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Location of contaminant emission source in atmosphere based on optimal correlated matching of concentration distribution

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ABSTRACT

Source location is crucial to manage contaminant emissions in atmosphere, In order to determine the source location without dependence on the absolute measurement data, a method based on optimal correlated matching of concentration distribution (OCMCD) was proposed. First, the estimation efficiency, accuracy and dependence on source strength of OCMCD were compared with the common method which estimates multiple parameters of the source term simultaneously. The results show that the method of OCMCD performs better than the common multiple parameters estimation method based on the mean errors between prediction and measurement in both estimation accuracy and efficiency. The test results with different sets of source strength manifest that OCMCD relies minimally on the source strength Then, a wind direction correction parameter and a weighted term of normalization concentration error were introduced into the model to compensate some missed information and improve the location results. The influence of data noises on the estimation accuracy of OCMCD method was also verified by adding extra manual noises on the measurement data. Then, the dependence of estimation performance with OCMCD method on atmosphere conditions were investigated statistically with experiment release cases. The results showed that source location was identified well in most of cases. Finally, OCMCD method was extended to determine the source location during the source trace process with a mobile sensor. The test results with a simulation scenario based on Zigzag search strategy demonstrate that the source location determined by OCMCD source criterion is much closer to the real source position than that determined by the criterion of the maximum concentration. Therefore, the results have proven the feasibility and superiority of OCMCD proposed in this paper to estimate source location in cases of both static sensor distribution and mobile sensors. OCMCD will be a potentially useful method to identify emission source location in atmosphere.

1. Introduction

The leak of hazardous materials in atmosphere can lead to serious consequences to public. Once the dangerous materials are emitted from a storage or transportation processing, there will be a potential threat on residences, environment and public (Ma et al., 2012; Joshi et al., 2016; Cen et al., 2017). Thus, it is of significant importance to trace the emission source, which can provide essential information for controlling and managing accidents. More attention has been paid to emission source determination in recent years (Ma and Zhang, 2016; Zhang et al., 2016; Ng and Hassim, 2017). The methods to trace emission source can be grouped into two types: direct location methods and indirect methods. For direct methods, the location of emission source is determined by a portable or static sensor and analysis instrument, and then the site of the source is judged by the positon of the sensors or instruments (Hodgkinson et al., 2006; Yang et al., 2016). In this case, the instrument should be moved continuously, which will increase the risk to the operator. Alternatively, mounted sensors could be distributed in the field, which may increase the cost. If economic sensor nodes

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are available, a wireless sensor network (WSN) may be a potential practical method to locate the emission source (Manes et al., 2016). However, WSN technology is still under developing, and the sensor nodes with micro sizes and cheap price are still unavailable. Therefore, indirect emission location methods which combine the monitoring data with inverse algorithms are becoming popular.

In fact, gas source estimation is an inverse problem that corresponds to the forward dispersion process. For the forward problem, information about the source term, atmospheric and terrain condition is employed to predict the gas distribution. Inversely, the source term must be determined based on the information about concentration distribution and other conditions. One type of method to solve the inverse gas dispersion problem is to resolve the gas dispersion equations directly (Pang et al., 2013). But the results may greatly depend on conditions such as boundary and initial parameters, and it is difficult to solve this ill-posed problem (Kabanikhin, 2011). The method based on probability statistics can provide an estimation result with probability distribution, thus it seems to be more rational and acceptable (Ma et al., 2014a,b; Wang et al., 2017a,b); Keats et al. (2007); Chow et al. (2008), Xue et al. (2017), Wang et al., 2017a,b reconstructed the source term based on Bayesian inference. Kopka et al. (2016) applied approximate Bayesian computation method to the problem of the atmospheric contamination source identification. Pudykiewicz (1998), Sharan et al. (2009, 2012), Kumar et al. (2015, 2016) utilized a method based on adjoint source-receptor model to retrieve a point source. Zhang et al. (2015) used Kalman filter to trace the radioactive materials. Flesch et al. (2004) proposed a backward Lagragian stochastic (BLS) model to estimate the source term. Bocquet (2005) proposed a maximum entropy on the mean (MEM) method to reconstruct the atmospheric tracer source. However, above methods such as MCMC and BLS are always subjected to the computational cost as well as the requirement of prior information. Singh et al. (2015) utilized a least-squares inversion technique to identify a point release without initial guess of source information. but it needs to discretize the domain. Optimization method has been widely applied in multiple parameters identification. Some researchers have used different optimization algorithms such as Genetic algorithm (GA) (Haupt, 2005; Long et al., 2010), Simplex and Simulated annealing (SA) (Ma et al., 2013), and Particle swarm optimization (PSO) (Ma et al., 2017a,b) to identify the source term of gas emission. For the advantage of having less constraints in the model and the unnecessariness of resolving the inverse dispersion equations, it is proper to deal with the ill-posed problem and estimate multiple parameters simultaneously with optimization method. Additionally, optimization method always has high estimation efficiency. Hence, optimization method is an appropriate tool to identify source term, where source location is one of the most important parameter. Thus the estimation of source location parameters the main work in many researches. Long et al. (2010), Ma et al. (2013) have proposed different model to estimate source term including source strength and location parameters successfully with optimization methods. But most of the cost functions in optimization method to identify the source term are based on the mean errors between the measured and predicted concentrations with forward dispersion model. In this case, the accuracy of the estimation results is dominated by the accuracy of monitoring data and forward dispersion model. If large errors exist in measured concentration or prediction model, the location estimation will deviate from the real source significantly. Efthimiou et al. (2016) proposed a modified method to identify the location and source rate with 2 sequent steps. With their method, only the source coordination is determined with correlation function at the first step, and then the source rate is identified with a quadratic cost function. But the discussion of how to use it and the impact factors on this method are referred rarely.

Therefore, a method to estimate source location by considering the correlated matching of concentration distribution between measured and predicted data will be discussed to improve the dependence of the estimation results on the accuracy of absolute concentration information. The impact factors and the applications of this method to determine source location based on both stable and mobile sensors will also be discussed in the paper.

2. Basic principle

For some gas emission events, e.g. a leak event in oil or gas storage tank or pipeline, the location of leakage area should be determined in the first time. In this case, the leakage location parameters should be estimated as soon as possible for risk treatment in next time.

For the source location problem, it is an inverse problem to estimate location parameters with measured data and forward dispersion model. Optimization algorithms can obtain unknown parameters by solving the cost function. Ma et al. (2013) have compared different optimization algorithms to identify source term and proposed an assessment parameter to evaluate the estimation performance of different methods. The basic principle of optimization method to identify source parameter is to minimize the error between measured concentration from monitoring instruments and predicted data from forward dispersion model by optimization process. The basic cost function can be depicted with Eq. (1)

$$
\begin{aligned}
f = \quad & \min\,(Q, r, \theta)\, \| C_{\mathrm{mea}} - C_{\mathrm{pre}}(Q, r, \theta, \ldots) \|_2^2 \\
\mathrm{s.}t. \quad & Q > 0 \\
& r > 0 \\
& 0 < \theta > 360^{\circ} \\
& \quad \ldots
\end{aligned}
\tag{1}
$$

where C_{mea} is the monitoring data; C_{pre} is the results from prediction model; Q is emission strength (emission rate); r is the distance of the sensor to the source position and θ is the azimuth angle of the sensor to the source point.

According to the results Sharan et al. (2012), Ma et al. (2013), prediction model and monitoring data are the main factors affecting the source estimation results. Besides, the estimated parameters with some optimization methods such as Simplex and pattern search (PS) are also influenced by the initial values and boundary constraints. In this paper, only the location parameters are focused on. If the source strength is previously known, it is easy to estimate the source location with optimization method. However, if it is difficult to know the strength information, how can this problem be solved? There are two ideas to trace the source location with optimization method. The first method is to estimate both strength and location parameters simultaneously as previous methods have done. In spite of this, the addition of useless estimated parameters will increase the computation cost and complexity. Thus, another solution method is proposed. In this method, the source strength can be set as a constant, and then only the location parameters are required to be determined by optimization method. Therefore, the cost function becomes

$$
\begin{aligned}
f = \quad & \min\,(r, \theta)\, \| C_{\mathrm{mea}} - C_{\mathrm{pre}}(Q, r, \theta, \ldots) \|_2^2 \\
\mathrm{s.}t. \quad & Q = Q_c \\
& r > 0 \\
& 0 < \theta > 360^{\circ} \\
& \ldots
\end{aligned}
\tag{2}
$$

where Q_c is a constant, which is different from Eq. (1).