFO were prepared by mixing of AN and fuel oil, and placed at the room temperature for more than 24 hours before use.

3. Theoretical calculation

The ideal detonation parameters of ANFO were calculated by the thermohydrodynamic theory describing the state attained behind the detonation front. We used the CHEETAH code in combination with the BKW equation of state to calculate the Chapman-Jouguet parameters[4]. In the calculation of the C-J parameters of ANFO, n-Decane was used as the fuel oil. In the following sections the ratio of the experimentally observed detonation velocity and peak pressure to the theoretically calculated detonation parameters (D_{obs}/D_{cal}, P_{obs}/P_{cal}) are used to discuss the non-ideal detonation performance of ANFO[5].

The fraction reacted at the detonation front was also estimated with the CHEETAH code. We made calculation of the detonation parameters for the experimental loading density by assuming that a part of ANFO is reactive and the rest is non-reactive (inert).

4. Experimental

Fig.1 shows the experimental set-up for the detonation velocity and pressure measurements of ANFO in the steel tube. The steel tube used was made of JIS-G3454 equivalent and the inner and outer diameters were 35.5 mm and 42.7 mm respectively. The total length of the tube was 400 mm and the bottom of the tube was welded and closed with the same steel. 50 g of emulsion explosive (ρ=1160 kg/m^3, D=5.85 km/s, P~10 GPa) was used for the booster and initiated with the No.6 electric detonator.

In order to measure the stable detonation velocity four ionization probes were mounted at each 50 mm from the bottom plate and the detonation velocity was calculated by the distance of the probes and the arrival time difference of the shock wave. As the accuracy of the detonation velocity measurement is considered as within 3 %, the experimentally observed detonation velocity was determined with the accuracy of 0.05 km/s step.

Pressure profile was recorded with the commercially available piezo-resistive manganin gauge (Dynasen, MN4-50-EK). To minimize the short-circuiting effect we used a 5 mm PMMA gap between AN and the gauge. Peak pressures were determined by the correction using preliminary obtained shock attenuation relation of PMMA and impedance mismatch technique[6]. As the accuracy of the pressure measurement is considered as within 5%, the experimentally observed peak

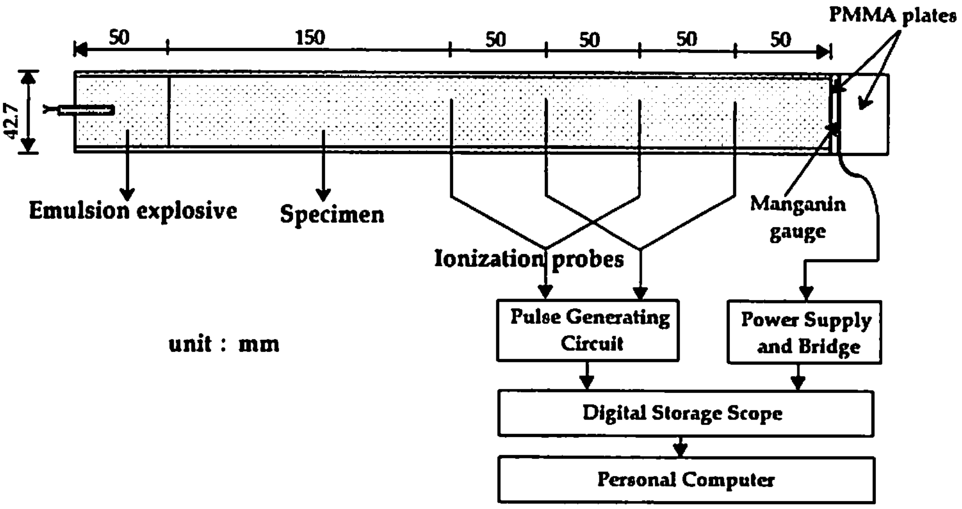

Fig. 1 Experimental set-up of detonation velocity and pressure measurement of ANFO using ionization probes and manganin gauge

Table 2 Experimentally observed and calculated detonation properties and estimated fraction reacted of detonating ANFO.

Sample	Loading density [kg/m³]	D_{obs} [km/s]	D_{cal} [km/s]	D_{obs}/D_{cal} [-]	E.F.R. [-]	P_{obs} [GPa]	P_{cal} [GPa]	P_{obs}/P_{cal} [-]	E.F.R. [-]
A-1	895	2.95	4.95	0.60	0.57	2.4	5.58	0.43	0.62
A-2	900	3.00	4.98	0.60	0.58	2.4	5.69	0.42	0.62
B-1	890	3.35	4.94	0.68	0.64	3.0	5.53	0.54	0.67
B-2	900	3.30	4.98	0.66	0.65	2.9	5.69	0.51	0.68
C-1	925	3.65	5.07	0.72	0.69	3.5	6.01	0.58	0.71
C-2	940	3.65	5.12	0.71	0.70	3.6	6.19	0.58	0.73

pressure was determined with the accuracy of 0.1 GPa step.

5. Results and discussions

The measured detonation parameters of ANFO are shown in Table 2 with calculated values. In this table the capital letters of the sample name (A, B, C) indicate the sample ANFO prepared with the AN given in Table 1 with the lower case (a, b, c). Two or more shots were carried out in the same condition and a stable detonation was observed in all shot and the ratio to the calculated value (D_{obs}/D_{cal}, P_{obs}/P_{cal}) were determined.

5.1 Influence of the physical properties of AN on the detonation parameters of ANFO

Detonation velocity and pressure showed a good reproducibility in each condition and detonation velocity and pressure increased with the decrease of the particle diameter i.e. with the increase of the specific surface area. Detonation velocity increased from 2.95 to 3.65 km/s, and the ratio of the observed detonation velocity to the calculated value (D_{obs}/D_{cal}) increased from 60 to 72 %. Peak pressure increased from 2.4 to 3.6 GPa, and P_{obs}/P_{cal} increased from 42 to 58 %. On the basis of the approximate classical detonation theory the C-J pressure is proportional to the square of the C-J velocity as given by;

$$P_{CJ} = [\rho_o / (\gamma+1)]\ D_{CJ}^2 \qquad (1)$$

where, P_{CJ} : C-J pressure, ρ_o : initial density, γ : adiabatic exponent of gas products, D_{CJ} : C-J velocity.

As indicated by Eqn (1), the square values of D_{obs}/D_{cal} are in reasonable agreement with P_{obs}/P_{cal} values.

5.2 Non-ideal detonation behaviour of ANFO

As shown in Table 2, the fraction reacted at the detonation front of ANFO was estimated with the CHEETAH code for each experimental detonation velocity and pressure by assuming that a part of

Table 3 Experimentally determined and calculated γ values.

Sample	Loading density [kg/m^3]	D_{obs} [km/s]	P_{obs} [GPs]	γ_{exp} [-]	γ_{cal} [-]
A-1	895	2.95	2.4	2.24	2.93
A-2	900	3.00	2.4	2.37	2.92
B-1	890	3.35	3.0	2.33	2.93
B-2	900	3.30	2.9	2.38	2.92
C-1	925	3.65	3.5	2.52	2.96
C-2	940	3.65	3.6	2.48	2.98

ANFO is non-reactive. The estimated fraction reacted (E.F.R.) increased with the increase of detonation velocity and pressure and the values were in a range of 57 to 73 %. These values show the coincidence with the calculation done by Mader[7]. E.F.R. of detonation velocity showed a good agreement with D_{obs}/D_{cal} values in each sample. While E.F.R. of pressure didn't show an agreement with P_{obs}/P_{cal} values. It is considered that the detonation velocity increases as a linear function of energy release at the detonation front and the detonation pressure does not increase as a linear but some other function such as a square of energy release. Further investigation is needed for more detailed discussion.

Table 3 shows the γ values of each experimental condition obtained by Eqn (1). In this table γ_{exp} is determined with observed detonation parameters and γ_{cal} is obtained as ideal detonation value with CHEETAH code. It is well known that γ of common high explosives usually shows in a range between 2.8 and 3.2, and γ_{cal} of ideal detonation also lies in this region. γ_{exp} of ANFO increased with the decrease of the particle diameter and with the increase of D_{obs}/D_{cal} and P_{obs}/P_{cal} values. Although γ_{exp} values lie in a range between 2.2 and 2.5 in experimental condition of this work, it is considered to be larger value when the detonation becomes more ideal, such as with larger diameter or with a stronger confinement[8]. It is concluded that γ value is a simple but useful index of the non-ideality of detonation.

6. Conclusions

From the detonation velocity and pressure measurement of ANFO prepared with three kinds of ammonium nitrate which had different particle size, following conclusions can be drawn:

[1] The detonation parameters increased with the decrease of the particle diameter, i.e. the increase of the specific surface area, and the highest values were observed as 3.65 km/s and 3.6 GPa for the smallest particle diameter. The values were corresponded to 72 and 58 % of the calculated values for ideal detonation with CHEETAH code.

[2] The fraction reacted at the detonation front was estimated as 57 to 73 % of the ideal detonation values by assuming that a part of ANFO was non-reactive.

[3] The γ value of each experimental condition was determined as 2.2 to 2.5 and it could be a simple but useful index of non-ideality of detonation.

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