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Blast Effects Evaluation Using TNT Equivalent

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This paper shows blast parameters of high explosives commonly used in explosive ordnance of Serbian armed forces regarding TNT equivalents. Primary blast wave parameters, overpressure, impulse and positive phase duration are calculated using modified Sadovskiy equations and the modified K-B equation. TNT equivalents of the observed explosives are determined using thermochemical calculations based on BKW EOS parameters. The calculated blast wave parameters show significant influence of used explosives concerning the TNT equivalent.

Key words: **explosive materials, physics of explosion, blast wave, blast wave effect, thermochemical calculation, TNT equivalent, equation of state, Sadovskiy equations.**

Introduction

AFTER the detonation occurs, the ambient pressure increases almost instantaneously and promptly begins to decay, forming a nearly triangular overpressure pulse. The peak pressure is called the peak positive overpressure. It represents the pressure seen at a point in space when the shock wave is unimpeded in its motion. The duration of the positive overpressure is called the positive phase. The peak overpressure and positive phase duration determine the specific impulse of the blast wave. All three blast wave parameters influence the property damage and injury that the blast wave can cause. All parameters need to be specified as some materials can resist rapid high level blast, but will fail as the duration is extended. Also, there exists a negative phase that succeeds the positive phase with its negative pressure (suction), negative phase duration and the specific impulse. These parameters are six main blast wave parameters. In addition, there are secondary blast parameters which can be determined from the primary blast wave parameters. These are: peak reflected pressure, peak dynamic pressure, shock front velocity, blast wave length, etc. [1].

The well-known Sadovskiy equations are used for blast parameters determination (overpressure, positive phase duration and impulse). Only the first equation, for blast pressure determination, is modified according to the experimental work [2, 3].

$$\Delta p_m = 1.02\frac{q^{1/3}}{r} + 4.36\frac{q^{2/3}}{r^2} + 14\frac{q}{r^3} \text{ (bar)} \quad (1)$$

$$\tau = 1.2\sqrt[6]{q}\sqrt{r} \text{ (ms)} \quad (2)$$

$$I = 200\frac{q^{2/3}}{r} \text{ (Pa·s)} \quad (3)$$

Where q is the explosive mass in kg and r is the distance in *m*.

The modified Kingery-Bulmash (K-B) equation (modified by the US DoD) for blast pressure and impulse determination using scaled distance is shown in eq.(4) [4].

$$P, I = \exp\left(A + B\ln Z + C(\ln Z)^2 + D(\ln Z)^3 + E(\ln Z)^4\right) \quad (4)$$

Where pressure is in kPa, impulse in Pa·s/kg$^{1/3}$, Z is in m/kg$^{1/3}$ and A, B, C, D and E empirical coefficients.

Using these equations for TNT charges shows good correlation comparing to experimental data [3]. But for other explosives they must be modified using the TNT equivalent obtained through thermochemical calculations based on BKW EOS [5, 6]. The thermochemical calculation of TNT equivalents offers possibility of obtaining very reliable values of detonation characteristics without extensive experimental work.

Determination of TNT equivalent of observed explosives

The proposed method for obtaining TNT equivalents is based on equation (5) and shows a very good correlation comparing to experimental data [3].

$$\Theta = \frac{(P + 20.9)}{40} \quad (5)$$

Where Θ is sign for a TNT equivalent and P is detonation pressure in GPa.

The values of TNT equivalents of CHNO type high explosives (HE) mainly represented in Serbian armed forces using eq. (5) are given in the Table 1.

Table 1. TNT equivalents of observed CHNO type (HE)

Explosive	Density ρ [g/cm^3]	Detonation pressure (calc.) P [GPa]	TNT equivalent Θ
TNT	1.60	19.13	1
Cyclotol 50/50	1.68	25.93	1.17
Cyclotol 60/40	1.70	26.59	1.19

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Octol 90/10	1.81	33.85	1.37
FH 5*	1.65	27.80	1.22
FO 3**	1.78	32.97	1.35
PPE-01***	1.50	24.25	1.13

Remarks: * Phlegmatized RDX
** Phlegmatized HMX
*** Plastic explosive based on PETN and polyurethane binder

Blast effects

Blast effects of blast wave parameters are well documented and subsequent calculations can be compared to them pointing out that even a small increase in blast wave parameters can generate more severe damage to personnel and structures.

Typical explosive ordnance containing CHNO HE in Serbian armed forces are shown in Table 2 [7].

Table 2. Typical explosive ordnance containing observed HE

Explosive ordnance	Explosive charge	Mass of HE (kg)
MINE, AT TMRP-6	TNT	5.20
PROJ, 122 mm HE M76	Cyclotol 50/50	3.53
RCKT, 90 mm HEAT M79	Cyclotol 60/40	0.75
PROJ, 125 mm HEAT BK-14M	Octol 90/10	1.85
PROJ, 125 mm HEAT M88	FH 5	1.75
RCKT WHD, 9M37M	FO 3	2.60
CHG, Demolition block PEP-500	PPE-01	0.50

As an example, for further calculations, a mass of 5 kg of explosive charge was taken, though equations and calculations are applicable for any mass. Positive phase blast wave parameters for the observed explosives can be determined using modified Sadovskiy equations taking into account TNT equivalent [3, 8].

$$\Delta p_m = 1.02\frac{(\Theta q)^{1/3}}{r} + 4.36\frac{(\Theta q)^{2/3}}{r^2} + 14\frac{\Theta q}{r^3} \tag{6}$$

$$\tau = 1.2\sqrt[6]{\Theta q}\sqrt{r} \tag{7}$$

$$I = 200\frac{(\Theta q)^{2/3}}{r} \tag{8}$$

Where k_1 = 1.02, k_2 = 4.36, and k_3 = 14 are the coefficients for TNT, as well as 1.2 and 200 in subsequent equations. The calculated coefficients for other observed explosives are given in Table 3.

Table 3. Calculated coefficients for Sadovskiy equations

Explosive	Δp_m			τ	I
	k_1	k_2	k_3		
TNT	1.02	4.36	14	1.2	200
Cyclotol 50/50	1.07	4.84	16.38	1.23	222
Cyclotol 60/40	1.08	4.90	16.66	1.24	225
Octol 90/10	1.13	5.38	19.18	1.26	247
FH 5	1.09	4.98	17.08	1.24	228
FO 3	1.13	5.33	18.90	1.26	244
PPE-01	1.06	4.73	15.82	1.22	217

Using 5 kg of high explosive not considering the influence of confinement and reflected shock waves, the positive blast wave parameters have been calculated at distances of 5, 7.5, 10, 15 and 20 m, due to the correlation with the experimental work [3]. A scaled distance could not be used due to the fact that the positive phase duration and the impulse do not depend entirely upon it like overpressure in Sadovskiy equations. The results of these calculations are presented in Tables 4-6.

Table 4. Calculated blast wave overpressure (bar) for the observed explosives

Explosives	*r* (m)				
	5	7.5	10	15	20
TNT	1.42	0.63	0.37	0.19	0.1278
Cyclotol 50/50	1.59	0.69	0.41	0.21	0.1375
Cyclotol 60/40	1.61	0.70	0.41	0.21	0.1386
Octol 90/10	1.78	0.77	0.45	0.23	0.1482
FH 5	1.64	0.71	0.42	0.21	0.1402
FO 3	1.76	0.76	0.44	0.23	0.1471
PPE-01	1.55	0.68	0.40	0.21	0.1353

Table 5. Calculated positive phase duration (ms) for the observed explosives

Explosives	*r* (m)				
	5	7.5	10	15	20
TNT	3.51	4.30	4.96	6.08	7.02
Cyclotol 50/50	3.60	4.41	5.09	6.24	7.20
Cyclotol 60/40	3.61	4.42	5.11	6.26	7.22
Octol 90/10	3.70	4.53	5.23	6.41	7.40
FH 5	3.63	4.44	5.13	6.28	7.25
FO 3	3.69	4.52	5.22	6.39	7.38
PPE-01	3.58	4.39	5.06	6.20	7.16

Table 6. Calculated blast wave impulse (Pas) for the observed explosives

Explosives	*r* (m)				
	5	7.5	10	15	20
TNT	117	78	58	39	29
Cyclotol 50/50	130	87	65	43	32
Cyclotol 60/40	131	88	66	44	33
Octol 90/10	144	96	72	48	36
FH 5	134	89	67	45	33
FO 3	143	95	71	48	36
PPE-01	127	85	63	42	32

Using the modified K-B equation and taking into account TNT equivalent, the calculated pressure and the impulse regarding the scaled distance is shown in Table 7.

Table 7. Calculated blast wave pressure (kPa) and impulse (Pas/kg$^{1/3}$) for the observed explosives using the K-B equation

Explosives		*Z* (m/kg$^{1/3}$)				
		2.92	4.39	5.85	8.77	11.70
TNT	*p*	122	54.6	33.2	17.9	12.1
	I	94.7	66.7	51.4	35.2	26.7
Cyclotol 50/50	*p*	137	60.2	36.2	19.3	12.9
	I	98.9	69.9	53.9	36.9	28.1
Cyclotol 60/40	*p*	139	60.8	36.5	19.4	13.0
	I	99.3	70.3	54.2	37.1	28.2
Octol 90/10	*p*	154	66.5	39.5	20.8	13.9
	I	103	73.2	56.6	38.8	29.5
FH 5	*p*	141	61.8	37.0	19.7	13.2
	I	100	70.8	54.6	37.4	28.5
FO 3	*p*	152	65.9	39.2	20.7	13.8
	I	103	72.9	56.3	38.6	29.4
PPE-01	*p*	133	58.9	35.5	18.9	12.7
	I	97.9	69.2	53.4	36.5	27.8

Due to simple comparison between the data obtained using Sadovskiy and K-B equations, the pressure calculated via the K-B equation divided by 100 gives a value in bar, and the impulse multiplied by the cubic root of the explosive charge mass (in this example by 1.71) gives a value in Pa·s.

The comparison between the blast wave overpressure values of the observed explosives calculated using Sadovskiy equation and TNT shows that the increase is significant and it is shown in Table 8.

Table 8. Increase of the blast wave overpressure values of the observed explosives in relation to TNT in %

Explosives	*r* (m)	
	5	10
Cyclotol 50/50	12.0	9.5
Cyclotol 60/40	13.4	10.6
Octol 90/10	25.7	21.6
FH 5	15.5	13.5
FO 3	24.0	19.0
PPE-01	9.20	7.30

For the positive phase duration and the blast wave impulse calculated using Sadovskiy equations the increase in values does not depend on distance. Tables 9 and 10 show the increased values in %.

Table 9. Increase of the positive phase duration values of the observed explosives in relation to TNT in %

Explosives	Increase
	%
Cyclotol 50/50	2.65
Cyclotol 60/40	2.94
Octol 90/10	5.39
FH 5	3.37
FO 3	5.13
PPE-01	2.06

Table 10. Increase of the blast wave impulse values of the observed explosives in relation to TNT in %

Explosives	Increase
	%
Cyclotol 50/50	11.03
Cyclotol 60/40	12.30
Octol 90/10	23.35
FH 5	14.18
FO 3	22.15
PPE-01	8.489

The comparison between the blast wave overpressure and impulse values of the observed explosives calculated using the modified K-B equation and TNT shows the increase in values shown in Table 11.

Table 11. Increase of the blast wave overpressure and the impulse values of the observed explosives in relation to TNT using the K-B equation in %

Explosives		Z (m/kg$^{1/3}$)	
		2.92	5.85
Cyclotol 50/50	*p*	12.0	9.05
	I	4.40	4.93
Cyclotol 60/40	*p*	13.4	10.1
	I	4.88	5.48
Octol 90/10	*p*	25.8	19.2
	I	8.96	10.1
FH 5	*p*	15.5	11.6
	I	5.60	6.28
FO 3	*p*	24.4	18.2
	I	8.53	9.62
PPE-01	*p*	9.21	6.96
	I	3.41	3.82

Conclusion

Difficulties in obtaining values of TNT equivalent through experimental methods exist because extensive experimental research is often required. Using a method based on thermochemical calculations TNT equivalent can be obtained in a quite simple, but reliable and accurate manner. The method presented in this paper shows differences between the blast wave parameters calculated taking into account TNT equivalent, which are significant and of the utmost importance regarding ammunition and explosive safety issues.

It has been shown that the increase in blast wave overpressure values using a modified Sadovskiy equation is higher at smaller distances especially for Octol where the increase at 5 m distance is 25.7%, and at the 100 m distance is 12%. In reality, due to reflected shock waves, the increase can be a great deal higher. The reflected shock waves actually increase the values of positive phase duration and the blast wave impulse as well, contrary to confinement which has the opposite influence. Neither of these influences was considered during these calculations and they are going to be a part of future work.

The increase in the positive phase duration is rather low, only 2.06-5.39%, but is significant because it directly causes the increase in blast wave impulse values which are, as it is showed, between 8.489 and 23.35% (at 5 m), calculated using a modified Sadovskiy equation.

The comparison between the values calculated via the modified K-B and the modified Sadovskiy equation shows significant differences, but relative increase is very similar regarding the blast wave pressure. The blast wave impulse values calculated using different equations show different trends and dissimilar values. The increase in the blast wave pressure values is between 9.21 and 25.8% (at 5 m), and in the blast wave impulse values is between 3.41 and 8.96% (at 5 m).

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Ocena rušećeg dejstva primenom TNT ekvivalenta

U ovom radu su date razlike između vrednosti parametara udarnog talasa kod eksplozivnih materija koje su uglavnom zastupljene u ubojnim sredstvima srpskih oružanih snaga. Osnovni parametri udarnog talasa, nadpritisak, impuls i trajanje pozitivne faze su izračunati korišćenjem modifikovanih jednačina Sadovskog i modifikovane K-B jednačine uzimajući u obzir TNT ekvivalent. TNT ekvivalent posmatranih eksplozivnih materija je određen pomoću termohemijskih proračuna zasnovanih na parametrima jednačina stanja po BKW. Izračunati parametri udarnog talasa pokazuju da postoji značajan uticaj vrste eksplozivne materije, uzimajući u obzir TNT ekvivalent.

Ključne reči: **eksplozivne materije, fizika eksplozije, udarni talas, rušeće dejstvo, termohemijski proračun, TNT ekvivalent, jednačina stanja, jednačina Sadovskog.**

Оценка взрывчатого действия при применении ТНТ-эквивалента

Основное намерение этой работы показать разницы между значениями параметров ударной волны у взрывчатых веществ, которые в основном находятся в употреблении в боевых средствах сербских Вооружённых Сил. Главные параметры ударной волны, избыточное давление, импульс и продолжительность положительной фазы вычислены при пользовании модифицированных уравнений Садовского и модифицированного К-Б уравнения учитывая ТНТ-эквивалент. ТНТ-эквивалент рассматриваемых взрывчатых веществ определён при помощи термохимических расчётов обоснованых на параметрах уравнений состояния по BKW. Вычисленные параметры ударной волны указывают, что существует значительное влияние типа взрывчатого вещества учитывая ТНТ-эквивалент.

Ключевые слова: **Взрывчатые вещества, физика взрыва, скачок уплотнения (ударная волна), взрывчатое действие, термохимический расчёт, ТНТ-эквивалент, уравнение состояния, уравнение Садовского.**

L’évaluation du souffle à l’aide de l’équivalent TNT

L’intention principale de ce papier est de présenter les différences existantes parmi les valeurs des paramètres chez l’onde de choc pour les matières explosives qui sont représentées dans les moyens de combats des Forces armées de Serbie. Les paramètres principaux de l’onde de choc – surpression, impulsion et la durée de la phase positive – ont été calculés au moyen des équations modifiées de Sadovski ainsi que à l’aide des équations modifiées K-B , considérant TNT équivalent aussi. L’équivalent TNT des matières explosives étudiées a été déterminé par les calculs thermochimiques basés sur les paramètres des équations de l’état selon BKW. Les paramètres de l’onde de choc calculés démontrent qu’il existe une influence signifiante des matières explosives utilisées considérant l’équivalent TNT.

Mots clés: **matières explosives, physique de l’explosion, onde de choc, effet brisant, calcul thermochimique, équivalent TNT, équation d’état,équation de Sadovski.**