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A MCREXS modelling approach for the simulation of a radiological dispersal device

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ABSTRACT

Assessing the risks of radioactive dose in a radiological dispersal device (RDD) attack requires knowledge of how the radiological materials will be spread through the air surrounding the site of the detonation. Two essential parts of the accurate prediction of the behaviour of this dispersion are a characterization of the initial cloud size, directly after the blast, and detailed modelling of the behaviour of different size particulates. Capturing the transport of contaminants from the initial blast wave is integral to achieving accurate predictions, especially for regions where the blast dynamics dominates, but performing such calculations over a wide range of particle sizes and spatial scales is computationally challenging. Formulation of efficient computational techniques for such advanced models is required to provide predictive tools useful to first responders and emergency planners. In this work, a Multi-Cloud Radiological EXplosive Source (MCREXS) modelling approach for RDD is investigated. This approach combines a stochastic, particle-based, mechanistic model with a standard atmospheric dispersion model. The former is used to characterize the distribution of radioactive material near the source of the explosion, where the blast wind effects are important, while the latter is used to model the transport of the contaminant in the environment over large areas. The particle transport in the near-field of the explosion site is computed based on a Lagrangian description of the particle phase and a reconstructed-Eulerian field for the carrier phase. The information inferred from this physics-based model is then used as a starting point for a subsequent standard Gaussian puff model to calculate the dispersion of the radioactive contaminant. The predictive capabilities of the MCREXS model are assessed against the 2012 DRDC Suffield full-scale RDD experiments. The results demonstrate improved predictions relative to those performed using only a Gaussian puff calculation from an empirical initial cloud distribution.

1. Introduction and motivation

The potential threat posed by deliberate dispersal of radioactive material has been the subject of significant safety and security concerns (Andersson et al., 2008; Committee on Opportunities for U.S.-Russian Collaboration in Combating Radiological Terrorism and Eurasia, 2007; Committee on the Atmospheric Dispersion of Hazardous Material Releases, 2003; Ford, 1998; Smith and Ferguson, 2009; Sohier and Hardeman, 2006; Thiessen et al., 2009). A radiological dispersal device (RDD) that employs explosive dispersal of material, a so-called "dirty bomb", has received specific attention and has been considered in several hypothetical terrorist attack scenarios (Acton et al., 2007; Sohier and Hardeman, 2006). Typically, it is assumed that such a RDD consists of a conventional explosive charge and a commercial or industrial radioactive source (Magill et al., 2007). Even if the direct health effects from radiation exposure were minimal, the resulting disruption, public anxiety, and associated remediation costs could be considerable (Kamboj et al., 2009). These observations have demonstrated a need, and provided strong motivation, for the development of models that can inform emergency planning and first response strategies (Andersson et al., 2008; Committee on the Atmospheric Dispersion of Hazardous Material Releases, 2003).

Since a RDD attack would be expected to take place in an urban centre, where the disruptive effect on society as a whole (and the doses to affected people) would be greatest, RDD scenarios have their own modelling challenges which are generally different than those associated with other environmental dispersion events of radioactive material such as accidental releases from nuclear power plants or nuclear explosions. For typical amounts of explosive mass applied, which is within the range of 0.25–100 kg of equivalent TNT (Sharon et al., 2012), the plume transport from a RDD is expected to occur at low altitude, which is much lower than that traditionally assumed in meso-

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and long-range dispersion models suitable for other hazards. At low altitudes and in an urban environment, the interaction with obstacles like buildings, trees and bushes play a major role. Such interactions and street canyon effects should be considered as an important part of the dispersion in an urban area. Andersson et al. (2008) point out that although most of the contaminant mass is expected to be deposited within a downwind distance of a few hundred meters from the explosion site, radioactive matter that becomes aerosolized as small particles may contaminate a large and complex urban area of several kilometres. The particle size distribution however, and consequently what is dispersed following the fragmentation of the radioactive material, is greatly affected by the construction details of the explosive device, packing of contaminants, physico-chemical form of the contamination and any phase transitions which may occur. For obvious reasons, these details are usually not known *a priori* in a terrorist attack, thereby exacerbating the difficulties in providing dependable predictions.

In response to the aforementioned challenges and needs, RDDs have been studied both computationally (Andersson et al., 2008; Grinstein et al., 2011; Lebel et al., 2016a; b; Thiessen et al., 2009) and experimentally (Erhardt et al., 2016; Green et al., 2016; Korpach et al., 2016; Prouza et al., 2010). The presence of a wide variety of complex physical phenomena makes development of practical and reliably-accurate models of RDDs quite challenging. The range of temporal and spatial scales on which the relevant physics occurs poses its own challenges relating to computational costs, especially when there is a need for models capable of rapid predictions useful to first responders.

In previous studies with plume models (see e.g., Lebel et al. (2016a,b)), differences of up to two orders of magnitude relative to experimental data have been observed in all cases, which can be attributed to two factors: i) inherent variability in atmospheric turbulence and ii) unresolved characterization of the source term.

The scope of the current study is to address the second issue. Our study builds upon the recent work of Hummel and Ivan (2017), which provided insight into the extent of various effects driving the dispersion of particulates following detonation of a RDD. More specifically, the influence of the dynamics of the blast flow on the transport of several particulates relevant to RDD modelling was examined based on a relatively simple, but demonstrably robust, particle transport model that relied on interpolation of precomputed TNT blast curves. In that study (Hummel and Ivan, 2017), which considered the transport of only a single particle, the effect of the blast wave was found to be strongly dependent on the particle size and inertia. These parameters determined whether or not the particle would overtake the leading shock and be slowed by the resistance of atmospheric wind, or remain behind the shock and be strongly decelerated by the reverse blast wind (Hummel and Ivan, 2017). Therefore, the spatial distribution of the particulates cloud near the explosion site, and thus, the characterization of the source term, is determined by this differential behaviour. Given the scope of the current study, no attempt has been made here to deal with the complexities raised by an urban environment, but rather to place the focus on the validation of the proposed approach.

In the current work, the technique proposed in Hummel and Ivan (2017) for the transport of a single particle is extended to model the transport of multiple particles of various diameter sizes to generate an initial particle source distribution that is input to a longer-range, more classical, atmospheric dispersion prediction. The proposed MCREXS (Multi-Cloud Radiological EXplosive Source) model is used to perform high-fidelity physics-based computations using multiple particles in the near-field of the explosion site, convert particles to puffs beyond this zone, and subsequently carry out atmospheric dispersion modelling with Gaussian puffs on large distances. The hybrid approach avoids major empirical assumptions about the particle source term used in previous studies by Lebel et al. (2016b), and it is capable of providing improved prediction accuracy in a computationally efficient manner.

This paper is organized as follows: in Section 2 a brief review of RDD modelling is presented which provides some additional context to the current work, while illuminating the need for accurate particle source characterization. In Section 3 the computational model to generate a particle source distribution useful for further atmospheric dispersion modelling is described. In Section 4 the set of experimental data from the Defense Research and Development (DRDC) Suffield full-scale explosive dispersal tests (Erhardt et al., 2016; Green et al., 2016) to which model results are compared against is briefly described, and in Section 5 the comparison between simulation and experiment is discussed. Finally, conclusions and future work are summarized in Section 6.

2. Computational modelling of RDDs

To cope with high computational costs, the more intricate details of the particle source and flow field are ignored in many prediction tools for a RDD-associated radiological plume (e.g., Lebel et al. (2016b), Thiessen et al. (2009)). Instead, stochastic and empirical models are employed to approximate the dispersal of the contamination material at large distances. Examples of such models are plume, puff, and Lagrangian particle transport models.

Plume models are widely used to determine atmospheric dispersion of airborne contaminants. Typically, plume models assume that the contaminants are normally distributed about the mean wind direction (i.e., the "Gaussian plume"), with the distribution widening the farther away it is from the source according to (semi)empirical dispersion parameters. The dispersion parameters are often based on simple categorizations of atmospheric stability (De Visscher, 2014). Given their relative simplicity, plume models are often used in rapid risk assessments and emergency response planning (Homann, 2009). Puff models, wherein airborne contaminants from instantaneous or continuous releases are modeled as a single Lagrangian packet or series of packets advected by the wind field, are comparatively more advanced and of higher fidelity than plume models. The concentration within each puff is assumed to be normally distributed about its centre (i.e., a "Gaussian puff"), and each is dispersed over a larger area the farther it travels from the source according to similar dispersion parameters as employed in plume models (De Visscher, 2014). Lagrangian particle models offer still higher fidelity, and track a statistical sample of free particles using the Monte Carlo method. In these models the Lagrangian particles stochastically diverge from the wind vector over time. The divergence of particles, which is associated with random turbulent fluctuations in the wind velocity, can be implemented as a diffusion process (Boughton and DeLaurentis, 1992).

Gaussian plume, puff, and Lagrangian particle models have all been used to simulate RDDs, an example being the recent work of Lebel et al. (2016a,b) using the ADDAM (Chouhan, 2010), RIMPUFF (Thykier-Nielsen et al., 1999) and MLCD (Flesch et al., 2002) computer codes. In addition, DIFFAL (Gaussian plume), HPAC (integrated puff), and HOTSPOT (Gaussian plume) were used in the recent work by (Purves and Parkes, 2016), and LODI (Lagrangian particle) was used in the recent work by (Neuscamman and Yu, 2016). All of these codes were used to model the full-scale explosive dispersal tests performed by DRDC Suffield in 2012 (Green et al., 2016). Significant differences between the experimental data and predicted values were observed in all cases, which can be attributed to two factors: i) inherent variability in atmospheric turbulence and wind, reflected in the mismatch between the actual and modeled plume position and the shape of the deposition pattern, and ii) unresolved characterization of the source term, including the size distribution of the particle source and the size-dependency on deposition velocity.

A sensible approach to address the first issue is to increase the fidelity in which the flow field is modeled. The aforementioned wind-field models function relatively well in open areas (Lebel et al., 2016b), but cannot be used to resolve the complex geometries and intricate fluid flows typical of urban settings, which are most relevant to RDD emergency response. Some attempts have been made to extend such models