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Modelling pollutants dispersion and plume rise from large hydrocarbon tank fires in neutrally stratified atmosphere

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ABSTRACT

Petrochemical industries normally use storage tanks containing large amounts of flammable and hazardous substances. Therefore, the occurrence of a tank fire, such as the large industrial accident on 11th December 2005 at Buncefield Oil Storage Depots, is possible and usually leads to fire and explosions. Experience has shown that the continuous production of black smoke from these fires due to the toxic gases from the combustion process, presents a potential environmental and health problem that is difficult to assess. The goals of the present effort are to estimate the height of the smoke plume, the ground-level concentrations of the toxic pollutants (smoke, SO_2, CO, PAHs, VOCs) and to characterize risk zones by comparing the ground-level concentrations with existing safety limits. For the application of the numerical procedure developed, an external floating-roof tank has been selected with dimensions of 85 m diameter and 20 m height. Results are presented and discussed. It is concluded that for all scenarios considered, the ground-level concentrations of smoke, SO_2, CO, PAHs and VOCs do not exceed the safety limit of IDLH and there are no "death zones" due to the pollutant concentrations.

1. Introduction

The recent accident in Buncefield Oil Storage Depots (B.O.S.D) (Hertfordshire, United Kingdom, 11 December 2005) does confirm that, despite the great improvements that have been achieved on safety issues in dangerous industries, it is still very difficult to ensure the absolute elimination of a potential accident with unanticipated consequences. Therefore, the need for new techniques to predict the consequences, and to reduce the frequency of industrial accidents, is obvious and indeed imperative.

The petrochemical industry normally uses large storage tanks, which contain considerable volumes of flammable and hazardous chemicals. Thus, the occurrence of a tank accident is possible and usually leads to fire and explosions. A thorough analysis of tank accidents with a classification of causes and contributing failures is presented by Chang and Lin (2006).

The most common consequence of a tank accident is fire. Although large-scale tank fires are very rare, they pose a severe challenge to fire fighters, oil companies and the environment, due to the multiplicity of the physical processes involved. According to the study of Persson and Lonnermark (2004), there are two ways of dealing with a tank fire, either to let it burn-out fully and thereby self-extinguish or, alternatively, to extinguish the fire actively, using firefighting foams. Tank fires produce large quantities of combustion products, such as sulphur dioxide (SO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), and lead to soot and particulates formation. More specifically, the transport of combustion products by a wind-blown smoke plume can distribute potentially hazardous materials over a large area and may lead to serious consequences for the health of people and for the environment.

Currently available fire-plume models belong to two main categories, integral and field models. Extensive investigation with integral models has been undertaken by many researchers (Turner, 1985; Carter, 1989; Wilson, 1993; Zonato et al., 1993; Fisher et al., 2001). The major characteristic of this approach is the use of a Gaussian profile having as a drawback the inability to outline the formation of the plume in strongly interacting regions. Field or Computational Fluid Dynamics (CFD) models are based on the partial-differential equations of motion and heat/mass transfer and have been used successfully by many researchers. Nevertheless, CFD models have also disadvantages: they are rather costly and time consuming, therefore not frequently suitable for real time applications, while their pronouncements are never 100% reliable.

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Markatos et al. (1982) presented the first effort to simulate fires using CFD models, while Ghoniem et al. (1993) and Zhang and Ghoniem (1993, 1994a,b) presented Lagrangian numerical techniques for the solution of the governing equations, based on the extension of the vortex method to variable-density flows for different stratified atmospheres.

McGrattan et al. (1996) used Large Eddy Simulation (LES) for the smoke plume arising from large oil fires, where particulate-matter motion is simulated by Lagrangian particle-tracking techniques. Extension of that work is the research of Trelles et al. (1999a), who studied the problem of multiple-plume sources. Some years later, McGrattan (2003) compared numerical results and experimental data from large offshore fires, and managed to collect the appropriate information for the development of the numerical model ALOFT (A Large Outdoor Fire plume Trajectory) for the calculation of smoke and other toxic combustion products concentrations, for different meteorological and topographical conditions.

The plume trajectory from tank fires depends on physical processes, which are highly complex and difficult to predict. The horizontal movement of the plume is determined by the prevailing wind, while its vertical movement is defined by the fire buoyancy forces (Ghoniem et al., 1993). The most significant plume parameters, such as pool geometry (diameter, depth, substrate, heat-release rate (HRR)), fuel composition, ventilation conditions (wind velocity, air entrainment), humidity, temperature, atmospheric stratification and topography of the surrounding terrain, contribute, each in its own way, to the formation of the plume; the overall effect, however, is a complex combination of them, as presented in Steinhaus et al. (2007). It is worth mentioning that the plume from tank fires will rise higher into the atmospheric layer than that of other fires and it is rather difficult to predict this rise based on empirical correlations and observations. McGrattan (2003) claims that empirical correlations such as those of Briggs (1975) cannot describe fire plumes created by the burning of large quantities of liquid fuel.

The present work was motivated by the relatively recent unfortunate accident in the B.O.S.D, which took place in England. The purpose was to develop and then demonstrate a computational prediction model for estimating the dispersion of combustion products and the consequences to the environment from tank fires, together with the prediction of the toxic plume rise. The model determines also the "lift-off" condition for buoyant plumes released from tank fires, so that the results are applicable without recourse to other simulation models (e.g. for the rate of discharge, the gases temperature, the rate of the toxic substances release, etc).

2. Description of accident considered and scenario analysis

2.1. Description of site and the incident initiation

Although not similar (the Buncefield accident was a multi-source event and there are other differences as well) the Buncefield accident has formed the basis for the definition of the accident scenarios studied, because of lack of other more realistic data.

B.O.S.D receives different types of fuel such as petrol, aviation fuel, gas oil and diesel by three pipeline systems. The major function of the site was the storing and distribution of fuel by pipeline and road tankers to London and South-East England, including the Heathrow airport. It is interesting to mention that the Depot covered the 40% of Heathrow's demand for aviation fuel. The initial estimation of the total volume of fuel on site was 105 million liters (82,359 tonnes) according to the information provided by the U.K Petroleum Industry Association (UKPIA) and Total (Targa et al., 2006).

On Sunday 11th December 2005, there was a major explosion, followed by a series of smaller ones in B.O.S.D, Hemel Hempstead, Hertfordshire. The result of the explosions was the development of a massive fire which engulfed over 20 large fuel storage tanks and the facilities. The fire was burning for days, until Wednesday, 14th December, when the last major fires were finally extinguished. A number of smaller fires continued burning until Thursday, 15th December. The massive fire caused a huge smoke plume that covered a space of hundreds of kilometers and was also clearly visible in satellite images. From the fire and explosions 43 people were injured, fortunately no one seriously. There was an evacuation of 2000 people from damaged homes and workplaces. Finally 786,000 L of foam concentrate and 68 million liters of water were used overall, to mitigate the incident during the period of the firefighting operations (Buncefield Major Incident Investigation Board, 2006).

2.2. Selection of accident scenarios and assumptions used

The available data for the accident was not adequate for its thorough description and for accurate modelling of plume dispersion. The U. K. Met Office used for the simulation of the smoke plume in Buncefield the atmospheric dispersion model NAME (Numerical Atmospheric Modelling Environment) with great uncertainties (Buncefield Major Incident Investigation Board, 2006). NAME belongs to the category of Lagrangian models and uses either a three-dimensional meteorology or single-site meteorological data, while turbulence is modelled with the use of random-walk techniques. The numerical simulation of U.K. Met Office included the total number of tanks involved in the fire accident.

The current trend for the study of fire accidents is the assumption of steady-state conditions, although it is known that the burning rate varies with time. The present study examines therefore the dispersion of the plume as a steady-state phenomenon and considers the "worst-case scenario" for the estimation of consequences, as knowledge of the exact source-term strength is not always available. Other assumptions are that the plume is generated from one tank only, another that small particles created from the fire and entrained into the plume are sufficiently fine so that the system remains single phase.

The selection of accident scenarios in the present work involves the study of six different situations and one case study for Tank 12 of BOSD (Fig. 1) all for an adiabatic atmosphere. This selection was made because Tank 12 was the largest tank of BOSD and had the most significant contribution to the smoke plume creation (Hailwood et al., 2009). More specifically, two types of fuel, crude and diesel oil, with three values of wind velocity, 8, 10 and 12 m s^{-1} were examined for the six scenarios, while for Tank 12 kerosene has been assumed as representative fuel with HRR of 1.20 MW m^{-2} (Babrauskas, 1983) and 5 m s^{-1} wind velocity (Targa et al., 2006). These parameters are close to those of Buncefield Tank 12 but not for the entire accident which was a multi-source event.

3. The physical problem

The flow in cases of large fires is dominated by buoyancy and the generation of large-scale turbulence serves to promote the rate of diffusion of mass, momentum and heat. Hoffmann and Markatos (1988) claim that the mixing of air is, in general, controlled by this relatively slow turbulent mixing process rather than the fast chemical kinetics.

The characteristics of the physical problem considered are as follows. The 3-D domain for the simulation extends to 34,521 m length (Z), 2400 m width (X) and 3000 m height (Y). Numerical