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A forward-backward coupled source term estimation for nuclear power plant accident: A case study of loss of coolant accident scenario

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ABSTRACT

Source term information of radioactive release in a nuclear accident is important for emergency response. Two major categories of source term estimation techniques are forward method based on the status data of nuclear power plant and backward method based on environmental monitoring data. Both data contain considerable uncertainties which can propagate through estimation and result in a biased estimate. To solve the problem, a coupled estimation method is proposed in this study, which combines forward method (Response Technical Manual, RTM-96) and backward method (ensemble Kalman filter). The coupled method builds an evolution model based on a forward estimate and uses it to constrain the temporal correlation of estimates in the backward part, so that the propagation of uncertainties is reduced. Numerical experiments and sensitivity analysis are performed to verify the proposed method, based on a hypocritical loss-of-coolant (LOCA) accident process and the records of a tracer field experiment for Sanmen nuclear power plant. The results demonstrate that the coupled method provides the most accurate estimate in all tests and is more robust to uncertainties in various parameters than both RTM-96 and ensemble Kalman filter.

1. Introduction

In case of a severe nuclear accident, the radioactive source term information that presents the temporal profile of the release rate of radionuclides, is critical for nuclear accident consequences evaluation and emergency response (Addis et al., 1998). In order to obtain this information, various source term estimation methods have been developed, which can be classified into two major categories: forward method and backward method.

The forward method uses assumptions on the core inventory and efficiencies of radionuclide removal processes to simulate the behavior of the nuclear power plant's (NPP) source term, which has been widely used in the emergency response system of nuclear power plants (Zhao et al., 2015; Cheng et al., 2008). There are abundant nuclear emergency guiding reports and NPP safety study publications based on these models, including Response Technical Manual (RTM-96, U.S. NRC) (McKenna et al., 1996), Generic Assessment Procedures for Determining Protective Actions during a Reactor Accident (IAEA-TECDOC-955, IAEA) (IAEA, 1997), and Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants (NUREG-1150, U.S. NRC) (U.S. NRC, 1990). In Fukushima Daiichi nuclear power plant accident, the method of IAEA-TECDOC-955 was used to estimate the source term (Zheng et al., 2012).

The forward method relies on reactor status monitoring data and empirical judgement. In nuclear accidents, the former can usually be unavailable or of low-quality, which may introduce large uncertainties. These uncertainties can make the prediction of the accident process in the forward method deviated from the reality, which will correspondingly lead to a biased estimate of the source term. And the latter is subjective, which may amplify the uncertainties in the reactor status monitoring data and aggravate the propagation of uncertainties (Hirose, 2012). Besides, the environmental monitoring data could not be adopted in the forward method for correction.

The backward method takes the environmental monitoring data as input parameters and estimates the source term by using certain atmospheric dispersion model and inverse modelling method (Astrup et al., 2004; Rojas-Palma et al., 2003; Liu et al., 2014; Tricard et al., 2013), which has drawn increasing interest in recent years (Zheng et al., 2009; Ma et al., 2012). Various atmospheric models have been applied in the backward source term estimation, including FLEXPART, Polair3D, RIMPUFF, etc (Astrup et al., 2004; Stohl et al., 2012; Winiarek et al., 2014). For the inverse modelling, there is a variety of choices such as optimal interpolation, Kalman filter and its derivations, and variational methods (Mallet et al.,

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2007; Hanea et al., 2004; Bocquet, 2012). Ensemble Kalman filter (EnKF) is one of the widely used assimilation methods for estimating source term, which can improve model predictions simultaneously in nuclear accident (Astrup et al., 2004; Zheng et al., 2009; Ma et al., 2012). Meanwhile, three-dimensional and four-dimensional variational data assimilation techniques have also been applied to nuclear accidents assessment (Winiarek et al., 2014; Bocquet, 2012; Estournel et al., 2012).

Because the environmental monitoring data are usually easier to obtain than the reactor monitoring data in an accident, the backward method may be readier to implement than the forward method. For example, in Fukushima Daiichi nuclear power plant accident, the backward method might be the only feasible way for source term estimation, because there were few valid reactor status data for the implementation of the forward method (Stohl et al., 2012). However, there are also uncertainties in the backward methods, due to the initial guess, the unpredictable temporal variation of the release, the meteorological complexity and the quality of the monitoring data. Furthermore, as an inverse problem, the backward source term estimation is usually ill-posed, which amplifies the input uncertainties and leads to increased bias in the solution of the problem. These uncertainties have to be carefully handled in order to reduce the bias in the backward estimation (Astrup et al., 2004).

Some study tries to reduce the above uncertainties by using a first guess which is pre-calculated based on radionuclide inventory and comprehensive off-line accident analysis models (Stohl et al., 2012). However, the inventory calculation and the accident analysis of reactors are usually conservative for safety consideration. The direct usage of these quantities in source term estimation can introduce over-estimation, as reported by several researchers (Winiarek et al., 2014; Hirao et al., 2013).

In order to avoid the above problems, a forward-backward coupled source term estimation method is proposed, which incorporates both reactor status data and environment monitoring data for uncertainty reduction. The proposed method extracts a temporal evolution model from a forward estimate and uses this model to impose constraints on the temporal correlation of the backward estimate, so that the propagation of uncertainties in data is controlled. Because the specific value of the forward estimate is not involved directly, the transfer of the bias in the forward estimate to the final estimate can be reduced. For the purpose of fast response, RTM-96 (McKenna et al., 1996) method is chosen as the forward part of the coupled method and EnKF is chosen as the backward part.

A LOCA (loss of coolant accident) scenario at the Sanmen NPP is simulated to validate the proposed method. The transfer and removal processes of the radionuclides in the containment are both considered, which results in a temporally-varying release to the environment. The positions of the release and the monitoring sites are set according to the SF6 tracer experiment preformed at the Sanmen NPP site, so as to be close to the real world.

The coupled method is compared with the forward method and backward method based on the LOCA scenario. Both single-factor and multi-factor sensitivity analysis are performed to investigate the influences of multiple parameters on the performance of the three methods.

2. Methods

2.1. Forward method

The forward method applied in this work is based on the parametric formula introduced in RTM-96 (McKenna et al., 1996), which is designed for fast response in a nuclear accident. This method uses NPP parameters to estimate source term, which primarily includes core inventories, coolant inventories, reactor coolant system water mass, reactor containment air volumes and reactor power levels (McKenna et al., 1996). In this method, a NPP is modeled as several connected parts, including reactor pressure vessel (RPV), steam generator, containment vessel (CV), auxiliary building and the atmosphere. The source term is obtained by calculating the fission products which are transferred between these parts and removed in each part. For radionuclide i, the source term is calculated by Eq. (1).

$$source\,term_i = FPI_i \times CRF_i \times \left(\prod_{j=1}^{n} RDF_{(i,j)}\right) \times EF_i, \tag{1}$$

where FPI_i is the core or coolant inventory of radionuclide i, CRF_i is the ratio of the amount of core-released radionuclide i to its inventory in core. $RDF_{(i,j)}$ is the ratio of the amount of radionuclide i available for release after reduction mechanism j to that available for release before this reduction mechanism. And EF_i is the ratio of the amount of radionuclide i released to atmosphere to that available for release, i.e. the leakage rate of CV.

It takes four steps to estimate the source term with Eq. (1). First, the amount of fission products inventory in reactor core and primary coolant is calculated. Second, the amount of fission products released from pressure vessel is figured out. Third, fission products removal on release paths are computed. Finally, fission products release to the atmosphere are estimated.

RTM-96 method has the benefit of fast computation, but it highly depends on the availability and accuracy of the operating data of the NPP. The bias in an NPP parameter may propagate and result in an amplified deviation in the final source term estimate. For RTM-96, the leakage rate of CV (the EF_i ratio in Eq. (1)) is the dominant parameter that affects the estimation accuracy. The uncertainty in the leakage rate of CV may directly lead to a biased estimate.

2.2. Backward method

In the backward method, the environment monitoring data are the primary input parameter. And some inverse modelling method is used to update the source term estimate by comparing the environment monitoring data and the air dispersion model predictions. Because the environment monitoring data in a nuclear accident are sequentially obtained, the sequential ensemble Kalman filter (EnKF) is a natural choice of source term estimation in nuclear emergence response. EnKF is an extension of Kalman filter, which uses ensembles of random samples to describe the possible state and the corresponding error statistics of variables or model parameters (Evensen, 1994). The initial ensemble samples are obtained by perturbing the preset background state vector x:

$$x_0(i) = x_0^b + \delta(i), \quad i = 1, 2, \ldots, N \tag{2}$$

where δ represents the random noise added to the background value. N is the ensemble size, which is set to be 50 based on sensitivity tests, with the consideration of both the accuracy and the computation time. Each of these ensembles is integrated forward by EnKF in time using a model equation, which generally takes the following form:

$$x_t(i) = M_k(x_{t-1}(i)) + \eta(i), \quad i = 1, 2, \ldots, N \tag{3}$$

where $x_t(i)$ is the state vector of the i-th ensemble. M_k is the evolution model and η is the model error which follows the Gaussian distribution. In this study, the mean of this Gaussian distribution is zero and the standard deviation of it is 30% of $x_{t-1}(i)$. This is the forecast step of EnKF.