

THE MODELLING OF BLEVE FIREBALL TRANSIENTS

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An existing physically based BLEVE fireball model has been developed to predict the shape of the transient heat pulse to a receiver, to model "cold" BLEVEs, and to assess the consequences to structures and people. This has been achieved by finding a correlation to predict the size of a characteristic liquid drop within the flashing cloud. These drops burn out to predict the time to fireball break-up and extinction, and their height is tracked to find the rise of the fireball, agreement with small and large scale data being satisfactory. The model is semi-empirical in that, when the level of pre-heating is low, a heat balance cannot predict the development of fireball temperature with time since the fuel is pyrolysing. Also, the modelling of the transition from "cold" BLEVE fireball to pool fire is a cautious best estimate. Using both traditional and more recent models, the prediction of pain, burns and fatality have been incorporated into the model. Whatever criterion for a safety distance is used, the effect of modelling the transient is to reduce the calculated safety distances by up to a factor of two, which brings fatality predictions for real incidents much more in line with the historical record.

Key Words: BLEVE, fireball, thermal radiation transients

INTRODUCTION

A BLEVE model [1] was created following a set of up to 2 tonne LPG BLEVE experiments where the mass, type, initial pressure and fill level of fuel were varied in a systematic manner, allowing the observed variation in fireball characteristics to be related to the initial conditions at vessel rupture. Satisfactory agreement was demonstrated between the model and all other experimental BLEVEs which had been carried out, and with the (few) large scale real BLEVE events where the initial conditions could be predicted with some confidence. More recently, the need for model refinement in two areas was established. First, in order to model the consequences of a received heat radiation transient more realistically, it was necessary to predict more than the peak incident flux and total dose. In fact it became apparent that it was necessary to model the transient as accurately as possible since a safety distance based on, say, Eisenburg's probit variable, V , defined by:

$$V = \int I^{4/3} dt$$

where I is the incident heat flux at the receiver, and V is the integral over time, varies dramatically depending on the shape of the transient.

Secondly, recent publications [2] show that when the level of pre-heat is low, a "cold" BLEVE might occur. Here, an event more like a ground level cloud fire with a weak fireball on top, the fireball not rising to an appreciable height, characterises the event. The approach taken was to try and find a unifying model which would both reproduce the heat transient, and give a "cold" BLEVE from storage conditions, with minimum alteration to the BLEVE code as written.

FIREBALL MODELLING

The fireball was already modelled as developing in stages. Briefly, in Stage 1, the vessel fails, ejecting any missiles as the walls collapse, and generating an initial pressure pulse whose source is the energy in the vapour in the vessel just before failure. In Stage 2, the bursting vessel ejects a cloud of liquid droplets which flash adiabatically as the pressure in the cloud drops. There is little mixing with the surrounding air, and, if the expansion velocity exceeds the speed of sound in the rarefaction wave following the initial pressure pulse, a flashing liquid blast wave is generated. When the flashing is complete, this blast wave leaves the outer edge of the cloud, generating a large degree of turbulence. In Stage 3, the cloud continues to grow, and air is entrained due to the turbulence. In Stage 4, the ignited cloud grows to a fireball as the flashed vapour is consumed. In Stage 5, combustion continues, fuelled by evaporation of the remaining droplets, and the fireball rises into the air before extinction.

Clearly, droplets are formed in Stage 2, and their combustion dictates the lifetime of the burning cloud, so a droplet model was required to generate a more accurate heat pulse. Unfortunately, the formation of droplets during flashing has not yet been characterised, but a great deal is known about droplet behaviour, investigations having been undertaken to facilitate the design of atomisers and reactors. A full review is that of Lefebvre, [3], and the results presented here are an extension of the theories and references which he describes.

First, a whole range of drop sizes will exist in a spray. The size distribution is difficult to measure and impossible to predict in the absence of data. Thus it is necessary to model a representative drop size, which, since large drops take longer to burn than small ones, will be representative of the largest drops present in the cloud. Second, Taylor carried out the first basic experiments on the splitting of drops under the action of viscous and surface tension forces, both of which must be of importance in Stage 2 before the cloud becomes turbulent. He observed that the deformation is governed by a dimensionless group, $\frac{\mu_c SD}{\sigma}$, where μ_c is the viscosity of the continuous phase, S the maximum velocity gradient in the external flow field, D the drop diameter, and σ the surface tension. This dimensionless group also characterised the largest stable drop diameter in the (very) viscous flows that he studied.

The BLEVE model is built upon a turbulence model which makes an equivalence between the developing turbulence to that found near the source of a steady state jet, i.e. in the region where the eddies are forming, rather than in the later self-similar regime, and the necessary turbulent lengthscales and velocities are already generated within the code. At the end of Stage 2, the turbulent velocity of the largest eddies, lengthscale L/N , is Nu_L , where L is a lengthscale such that L^3 is equal to the total volume of flashed vapour, u_L is the characteristic turbulent velocity once the eddies have expanded from L/N to L by entraining air, and N is an multiplier (around 2.66) solved for by an energy balance. The model is based on a correlation for u_L , which could not previously be explained. This was, approximately:

$$u_L = const.(\alpha\beta)^{1/9}$$

where α and β are the initial liquid and final (post flashing) vapour mass fractions, and the constant was slightly fuel dependent, correlated with vapour densities. The important, and

surprising, observation is that the formulation for u_L is independent of the original mass of fuel in the vessel.

Imagine that during Stage 2, drops of uniform size are flashing, and pushing each other apart. The cloud is expanding at $U_0 = N^2 u_L$, so that, ignoring (for clarity) multipliers in N , α or β here, there are L/D drops in a radius pushing each other apart, and the maximum local shear is given by:

$$S \approx \frac{\left(\frac{u_L L}{D}\right)}{L} \approx \frac{u_L}{D}$$

and, for $\frac{\mu_c SD}{\sigma}$ to be constant, then:

$$u_L \approx \frac{\sigma}{\mu}$$

which, as a fluid property dependent velocity, will vary lightly with initial conditions, but not with the mass of fuel. Next, we turn to the Weber number formulation originally due to Kolmogorov and Hinze. They assumed that the dynamic pressure forces of the turbulent motion determine the size of the largest drops. Since the kinetic energy of a turbulent eddy increases with size, eddies of the same size as a drop will generate the highest dynamic pressures on it (much larger eddies will just move the drop around, smaller ones will bounce off it). The critical Weber number becomes:

$$We_{crit} = \frac{\rho u_D^2 D}{\sigma}$$

where ρ is the density of the gaseous phase (in our case fuel vapour at atmospheric pressure), and u_D the turbulent velocity of an eddy whose size is equal to the drop diameter, D . The value of the Weber number depends on the assumptions made in its calculation when fitting to data (for example, a typical assumption is that the turbulence is isotropic). Modelling the turbulent cascade at constant energy dissipation rate per unit mass, ϵ (m^2/s^3), gives:

$$D \approx \frac{\sigma}{\rho u_D^2} = \frac{\sigma}{\rho \epsilon^{2/3} D^{2/3}}$$

so that:

$$D = \left(\frac{\sigma}{\rho}\right)^{0.6} \epsilon^{-0.4}$$

and the best correlation found for droplet size was of this form, ϵ being a product of the existing turbulence model:

$$D = 2.805 \alpha^{2/15} \beta^{1/6} \left(\frac{\sigma}{\rho_{v0}}\right)^{0.6} (\beta N^3 \epsilon)^{-0.4}$$

As will be seen, the burn time of these droplets agrees well with observed fireball lifetimes, and the droplets track the fireball rise quite adequately. We see that the first dimensional controlling group, $\frac{\mu_c SD}{\sigma}$, implies that, for the flashing cloud modelled as stage 2, the expansion velocity, and therefore u_L should be independent of mass, which it appears to be, and that the Kolmogorov Weber number criterion also relates u_L and D . Ignoring multipliers and initial condition dependent terms:

$$\frac{u_L D}{v} \approx \left(\frac{L}{D}\right)^{2/3}$$

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which can only be given as a scaling observation, since the cause and effect sequence of the process has not yet been unscrambled. Future work in this area might well result in the BLEVE model being reconstructed in simpler form, and allow mixtures (and other fuels) to be modelled with confidence.

Once formed, and if the fireball ignites, the droplets evaporate in the fireball, fuelling its existence during Stage 5. If the temperature in the fireball were constant, then the drop lifetime is proportional to D^2 [3]. In practice, the variation of the effective fireball temperature with time as the fireball burns is not predictable, since the main process of combustion is by pyrolysis, and the heat released at any stage before combustion has proceeded to completion cannot be predicted. Therefore a semi-empirical approach was taken to predicting the remainder of the transient.

- a) From ignition to peak diameter, the fireball parameters are taken from the existing model, the radius and surface emissive power increasing linearly with time.
- b) The average temperature of the fireball at break-up, T_{end} , is found by an energy balance which assumes complete combustion of as much fuel as can be burned by the air contained within the fireball. This is satisfactory for "hot" BLEVEs, but, where this calculated temperature is less than 0.88 of the peak, it is found by inspection of the data in the experimental BLEVEs studied that the temperature never fell below this value, so that T_{end} is set with $0.88T_{peak}$ as the minimum value.
- c) (Figure 1) The time to fireball break-up is calculated from the drop lifetime, using the standard equation for drop evaporation at constant temperature [3], and T_{end} both the effective fireball temperature, and for calculating the reference temperature (which is used to find the fluid properties). The agreement between observed and predicted time from ignition to break-up is good.

- d) (Figure 2) The fireball temperature (from which the surface emissive power is calculated) is modelled as decreasing linearly with time from T_{peak} to T_{end} when break-up commences, and thereafter is fixed at T_{end} .
- e) It was assumed that, since drops which ignited immediately burn out as the fireball began breaking up, then break-up would be complete (and the fireball cease being an effective emitter) once drops which were not ignited until the fireball had peaked at the end of Stage 4 had themselves burnt out. During this break-up phase, the radius of the fireball decreased linearly with time (taking the broken fireball as an equivalent sphere).
- f) (Figure 3) As the development of the fireball with time is calculated, the height of a single drop is tracked. The drop is assumed to start at the top of the (spherical) expanded fireball, with a rise velocity equal to one half the fireball expansion velocity (by symmetry). The rising fireball is tracked, and the parameters controlling the vertical motion of the drop (including its diameter) calculated from T_f if the drop is in the fireball, and ambient temperature if outside, at each time step. The fireball is, in fact, a rising vortex, but is represented as a rising column of air moving at fireball rise velocity (this is a conservative modelling method, since drops will be thrown outwards and downwards by the vortical motions in the fireball). For all the experimental BLEVEs, the drops tracked to within a few meters of the fireball centre at extinction (again taking the broken fireball as an equivalent sphere).
- g) Tracking the evaporating drop, the mass of fuel in the fireball is calculated at each time step, assuming that all the fuel is contained in drops of this size. If the fireball runs out of fuel, then it extinguishes after the break-up period. However, if the drops hit the ground, then the mass of fuel is assumed to form a pool extending over the maximum (spherical) fireball diameter. Well known LPG pool fire correlations are used to predict the flux from the resulting pool fire, and its burning time (which is normally short). Since the fireball collapses back into a pool fire, and in the absence of data, the following conservative method is employed to generate the flux transient. As the fireball develops, the height of its centre is set as equal to the height of the tracked drop, unless this becomes less than the height at the end of Stage 4, when the fireball is assumed to remain sitting on the ground at constant radius. The fireball flux transient is cut-off when all the air initially mixed into the fireball has been consumed, and the flux connected linearly to that emanating from the pool fire formed after the drops have hit the ground.
- h) In the case where the fireball runs out of air, but the drops evaporate prior to hitting the ground and forming a pool, then the fireball break-up model is used to generate the flux transient until drop evaporation is complete.
- i) Having generated the flux transient to the receiver using appropriate view factors, markers such as dose, mean flux, or Eisenburg's Probit Variable V ($V=I^{4/3}t$) can be found by numerical integration.

BURN AND FATALITY MODELLING

Eisenburg's probit variable is in general use as a marker for burns and fatality. "Slight second degree burns" which result in shallow partial skin loss, which recovers in about a week (medium to bad sunburn), but does not result in residual pigmentation changes or damage to hair follicles are found at around $V = 1100$ (Hymes^[4] gives 1200 for 2nd degree+).

Clearly, exposure to 1100 units should be avoided, and this has been taken as the marker for safety distance comparison below. Since the time to pain at this limit is about 1/10 of the time to slight burn, there will be time for mitigating action (turning round, ducking, finding shelter etc.) once the pain has alerted the observer to the fact that some evasive action would be a good idea.

Figure 4 illustrates the current position. The percentage fatality predictions for Eisenburg's original probit, and the TNO modifications^[5], are plotted against V . It will be seen that substantial fatality levels are predicted at $V=1100$, which is clearly very over-conservative.

Lees ^[6] has recently developed a method which offers the scope to overcome these deficiencies. Essentially, the method recognises from data published by the British Medical Association (BMA) that the % fatality is, with modern medical treatments, most strongly influenced by toxic shock. This is itself a function of the percentage area of skin burn, and the age of the victim (which influences the ability to recover). The data given is independent of burn depth, but covers all "significant" burns, i.e. 2nd degree +. Lees superimposes onto this data a variation in % fatality which depends on burn depth, and weights over a model population, to find the average percentage fatality. To account for the fact that only half the skin is exposed to radiation at a time, and that the body is not a perfect spherical receiver for radiation, a correction factor, ϕ , is incorporated into his model, which varies dependent on whether or not clothing is expected to ignite.

EFFECT ON SAFETY DISTANCES AND NUMBER OF FATALITIES

Figure 5 illustrates the effect of transient modelling for a half full 20 tonne butane vessel. The criterion $V=1100$ has been used, so that the distance reflects the onset of 2 degree burns to an observer who takes no evasive action. At low levels of pre-heat, the fireball remains attached to the ground and collapses into a pool fire. For the sake of this illustration, the consequence of the pool fire has been ignored, since it will only have a radiation effect on people who have already been seriously affected by the initial fireball transient. For the hot BLEVE, it may be seen that the criterion is met at around 1.5 fireball radii from the BLEVE centre. Also marked on the illustration is the distance to the same criterion calculated by the formulae given by Hymes^[4], who modelled the transient in the traditional way as a top-hat. It may be seen that the distance is reduced by a factor of two. As an example at large scale, the hot BLEVE (16 bar pressure) of a 500 m³ butane vessel, 85% full, predicts 1% fatality by Lees at 1.67 fireball radii.

Figure 6 illustrates an output from the modified BLEVE model for hot BLEVE of the above 20 tonne vessel. The vertical axis is the percentage fatality which, for simplicity, has been assumed to be 100% within the fireball (historical experience is that this is untrue for well protected

people, e.g. firemen). The solid line is derived from Eisenburg's probit formulation, and the dashed line by the formulation given by Lees. It is clear that the percentage fatality drops off very rapidly just outside the fireball, whichever formulation is used. In Quantified Risk Assessment work, the population at risk is convoluted with the percentage fatality coverage on an area basis, and the uncertainty in the population estimates will always overshadow the uncertainty in burn modelling. This is always true of BLEVEs where pre-heating has occurred, since the warning time causes the natural population to be increased by curiosity, or decreased by fire brigade induced controls, in an unpredictable manner.

Marshall^[7] gives many examples where BLEVEs have occurred, and the population at BLEVE could be assessed with some confidence. Generalising his analysis, some fatalities occur within about 1.5 radii of the vessel, exactly as is found here by modelling the fireball transient.

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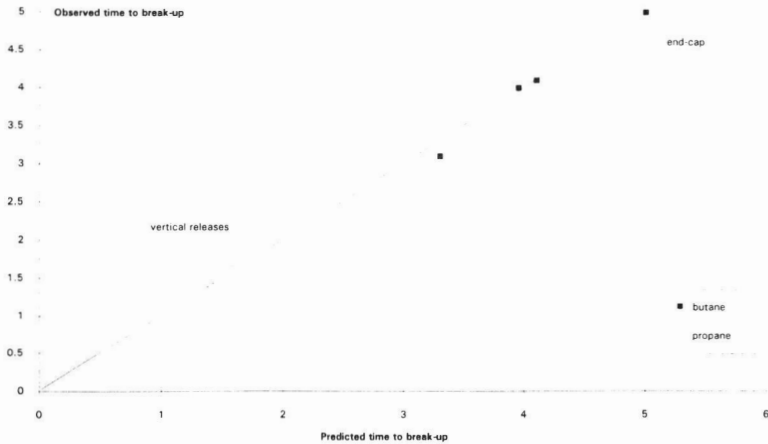


Figure 1. Predicted and Observed time to fireball break-up (seconds) for Hasegawa and Sato (HS) and Spadeadam data. The points marked "vertical releases" are HS small scale experiments. The point marked "end cap" rocketed some fuel away from the fireball.

Incident Radiation Flux (kW/m²)

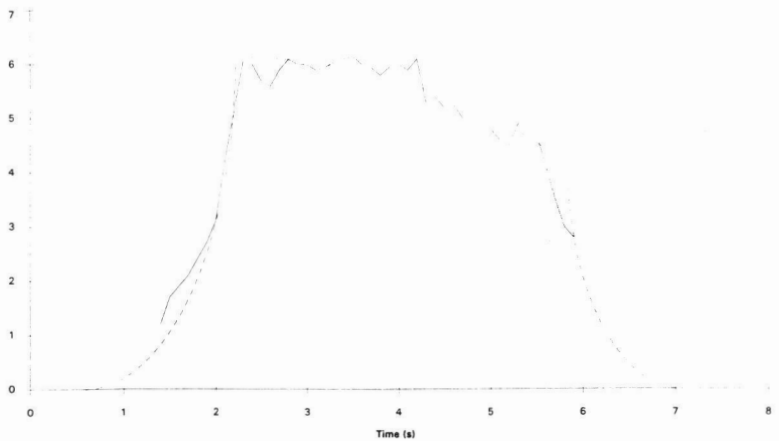


Figure 2. Typical representation of measured data. Incident heat flux at 175m west of a 2 tonne butane BLEVE from an initial pressure of 7.7 bar gauge.

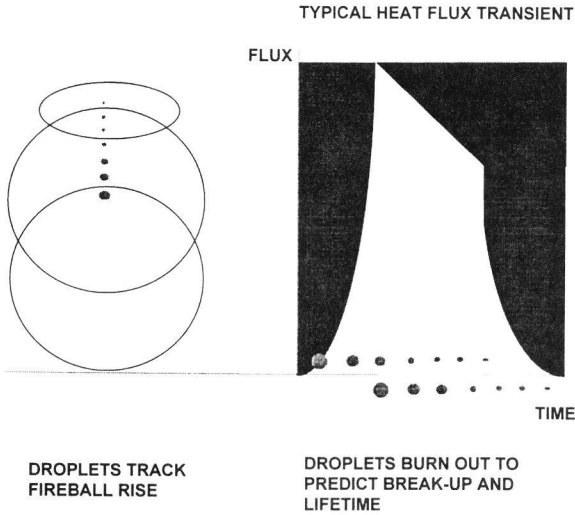


Figure 3. Illustration of transient and droplet modelling

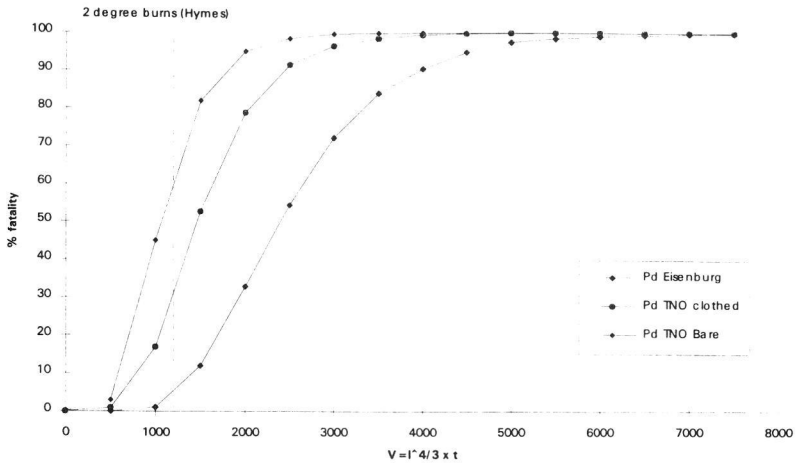


Figure 4. % fatality from various probit methods compared with 2 degree burn criterion

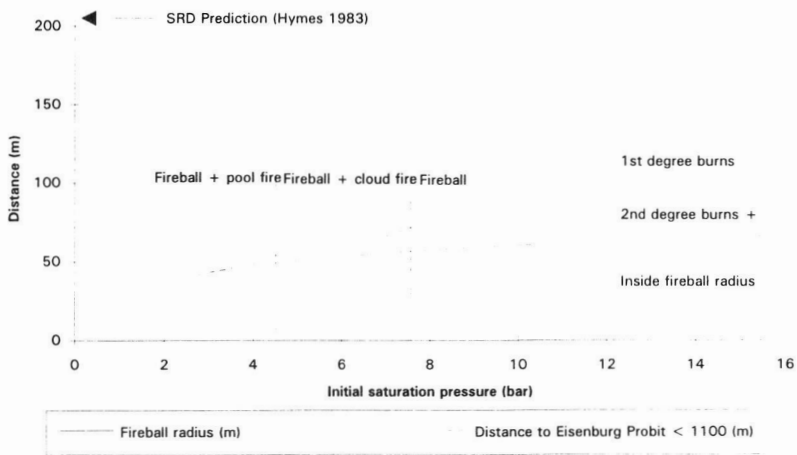


Figure 5. Predictions for a 40 m³ vessel containing 10 tonnes of butane

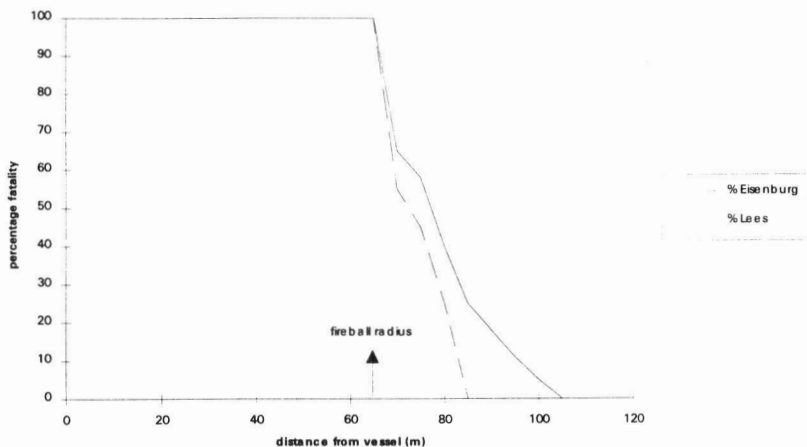


Figure 6. % fatality plotted against distance from fireball centre for 40 m³ vessel containing 10 tonnes of butane heated to a saturation pressure of 16 Bar.