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LARGE SCALE FIRES AND EXPLOSIONS

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ABSTRACT

The release of hazardous substances into the atmosphere is one of the major factors of danger in modern industry. Vapour clouds of flammable substances resulting from the accidental release, may be ignited, burn, explode or detonate. The consequent pressure waves, high-velocity fragments, fire and fireballs emitting strong heat fluxes may destroy properties and cause human casualties. Major accidents, such as those at Flixborough (1974, UK), Mexico City (1984) and Ufa (1989, former USSR), are extreme examples of how dangerous the releases of liquefied hydrocarbons into the atmosphere are.

Over the past decades increasing awareness of hazards posed by accidental fuel releases has stimulated worldwide research into formation, evolution, combustion, explosion of fuel clouds and their consequent effects.

Large-scale fires and explosions following hydrocarbon releases into the atmosphere are analysed with the emphasis on the role of fluid dynamics. Recent results obtained in the Centre for Research in Fire and Explosion Studies, are used to discuss the following issues.

Keywords: Fire and explosion safety, risk assessment, fuel cloud, hydrocarbon release, fireball, burning time, modelling, case studies.

CRITERION FOR THE FORMATION OF A 'CLOUD-LIKE' RELEASE UPON DEPRESSURISATION OF A GAS VESSEL

A single-phase gas escape from a depressurised vessel and the subsequent mixing with the ambient air is analysed. Two main cases of release are normally considered in source models being used in the chemical process quantitative risk analysis. If the breach in the containment is relatively small the escaping gas forms a jet. This type of release is referred to as "continuous" and ignition of the escaping gas gives rise in this case to a jet fire. On the other hand, catastrophic failure of the pressurised tank leads to rapid ("instantaneous") escape of the substance into the atmosphere and to formation of a fuel-rich cloud which upon immediate ignition burns as a fireball. Though the two limit cases of escape have been studied extensively, the accurate criterion for classifying the release into the instantaneous or continuous type is required. Such a criterion is formulated which enables the release to be classified as the instantaneous (leading to formation of a gas cloud), continuous (giving rise to a jet) or intermediate ("cloud-like") type. The method is based on comparison of the characteristic time of the single-phase release (determined from the solution of the "internal" problem) with the characteristic times of turbulent mixing in an instantaneously released cloud, impulsively started transient jet as well as in a steady-state jet. Quantitative relationships defining the critical breach size are obtained for the cases of gas escape from a high-pressure storage vessels and from a pressure-supported gasholder.

BURNING REGIMES FOR THE FINITE-DURATION RELEASES OF FUEL GASES

The influence of the ignition delay time on the deflagration regime is discussed and the ranges of the delay for which the ignition can lead to formation of either jet fire or fireball are given. To estimate the effect of the mixing processes on the parameters of the fireball that can arise upon ignition of the release, the mass of fuel that can be involved into the burning cloud is assessed as a function of the outflow conditions and the delay time. The most probable range of the fuel mass for finite-duration releases is obtained. Example calculations demonstrating the capabilities of the criterion and its application to analysis of accidents on low- and high-pressure storage vessels and constant high internal pressure (pipe lines) are presented. The results are compared with available experimental data. A case study (1993, Warrington, UK) is considered.

NUMERICAL MODELLING OF FIREBALLS FROM VERTICAL RELEASES OF FUEL GASES

Numerical modelling of formation, evolution and combustion of gas clouds upon fuel gas releases into the atmosphere are presented. Finite-duration vertical releases are considered, the ignition occurring on the axis at some elevation above the source. The main stages of the release and burning are studied, the internal structure of the fireball is shown by the spatial distributions of concentrations, temperature and reaction rate at different moments from ignition up to total burnout. The transformation of initial transient burning jet into a fireball is revealed. The influence of the release parameters (fuel mass, injection velocity, orifice size, ignition source height) on the lifetime of the fireball is studied. The dependence of the non-dimensional burning time on the Froude number is obtained, the influence of the source size and ignition source location is found to be much less significant. Quantitative estimates of parameter ranges in which the release time is short enough, so that the burning time may be scaled as a function of the Froude number rather than the release duration, are given. It is shown that the release duration/burning time ratio is always small for high-speed releases. For slow releases the outflow time is short provided that the Froude number exceeds some critical value which decreases with increase in the opening diameter.

The results of calculations are compared with the experimental data on small-scale methane and propane releases. Fairly good agreement in fireball geometry and burning times is obtained. The calculated fireball diameter is within 5% of the experimental value, while the calculated fireball durations are within 15% of observed data. The results are presented in non-dimensional form, which facilitates the scaling and makes them applicable to a wide range of physical parameters.

COMBUSTION OF TWO-PHASE HYDROCARBON FUEL CLOUDS RELEASED INTO THE ATMOSPHERE

When a flammable substance escapes into the atmosphere, in many cases two-phase outflow occurs so that the fuel cloud, which builds up in the atmosphere, contains a mixture of fuel vapour and liquid fuel droplets. Two-phase releases are considered as the most probable outcome of depressurisation of vessels containing pressure-liquefied gases (liquefied petroleum gas, LPG). Even if the breach in the containment is located above the liquid surface, bubble formation and swelling of liquefied gas results in discharge of a liquid-vapour mixture. Dispersion and combustion of two-phase releases are affected by heat and mass transfer between the phases, which makes these flows more scale-dependent than those in the case of single-phase fuel gas release.

Numerical modelling of the evolution, behaviour and combustion of two-phase hydrocarbon clouds released into the open atmosphere is presented. A Eulerian-Lagrangian model for transient flows of fuel vapour-droplet mixtures is formulated taking into account heat, mass and momentum exchange between the gaseous and dispersed phases, soot formation and radiative heat transfer. The calculations are performed for releases of pressure-liquefied propane, the total mass of fuel released varied in a wide range from 1 g up to 1000 kg and pre-release temperature 268 to 351 K. Formation and evolution of a two-phase cloud following a short-duration release of pressure-liquefied gas is first considered without ignition. Parameter ranges corresponding to mixing-controlled and diffusion-controlled regimes of evaporation are obtained. The time for total evaporation of liquid fuel droplets is determined and the structure of the cloud is analysed. Fireball development upon ignition of the fuel cloud is studied and the main stages of its evolution from reaction initiation until total fuel burnout are considered in detail. The calculated fireball shape and dynamics of ascent are shown to correlate quite well with the data from the Hasegawa-Sato experiments. The role of scale effects is studied by comparing the structure and gross characteristics of fireballs calculated for different fuel masses and storage conditions. The calculated dependence of the non-dimensional fireball burning time on the Froude number agrees well with the experimental data. Radiation field distributions in fireballs of different scales are obtained and differences between optically thin and thick clouds are demonstrated. The radiative fraction of total combustion energy is shown to correlate well with available experimental data on turbulent propane flames.

Fireballs from accidental releases of various hydrocarbons are studied for storage conditions below and above the boiling temperature. A unified description of fireball characteristics is offered.

RISK ANALYSIS OF NEAR-SURFACE VAPOUR CLOUD EXPLOSION BASED ON ITS FLUID DYNAMICS CONSEQUENCES. CASE STUDY

The Ufa catastrophe, considered the world's largest accident connected with release and explosion of hydrocarbons in the open atmosphere, gave clear evidence of an additional factor of danger which is important for the burning of large masses of hydrocarbon. This is a strong short-duration hurricane wind generated by the fireball and developing near the epicentre of the energy release. In Ufa this fireball-induced wind led to breaking and blowing down the trees on huge forest territory. Its consequences for environment were comparable with (and in the near zone even exceeded) those caused by the blast waves.

Fluid dynamics consequences (large- scale fluid dynamics flows and near-ground winds) induced by vapour cloud explosion are analysed. Three major accidents involving hydrocarbon vapour cloud explosions which occurred in Port Hudson (09.12.70, Missouri, USA), Donnelson (04.08.78, Iowa, USA) and near Ufa are compared from the viewpoint of their effects and consequences. Importance of taking into account the fluid dynamics of vapour cloud combustion and the strong afterwinds generated by the fireball are demonstrated by case history studies and by mathematical modelling of the unconfined fuel cloud behaviour and deflagration. Results of CFD modelling of large-scale propane vapour cloud combustion upon central and peripheral ignition are presented.

A detailed study of the fluid dynamics consequences of vapour cloud explosions and of the relationship between the characteristics of accidental release and parameters of the afterwinds not only allows possible effects of large-scale cloud combustion to be determined more precisely, but also might give an independent method for the assessment of the mass of the fuel involved in the accident basing on its fluid dynamics consequences. The methods currently available for assessment of the fuel mass and basing on the TNT-equivalent concept for gaseous explosion may often lead to contradictory results and require great care in their application. An independent estimation method based on the analysis of another type of effects would be a useful tool in design of respective facilities as well as in investigation of accidents.

The results presented clearly show that for accidents involving combustion of large quantities of fuel, the fluid dynamics impact on the environment of gases released into the atmosphere becomes an important danger factor. This has to be taken into account along with such normally analysed effects as blast waves and heat radiation. Future work aimed at further analysis of case histories by CFD methods can result in implementation of a new independent method for estimation of consequences and parameters of liquefied hydrocarbon releases.

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