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NEW EQUATION FOR DETERMINATION OF OVERPRESSURE OF FUEL-AIR MIXTURE BLAST

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НОВОЕ УРАВНЕНИЕ ДЛЯ ОПРЕДЕЛЕНИЯ ИЗБЫТОЧНОГО ДАВЛЕНИЯ ВЗРЫВА ТОПЛИВОВОЗДУШНЫХ СМЕСЕЙ

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TNO, Dorofeev, Rostechnadzor, Gosatomnadzor, EMERCOM of Russia, BS, BST, blast overpressure, reduced distance, Sachs’s parameter, detonation, deflagration, explosion of fuel-air mixture, multi-energy method TNO, forecasting.

The problems of assessing the consequences of fuel-air mixtures and their prevention are topical and of practical interest. Such the explosions pose a real danger during processing, transportation and storage of fuels at various industrial and civil facilities. Forecast of possible consequences of explosions of fuel-air mixtures is a key element in development of protective measures. Today, various calculation methods have been developed and approved by different departments and organizations. The authors of the article have previously verified methods of Gosatomnadzor (RB G-05-039-96), Rostechnadzor (RD 03-409-01, PB 09-540-03, Method for assessment of consequences of accidental explosions of fuel-air mixtures, General explosion safety rules for explosive chemicals, petrochemicals and refineries), EMERCOM of Russia (GOST R 12.3.047-98, GOST R 12.3.047-2012, SP 12.13130.2009), Netherlands Organisation for Applied Scientific Research, Dorofeev, Baker-Strehlow and Baker-Strehlow-Tang for prediction of consequences of air-fuel mixture explosions at the example of real explosions. It is established that the detonation regime is best described by the Dorofeev's method and multi-energy method of Netherlands Organisation for Applied Scientific Research (ME-TNO) for deflagration regime. Thus, it is promising to create a synthesis method that could combine approaches of the methods. Detonation mode was picked out using the ME-TNO method and replaced by Dorofeev's method. Such a technique allowed proposing a new equation for predicting explosion pressure of fuel-air mixtures: $\Delta P = P_0\left(a + \frac{b}{R_x} + \frac{c}{(R_x)^2} + \frac{d}{(R_x)^3} + \frac{e}{(R_x)^4} + \frac{f}{(R_x)^5} + \frac{g}{(R_x)^6} + \frac{h}{(R_x)^7}\right)$, where P_0 is atmosphere pressure, R_x is reduced distance (Sachs’s parameter), *a–h* are empirical constants that depend on the class of blast transformation. As a result of the research, a new equation is proposed. An equation allows calculating the overpressure of explosion, which more accurately predicts the consequences of fuel-air explosions at petroleum and gas, petrochemical and chemical industries.

Ключевые слова:
TNO, Дорофеев, Ростехнадзор, Госатомнадзор, МЧС России, BS, BST, избыточное давление взрыва, приведенное расстояние, параметр Сахса, детонация, дефлаграция, взрыв топливовоздушной смеси, мультиэнергетический метод TNO, прогнозирование.

Проблемы оценки последствий взрывов топливовоздушных смесей и их предупреждения являются злободневными и имеют практический интерес. Эти взрывы представляют реальную опасность при переработке, транспортировке и хранении топлив на различных промышленных и гражданских объектах. Прогнозирование возможных последствий взрывов топливовоздушных смесей является основным элементом в разработке защитных мероприятий. В настоящее время различными ведомствами и организациями разработаны и утверждены разные расчётные методики. Ранее авторами была проведена верификация методов Госатомнадзора (РБ Г-05-039-96), Ростехнадзора (РД 03-409-01, ПБ 09-540-03, Методика оценки последствий аварийных взрывов топливо-воздушных смесей, Общие правила взрывобезопасности для взрывоопасных химических, нефтехимических и нефтеперерабатывающих производств), МЧС России (ГОСТ Р 12.3.047-98, ГОСТ Р 12.3.047-2012, СП 12.13130.2009), Нидерландской организации прикладных научных исследований (TNT, ME-TNO), Дорофеева, Бейкера–Стрелоу и Бейкера–Стрелоу–Танга для прогнозирования последствий взрывов топливовоздушных смесей на примере реальных взрывов. Установлено, что режим детонации лучше всего описывает метод Дорофеева, а режим дефлаграции мультиэнергетический метод Нидерландской организации прикладных научных исследований (ME-TNO). Таким образом, создание синтез-метода, в котором сочетались бы подходы этих методик, является перспективным направлением. Из метода ME-TNO был вычленен режим детонации и заменен методикой Дорофеева. Данный прием позволил предложить новое уравнение для прогнозирования давления взрыва топливовоздушных смесей, которое описывается следующей формулой: $\Delta P = P_0\left(a + \frac{b}{R_x} + \frac{c}{(R_x)^2} + \frac{d}{(R_x)^3} + \frac{e}{(R_x)^4} + \frac{f}{(R_x)^5} + \frac{g}{(R_x)^6} + \frac{h}{(R_x)^7}\right)$, где P_0 – атмосферное давление; R_x – приведенное расстояние (параметр Сахса); *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h* – эмпирические константы, зависящие от класса взрывного превращения. В результате проведенного исследования предложено новое уравнение для расчета избыточного давления взрыва, которое более точно прогнозирует последствия взрывов топливовоздушных смесей на объектах нефтегазовой, нефтехимической и химической отраслей промышленности.

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Introduction

The problems that emerge with estimation of explosiveness of fuel-air mixtures (FAM) and prevention of explosions of FAM are topical and of practical interest, because they pose a real danger in processing, transportation (pumping) and storage fuels in various industrial and civil facilities. Prediction of the possible consequences of FAM explosions is the key element in development of protective measures [1-10]. Today, various computational methods have been developed and approved by various departments and organizations. Previously, we conducted studies on the capabilities of domestic and foreign techniques for predicting the consequences of FAM explosions. On examples of solving similar types of computational problems, poor compatibility of the methods of Gosatomnadzor, Rostechnadzor, EMERCOM of Russia, Netherlands Organisation for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, in short TNO), Dorofeev, Baker-Strehlow (BS) and Baker-Strehlow-Tang (BST) [11-23]. An analyzis of the consequences of real FAM explosions allowed to establish that the Dorofeev method describes the detonation mode best when the deflagration mode is described best by the multi-energy method TNO (ME-TNO). A Rostechnadzor's method gives satisfactory results [21-23] at a known flame propagation velocity. Thus, creation of a synthesis method where approaches of Dorofeev and ME-TNO would be combined is a promising direction.

The main aspects of the Dorofeev and ME-TNO methods

Since S.B. Dorofeev is one of the developers of the RD 03-409–01[1] [27] the Dorofeev's method [24-26] can be considered as a further development of the approach of the Rostechnadzor method. The main difference between these methods lies in the method for determination of the explosion parameters of FAM in the detonation mode. The RD 03-409–01 [27] and RB “Method for assessment of consequences of accidental explosions of fuel-air mixtures” [28] use following equations:

$$\ln(P_x) = -1.124 - 1.66\ln(R_x) + 0.26\left(\ln(R_x)\right)^2, \quad (1)$$

$$\ln(I_x) = -3.4217 - 0.898\ln(R_x) - 0.0096\left(\ln(R_x)\right)^2, \quad (2)$$

$$\Delta P = P_x P_0, \quad (3)$$

$$I = \frac{I_x \sqrt[3]{P_0^2 E}}{C_0}, \quad (4)$$

the Dorofeev’s method uses formulas (3), (4) and

$$P_x = \frac{0.34}{\left(R_x\right)^{4/3}} + \frac{0.062}{\left(R_x\right)^2} + \frac{0.0033}{\left(R_x\right)^3}, \quad (5)$$

$$I_x = \frac{0.0353}{\left(R_x\right)^{0,968}}, \quad (6)$$

where P_x, I_x are for reduced explosion pressure and the momentum of a positive air shock wave compression phase (ASW); R_x is for the reduced distance or the Sach’s parameter $R_x = \frac{R}{\left(E/P_0\right)^{1/3}}$; R is for distance from the center of the explosion, m; E is for explosion energy, J; P_0 is for normal pressure, kPa; C_0 is for sound speed in the air, m/s.

There is in the ME-TNO method for FAM description formula (3) and following ones are used

$$t_p = t_p' \frac{\sqrt[3]{E/P_0}}{C_0}, \quad (7)$$

$$I = \frac{P_x t_p}{2}, \quad (8)$$

where t_p is for the time of ASW (s) and special nomograms describing the dependence of the reduced explosion pressure (P_x) and time of the positive compression phase of the HSV (t_p') on the Sach’s parameter (R_x) are also used. In this case, all explosions are divided into 10 classes (Table 1) [29].

[1] Today, RD 03-409–01 is countermanded and replaced by the RB “Method for assessment of consequences of accidental explosions of fuel-air mixtures” [28]. Nevertheless, the method of calculating the explosion pressure and compression phase pulse remained unchanged in a new document of Rostechnadzor.

Table 1

Classification of explosive situations by TNO [26]

Class	Conditions of ignition[1]	Clutter of space[2]	Parallel constraint[3]	View of the surrounding area [4]
7-10	Favorable	Strong	Yes	Closed
7-10	Favorable	Strong	No	Non-closed
5-7	Scarcely favorable	Strong	Yes	Closed
5-7	Favorable	Weak	Yes	Closed
4-6	Favorable	Weak	No	Non-closed
4-6	Favorable	None	Yes	Closed
4-5	Scarcely favorable	Strong	No	Non-closed
4-5	Favorable	None	No	Closed
3-5	Scarcely favorable	Weak	Yes	Closed
2-3	Scarcely favorable	Weak	No	Non-closed
1-2	Scarcely favorable	None	Yes	Closed
1	Scarcely favorabler	None	No	Non-closed

Note: 1. “Favorable” means any source of ignition in conditions of limited ventilation. “Scarcely favorable” means open source of ignition (spark, open flame, heated surface etc.).

2. “Strong” means that in the field of an explosive cloud there are numerous obstacles that make it difficult to move the cloud freely. At the same time, more than 30 % of the total volume of FAM is located on the territory with obstacles and barriers, the distance between that is no more than 3 m. “Weak” means that in the FAM there are obstacles and barriers. The distance between them is more than 3 m. The total volume of gas and steam-air cloud in the territory with obstacles and barriers does not exceed 30 %. “None” means in FAM there are no obstacles and barriers for its free diffusion. In adoptation to the approach of Rostechnadzor, the classification of TNO cluttering of space (strong – weak – none) should be interpreted as “strong – medium – weak (no)” [21].

3. “Yes” means FAM is bounded by walls and barriers from two or three sides. “No” means that there is no restrictions for an explosive cloud, excluding the ground (floor) surface.

4. “Closed” is a room. “None-closed” is an open space.

Synthesis technique

In order to create a synthesis technique that could combine the approaches of the Dorofeev and ME-TNO methods, it is necessary to isolate the detonation mode in the ME-TNO method and replace it with Dorofeev's approach. In fact, in the ME-TNO method there is no separation of FAM explosions into detonation and deflagration [29]. However, it is clear that explosions of high classes (see Table 1) will correspond to the detonation regime. To solve this problem, we use the approach of Rostechnadzor, which for deflagration FAM explosions consider to choose the smallest value of P_x, which is obtained by calculation from the formulas for explosive conversion in detonation and deflagration regimes [27, 28]. In this case we take into account that equation (5) starts to work at $R_x \geq 0.33$ [25, 26]. Since in the ME-TNO method the I_x indicator is not determined, only one parameter is chosen for the comparative analysis such as reduced explosion pressure P_x. Calculations were performed using Excel 2010 and a previously developed computer program “Calculation of parameters of gas-steam-air mixture explosion” [30] (Table 2).

Table 2

Results of calculations of P_x by the methods of Dorofeev and ME-TNO under $R_x = 0.33$

Parameter	Dorofeev	ME-TNO			
		Explosion class			
		10	9	8	7
P_x	2.15	6.23	4.66	2.00	1.00

Based on the data of Table 2, it can be concluded that the 9th and 10th classes of TNO explosions belong to the detonation mode of FAM. Thus, the 10th class in the synthesis methodology, which unites the approaches of Dorofeev and ME-TNO, is excluded. The 9th class is replaced by Dorofeev's method. With help of the program TableCurve 2D (version 5.01.05) it is established that the reduced explosion pressure in the synthesis technique is well described by the equation with the correlation coefficients (0.998–0.999):

$$P_x = a + \frac{b}{R_x} + \frac{c}{(R_x)^2} + \frac{d}{(R_x)^3} + \frac{e}{(R_x)^4} + \frac{f}{(R_x)^5} + \frac{g}{(R_x)^6} + \frac{h}{(R_x)^7}. \quad (9)$$

Thus, the excess explosion pressure can be calculated depending on the explosive conversion class according to the formula

$$\Delta P = P_0\left(a + \frac{b}{R_x} + \frac{c}{(R_x)^2} + \frac{d}{(R_x)^3} + \frac{e}{(R_x)^4} + \frac{f}{(R_x)^5} + \frac{g}{(R_x)^6} + \frac{h}{(R_x)^7} \right), \quad (10)$$

where *a*–*h* are for empirical constants that depend on the class of explosive transformation (Table 3).

Table 3

Empirical constants for the equation (9)

Class	Constants							
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*
9*	–0.00113	0.14003	0.42948	–0.26310	0.13025	–0.03291	0.00326	0.00000
8	–0.00115	0.18519	1.03553	–3.31372	4.53397	–2.52705	0.61063	–0.05355
7	–0.00486	0.42504	–1.21857	3.18796	–2.77262	1.10151	–0.20798	0.01517
6	0.00106	0.16827	0.51056	–0.48531	0.17496	–0.02869	0.00178	0.00000
5	0.00067	0.10223	0.06329	–0.04327	0.00138	0.00274	–0.00039	0.00000
4	–0.00017	0.07668	–0.05025	0.09424	–0.07766	0.02803	–0.00462	0.00028
3	–0.00002	0.03459	0.00359	–0.01747	0.02022	–0.01163	0.00298	–0.00027
2	0.00078	0.00542	0.03084	–0.03664	0.01947	–0.00577	0.00093	–0.00006
1	–0.00017	0.01057	–0.01574	0.02993	–0.02616	0.01087	–0.00215	0.00016

Note. * detonation mode.

As a result of the study, the synthesis technique and new equation for calculation of the excess pressure of FAM are proposed. Both combine the approaches of the Dorofeev and ME-TNO methods.

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