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Estimating Characteristics of Industrial BLEVEs and VCEs from Observed Condensation Clouds

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It is known that the passage of a shock wave in a moist atmosphere can produce a condensation cloud that is briefly visible to the human eye. Recent accidents (e.g. Toronto August 2008) involving boiling liquid expanding vapour explosions (BLEVE) and vapour cloud explosions (VCE) have shown such condensation clouds.

In this age where video footage of an explosion incident is the norm (i.e. from the smart phone of a remote observer, or from a security video camera) it is very likely that there will be visual evidence of explosions. This evidence may include the size of a condensation cloud from a shock wave. This paper presents an analysis that allows us to estimate the overpressure of the shock wave at the edge of this condensation cloud. In many cases we can also determine the distance to this shock overpressure from the video image. With this overpressure and distance data it is possible to estimate the energy of the explosion and the overpressure and expected damage at other distances. This could be very useful for accident analysis. Limited video footage of BLEVE tests is used to provide and limited validation the method.

1. Introduction

A shock wave is a supersonic pressure wave. Such a wave can be caused by the sudden release of energy. We call this sudden release of energy an explosion (Baker et al., 1983) if it produces a shock. Shocks can be produced by many mechanisms. Two examples of shock producing explosions are boiling liquid expanding vapour explosions (BLEVE) (Reid, 1979) and vapour cloud explosions (VCE) (AIChE, 1994).

When a shock wave passes over a point in space there is a very rapid pressure and temperature increase (Kinney and Graham, 1985), this is then followed by a rapid drop in pressure and temperature, and this is followed by a blast of wind, and then finally a recovery to the normal ambient pressure.

The shock overpressure compresses the air adiabatically and this causes the temperature to rise. Entropy is produced in the shock and this also increases the temperature. The sudden pressure drop after the shock and adiabatic expansion causes the air temperature to drop. This negative phase or underpressure typically drops the pressure below the normal local atmospheric pressure and therefore the temperature may drop below the local ambient temperature. If the air is laden with moisture it is possible that the temperature will drop below the dew point (Moran and Shapiro, 1995) and this may lead to the nucleation of liquid droplets in the air that appear as a fog. As a shock passes these liquid drops only appear very briefly as a fog because the pressure will quickly rise back to ambient or above. In our BLEVE experiments (Birk et al., 2007) we were only able to capture the condensation clouds in some experiments using regular video frame rates and this cloud only appears in one video frame. In the next frame the cloud is gone. This is because the underpressure is immediately followed by an overpressure that would evaporate the drops.

Figure 1 shows an example of a condensation cloud captured from a 1.9 m^3 propane tank that suffered a Hot BLEVE type failure (Birk, 2012).

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Figure 1: Image of a BLEVE with condensation cloud present (Birk, 2012).

Recent video footage available on the internet (You Tube) clearly shows condensation clouds produced by both a vapour cloud explosion and a BLEVE during the Toronto explosions of August 2008. The first explosion (see Figure 3) was a vapour cloud explosion (VCE) from a large propane vapour release. This VCE produced a clear shock wave that propagated out as a near hemisphere. The explosion was at night and the video footage clearly showed the extent of the condensation cloud because it was illuminated by fires from underneath. The image looks like a fireball, but it was not a fireball but rather a very fast (supersonic) moving pressure wave (shock) that created a condensation cloud. The camera was saturated by the sudden change in light intensity. The video clearly showed where the condensation cloud ended. This cloud was estimated to be around 300 m in diameter. The humidity that night was 92 %.

In this same Toronto incident, a second major explosion followed about six minutes after the vapour cloud explosion (see Figure 2). This second explosion was at least one BLEVE of a tank truck containing propane. This also produced a shock and a brief condensation cloud. It was not possible to estimate the diameter of this cloud based on the information available.

Figure 2: Video frame of Toronto BLEVE (August 2008) showing condensation cloud from BLEVE illuminated by fire from below (from You Tube).

If the ambient temperature and relative humidity are known, this visual data can be used to estimate the actual overpressures produced by the explosions at the edge of the condensation cloud. From this it is then possible to estimate other important properties such as the mass of product, energy content, etc.

2. Analysis Approach

The relative humidity of atmospheric pressure and temperature air is defined as:

$$rh = \frac{p_g}{p_v} \tag{1}$$

Where p_v is the saturation pressure of water vapour at the air temperature T and p_g is the partial pressure of the water vapour in the air at pressure P and temperature T. The dew point is reached when the temperature drops under constant P so that $p_v = p_g$.

The following model was used to estimate the shock overpressure at the edge of the condensation cloud:

- assume ambient pressure 101.3 kPa and temperature 10 or 20 °C with relative humidity between 0.2 to 1.0
- normal shock relations apply
- adiabatic irreversible pressurization by a normal shock with pressure ratio P_y/P_x (P_x pressure before shock arrives, P_y from shock peak overpressure).
- isentropic expansion due to underpressure from P_y to P_z where $P_z = P_y - 2F(P_y - P_x)$ where F is a factor based on experimental data.
- dew point (visible condensation) when relative humidity rh = 1 at z.

For a normal shock the pressure and temperature before and after the shock are (White, 1986):

$$\frac{P_y}{P_x} = \frac{M_x}{M_y}\frac{\sqrt{1+\frac{k-1}{2}M_x^2}}{\sqrt{1+\frac{k-1}{2}M_y^2}} \tag{2}$$

$$\frac{T_y}{T_x} = \left[\frac{M_y}{M_x}\right]^2\left[\frac{P_y}{P_x}\right]^2 \tag{3}$$

where M is the Mach number and k is the ratio of specific heats. For the negative phase (y to z) we assume the process is isentropic and the change in temperature comes from the isentropic relation:

$$\frac{T_y}{T_z} = \left[\frac{P_y}{P_z}\right]^{\frac{k-1}{k}} \tag{4}$$

3. BLEVE

Figure 3 shows the blast wave measured at 20 m from the side of a BLEVE from a 1900 litre cylindrical propane tank (Birk et al., 2007). The initial shock is the first peak around 0.05 seconds. As can be seen this is followed by an underpressure of similar magnitude and then this is followed by a second shock that brings the pressure back above ambient. The condensation cloud is believed to be caused by the underpressure or negative phase of the blast wave. Notice that for a BLEVE the magnitude of the negative phase is similar to that of the positive phase. Figure 4 shows experimental data for the factor F = -dPs neg/dPs peak from BLEVE experiments involving a 1.9 m^3 propane tank (Birk et al., 2007).

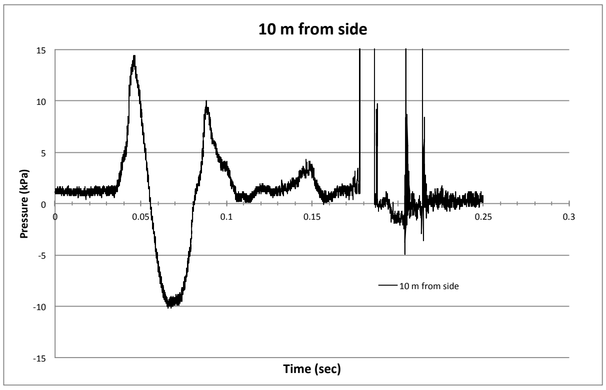

Figure 3: Sample pressure wave from a BLEVE of a 1.9 m^3 propane tank (Birk et al., 2007).

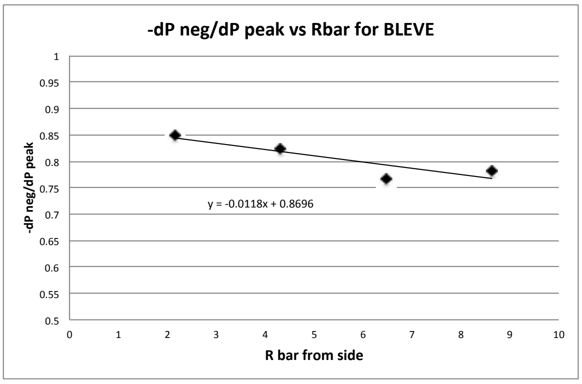

Figure 4: Ratio of peak overpressure magnitude to underpressure vs distance for BLEVE of 1.9 m^3 propane tank.

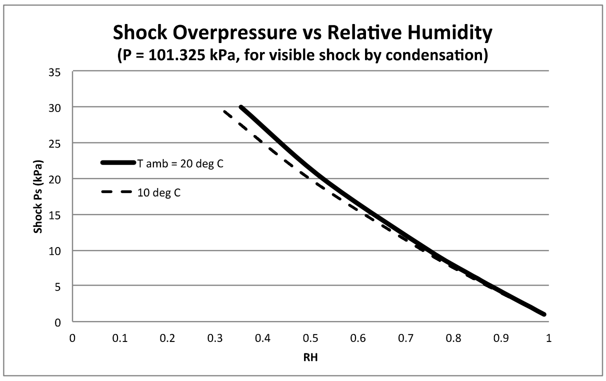

Figure 5: Calculated overpressure needed for a condensation cloud vs air relative humidity (ambient pressure 101.325 kPa).

Figure 5 shows the results of this analysis for a BLEVE overpressure required for a condensation cloud where the negative phase underpressure is based on F = -0.0118 Rbar + 0.87. Rbar is the energy scaled distance and is defined as:

$$\bar{R} = R\left[\frac{P_o}{GE}\right]^{1/3} \tag{5}$$

and

R = range to pressure in metres
P_o = ambient pressure = 101.3 kPa
E = isentropic expansion energy of vapour space (or liquid if tank is near 100 % full) of release in kJ
G = 2 for half space from ground effect

As can be seen in the Figures, the overpressure required for the condensation cloud front increases as the humidity decreases. For example, for 80 % relative humidity, we estimate the positive phase overpressure from a BLEVE required to give a condensation cloud is around 8 kPa.

Once we have the overpressure at one radius it is possible to determine the energy scaled distance for that overpressure from the overpressure decay curve for a BLEVE. The overpressure decay curve for propane (Baker et al., 1983; van den Berg, 2006) is shown in Figure 6 for BLEVE failures that occur around 2 MPa pressure.

An approximate fit to the propane overpressure decay curve is:

$$dPs = S\frac{33.1}{\bar{R}^{1.145}} \tag{6}$$

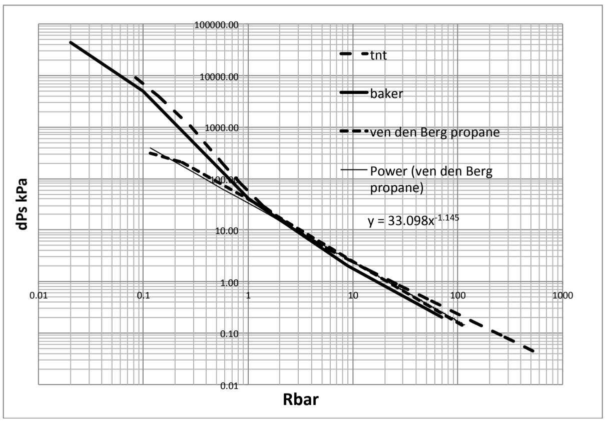

Figure 6: Overpressure decay curve for propane BLEVE.

where

S = shape factor for cylindrical tank (1.0-1.8) depending on how the vessel opens
dPs = peak overpressure in kPa

We can now take the calculated overpressure for the condensation cloud for a range of RH values (say 0.7, 0.8, and 0.9) and from this we can determine the scaled distance. The scaled distance can then be converted into a radius as a function of isentropic expansion energy input. Here we have assumed the shock is produced by the vapour space energy (Birk et al., 2007). This result is shown in Figure 7 for S = 1.0.

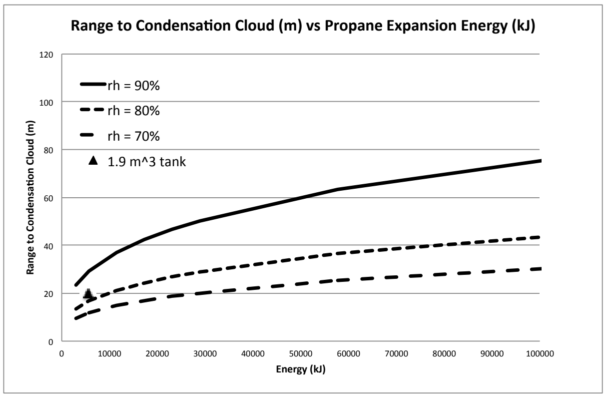

Figure 7: Radius R to edge of condensation cloud from BLEVE vs isentropic expansion energy (saturated at 1.9 MPag) assuming S = 1.0.

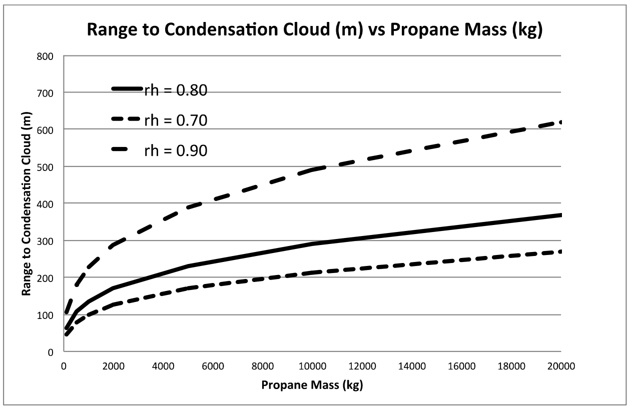

Figure 8: Estimated range to condensation cloud for propane VCE (yield = 10 %, F = 0.8). Not validated.

Let us now consider the case of a 1.9 m^3 propane tank that suffers a BLEVE at 1.9 MPa pressure with a fill level of 50 % liquid. If we assume the shock overpressure comes from the vapour energy, then we can calculate the expected distance to the edge of the condensation cloud. The isentropic energy in the vapour space for this case is 5.4 MJ. Figure 8 shows this result plotted (i.e. radius to condensation cloud around 20 m). If we compare this calculation to Figure 1 we can validate the method. The condensation cloud in Figure 1 has a radius of approximately 20 m. The humidity was around 80 %. Of course this is a very limited validation with only one data point. More data is needed to verify this methodology.

4. Vapour Cloud Explosion

The same method can be used for a VCE but we need the F factor to determine the underpressure as a function of the peak overpressure. With a VCE the blast wave starts with little or no negative phase. The negative phase develops in the far field. We have assumed a constant F = 0.8 for the far field of a VCE. We have also assumed a yield of 0.1 as per the US EPA guidelines (EPA, 2000). With these assumptions we get RH vs dPs for the edge of the condensation cloud in a similar way to that of the BLEVE. The conversion to kg of propane is different because we are now considering chemical energy rather than thermo-mechanical expansion energy. We have assumed the following:

- air fuel ratio of 15.7 by mass
- yield 0.1
- combustion energy 3.5 MJ/m^3
- overpressure decay from TNT as in Figure 6

A VCE has the potential to generate much higher shock over pressures than a typical BLEVE so we expect much larger distances to the edge of the condensation cloud. Figure 9 shows the calculated ranges for the condensation cloud. If we assume a humidity of 90 % and a radius of 150 m, we estimate the total propane mass in the vapour cloud to be about 300 kg assuming a 0.1 yield. We have no data to confirm this.

5. Conclusions

A method has been presented to calculate the overpressure required for the formation of a condensation cloud as a result of a BLEVE or VCE explosion. The only inputs needed are the air temperature and relative humidity, and the radius to the edge of the condensation cloud. With this data it is possible to estimate the overpressure at the edge of the cloud. With this data it would be possible to estimate the overpressure decay curve and energy from this incident. This could then be compared to observed damage. Further validation is needed to determine how accurate the method is.

Acknowledgments

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