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Cloud rise model for radiological dispersal devices events

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ABSTRACT

As a part of the preparedness and response to possible radiological terror events, it is important to model the evolution of the radioactive cloud immediately after its formation, as a function of time, explosive quantity and local meteorological conditions. One of the major outputs of a cloud rise models is the evaluation of cloud top height, which is an essential input for most of the succeeding atmospheric dispersion models. This parameter strongly affects the radiological consequences of the event. Most of the cloud rise models used today, have been developed according to experiments were large quantities of explosives were used, within the range of hundreds of kilograms of TNT. The majority of these models, however, fail to address Radiological Dispersion Devices (RDD) events, which are typically characterized by smaller amounts of TNT. In this paper, a new, semi-empirical model that describes the vertical evolution of the cloud up to its effective height as a function of time, explosive quantity, atmospheric stability and horizontal wind speed, is presented. The database for this model is taken from five sets of experiments done in Israel during 2006–2009 under the "Green Field" (GF) project, using 0.25–100 kg of TNT.

1. Introduction

The problem of atmospheric dispersion of contamination, either triggered by accident or by intentionally-driven explosion, is difficult to resolve without using complex models, which are mostly non-linear. These models describe the dynamics of the contamination motion in the air according to the variety of processes and constraints along its trajectories. Formation of a fireball is the first phenomenon occurring immediately following an explosion of high explosive containing some radiological material. The fireball cools down within milliseconds creating the initial explosion cloud, which is composed of hot explosive gaseous, radioactive material and entrained material (dust, air, etc.). The cloud then rises up, cools down, mixes up with the ambient atmosphere and is eventually dispersed downwind. The evolution of the explosion cloud up to its effective height (i.e., the height at which the cloud is at thermal equilibrium with the environment and thus influenced by the atmosphere only), is important for any dispersion model. The final cloud dimensions and the particle distribution within it are affecting the ground and the aerial concentrations of contamination and, of course, the consequent doses, from the close vicinity up to few kilometers from the explosion. The cloud's dimensions evolution depends on the amount and type of explosive (its energy capacity, Thielen and Schrodl (2004)), the geometry of the explosive, the contaminant coupling to the explosive, the ground surface type, the explosion height above the ground and the behavior of the ambient atmosphere in the close vicinity of the explosion site. The atmospheric stability and its turbulent behavior will strongly affect the shape, the rate of evolution, the concentration of the radioactive material in the cloud, and of course, the top height of the cloud. The related problem of particles' size and density distributions inside the cloud will not be discussed in this paper.

The problem of an explosive cloud evolution as a function of time can be solved analytically, (see, Boughton and DeLaurentis (1992), Kanza (1997), Nasstrom et al. (2007), Sullivan et al. (1993)) or experimentally (see, Church (1969), Harper et al. (in press), Gostintsev et al. (1980), Julie and Frederick (2001), Reshetin (2004) and Harper (2007–2010)). Analytical methods involve solution of the Navier-Stock's equation with the proper initial and boundary conditions. At the very early stage of the evolution, the so-called "fireball" stage, one should take into account also the shock wave properties due to the detonation and the high rate of entrained dirt from the ground below and around the detonation point. This stage involves very complex physics, which makes it difficult to formulate the full set of equations and to include all the involved uncertainties in the different parameters of the problem. Analytical solution of the problem-related equations

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will, therefore usually include some severe (non-realistic) assumptions and will consequently not guarantee an accurate prediction of the cloud dimensions (e.g., top height,). Moreover, solution of analytical models usually requires a great amount of CPU time and computational efforts.

Experimental approach requires performing a set of explosion experiments using different explosive amounts under various conditions of atmospheric stability (i.e., temperature and wind profiles), different types of surfaces and different explosive geometries. A correct analytical analysis of the experimental results will yield a simple and a reasonably accurate empirical model that can be used in order to predict the evolution of the explosion cloud as a function of the above-mentioned parameters. A combination of the experimental and analytical approaches is made possible by incorporation of some well-understood theoretical processes into the empirical model.

In this work, we demonstrate an empirical approach based on the framework of the GF field experimental plan conducted in Israel during the years of 2006–2009. In this plan, more than 70 explosion tests were conducted and analyzed as a part of an ongoing project aimed at resolving the so-called source term enigmas, where source term refer to material to be disperse, explosive amount, device geometry, aerosolized material, cloud rise etc. Explosive amounts within the range of 0.25–100 kg of TNT were used in these tests, typical amounts for the majority of the Radiological Dispersal Devices (RDD) terror scenarios.

Section 2 of this paper presents the qualitative description of an explosive cloud evolution. Experimental setups are described in Section 3. Section 4 presents the experimental results and data analysis, whereas error considerations are discussed in Section 5. Evaluation and testing of the new model are presented in Section 6 and a summary and conclusions are brought in Section 7.

2. Qualitative description of the cloud evolution following an explosion

One of the most remarkable phenomena that characterize an explosion is the formation of a cloud composed of hot air, smoke and dust at the point of detonation. The extent and composition of the formed cloud depend on the amount and type of the explosive, local meteorological conditions, surface type below the detonation point and the explosion's (charge) height above ground. Charge height above ground will determined the contribution of the reflected waves (amount of absorbed energy in the ground) as well as the amount of entrained dirt to the fireball.

Although the evolution of the cloud is a continuous process, it is sometimes convenient to divide this process into several stages due to the different mechanisms during each stage.

Stage 1: Fast expansion of the hot products, generated in the explosion. This stage results in the heating of the air in close vicinity to the detonation point. This stage lasts from several tens of milliseconds up to one second and is the fastest and the least meteorology-dependent part of the entire process.

Stage 2: Expansion and elevation of the cloud formed from detonation products, hot air and entrained dirt from the ground. During this stage, the average temperature inside the cloud is significantly higher than the temperature of the ambient atmosphere. The cloud dimensions and its vertical speed are determined by the average density inside the cloud, the atmospheric conditions around it, the aerial viscosity and the speed and temperature distribution inside the cloud. When the amount of explosives is large, the amount of heat stored in the cloud may be still increasing due to the presence of still-burning products of detonation. At this stage, the active processes that cool the cloud down are radiation, convection inside the cloud and heat transport to the atmospheric coating and expansion of the cloud. This step lasts from seconds to several tens of seconds, when large amounts of explosives are present.

Stage 3: The continuation of the cloud expansion and elevation. At this stage, the average temperature of the cloud is close to that of the ambient atmosphere and the elevation of the cloud is continued due to buoyancy and inertia of gases inside it. The expansion of the cloud is caused mainly due to diffusion and turbulence. This stage lasts up to hundreds of seconds for large amount of explosives and ends when the cloud reaches its effective height.

Generally, during the first stage the cloud's shape and motion is not influenced by the ambient atmosphere (i.e. local micrometeorology). The atmosphere, however, becomes an increasingly dominant factor with the propagation of the cloud evolution. After the cloud reaches its effective height, it moves downwind and all its dimensional properties are determined by the atmospheric conditions.

The new cloud evolution model was formulated based on the analysis of the above-mentioned stages one to three. The primary analysis was based on the assumption that the duration of the first stage is approximately one second. Experimental evidences presented further in this paper supported this assumption.

3. Experimental considerations

This part includes a description of the experimental setup used during the GF set of experiments for measuring the cloud dimensions. The description consists of three parts: explosions description, photography array considerations and meteorological array considerations.

3.1. Explosions description

The GF1 set was conducted in March 2006 near the city of Bet-Shemesh, Israel (31°47′41.47″N, 35°01′22.67″E) and included two sets of four explosions conducted using 0.25, 0.5, 1 and 2 kg of TNT of a rectangular shape. The first set was performed early in the morning under stable atmospheric conditions (stable temperature (ground inversion) lapse rate). The second set was performed at noontime under unstable atmospheric conditions (super adiabatic lapse rate).

The GF2 set was conducted in January 2007 near Oron plan, Israel (30°53′53.44″N, 35°59′57.27″E). The set of explosions included four days of experiments conducted under various atmospheric conditions. This set was conducted using 2, 5, 10, 20, 50 and 100 kg of TNT, made from molded TNT in a hemispherical shape.

The GF3 set was conducted in January 2008 in the southern part of Israel (31°02′11.16″N, 35°14′04.89″E), using TNT cylindrical charges of 2, 5, 10, 20 and 50 kg, bottom detonated.

The GF4 set conducted in March 2008 near Oron, Israel (30°53′45.92″N, 35°01′36.71″E) with amounts and geometrical shapes of explosives similar to those used in the GF3 set. This set was also conducted under various atmospheric conditions.

The GF7 set was conducted in March–April 2009 near Oron, Israel (30°53′45.92″N, 35°01′36.71″E), and included 4 times of: 0.25, 0.5 and 1 kg of TNT of cylindrical geometry. This set was also conducted under different conditions of atmospheric stability.

3.2. Photography array description

The photography array included three visible light video cameras located in three different positions several hundred meters from the detonation point, several types of thermal (infrared, IR) cameras (used in GF1 and in GF4), a LIDAR system (used in GF4) and a fast camera (used in GF2, GF3, GF4 and GF7). Due to the 3D-motion of the cloud, its height and volume can only calculated by