REVIEW OF METHODS FOR ESTIMATING THE OVERPRESSURE AND IMPULSE RESULTING FROM A HYDROGEN EXPLOSION IN A CONFINED/OBSTRUCTED VOLUME

Mélani, L.[1,2], Sochet, I.[1], Rocourt, X.[1] and Jallais, S.[2]
[1] ENSI de Bourges, PRISME Institute, 88 bd Lahitolle, 18020 Bourges cedex, France, isabelle.sochet@ensi-bourges.fr
[2] Air Liquide R&D, 1 chemin de la Porte des Loges, Les Loges en Josas B.P. 126, 78354 Jouy-en-Josas, France, simon.jallais@airliquide.com

ABSTRACT

This study deals with the TNO Multi-Energy and Baker-Strehlow-Tang (BST) methods for estimating the positive overpressures and positive impulses resulting from hydrogen-air explosions. With these two methods, positive overpressure and positive impulse results depend greatly on the choice of the class number for the TNO Multi-Energy method or the Mach number for the BST methods. These two factors permit the user to read the reduced parameters of the blast wave from the appropriate monographs for each of these methods, i.e., positive overpressure and positive duration phase for the TNO Multi-Energy method, and positive overpressure and positive impulse for the BST methods. However, for the TNO Multi-Energy method, the determination of the class number is not objective because it is the user who makes the final decision in choosing the class number, whereas, with the BST methods, the user is strongly guided in their choice of an appropriate Mach number. These differences in the choice of these factors can lead to very different results in terms of positive overpressure and positive impulse. Therefore, the objective of this work was to compare the positive overpressures and positive impulses predicted with the TNO Multi-Energy and BST methods with data available from large-scale experiments.

Keywords: Hydrogen, TNO Multi-Energy Method, BST Methods, Overpressure, Impulse

1.0 INTRODUCTION

If a quantity of hydrogen is accidentally released, it will mix with air and form a flammable cloud. If an ignition source is in the vicinity of this cloud, an explosion can occur. Three approaches are classically used to quantify the properties of blast waves produced by such an explosion: the TNT equivalency method, the TNO Multi-Energy method and the BST methods. In this study, only the TNO Multi-Energy method and the BST methods will be treated in detail. In fact, the TNT equivalency method is considered to be too conservative due to its application for detonation. This method considers only one explosion, where the calculation takes into account the total mass of combustible material in the gaseous cloud. The strength of the explosion is expressed as an energetically equivalent charge of TNT in the cloud center. The TNO Multi-Energy and BST methods consider an explosion as a number of sub-explosions. This fact leads to the construction of monographs with several curves for obtaining positive overpressures and positive duration phases for the TNO Multi-Energy method, or positive overpressures and positive impulses for BST methods, versus scaled distance. These different curves correspond to a class number or a Mach number. The concept of these methods is based on the flame acceleration due to turbulence, which can be created by a source term, e.g., high pressure, jet, etc., and by obstructed area. These methods also assume that turbulence governs the strength of the blast wave independently. The explosive potential is determined by the environment of the gaseous explosion (obstructed or not, confined or not). However, the choice of the class number for the TNO Multi-Energy method is not objective, and is instead left to user judgment, whereas the choice of Mach number is more guided, as discussed in the following.

Two recent projects have attempted to improve the application of the TNO Multi-Energy method to include a more objective determination for the class number. These two projects are GAME [1] (1998) and GAMES [2] (1998). Based on the experimental literature, the GAME project arrived at a proposal for a new correlation to calculate maximum positive overpressure resulting from an explosion, which depends on the VBR (Volume Blockage Ratio, e.g., the sum of all obstacle volumes in the total studied volume), the length traveled by the flame, the obstacle diameter and the laminar combustion speed of the mixture. An initial class number is determined, and the positive overpressure is calculated with the TNO Multi-Energy method. If the initial choice of the class number gives results seem too conservative to be applied, a correction to the class number is possible by applying the GAME correlation. However, this correlation has been obtained with experiments using only low-reactivity fuels (propane or methane). Thus, this correlation is not valid for hydrogen due to its high laminar combustion speed compared to propane or methane. This fact has been put in evidence by the applications realized during the GAMES project concerning hydrogen storage. More recent work (Melton et al. (2009) [3]) has provided some "guidelines" to apply a systematic approach to calculate overpressure based on BST methods and the GAME and GAMES projects. A correlation for flame speed was obtained via an analysis of the important parameters: reactivity, congestion and confinement. This correlation is based on the equation by Tang et al. (1999) [4], which links overpressures for a range of M_w (the Lagrangian Mach number, i.e., the gas velocity over the speed of sound in a gas) to M_f (the Eulerian Mach number, defined in section 2.2.3) and the GAME correlation. The resulting expression produces the M_f (Eulerian Mach number) via a more objective process. This expression is first established for 3D and 2D flame expansions. Then, a general expression is obtained for all types of flame expansion. This determination of M_f (Eulerian Mach number) for the BST method leads to a better value for overpressure. This article also makes it evident that a Mach number corresponding to a deflagration-to-detonation transition (DDT) regime can be between 3 and 5.2. Nevertheless, these recent works do not take into account the impulse.

Thus, the aim of this study was to compare overpressures predicted with the TNO Multi-Energy and BST methods with data available from large-scale experiments concerning hydrogen explosion. Indeed, these two methods have been developed from the behavior of low-reactivity gases like methane. Therefore, it was of interest to investigate whether these methods are able to predict good positive overpressure and positive impulse for highly reactive gases like hydrogen.

2.0 DESCRIPTION OF THE DIFFERENT METHODS

2.1 TNO Multi-Energy method

In this concept, the explosion of a gaseous cloud is defined as numerous sub-explosions corresponding to multiple ignition sources present in the cloud. The procedure for the application of the TNO Multi-Energy method has been presented in the Yellow Book (1995) [5]. A brief description follows:

- Determine the position of the potential acceleration sources such as car parks, chemical plants, bridge, pipe, high pressure jet;

- Determine the cloud size with: $V_c = Q_{ext} / (\rho \times c_S)$, (1)

where V_c - the cloud volume, m^3; Q_{ext} - the quantity of flammable gas, kg; c_S - the stoichiometric concentration, % vol; ρ - the density of flammable gas, $kg \cdot m^{-3}$,

This step is used only if there are heavy gases. In most cases, the mass or volume is directly calculated.

- Define obstructed and/or unobstructed regions;

- Estimate the source strength or class number for each region;

- Calculate the radius of the cloud;

- Calculate the blast parameters: scaled distance, positive scaled overpressure and positive scaled duration phase;

- Calculate the real parameters: positive overpressure, positive duration scaled and positive impulse.

Depending on the class number and scaled distance, the scaled overpressure and the scaled positive duration time will be read from reference curves on the monographs. The overpressure, duration phase and impulse are calculated as the following:

$$\bar{r} = r \times \left(p_a/E\right)^{1/3} \quad , \quad P = \bar{P}_S \times p_a \quad , \quad T = \bar{T}_S \times \left(\frac{E}{p_a}\right)^{1/3} \times \frac{1}{a_0} \quad , \quad I = \frac{1}{2} \times P \times T \quad , \qquad (2), (3), (4), (5)$$

where $\bar{r}$ - the scaled distance, (-); r - the distance to the center of the ignition, m; E - the combustion energy of the fuel-air mixture in stoichiometric quantity, J; p_a - the atmospheric pressure, Pa; P - the positive overpressure, Pa; $\bar{P}_S$ - the positive scaled overpressure, (-); T - the positive duration time, s; $\bar{T}_S$ - scaled positive duration time, (-); a_0 - sound speed in ambient conditions, m/s; I - the positive impulse, Pa·s.

The class number allows one to calculate (or read from the monographs) the positive duration phase and positive overpressure. The choice of this parameter depends on the ignition energy, the obstacle density, the confinement and the fuel reactivity. For example, Kinsella (1993) has proposed some guidelines to choose the class number (Table 1). The experimental environment is defined by its obstacle density, its confinement and its ignition energy. In each category, sub-categories specify the type of each category to represent most of the experimental environment for which a range of class numbers is associated. However, the range of values for each sub-category is not explicitly defined. Moreover, the fuel reactivity is not explicitly taken into account. So, these guidelines do not resolve the problem of the parameter choice, because the user still makes the final decision.

Table 1. Guidelines by Kinsella (1993) for choosing the class number

Ignition energy		Obstacle density			Confinement		Strength
Low	High	High	Low	No	existing	no	
	x	x			x		7 – 10
	x	x				x	7 – 10
x		x			x		5 – 7
	x		x		x		5 – 7
	x		x			x	4 – 6
	x			X	x		4 - 6
x		x				x	4 – 5
	x			X		x	4 – 5
x			x		x		3 – 5
x			x			x	2 – 3
x				X	x		1 – 2
x				X		x	1

2.2 BST methods

2.2.1 Principles

There are three BST methods: i) Baker–Strehlow (BS), (Baker et al. (1996) [6]); ii) Baker-Strehlow-Tang 1 (BST1), using a new set of curves (Tang et al. (1999) [4]); and iii) Baker-Strehlow-Tang 2 (BST2), using a new matrix (Pierorazio et al. (2004) [7]). All of these models are based on the original work of Strehlow et al. (1976) [8].

All of the three methods have the same basis: the Baker and Strehlow (BS) method. This method is based on an experimental literature review with the objective of determining the flame speed of the explosion via the Mach number, M_w. With the flame speed value, two sets of curves are obtained to calculate positive overpressures and positive impulses. The overpressure is calculated in the same manner as in the TNO Multi-Energy method, whereas for BST methods impulse is deduced directly from the reference curves using the following expression (calculated only for M_w greater than 0.25). For an explosion on or near ground level, the energy is doubled to take into account the ground reflection.

$$\bar{r} = r \times \left(p_a / E \right)^{1/3}, \qquad P = \bar{P}_S \times p_a, \qquad \bar{I}_S = I \times a_0 / \left(E^{1/3} \times p_a^{2/3} \right) , \qquad (2), (3), (6)$$

with $E = E_{comb} \cdot V_{gr}$, for an explosion at altitude (7)

$E = 2 \cdot E_{comb} \cdot V_{gr}$, for an explosion on or near ground level (8)

where $\bar{r}$ - the scaled distance, (-); r - the distance to the center of the ignition, m; E - the combustion energy of the fuel-air mixture in stoichiometric quantity, J; p_a - the atmospheric pressure, Pa; P - the positive overpressure, Pa; $\bar{P}_S$ - the positive scaled overpressure, (-); I - the positive impulse, Pa·s; $\bar{I}_S$ - the scaled positive impulse, (-); a_0 - sound speed in ambient conditions, m/s; E_{comb} - the combustion energy of flammable gas, MJ·m^{-3}; V_{gr} - the volume of the obstructed area, m^3.

2.2.2 Choice for the matrix

For selection of the Mach number, two matrices are possible: i) the Baker et al. (1996) [6] matrix (Table 2) (valid for BS and BST1 – a new set of curves), and ii) the Pierorazio et al. (2004) [7] matrix (Table 3) (valid for BST1 – a new set of curves).

- *Baker et al. (1996) [6] matrix*

The matrix of Baker et al. (1996) [6] (Table 2) is based on a compilation of literature results on flame speed experiments. This compilation presents a correlation between fuel reactivity, obstacle density and confinement. For fuel reactivity, the classification of the TNO Multi-Energy method is adopted: L = Low reactivity (methane and carbon monoxide), M = Medium reactivity (all other gases) and H = High reactivity (hydrogen, acetylene, ethylene oxide and propylene oxide). The obstacle influence is determined by experiments where different types of obstacles (cylinders and plates), the VBR and the Pitch (space between two consecutive obstacles) were studied. The three categories which were determined are: High (H for VBR > 40%), Medium (M for 10% < VBR < 40%) and Low (L for VBR < 10%). The last category is the flame expansion: 1D flame expansion for smooth flame, 2D flame expansion for a cylindrical flame and 3D flame expansion for a spherical or hemispherical flame.

Table 2. Baker et al. (1996) [6] matrix for the choice of Mach number M_w

1D flame expansion (planar flame)			
Fuel reactivity	Obstacle density		
M_w	H	M	L

H	5.2	5.2	5.2
M	2.265	1.765	1.029
L	2.265	1.029	0.294
2D flame expansion (cylindrical flame)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	1.765	1.029	0.588
M	1.235	0.662	0.118
L	0.662	0.471	0.079
3D flame expansion (spherical or hemispherical)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	0.588	0.153	0.071
M	0.206	0.100	0.037
L	0.147	0.100	0.037

- *Pierorazio et al. (2004) [7] matrix*

This matrix (Table 3) is based on new experiments at a medium scale. The congestion regions are composed of modular cubic sections. The size of each cubic section is 1.8 x 1.8 x 1.8 m. The obstacles used are circular tubes. Different obstacle configurations have been studied to obtain different levels of congestion: i) 16 tubes for Low congestion (0% < VBR < 1.5%), ii) 49 tubes for Medium congestion (1.5% < VBR < 4.3%), and iii) 65 tubes for High congestion (4.3% < VBR < 5.7%). To test fuel reactivity, three mixtures have been used: i) a stoichiometric methane-air mixture for Low reactivity, ii) a stoichiometric propane-air mixture for Medium reactivity, and iii) a stoichiometric ethylene-air mixture for High reactivity. The fuel reactivity classification in the matrix corresponds to that of the BS matrix. For the level of confinement, the 1D flame expansion has been not considered due to the few corresponding industrial situations. The 2D flame expansion corresponds always to cylindrical flame and the 3D flame expansion to spherical or hemispherical flame. A new category of flame expansion, 2.5D, is included in this matrix. It represents a confinement which is made of either a frangible panel or by a nearly solid confining plane. Nevertheless, the choice for the VBR is not very clear and the differences between H, M and L levels are very small compared to the preceding matrix.

Table 3. Pierorazio et al. matrix (2004) [7] for the choice of Mach number M_w

2D flame expansion (cylindrical flame)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	DDT	DDT	0.59
M	1.6	0.66	0.47
L	0.66	0.47	0.079
2.5D flame expansion			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	DDT	DDT	0.47
M	1.0	0.55	0.29
L	0.50	0.35	0.053
3D flame expansion (spherical or hemispherical)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	DDT	DDT	0.36
M	0.50	0.44	0.11
L	0.34	0.23	0.026

2.2.3 Choice for curves

Two sets of curves are used in BST methods: the Baker et al. (1996) [6] curves and the Tang et al. (1999) [4] curves. The first set of curves is a function of M_w, which is the Lagrangian Mach number, and the second set of curves is a function of M_f, which is the Eulerian Mach number. These two Mach numbers are linked by the following correlation for a subsonic flame:

$$M_f = M_w \times \left(\rho_u / \rho_b\right)^{1/3} \quad , \tag{9}$$

where M_f - the Eulerian Mach number, (-); M_w - the Lagrangian Mach number, (-); ρ_u - the density of unburned gases, $kg \cdot m^{-3}$; ρ_b - the density of burnt gases, $kg \cdot m^{-3}$.

For a supersonic flame (Mach number greater than unity), M_w and M_f have the same value:

$$M_f = M_w \,, \tag{10}$$

Relations (9) and (10) are not applicable when M_f is close to unity. For a near-sonic flame, a known M_w is associated with an overpressure (Table 4) and the corresponding M_f is calculated. The relation that links overpressures and M_f is given by Tang et al. (1999) [4]:

$$\left(P_{max} - P_0\right) / P_0 = 2.4 \times Mf^2 / \left(1 + Mf\right), \tag{11}$$

where P_{max} - the maximal pressure, bar; P_0 - the atmospheric pressure, bar; M_f - the Eulerian Mach number, (-).

Table 4. Correspondence between overpressures and Mach number

M_w	M_f	P_{max}	M_w	M_f	P_{max}
0.037	0.07	0.010	0.500	0.70	0.680
0.074	0.12	0.028	0.750	1.00	1.240
0.125	0.19	0.070	1.000	1.40	2.00
0.250	0.35	0.218			

The curves used most often today are those of Tang et al. (1999) [4]. In the application of the methods, there are two ways to obtain overpressures and impulses. If the BS method is used, M_w will be chosen, and overpressures and impulses will be read directly from the monographs. But, if the BST1 or BST2 methods are used, M_w will first be employed to determine the associated M_f, and then the overpressures and impulses will be read from the appropriate charts.

3.0 DESCRIPTION OF EXPERIMENTS USED FOR THE COMPARISON OF OVERPRESSURES

Based on an extensive survey of the literature, six articles with sufficient reported information have been found comparing the two Multi–Energy methods (TNO Multi-Energy and BST methods).

3.1 Experiments without obstacles

The chosen experiment of Sato et al. (2006) [9], for the comparison with both Multi-Energy methods, concerns the deflagration of a stoichiometric hydrogen-air mixture contained in a rectangular plastic tent 5.2 m^3 in volume. The energy of the ignition source is 40 J and the two electrodes are located at the center of the tent.

For the experiments of Schneider et al. (1983) [10], a 20 m diameter polyethylene hemispheric balloon (total volume 2094 m^3) was located at the ground and filled with a homogeneous stoichiometric hydrogen-air mixture. The combustion was initiated by an ignition source of 150 J at the center of the hemisphere's base.

3.2 Experiments with obstacles

Groethe et al. (2007) [11] performed a series of hydrogen explosion experiments. Three experiments are taken into account in this paper. The first concerns a high ignition-energy experiment in a dome of 300 m^3 of a stoichiometric hydrogen-air mixture with an ignition source of 5.2 x 10^4 J. The second set of experiments deal with deflagration in a dome of 300 m^3 of a hydrogen-air mixture. The dome contained 18 obstacles (with a total volume of 8.97 m^3), so the VBR was about 3%. The ignition source had an energy of 40 J. The third experiment used a tent of 37 m^3 filled with a stoichiometric hydrogen-air mixture. The ignition (40 J) took place between two thin rectangular aluminum plates (6.4 mm thick) separated by 10 mm.

The study of Shirvill et al. (2007) [12], performed in the framework of the EU Hyapproval project, presents experiments which take place in the setting of a refueling station with one vehicle. The vehicle corresponds to an obstacle; this vehicle and the two hydrogen dispensers form a volume blockage ratio of 14%. In these experiments, a homogenous premixed stoichiometric hydrogen-air mixture was ignited between the two hydrogen dispensers. The ignition source was at 50 mJ.

The work of Royle et al. (2007) [13] concerns the potential for existing natural gas pipelines to transport hydrogen. The experiments were realized with stoichiometric hydrogen-natural gas-air mixtures with different concentrations: 100% methane, 75% methane and 25% hydrogen, 50% methane and 50% hydrogen, 25% methane and 75% hydrogen, and 100% hydrogen. The addition of methane led to a decrease of the overpressure as a result of the low reactivity of methane. Only the results obtained with the last composition were analyzed. The mixture was contained in a rectangular structure surrounded by a thin plastic film ($V_{structure}$ = 18 m^3; obstacle diameters of 26 mm, pitch of 125 mm and gas volume of 17.207 m^3). Metallic bars were positioned inside and outside of the volume to create obstruction (VBR = 4.40%). The value of the ignition source was 500 mJ.

4.0 RESULTS

In the present comparison, BS represents the results with the Baker et al. (1996) [5] curves, BST1 represents the results with the Tang et al. (1999) [6] curves and BST2 represents the results with the Pierorazio et al. (2004) [7] matrix. The TNO Multi-Energy levels have been calculated to fit the experimental points. The process to obtain overpressures and impulses for the comparison was composed of two steps. First, overpressures and impulses were obtained from the experimental results (curves of scaled overpressure or scaled impulse versus scaled distance) for a specific distance from the center of explosion. Then, with the description of the experimental environment (fuel reactivity, obstacle density and confinement), the class number or the Mach number were determined. With these parameters, the TNO Multi-Energy and BST methods were applied to calculate overpressures and impulses for the same distance to the center of explosion. For the TNO Multi-Energy method, two class numbers have been represented to obtain the best fit with experimental points or to obtain the best experimental point framing. In some cases, the first choice of class number has been modified to obtain overpressure and impulse values nearer the experimental values. For the BST methods, all three methods were tested.

For this study, hydrogen is classified as having high fuel reactivity and all of the experiments are unconfined. For the experiments of Sato et al. (2006) [9] and Schneider et al. (1983) [10], there are no obstacles and the ignition energy is low. So, the first choice of class number is 2 or 3 and for the Mach number 0.071 or 0.36. For the experiments of Groethe et al. (2007) [11] (the dome without obstacles), the ignition energy is very high. So the chosen class numbers are 8 or 9 and 0.071 or 0.36 for Mach numbers. All of the other experiments have obstacles (VBR between 0.07% and 14%) and low ignition energies. So the first choice of class number is 5 or 6, and 0.071, 0.153, 0.36 or the equivalent of DDT in the application of the different matrices for the Mach number. For a Mach number equivalent to DDT, the class number 10 or the Mach number 5.2 can be used. In this study the class number 10 was chosen to calculate the overpressure and impulse. A comparison between these two possibilities shows that for the near field, the Mach number is in better agreement, and for the far field, the class number gives better agreement.

4.1 Overpressures

A good correlation between the TNO Multi-Energy method and the literature dataset was observed particularly in the far field and for experiments without obstacles. The TNO Multi-Energy method was most often a better approximation than the BST methods.

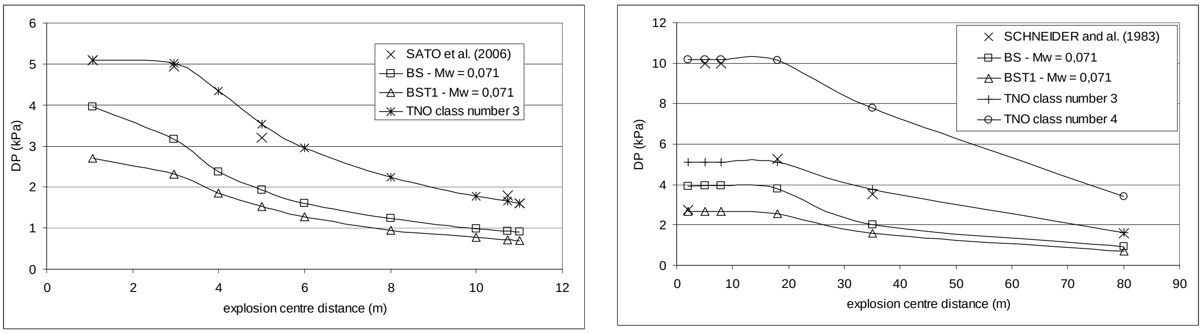


Figure 3. Overpressures versus explosion center distance for experiments in an open area

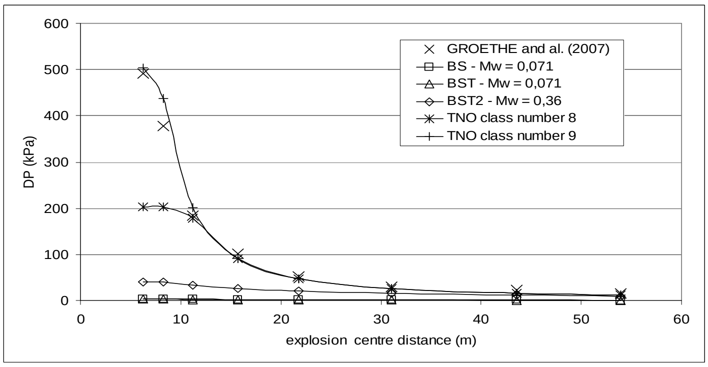
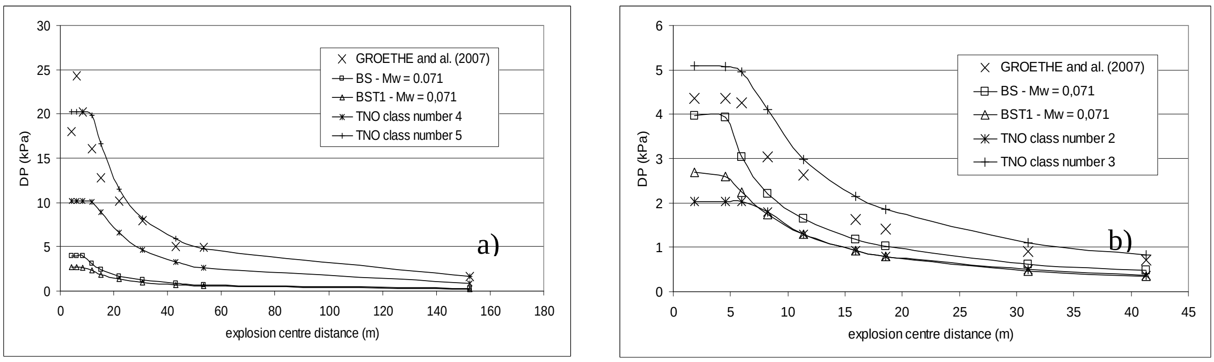


Figure 4. Overpressures versus explosion center distance for experiments with high ignition energy (dome without obstacles)



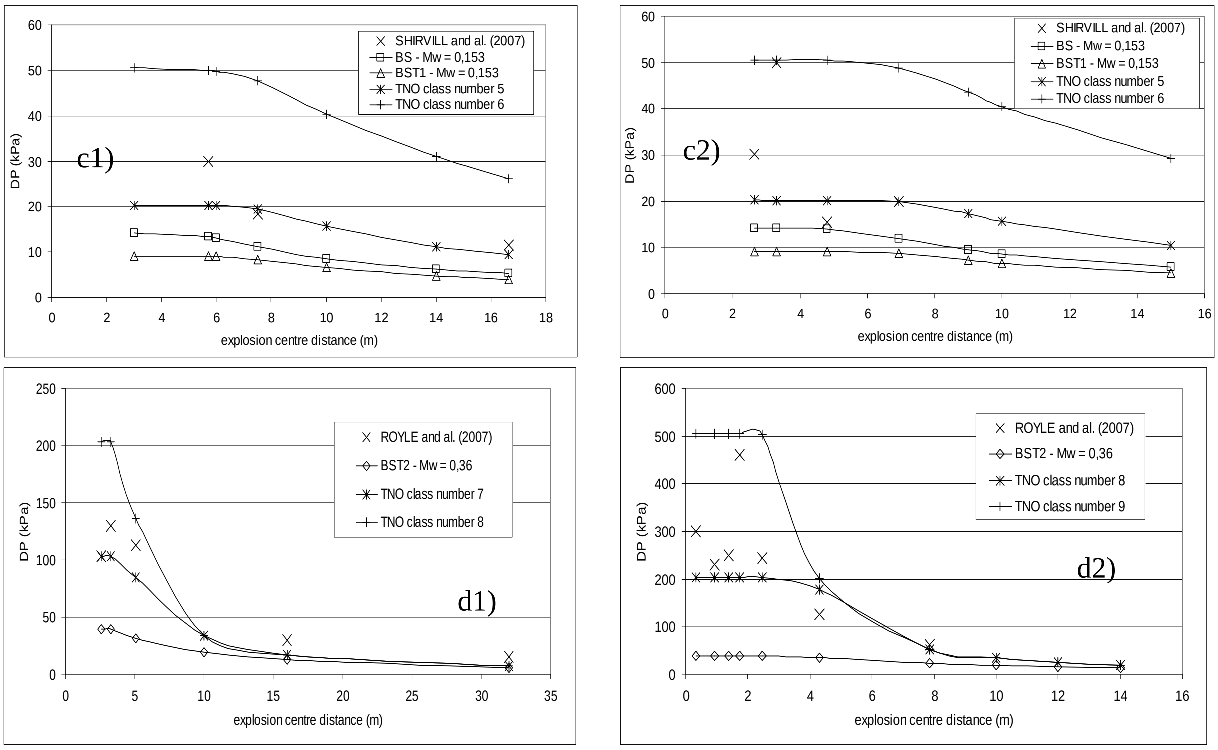


Figure 5. Overpressures versus explosion center distance for experiments in an obstructed area (a) dome with obstacles, b) tent with two plates, c1 and 2) Shirvill et al. (2007) [12] perpendicular and parallel to the wall, d1 and 2) Royle et al. (2007) [13] perpendicular and parallel to the wall)

Table 5 summarizes the comparisons between the experimental results and those obtained by calculation (BST and TNO).

Table 5. Summary of the parameters for both Multi-Energy methods

Authors	Fitted class numbers	BST Mach number		
		BS	BST1	BST2
Sato et al. (2007) [9]	3	(-)	(-)(-)	(+)(+)
Schneider et al. (1983) [10]	3	(-)	(-)(-)	(+)(+)
Groethe et al. (2007) (dome without obstacle) [11]	9	(-)(-)	(-)(-)(-)	(-)
Groethe et al. (2007) (dome with obstacle) [11]	5	(-)(-)	(-)(-)(-)	(+)(+)
Groethe et al. (2007) (tent) [11]	3	(-)	(-)(-)	(+)(+)
Shirvill et al. (2007) [12] (homogeneous)	5 (perpendicular) 5 (parallel)	(-)	(-)(-)	(+)(+)
Royle et al. (2007) [13]	7 (perpendicular) 8 (parallel)	(-)(-)	(-)(-)(-)	(-)

4.2 Impulses

For impulses, fewer articles have been analyzed because there is less data on this parameter. Only the BST2 method has been applied due to the minimum value of the Mach number (0.25) required to have curves for impulse. In most cases, the class numbers, which fit for overpressure, also give good agreement for impulse.

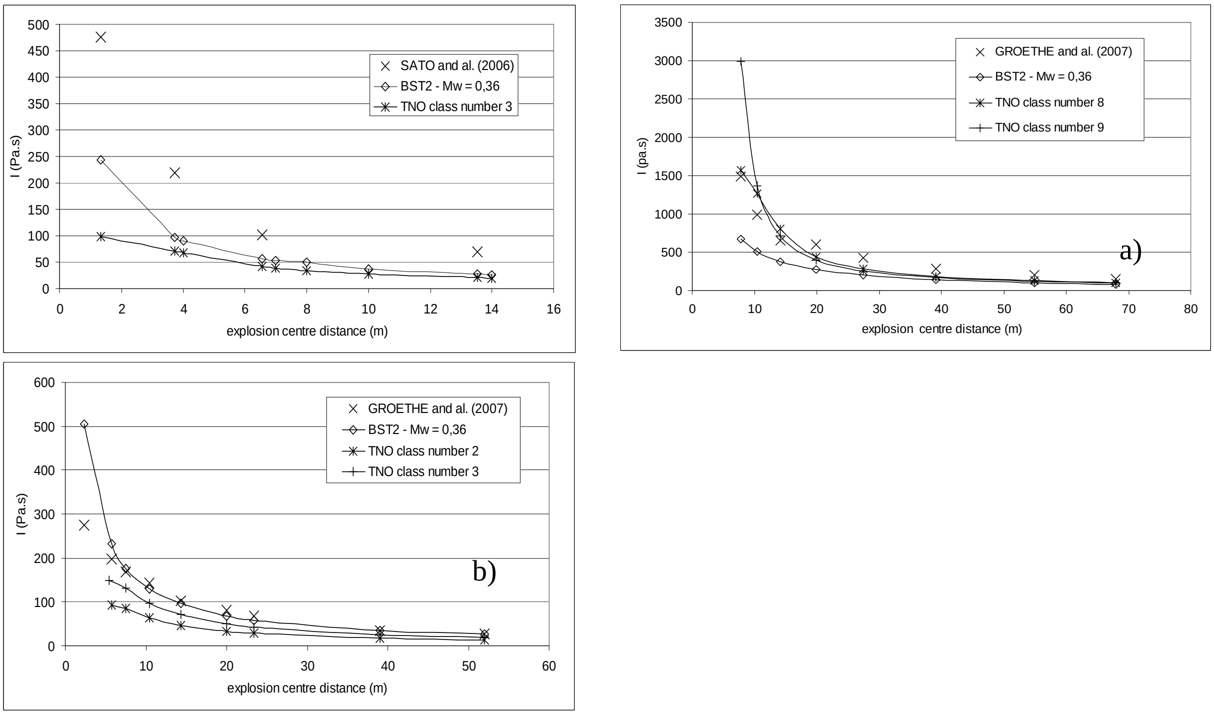


Figure 6. Impulses versus explosion center distance (a) dome without obstacle, b) tent with two plates)

4.3 Discussion

The differences between the results obtained with the different methods can be explained by the differences in the calculation processes of the TNO Multi-Energy and BST methods. For the TNO Multi-Energy method, the choice of class number is left to user discretion and it is less guided. Concerning the BST methods, the choice of the Mach number is highly guided. Indeed, the VBR ranges and confinement rates are defined in Table 6.

Table 6. VBR ranges and confinement rates for BST and TNO Multi-Energy methods

BST methods	
VBR rates	<u>For BS et BST1 methods:</u> H: VBR >40%, M: 10% <VBR < 40%, L: VBR < 10% <u>For BST2 method:</u> H: VBR = 5.7%, M: VBR = 4.3%, L:VBR = 1.5%
Confinement levels	<u>For BS et BST1 methods:</u> 1D (planar flame in a tube), 2D (cylindrical flame front) and 3D (spherical or hemispherical flame front) <u>For BST2 method:</u> 2D (cylindrical flame front), 2.5D and 3D (spherical or hemispherical flame front)
TNO Multi-Energy method	
Obstruction rates	Low, middle and high
Confinement rate	Present or not

The differences between the precision of input data for selecting the class number (TNO Multi-Energy method) or the Mach number (BST methods) lead to a more objective choice of the Mach number (BST methods) than the class number (TNO Multi-Energy method). However, the results obtained with the TNO Multi-Energy method are in better agreement with the experimental results than the BST methods. This is due to the fact that the class number has been chosen to fit with the experimental data. With these class numbers, and considering the environment of the experiments, some guidelines to choose the class number can be developed (Table 7).

Table 7. Guidelines for choosing the class number for the TNO Multi-Energy method applied to hydrogen explosion

High fuel reactivity			
Ignition power	Obstruction	Volume (m^3)	Class number
Low (0 to 150 J)	0 to 1 %	≅ 5 to 2094	3
	1 to 15 %	5 to 300	5 or 6
	4.40 %	≅ 17	7 or 8
High (150 to 5.2 x 10^4 J)	0 %	300	9

For the experiments of Schneider et al. (1983) [10], even if the volume of the hemisphere is very large, the class number remains at 3. These experiments do not permit an input of the effect of volume on the value of the class number. For the Royle et al. (2007) [13] experiments, this is not very representative of industrial situations. The associated class numbers (7 and 8) for the value of the VBR (4.40%) seems to be too conservative. Indeed, with this situation, a hydrogen explosion without obstacles is associated with class numbers 2 and 3, whereas for all other situations, the class numbers become 7 or 8, so the explosion can be compared to a detonation. This fact leads to a too conservative approach. For the experiments of Groethe et al. (2007) [11], some tests were performed with obstacles and high ignition energy (5.2 x 10^4 J); however, here, the presence of obstacles does not play an important role due to the high value of ignition energy and the combustion regime which is already a detonation.

The differences between the BST methods could be due to the different configurations of the experiments, which have led to the creation of the two matrices. The Baker et al. (1996) [6] matrix (valid for BS and BST1 methods) is based on a literature compilation dataset concerning flame speed. No experiments have been carried out for this matrix. The only known factors in these experiments concern the obstacle shapes, which were taken as cylindrical or rectangular. The varied parameters were VBR and pitch. The Pierorazio et al. (2004) [7] matrix is based on a series of experiments conducted by the authors. Moreover, two series of curves have been proposed for the BST methods, the first is the Baker et al. (1996) [6] curves and the second is the Tang et al. (1999) [4] curves (currently, the second series of curves are commonly used). The results obtained with the BS method are always higher than the results obtained with the BST1 method for overpressure. This fact may seem contradictory because the curves used for the BST1 method are in better agreement with the experimental data than the curves used with the BS method. Concerning the BST2 method results, when the Mach number corresponds to a DDT, the results over-predict the experimental results and seem to be too conservative. When the Mach number is different from the DDT, the results underestimate the experimental results. For impulse, only the results of BST2 method have been represented due to the value of Mach number, which must be higher than 0.25 (the Mach number for the BST2 method is 0.36). For experiments with high ignition energy by Groethe et al. (2006) [10], the BST methods give results which under-predict the results of the experiments. This is due to the fact that BST methods do not take into account ignition energy. So, a high value for the ignition energy does not influence the results of overpressures and impulses in the model.

5.0 Conclusions

For the BST methods, the Baker et al. (1996) [6] matrix always under-predicts the effects of a hydrogen explosion. The Pierorazio et al. (2004) [7] matrix strongly over-predicts overpressures in an open area. In the case of high ignition energy, the models under-predict the effects because the ignition strength is not a parameter of the BST model. For an obstructed area, the use of this matrix leads to over-prediction of overpressure for experiments with large objects and underestimation for small-scale obstacles. In all situations, the deflagration-to-detonation transition in the matrix is very conservative. This finding is similar to the work of Melton et al. (2009) [3], which proposed taking a Mach number of 3 for the beginning of the DDT. Results concerning impulses have the same tendencies seen in the results for overpressures. For the TNO Multi-Energy method, the results better fit the experimental data. Thus, BST methods are not applicable to the cases where hydrogen is present, whereas the TNO Multi-Energy method is applicable with some adaptations. The proposed guidelines (Table 7) will be improved by adding information concerning the Pitch. Indeed, in most of the experiments, obstacles were separated with the same space, which is not very representative of typical industrial configurations.

However, the results obtained with TNO Multi-Energy and BST methods are not exactly the same as the experimental results. The fact that hydrogen is a very reactive gas plays a part in explaining the differences in the overpressure and impulse values.

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