A New Set of Blast Curves from Vapor Cloud Explosion

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Past accidents have demonstrated that vapor cloud explosions (VCEs) are the most severe threat to refining and petrochemical industries. In order to estimate the air blast parameters at any given distance from a possible explosion source, a variety of prediction methods have been developed. A brief description of these prediction methods is first presented. Then, the focus of this paper is on an engineering method based on blast curves, which is the most frequently used prediction method.

Knowledge of blast effects from vapor cloud explosions has greatly improved due to the efforts of investigators in many countries during the last three decades; however, blast curves have not been reexamined. One of the aims of this paper is to present a new set of blast curves which have been validated with available experimental results and analytical solutions. Another aim is to present a comprehensive set of blast curves including blast parameters for both positive and negative phases.

The new blast curves, which are a modification of the Baker-Strehlow curves, improve the prediction for detonations and supersonic deflagrations as well as for subsonic flames. By changing the slope of the blast pressure versus distance curve, the overly conservative blast pressure predictions by the previous Baker-Strehlow curves at large standoff distances for detonations and supersonic deflagrations are reduced. By clarifying the labeling of the flame Mach number for each blast curve, the overly conservative pressure and impulse preditions for subsonic flames are also avoided.

The new blast curves have been validated against VCE experiments including detonations, fast deflagrations, and slow deflagrations. Particular attention was given to large scale deflagration experiments, which became available only recently. Good agreement is shown between the new blast curves and the experimental blast data for vapor cloud detonations and subsonic deflagrations. For supersonic deflagrations, the blast curve predictions are overly conservative in that blast pressure decays more rapidly with distance in experiments than the calculated curves.

INTRODUCTION

Since the Flixborough disaster, which occurred in June, 1974, it has been realized that the most severe threat to chemical and petrochemical industries is the hazard of vapor cloud explosions, which have been the predominant causes of the largest losses in these industries [1]. Unfortunately, these types of devastating accidents still occur. The focus of this paper is on the prediction of blast effects from vapor cloud explosions because the air blast parameters at any given distance from a possible explosion source must be estimated in order to evaluate the risk associated with a given installation or activity. Furthermore, with proper safety guidelines, appropriate structural design and safe distancing considerations, blast hazards from vapor cloud explosions may be reduced to acceptable levels.

VAPOR CLOUD EXPLOSION BLAST PREDICTION METHODS

Blast prediction methods for vapor cloud explosions (VCEs) may be grouped into three types of categories according to their nature and complexity.

TNT Equivalence Method

It had been common practice for many years to compare the air blast effects of a VCE with the blast from a TNT charge. The available combustion energy in the vapor cloud is converted into an equivalent charge weight of TNT. This approach was attractive since the blast effects of TNT as a function of distance from the explosion source are well known. However, case studies revealed that there is almost no correlation between the amount of fuel involved in a VCE and the total quantity of fuel released and/or the yield. Reported yield factors generally range from 0.1 to 10% with the majority less than 1 to 2% according to accident investigations; a limited number of higher yield values have been reported. Various institutions have recommended markedly different of yield factor [2] values. A portion of this spread in yield factor values is due to uncertanties in the amount of fuel released. In addition, some investigators have developed yield factors based on the total amount of fuel released, whereas others have used only that in the flammable range or even a portion of the flammable range (i.e. that assumed to be capable of supporting an explosion). However, a significant portion of the spread in yield factor values is due to differences in the vapor cloud combustion mode. The major drawback of the TNT equivalence method is that the blast yield is only associated with the amount of fuel involved and not the combustion mode.

It is now well understood that blast effects from vapor cloud explosions are determined not only by the amount of fuel burned, but more importantly by the combustion mode of the cloud. A wide spectrum of flame speeds may result from flame acceleration under various confinement and congestion conditions in industrial environments. In energy scaled coordinates, the TNT blast represents a single curve, whereas the blast waves generated by vapor cloud explosions are represented by a family of curves corresponding to various cloud combustion modes. Furthermore, there are dramatic differences between explosions involving vapor clouds and high explosives at close distances; for the same amount of energy, the high explosive blast overpressure is much higher and the blast impulse is much lower than that from a VCE [3].

Since control rooms and other blast resistant structures on plant sites are usually located close to potential explosions, we strongly recommend that the TNT equivalence method not be used for close-in VCEs blast load predictions. However, the TNT equivalence method is reasonable for far-field predictions of VCE overpressure except for very low flame speeds. Impulses from TNT blast curves are generally over-predicted in the far field.

Methods Based on Blast Curves

The use of a gas charge explosion to replace the TNT charge detonation has greatly improved the accuracy of VCE blast predictions. One-dimensional numerical studies of gas change explosions were carried out by several groups of researchers using different numerical techniques, which resulted in several sets of blast curves. Among these, the most frequently used and widely accepted are the Baker-Strehlow [4] blast curves for spherical free air explosions and TNO [5] blast curves for hemispherical explosions.

The Baker-Strehlow curves provide positive pressure and impulse as a function of distance. The pressure, impulse and distance are non-dimensionalized using Sach's scaling law as follows:

$$\bar{P} = \frac{p - p_0}{p_0} \qquad \bar{i} = \frac{i a_0}{E_t^{1/3} p_0^{2/3}} \qquad \bar{R} = \frac{R}{(E_t / p_0)^{1/3}}$$

Where p_0 *is* atmospheric pressure;
a_0 *is* acoustic velocity at ambient conditions;
p *is* absolute peak pressure;
R *is* stand-off distance;
E_t *is* total energy release from the explosion source;
i *is* specific impulse.

Both overpressure and impulse versus distance relations are presented as a famies of curves, with the flame speed diffentiating the curves within each family. In the non-dimensional form, flame speed is the only factor to determine the blast pressure and impulse at a given distance. A vapor cloud detonation is, of course, the worst case and produces the most severe blast effects.

The TNO curves consist of positive pressure and time duration as functions of distance. The parameters were also non-dimensionalized using Sach's scaling law with pressure and distance as defined above, and the positive phase duration as follows:

$$\bar{P} = \frac{p - p_o}{p_o} \qquad \bar{R} = \frac{R}{(E_t / p_o)^{1/3}} \qquad \bar{t_+} = \frac{t_+ a_0}{(E / p_0)^{1/3}}$$

where t_t is the time duration of the positive phase. Each curve in the TNO blast curve set is labeled by the initial explosion strength, ranging from 1 to 10, with 10 representing the worst case of a vapor cloud detonation.

In both Baker-Strehlow and TNO methods, the source energy is defined by a stoichiometric fuel/air mixture located within the confined and/or congested region. The flame speed or initial explosion strength is determined by empirical approaches based on the degree of confinement and obstruction within the source region as well as the distance available for flame acceleration [6-7]. As discussed above, one-dimensional numerical curves based on gas charges provide a better representation of VCE blast parameters than the TNT equivalence method. However, the one-dimensional curves are idealized symmetric representations that cannot describe the impact of non-symmetric vapor cloud shape, the location of turbulence generating obstacles, or the ignition location. Nevertheless, by simplifying real world scenarios, blast curve methods are still most frequently used as the engineering tool.

The Detailed Numerical Simulations

The application of three-dimensional numerical simulation based on computational fluid dynamics (CFD) to model vapor cloud explosions has developed rapidly during recent years. This approach has the potential of providing higher accuracy and directly addressing the details of real world scenarios without drastic simplifications; as a result, the empirical determination of the flame speed can be avoided. However, there are still significant difficulties in establishing combustion models capable of accurately representing the flame and flow field turbulence interactions in order to correctly simulate the flame acceleration process.

As a result of several intensive research programs, CFD codes are being developed and improved. However, the accuracy of a CFD simulation is limited by the accuracy of the numerical method and the underlying physical sub-models. Experimental validation is critical because the model employed to simulate the positive feedback loop for turbulent combustion rely to a great extent on empirical coefficients. Therefore, the application of any computer code for the detailed numerical VCE modeling should be limited to the type of problems for which the code has been validated by experiments. Also, a number of variables, such as grid and time resolution, have significant effects on the results, hence a high level of user expertise is required. It should also be noted that this type of simulation may also require a significant amount of time to setup and execute: this is particularly relevant where a number of scenarios must be investigated.

IMPROVEMENTS TO THE BAKER-STREHLOW BLAST CURVES

As discussed above, although detailed numerical methods are being developed, there is still a great need for less complex approaches which can be used on a routine basis to predict VCE blast effects for a large number of scenarios. The type of detailed information required for CFD modeling may not be available. Furthermore, the requisite experimental validation is not available for many cases. Moreover, blast curve methods are comparatively cost effective and easy to use. Therefore, concurrent with promoting the development of sophisticated CFD numerical simulations, efforts have been undertaken by WBE to improve the one-dimensional blast curves.

Two basic improvements have been made to the Baker-Strehlow blast curves. The first is a change in the slope of blast pressure decay curve that resulted in a considerable reduction of the predicted blast pressure at large standoff distances for supersonic flames. The other is a clarification in the labeling of the individual blast curves that resulted in a nearly two-fold decrease of blast pressure and impulse at all distances for subsonic flames. Here, the terms “supersonic” and “subsonic” refer to the flame Mach numbers with respect to the ambient sound velocity.

The comparison of the blast curves obtained by several numerical methods showed that the Baker-Strehlow supersonic curves decay too slowly in the far field and depart significantly from the other curves [8-9] in this range. Actually, the numerical calculation associated with the original Baker-Strehlow curve was only carried out to scaled distance of about two and was extrapolated to ten. The TNO curves give higher blast pressures at close distances, but decay more rapidly to provide the lowest blast pressures at medium and far distances.

The new blast curves were obtained by optimizing the numerical calculations. They are denoted as the Baker-Strehlow-Tang blast curves in order to distinguish them from the previous Baker-Strehlow curves. The Baker-Strehlow-Tang curves are similar to other numerical results, but still conservative in that a comparatively slow blast wave decay is maintained.

The other improvement in the Baker-Strehlow-Tang curves relative to the Baker-Strehlow curves is the labeling of each blast curve. The previous Baker-Strehlow curves were labeled by M_w, which refers to the velocity of heat addition in the numerical calculations in a Lagrangian coordinate system. However, the flame speed, M_f, measured in experiments is the velocity relative to a fixed observer (i.e., the velocity in an Eulerian coordinate system). As a consequence, a misuse of the blast curve often occurs due to the misinterpretation of the flame Mach numbers. Nearly twice of the blast overpressure is predicted when an empirical flame speed is used to select the blast curves for subsonic flames labeled according to M_w.

The blast curves obtained by one-dimensional numerical calculations, such as the Baker-Strehlow and TNO curves, were published in 1970’s and have since been frequently used in a variety of plant safety applications. However, since systematic experimental data became available only in recently years, they have not been validated by experiments. As part of this work, the Baker-Strehlow-Tang curves were validated by experiments. The validation was carried out in three different combustion mode regimes: vapor cloud detonation, supersonic deflagration and subsonic deflagration. The primary sources of experimental data for VCE detonation are the publications by Brossard et al. [10] and the empirical equations summarized by Dorofeev [11]. The experimental data used in the comparison for supersonic and subsonic vapor cloud deflagrations were taken from the MERGE (Modeling and Experimental Research into Gas Explosions) [12] and EMERGE (Extended Modeling and Experimental Research into Gas Explosions) [13] summary reports. The validation comparisons were presented in previous papers [9, 14] and are omitted here for the sake of brevity.

RELATIONSHIP BETWEEN FLAME VELOCITIES

The following relationship between M_{su} and M_f is derived from the mass conservation for low flame velocities:

$$M_f = (\rho_u / \rho_b) M_{su}$$

where M_f	*is*	apparent flame Mach number relative to a fixed observer (flame speed)
M_{su}	*is*	flame Mach number relative to the moving gas ahead of the flame (burning velocity;
ρ_b ρ_u	*are*	gas densities behind (burnt) and ahead of the flame unburnt), respectively;

The Mach number, M_w, refers to the Lagrangian velocity of the heat addition in numerical calculations and a correction factor to relate M_w and M_{su} was derived by Stehlow and Luckritz [4] is given below:

$$M_{su} = (\rho_b / \rho_u)^{2/3} M_w \qquad (1)$$

Thus, the relation between M_w and M_f is:

$$M_f = (\rho_u / \rho_b)^{1/3} M_w \qquad (2)$$

The above relations are invalid when M_f approaches unity. For supersonic flames, $M_f = M_w$. For near sonic flames, the relationship between M_f and M_w was established by using the approximate equation for the apparent flame Mach number and the overpressure at the flame front. Assuming an expansion ratio, $\alpha = (\rho_b / \rho_u)$ of 7 for stoichiometric mixtures of commonly used hydrocarbon - air mixtures and a specific heat ratio of 1.4 (ambient air), this equation can be written as:

$$\frac{p_{\max} - p_0}{p_0} = 2.4 \frac{M_f^{\,2}}{1 + M_f} \qquad (3)$$

where p_{max} is the maximum pressure at the flame front. Although the above equation was derived from acoustic theory [15], comparison with experimental measurements shows that it is valid for a wide range of flame speeds [16]. The procedure employed was to determine the maximum overpressure for a range of M_w values of by numerical calculations. Then, M_f was calculated for a given p_{max} using equation (3). The previous Baker-Strehlow curves were labeled by M_w while the new Baker-Strehlow-Tang curves are labeled by M_f. Table 1 presents the relationships among M_w, M_f and the scaled value of p_{max}.

TABLE 1. M_f and M_w Relations

M_w	M_f	P_{max}
0.037	0.07	0.010
0.074	0.12	0.028
0.125	0.19	0.070
0.250	0.35	0.218
0.500	0.70	0.680
0.750	1.00	1.240
1.000	1.40	2.000

PRESENTATION OF THE BAKER-STREHLOW-TANG CURVES

The families of blast curves for the positive and negative overpressure, positive and negative impulse, arrival time of the shock front and the maximum particle velocity versus distance for a spectrum of flame Mach numbers are presented in Figures 1 - 6. The blast curves for negative phase parameters are included in this presentation due to the importance of negative phase blast loading on structure response. A brief discussion of the blast curves characteristics in different flame speed regimes is presented in the following sections:

Detonation and Fast Deflagrations

As can be seen from Figures 1 and 2, the overpressure versus distance curves merge into a single curve

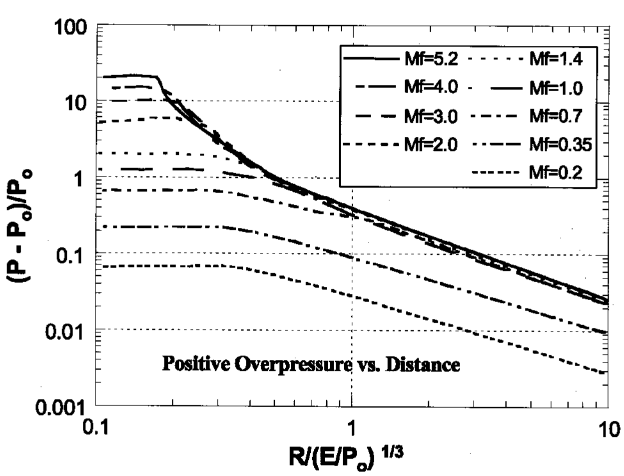

FIGURE 1. Positive Overpressure vs. Distance for Various Flame Speeds

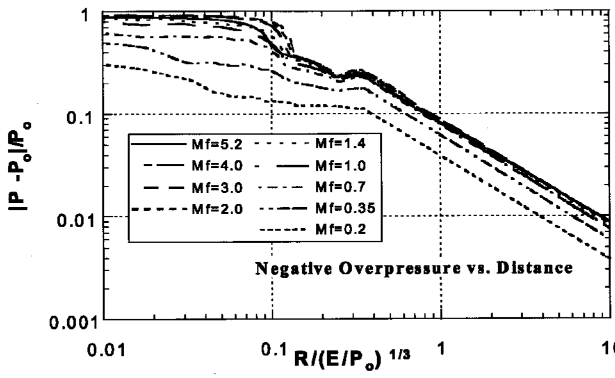

FIGURE 2. Negative Overpressure vs. Distance for Various Flame Speeds

for various flame speeds in the supersonic regime for locations outside the vapor cloud. The overpressures inside the vapor cloud are nearly uniform and the pressure increases with the flame speed for positive overpressure. As can be seen by comparing Figures 1 and 2 the negative overpressure (absolute value) never exceeds the positive overpressure for supersonic flames. This generalization does not hold true for subsonic flames.

The impulse versus distance curves for the supersonic regime also merge outside the cloud, as shown in Figures 3 and 4. The highest flame speed (detona-

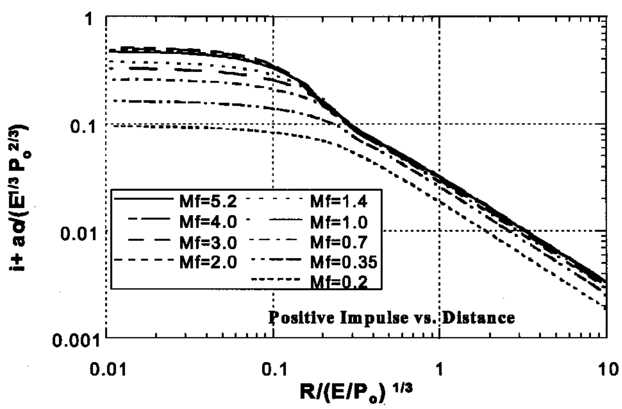

FIGURE 3. Positive Impulse vs. Distance for Various Flame Speeds

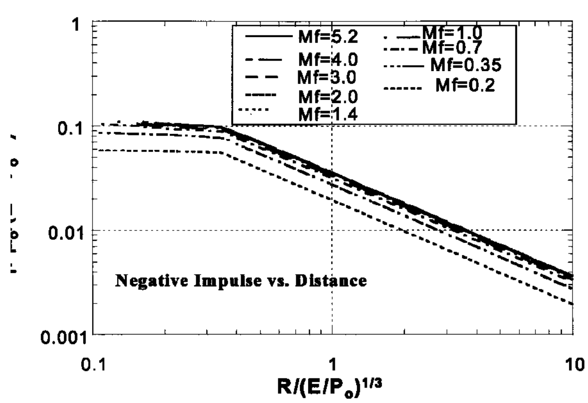

FIGURE 4. Negative Impulse vs. Distance for Various Flame Speeds

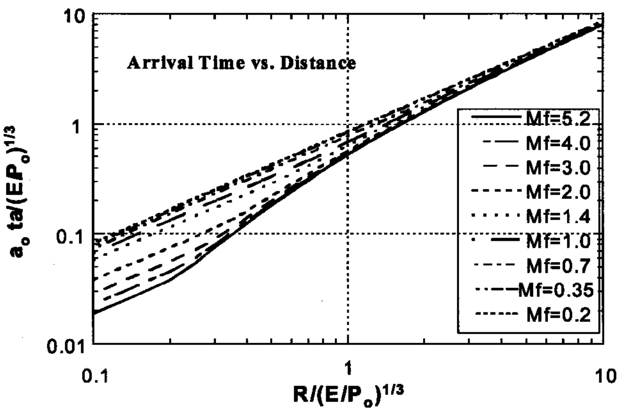

FIGURE 5. Arrival Time vs. Distance for Various Flame Speeds

tion with M_f = 5.2) generated the lowest positive impulse inside the cloud. The negative impulse versus distance curves for various flame speeds in the supersonic regime merge at all distances. The magnitude of the negative impulse is comparable with that of the positive impulse for locations outside the combustion zone (about $R/(EP_o)^{1/3} > 0.4$).

Good agreement between numerical calculations and experimental measurements was achieved for the detonation mode [9,14], as expected. In the detonation experiments, a strong ignition at the cloud center was applied which resulted in a detonation involving the entire cloud. In the numerical calculations, constant flame propagation at the maximum flame speed is assumed, which provides a good simulation of the detonation experiments.

Although the detonation combustion mode, which produces the most severe damage, is extremely unlikely to occur, fast deflagrations of the cloud can result from flame acceleration under confined and congested conditions in industrial environments. A comparison was made between the EMERGE experimental data and the Baker-Strehlow-Tang blast pressures in the supersonic deflagration regime [14]. The decay of the experimental blast pressures is much faster than the calculations in this regime. This may be

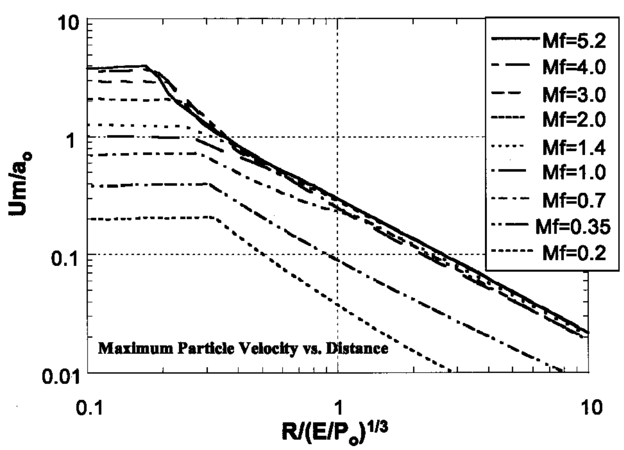

FIGURE 6. Maximum Particle Velocity vs. Distance for Various Flame Speeds

explained by the fact that a constant flame speed at the maximum value was used in the calculations, whereas in the experiments a large portion of the cloud burned at very low velocities before the flame accelerated to the maximum speed. Therefore, the fraction of the source energy released at a rate sufficiently high to support the shock wave is much less in the experiments than in the calculations. This argument is supported by the fact that the deviation of experimental data from the calculated blast curve is more pronounced for less reactive mixtures, for which flame acceleration is slower than with more reactive fuels.

Sonic Deflagrations

For a VCE with a flame Mach number close to unity, the overpressurecurves merge into a single curve outside the vapor cloud, the magnitude of which is only marginally below the supersonic curve (see Figure 1). This can be explained by the shock formation due to a piston moving at subsonic speed. In fact, the blast waves produced by sonic flames have the features of a shock wave that decays faster than the acoustic waves generated by subsonic flames. The comparison of the blast curves with experimental data in the sonic regime is similar to that in supersonic regime. The decay of the experimental pressures is also much faster than the calculations in this regime.

Subsonic Deflagrations

Unlike the blast waves generated by supersonic and sonic flames the pressure versus distance curves produced by slow subsonic flames do not merge. The flame propagation speed has a significant influence on the blast parameters both inside and outside the source volume. The fact that the blast curves for various flame speeds are nearly parallel indicates that the blast waves produced by slow subsonic flames (M_f less than 0.7 or M_w less than 0.5) follow the acoustic decay law and the decay rate is not influenced by the flame speed.

Good agreement was found between the numerical results, analytical solution by acoustic theory, and experimental data in the subsonic regime. According to the acoustic solution, the overpressure is inversely proportional to the distance. Thus, the inverse-radius law, can be used to extend the blast curves to far distances.

CONCLUSIONS

A newly developed set of VCE blast curves provides an improved representation of blast parameters in both the positive and negative phases. Labeling of the curves has been modifed to allow direct use of empirical flame speed data to select a blast curve. Validation against VCE experiments has shown good agreement in the supersonic and subsonic regimes, and conservative predictions in the sonic deflagration regime.

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This paper (29e) was presented at the 33rd Loss Prevention Symposium held during the AIChE Spring National Meeting in Houston, Texas, March 14-18, 1999