

REVIEW OF INVESTIGATIONS ON RISING FIREBALLS AND NEW IMPLICATIONS FOR MITIGATION OF HAZARDOUS FUEL RELEASES

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ABSTRACT

Development of large-scale fireballs is a typical result of explosions associated with accidental fuel releases. One of the possible mechanisms, which can lead to fireball formation, is a vapour cloud explosion. Such events occur in the chemical and process industries and often result in huge property damage and human casualties. The present paper consists of two parts. In the first part, a simple model is proposed to estimate a rate of surrounding air entrainment into a rising fireball. The model is applied to estimation of the mass of fuel involved in the explosion. The results are compared to CFD modeling of the problem. In the second part, estimation is made of possible use of the entrainment effect for mitigation of fireballs. It is shown that the typical rates of air entrainment are sufficient to deliver significant amounts of fire suppressant, such as aerosols, into the core of a fireball.

INTRODUCTION

Vapour cloud explosions, along with the BLEVE (Boiling Liquid Expanding Vapour Explosion) are major hazards in the chemical process industries^{1,2}. Such explosions are caused by release and vaporisation of hydrocarbon fuels into the atmosphere, which results from the rupture of vessels, tanks or pipelines. In the case of fuels that are heavier than air, the vaporised cloud “sticks” to the ground and may explode upon accidental ignition. Quite often such accidents involve significant property damage and human casualties.

Vapour cloud explosions have been subjected to scientific analysis for the last few decades. Most studies used small- or medium-scale experiments and were focused primarily on measuring the maximum diameter, elevation, lifetime, surface temperature and emissive power of fireballs resulting from LPG release³⁻⁵.

Mathematical modeling of fireballs is much less developed. A few simple analytical models have been developed using the approximation that a fireball can be treated as a rising sphere^{6,7}. Recently, attempts have been made to apply a rigorous CFD approach, including turbulent combustion modeling, to the prediction of fireball behaviour and associated parameters^{8,9}.

A typical problem, which arises during investigations of vapour cloud accidents, is the estimation of the amount of fuel involved in combustion. Some estimations are based on the destruction caused by shock waves. However, a single method of assessment may lead to large errors due to the complexity of the phenomenon. It is desirable to have several independent methods for such estimations.

In the studies^{10,11} a novel method has been proposed which is based on the estimation of entrainment of surrounding air into a fireball. Air currents caused by fireball motion can cause certain types of damage, for example, forest or building destruction. Knowledge of the connection between the power of an explosion and the speed of air entrainment allows reconstruction of the accident to be made, based on observed damage in the affected area^{10,11}.

In the present study, a much simpler model is presented which can be used for the same type of estimations as in^{10,11}. The results obtained with this simple analytical model are compared with the results of CFD simulations.

Another problem of significant importance is the mitigation of accidental explosions. Using the model developed in this study, it is demonstrated that the air entrainment effect can be potentially used to effectively deliver suppressing agents into the flaming region of a fireball. Both analytical and numerical results are presented on this matter.

Vapour cloud explosion development

Vapour cloud explosions involve several stages. In the first stage, fuel is vaporised and released into the atmosphere. The cloud is formed. The exact shape of the cloud may vary, but numerous observations^{1,2} suggest that it is generally half-ellipsoidal and elongated along the ground. As a limiting case, a hemispherical cloud is possible, although such a situation is not very likely.

A schematic illustration of a vapour cloud explosion is presented in Figure 1. After ignition, there is a very rapid (shorter than 1 second) period of fireball growth. At this stage, radiation transfer dictates the growth rate. Clouds at this stage still stick to the ground, and shock waves are formed. The next stage is a convective stage. Due to heat release of combustion and accumulation of buoyancy, the fireball detaches from the ground and takes a typical shape of a mushroom cloud. Surrounding air is entrained into a stem of the "mushroom". Combustion in the fireball continues in a relatively slow deflagration mode as surrounding air mixes with the remaining fuel.

An impressive illustration was an explosion in Russia's Ural region (near the town of Ufa) that occurred in 1989 at a railway track in a forest area. The rupture of a pipeline running parallel to a railway line caused the accident. The pipeline transported a mixture of various liquefied hydrocarbons. Huge amounts of hydrocarbons were released forming a vapour cloud that covered an area of several square kilometers. Ignition occurred as two trains, passing in opposite directions, met in the cloud. The ignition source was apparently inside one of the trains. It is believed that movement of the trains inside the cloud contributed to fast mixing of vapour and air, increasing the potential for devastating deflagration. Ignition of the cloud resulted in a huge explosion, which was accompanied by strong shock waves and fireball formation. The accident resulted in over a thousand casualties.

The accident resulted in two types of damage. Firstly, damage was caused to villages at various distances from the explosion, due to shock waves. Secondly, there was massive forest destruction on the site. In various works^{10,11} it has been demonstrated that massive forest destruction and the directions of the fallen trees can be explained by air entrainment into a huge fireball. This is consistent with the observation that the crowns of the fallen trees were directed towards the epicentre.

Based on the results of CFD simulations, a relation has been derived in^{10,11} based on the near-ground entrainment velocity (and therefore, the type of damage caused by such entrainment) and the power (or fuel mass) of the explosion. The Beaufort Wind Scale was used to classify the types of damage.

A simpler model for estimation of air entrainment velocity is presented in the next section.

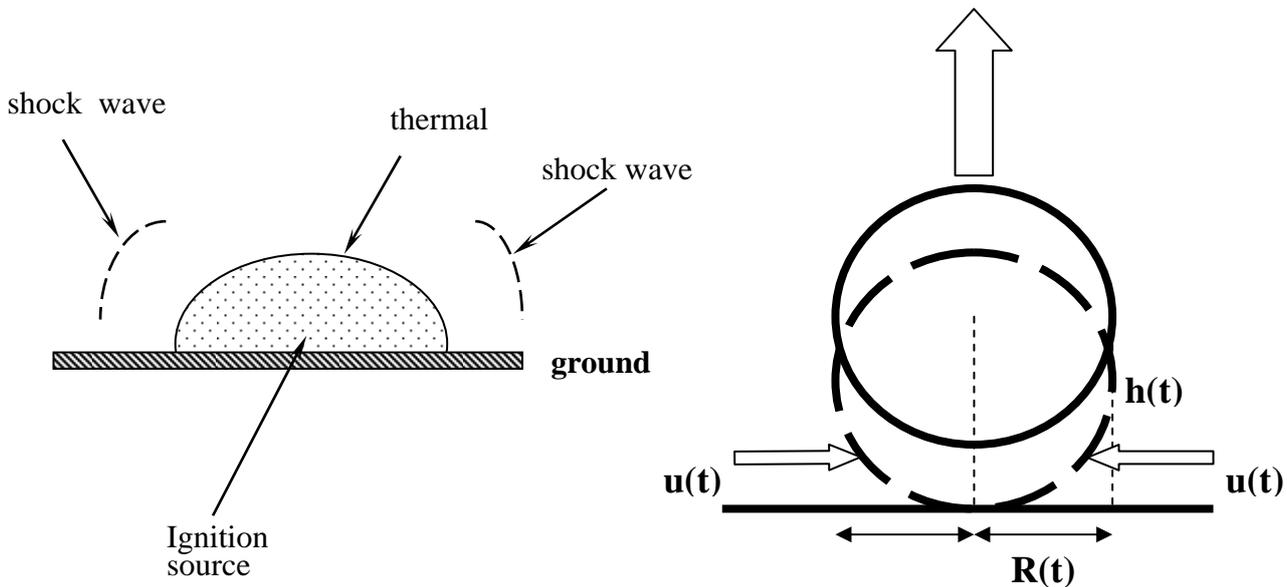


Figure 1: Illustration of a vapour cloud explosion development.

Figure 2: Schematic of flow structure for analytical model development.

Analytical model for the rate of air entrainment

In this section a simple model is developed to predict air entrainment rates into rising fireballs. This model can be used as an alternative to detailed CFD simulations performed in^{10,11}.

Consider the schematic of fireball development presented in Figure 2. The initial shape of the fireball is assumed to be spherical. The air density inside the fireball is ρ_* , and the density of the surrounding air is ρ_0 . The air is entrained through the surface of the cylinder with the radius $R(t)$ and the height $h(t)$ (Figure 2).

A simple model of entrainment rate can be developed using ideas similar to Bader's model¹². This model has been designed to describe the stage of fireball transformation from hemispherical to spherical shape. The model assumes balance between the buoyancy force:

$$F_B = \frac{4}{3} \pi R^3(t) \rho g \quad (1)$$

and the fluid resisting force:

$$F_R = \frac{2}{3} \pi R^3(t) \rho \left[\frac{2}{R} \left(\frac{dR(t)}{dt} \right)^2 - \frac{d^2 R(t)}{dt^2} \right] \quad (2)$$

The latter equation includes the inertial term $\frac{d^2 R}{dt^2}$ and the added mass term, $\frac{2}{R} \left(\frac{dR}{dt} \right)^2$.

The equation for fireball radius growth is obtained by equating (1) and (2) as:

$$\frac{d^2 R}{dt^2} - \left(\frac{2}{R} \right) \left(\frac{dR}{dt} \right)^2 + 2g = 0 \quad (3)$$

Solution of this equation gives the following law of fireball growth:

$$R = \frac{2}{3} \left(\frac{g}{2} \right) \cdot t^2 \quad (4)$$

In addition, it is assumed in the model¹² that the liftoff time (the instant at which fireball becomes spherical, the dashed image in Figure 2) and fuel burnout time coincide.

The burnout time can be found from a number of experimental correlations. One of the most reliable is the correlation due to Hasegawa and Sato¹³:

$$t_b = 1.07 \cdot M_F^{0.181} \quad (5)$$

where t_b is the fuel burnout time (s) and M_F is the fuel mass (kg).

Bader's model is supplemented with the following assumptions to derive the required entrainment rate. First, since the forces are balanced during the burnout time, the centre of fireball moves up at a constant speed, i.e. without acceleration. This speed is given by:

$$\frac{dh(t)}{dt} = \frac{g}{3} t_b \quad (6)$$

Furthermore, it is assumed that the fireball moves up at the same constant rate for some time after the burnout time, t_b . This is in agreement with, for example, the data produced by High¹⁴ which shows the rate of fireball rise to be very close to linear. Therefore, the following relationships would apply (if time is calculated from the moment t_b):

$$h(t) = R(t_b) + \frac{g}{3} t_b t \quad (7)$$

$$R(t) = \frac{2}{3} \left(\frac{g}{2} \right) (t + t_b)^2 \quad (8)$$

$$\frac{dR}{dt} = \frac{2}{3} g(t + t_b) \quad (9)$$

During fireball motion, the mass of air inside a fireball is given by:

$$M(t) = \frac{4}{3} \pi \cdot \rho_* \cdot R^3(t) \quad (10)$$

The rate of air entrainment from the surroundings can be expressed as (from Figure 2):

$$\dot{M}_1 = 2\pi\rho_0 R(t) \cdot h(t) \cdot u(t) \quad (11)$$

The mass balance, written as:

$$\frac{dM}{dt} = \dot{M}_1 \quad (12)$$

results in the following expression for the average entrainment velocity:

$$u(t) = 2 \frac{\rho_*}{\rho_0} \frac{R(t)}{h(t)} \frac{dR}{dt} \quad (13)$$

Taking into account the laws of motion (Equations 7 to 9) the latter result can be expressed as:

$$u(t + t_b) = 2 \frac{\rho_*}{\rho_0} \frac{R(t + t_b)}{R(t_b) + \frac{g}{3} t_b t} \frac{2}{3} g(t + t_b) \quad (14)$$

where $t \geq 0$. $t = 0$ is taken as a starting point corresponding to initial conditions provided by Bader's formulas at $t = t_b$).

A characteristic entrainment velocity for a given mass of released fuel can be taken at the point of spherical thermal formation ($t = 0$), and is given by a very simple formula:

$$u_*(t_b) = \frac{4}{3} \frac{\rho_*}{\rho_0} g t_b \quad (15)$$

The dependence on the released mass, which follows from this formula, is apparently the same as for the burnout time:

$$u_* \sim M_F^{0.181} \quad (16)$$

RESULTS AND DISCUSSION

Comparison with the results of numerical simulations

To verify the derived velocity relationship (Equation 14), it is compared to the results of numerical simulations. The CFD analysis performed in the present study is very similar to^{10,11}, with the exception that a more advanced level of turbulence modeling was used in the present study.

The evolution of a thermal in the atmosphere is described by the following set of Favre-averaged Navier-Stokes equations for mass, momentum and enthalpy:

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla(\rho\vec{V}\phi) = \nabla(\Gamma_\phi \nabla\phi) + S_\phi \quad (17)$$

Turbulence is modeled via a conventional $k - \varepsilon$ approach, in contrast to an algebraic turbulence model which was used in^{10,11}. The exchange coefficients and source terms can be found elsewhere¹⁵.

Pressure distribution over height is taken to comply with the ‘‘Standard Atmosphere’’ model. Radiation heat transfer is not directly modeled, instead, it is assumed that a fireball emits a prescribed fraction of energy, depending on its temperature. The average value for this parameter is $\chi = 0.25 - 0.3$ ¹. Energy loss to shock waves is taken as 10%.

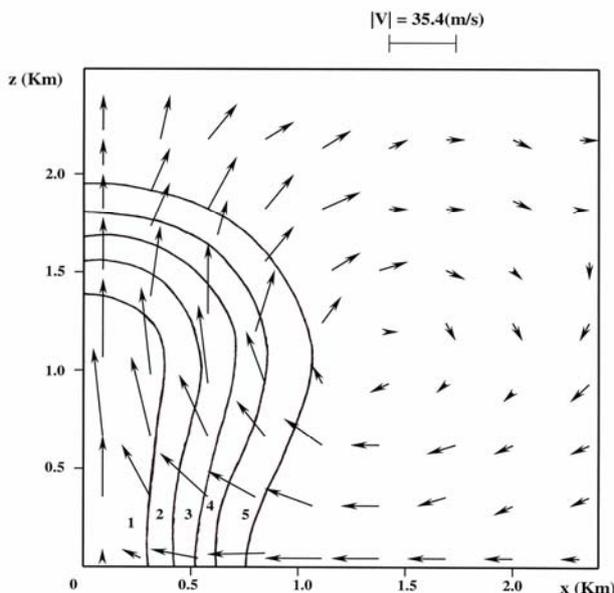
Combustion is not modeled as heat release as the explosion stage occurs virtually instantaneously. At the convective stage, only short times need to be considered (up to about 20 s) so that the cloud does not cool down and consideration of combustion contribution to buoyancy is not necessary. Initial temperature distribution in the thermal is taken in the following form:

$$T(\vec{X}, 0) = T_*; L = \left(\sqrt{x^2 + y^2} / d \right)^2 + (z / (\sigma \cdot d))^2 \leq 1 \quad (18)$$

$$T(\vec{X}, 0) = T_0 + (T_* - T_0) \cdot \exp\left(-p_*^2 \cdot d^2 \cdot (\sqrt{L} - 1)^2\right); L \geq 1$$

The parameter p_* is found from the initial heat content of the cloud using the distribution (Equation 18). Determination of this parameter requires solution of a few algebraic equations.

According to Equation 18, the initial temperature is constant in the half-ellipsoidal region with the axes d , d , $\sigma \cdot d$. The parameter $0 < \sigma \leq 1$ describes the degree of sphericity of the cloud. Small values of σ correspond to clouds strongly elongated along the ground; $\sigma = 1$ corresponds to an initially hemispherical thermal.



s. Initial temperature was taken to be $T_* =$ contained 50 x 50 x 70 cells. Only the flow that develops after the shock waves

presented in Figure 3. For different initial shape, detailed distributions of radial near-

and numerical simulations are compared in minimum fuel required to achieve a given analytical estimations of the characteristic

entrainment velocity are quite reasonable in the range of fuel mass between 200 t and 1000 t. It is also seen that the results of CFD simulations very closely reproduce the type of velocity dependence on fuel mass (Equation 16).

To relate observed damage with the explosion power, it is necessary to recall a wind strength scale, or the Beaufort Scale. Extraction from the Beaufort Scale (for Beaufort numbers larger than 5) which is presented in Table 1.

For the Ufa explosion, wind strength of the “storm” grade was considered (Beaufort number 10). This range corresponds to wind velocities between approximately 24.5 m/s and 28 m/s.

The result of computations identifies the region where the wind velocity is enough to snap trees, as a function of the initial fuel content in the cloud. The critical wind velocity that is monitored in CFD computations is taken as 24 m/s in accordance with the number 10 on the Beaufort Scale (Table 1).

By varying the mass of released fuel in computations, it is possible to give estimations for that mass, based on observed entrainment velocity. For the case of the Ufa explosion, in a way similar to^{10,11}, the estimate of mass is $2200t < M_F < 3600t$.

Figure 3: Flow associated with ascending fireball at $t = 20.06$ s after formation. Temperature isolines: $T/T_0 = 5.56$ (1), 4.92 (2), 2.53 (3), 1.02 (4), 1.00 (5).

Figure 4: Minimum fuel mass resulting in entrainment velocity of a given magnitude
 ♦ - numerical simulations;
 o - analytical model.

Table 1: The Beaufort Scale.

Wind Force	Speed (km-h)	Wind type	Effects
6	39-50	strong breeze	large branches in continuous motion; telephone wires whistle
7	51-61	near gale	whole trees in motion; wind affects walking
8	62-74	gale	twigs and small branches break off trees
9	75-87	strong gale	branches break; shingles blown from roofs
10	88-101	storm	trees snap and uproot; some damage to buildings
11	102-117	violent storm	property damage widespread
12	118 --	hurricane	severe and extensive damage

The correctness of this estimation has been confirmed^{10,11} by considering alternative ways to estimate the power of explosions. Such alternative methods are essentially based on comparing the magnitude of shock waves with the observed damage^{17,18}. Since CFD and analytical results are close, and the results of CFD simulations give good agreement with the observed entrainment velocity for the real case, the analytical model is also in a reasonable agreement with the real case data. Therefore, the simple model (Equations 14 and 15) can be used for quick estimations of the amount of fuel involved in explosions. Using this formula, critical mass of the fuel can be found for the characteristic points of the Beaufort Scale.

Implications for fireball mitigation

Currently, no fireball suppression mechanism is triggered upon accidental explosions at chemical facilities. However, the nature of entrainment flow seems to suggest the theoretical mechanism for automatic fireball mitigation. One example of the use of flow nature in fire protection engineering is very well known: this is the use of ceiling jets to automatically activate fire suppression devices or detectors.

In the same way as ceiling jet flows are utilized to activate sprinklers and fire detectors, air entrainment flows may be possibly utilised to mitigate fuel releases resulting in fireballs. The idea here is that at the moment of its formation, a fireball should be surrounded by cloud of fire suppressant. The suppressant will be sucked into the fireball due to strong air entrainment. As a result, the flame may be completely suppressed, or at least the fireball size may be significantly diminished. The technical implementation of this idea is outside the scope of the present paper. Possibly, fire suppressant may be stored in containers that will be automatically destroyed in the case of an explosion.

The choice of possible suppressant is an important question. The use of water mist is very problematic, since complete evaporation is likely to occur long before droplets will be sucked into a fireball. However, water vapour will still have certain suppressing effects.

A better choice seems to be the use of aerosol fire extinguishing agents (AFEAs). Fine aerosol particles are not subjected to phase change. Their primary fire suppressing mechanism is destruction of active centers, which are necessary to support flame on the surface of solid particles. AFEAs may be, for example, obtained by combustion of solid propellants¹⁹. Aerosol particles obtained in this way have a very small size (of the order of 1 μm).

Table 2: Characteristics of AFEA in comparison with other agents of volumetric extinction. Adopted from Baratov et al.¹⁹.

Characteristics	AFEAs	CF_3B_2	CO_2	Dry chemicals	C_4F_{10}
Fire control capability, kg/m^3	0.05	0.3	0.7	0.25	0.5

To obtain a theoretical estimation of entrainment flow capability, to “suck” flame suppressant into fireball, consider a layer with uniform aerosol concentration C , surrounding a fireball (Figure 5). Due to very small size ($\sim 1 \mu\text{m}$), particles will follow the flow streamlines.

Considering again the process starting from the point of formation of a spherical fireball, the mass of aerosol accumulated in the thermal will be given by:

$$M_a(t) = 2\pi \cdot C \cdot \int_0^t R(t) \cdot h(t) \cdot u(t) dt \quad (19)$$

Upon substitution of Equations 7 to 9, and 14, Equation 19) takes the form:

$$M_a(t) = \frac{4}{81} \cdot \pi \cdot g^3 \cdot \frac{\rho_*}{\rho_0} \cdot C \cdot [(t + t_b)^6 - t_b^6] \quad (20)$$

The average concentration of aerosol in the fireball is obtained by dividing mass by volume at certain point in time:

$$\tilde{C}(t) = \frac{M_a(t)}{4/3\pi R^3(t)} = C \cdot \frac{\rho_*}{\rho_0} \cdot \left[1 - \frac{t_b^6}{(t + t_b)^6} \right] \quad (21)$$

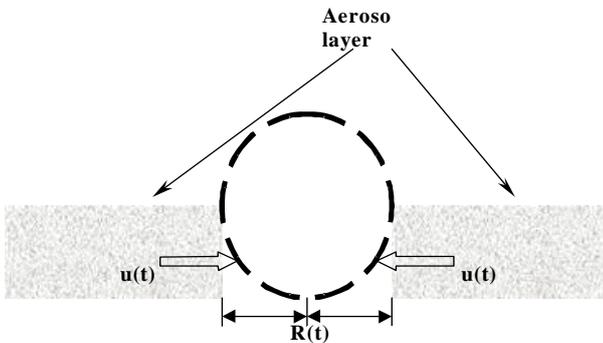


Figure 5: Possible arrangement of suppression agent for mitigation of accidental fireballs.

Time histories of average aerosol concentrations are presented in Figure 6 for various masses of released fuel. It is apparent that accumulation happens quickly, with aerosol concentration reaching its limiting value of $C \cdot (\rho_*/\rho_0)$ within about 10 s. There is a weak dependence on initial fuel mass.

As Figure 6 demonstrates, it is sufficient to provide ambient aerosol concentration about five times higher than that required for flame suppression. This figure is dictated by the difference between the ambient density and the density of combustion products inside fireballs.

For typical AFEAs, the critical flame suppression concentration is about 0.05 kg/m^3 (Table 2). To achieve such a concentration inside fireball (limiting

value in Figure 6), the ambient density must be of the order of 0.25 kg/m^3 .

Numerical simulations using the CFD methodology outlined above can produce more accurate results. In Figure 7, the minimum ambient aerosol concentration required to achieve suppression (i.e. average concentration of 0.05 kg/m^3 inside a fireball) is presented. Apparently, this ambient concentration is not constant (in contrast to Figure 6), but increases with the fireball fuel mass.

The difference in required ambient concentration between the approximate results (Figure 6) and the numerical simulations are due to obvious simplifications of the analytical model. Nevertheless, the difference between the approximate model and CFD simulations is no larger than a factor of two, showing that the analytical model can be applied with reasonable success for estimations. For relatively small fireballs (up to 80 t of released fuel), the agreement between analytical and CFD results (Figures 6 and 7) is quite good.

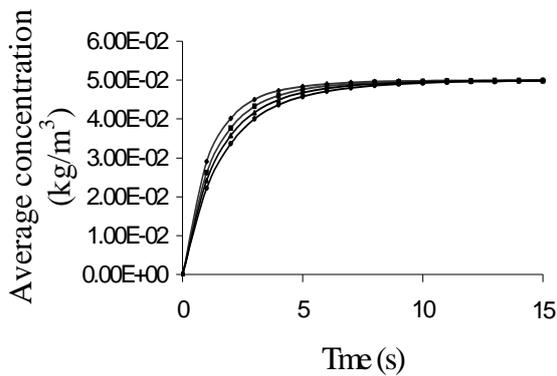


Figure 6: Average concentration of entrained aerosol within a fireball as a function of time. Prediction according to the model (21). Ambient aerosol concentration 0.25 kg/m^3 . Released fuel mass: \blacklozenge - 20 t; \blacksquare - 50 t; \blacktriangle - 100 t; \bullet - 200 t.

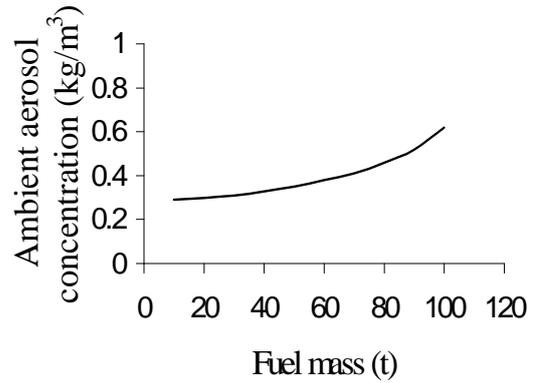


Figure 7: Minimum ambient aerosol concentration required to achieve critical average concentration 0.05 kg/m^3 inside fireball. CFD predictions.

CONCLUSIONS

A simple analytical model has been presented to describe the rate of air entrainment into a rising fireball. The approach can be used for two purposes. Firstly, the model can be used for estimations of explosion power, based on its hydrodynamic consequences. The results obtained with the analytical model are in agreement with the CFD simulations and reconstruction of the real explosion accident. Secondly, the theoretical method of mitigation of fireballs resulting from accidental explosions has been proposed. It has been demonstrated that the structure of the flow developing during fireball formation and rise can be naturally used to deliver suppressants into the flaming region. The estimations of ambient aerosol concentrations, necessary to achieve critical concentration inside fireball, have been presented.

NOMENCLATURE

C	aerosol concentration in the layer surrounding fireball
\tilde{C}	aerosol concentration inside fireball
d	characteristic dimension of a thermal
g	acceleration due to gravity
h	height of fireball above the ground
M	mass

R	radius of fireball
S_ϕ	source term for variable ϕ
t	time
t_b	burnout time
\vec{V}	velocity
$\vec{X}(x, y, z)$	cartesian coordinate

Greek symbols

Γ_ϕ	exchange coefficient for variable ϕ
ρ	density
σ	sphericity parameter

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