The influence of turn-on time of source on the estimation of source location and release rate in time-varying flow

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SUMMARY:
Although Bayesian inference coupled with computational fluid dynamics (CFD) has been widely used in the source term estimation (STE), the attentions of most scholars are focused on the pollution source released in the time-invariant flow and the turn-on time of the source is often regarded as a known parameter which requires no estimation. However, the flow field tends to change with time and the turn-on is usually unknown in advance. To solve this problem, a feasible method is assuming the turn-on time as a known value (maybe different from the true turn-on time) and then estimating other source parameters. In this paper, the source parameters in the time-varying flow are estimated based on Bayesian inference coupled with adjoint equation. Besides, by assuming turn-on time as different values, its influences on the estimated results are investigated. The results show that the source location and release rate can be estimated accurately when the turn-on time is assumed between the correct turn-on time and the moment when sensors first detect the measured concentrations.

Keywords: source term estimation (STE); turn-on time; time-varying flow

1. INTRODUCTION

Over the past few decades, there has been an increasing number of the incidents involving the releases of hazardous substances into the atmosphere. In light of this context, the source term estimation (STE) techniques that can provide the sources information are being developed (Hutchinson et al., 2017).

At present, most researchers have estimated the pollution source which is released in the time-invariant flow (Xue et al., 2017). However, the flow in the real world tends to vary with time. Considering the time-varying characteristics of flow field in the STE is necessary. Besides, the turn-on time is often regarded as a known parameter but it is unknown in advance. Therefore, in this paper, the source parameters in the time-varying flow are estimated and the influences of turn-on time on the estimated results of other source parameters (the source location and release time) are investigated by assuming the turn-on time as different values.

2. METHODS AND CASE STUDY

2.1. Bayesian inference

Bayesian inference is a method of solving inverse problem. In the case of the STE, the probability of source parameters can be obtained based on the measured concentrations. The Bayesian formula can be expressed as:

$$P(\boldsymbol{m}|\boldsymbol{d}) = \frac{P(\boldsymbol{m})P(\boldsymbol{d}|\boldsymbol{m})}{P(\boldsymbol{d})} \tag{1}$$

where $\boldsymbol{m}$ is the source parameters vector; $\boldsymbol{d}$ is the measured concentrations vector; $P(\boldsymbol{m}|\boldsymbol{d})$ is the posterior probability; $P(\boldsymbol{m})$ is the prior probability; $P(\boldsymbol{d}|\boldsymbol{m})$ is the likelihood probability; $P(\boldsymbol{d})$ is the evidence. If an assumption of no prior information is considered, the prior probability $P(\boldsymbol{m})$=constant. The likelihood probability $P(\boldsymbol{d}|\boldsymbol{m})$ which quantifies the discrepancies between the measured concentrations and the predicted concentrations are considered following the normal distribution (Jia and Kikumoto, 2021). Thus, $P(\boldsymbol{d}|\boldsymbol{m})$ can be expressed as:

$$P(\boldsymbol{d}|\boldsymbol{m}) \propto \exp\left\{-\frac{1}{2}\sum_i^N \sum_j^M \left[\frac{c_i^{(j)}(\boldsymbol{m}) - d_i^{(j)}}{\sigma}\right]^2\right\} \tag{2}$$

where $d_i^{(j)}$ and $c_i^{(j)}(\boldsymbol{m})$ are the measured concentration and the predicted concentration of the i-th sensor at the j-th measurement time, respectively; N is the number of the sensors; M is the number of samplings of each sensor. The posterior probability $P(\boldsymbol{m}|\boldsymbol{d})$ is the probability of source parameters when the measured concentrations detected by sensors are $\boldsymbol{m}$.

2.2. Source-receptor relationship

In Eq. (2), the measured concentration is obtained by sensors and the predicted concentration is obtained by numerical simulation. The traditional method of calculating the predicted concentration is solving the convection-diffusion equation. However, this method would bring large computational cost because the source can be located at anywhere and released at anytime. Keats et al. (2007) proposed a method of STE company with adjoint equation. The adjoint equation can be expressed as:

$$-\frac{\partial C^*(\boldsymbol{x},t)}{\partial t} - \boldsymbol{U}(\boldsymbol{x},t) \cdot \nabla C^*(\boldsymbol{x},t) - \nabla[K(\boldsymbol{x},t)\nabla C^*(\boldsymbol{x},t)] = h(\boldsymbol{x} - \boldsymbol{x}_i, t - t_j) \tag{3}$$

with the boundary condition

$$[C^*(\boldsymbol{x},t)\boldsymbol{U}(\boldsymbol{x},t) + K(\boldsymbol{x},t)\nabla C^*(\boldsymbol{x},t)] \cdot \vec{\boldsymbol{n}} = \boldsymbol{0} \quad at\ \partial\Omega$$
$$C^*(\boldsymbol{x},t_j) = 0$$

The predicted concentration of the i-th sensor at the j-th measurement time can be expressed as:

$$c_i^{(j)}(\boldsymbol{m}) = \int_0^{t_j} \int C^*(\boldsymbol{x},t)[q_s h(\boldsymbol{x} - \boldsymbol{x}_s)H(t - t_{on})]d\boldsymbol{\Omega}dt \tag{4}$$

The total number of the adjoint equations that need to be solved is N×M, which is much smaller than the number of the potential source locations. Thus, the computational cost of predicted concentrations is largely reduced.

2.3. Research Object

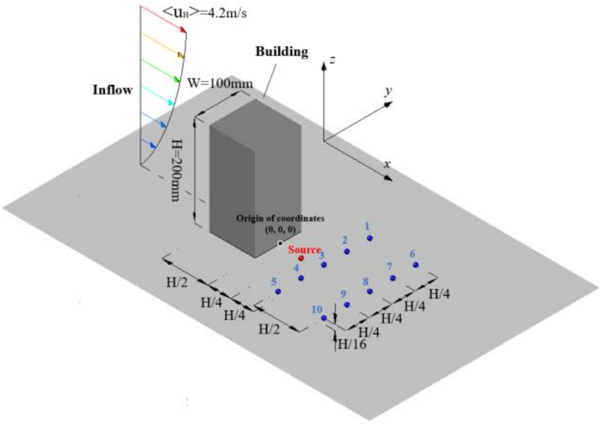


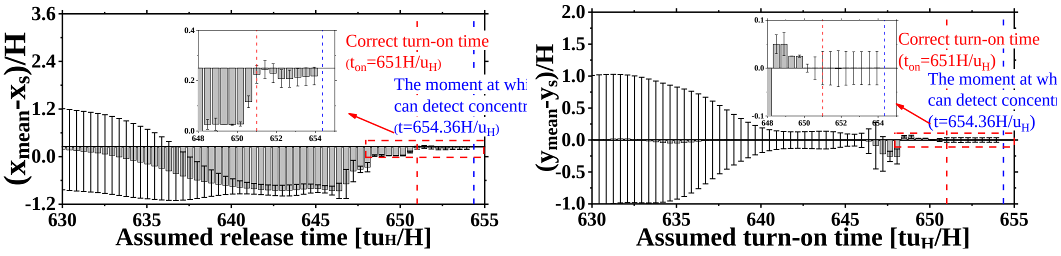
Figure 1. Layout of the source, the sensors and the building model of wind tunnel experiment.

Fig. 1 shows the layout of the experiment which is used to validate our method. A building model is 0.1 m in length (*L*), 0.1 m in width (*W*) and 0.2 m in height (*H*). Ethylene is released at the rate of q_s =5.83×10^{-6} m^3/s from a hole (the red dot in Fig. 1). Ten sensors (the blue dots in Fig. 1) are located in the plane at the height of 0.0125 m (0.0625*H*) above the ground. The velocity profile of the inflow follows the exponential law. The reference velocity is $<u_H>$=4.2 m/s and the exponent θ of the velocity profile is 0.25. The dimensionless concentration is defined as $c^*= c/<c_0>$, where $<c_0>=q_s/(<u_H>H^2)$. The dimensionless time is defined as $t^*=t/t_0$, where $t_0=H/<u_H>$.

2.4. Settings for Numerical Simulation

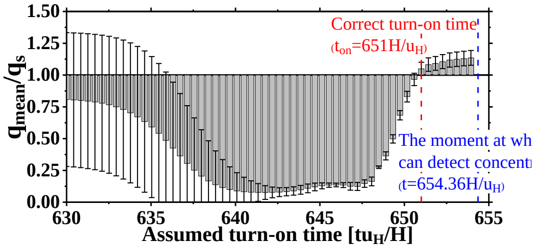
The length, width and height of the computational domain are 12.5*H*, 6*H* and 4*H*. The grid sensitivity analysis was conducted by the coarse mesh (422,649), basic mesh (991,764) and fine mesh (2,167,312). Little difference can be found between the simulated results of basic mesh and fine mesh. Thus, the basic mesh was used in the STE. Due to the lack of the transient measured concentrations in the experiment, we used the synthetic data obtained by forward simulation substituting the measured concentrations. In order to reduce the computational cost of the predicted concentrations, the adjoint equation is employed.

3. RESULTS



(a)

(b)



(c)

Figure 2. Mean and standard deviation of posterior probability of source parameters with different assumed turn-on time of source: (a) x-coordinate, (b) y-coordinate, (c) release rate.

Fig.2 shows the estimated results of source location and release rate when the turn-on time is assumed as different values. The histogram is the error between the mean of posterior probability and the correct source parameter. The error bar is standard deviation of posterior probability. It is found that the source parameters are estimated accurately when the turn-on time is assumed between the correct turn-on time and the moment when sensors first detect the measured concentrations. When the turn-on time is assumed far earlier than the correct value, the errors and the uncertainties of the estimated result are large.

4. CONSLUSIONS

In this paper, the source parameters in the time-varying flow are estimated and the influences of turn-on time on the estimated results of source parameters are investigated. Conclusions are as follows:

(1) The source parameters such as location and release rate can be estimated accurately when the turn-on time is correctly assumed.
(2) The errors and the uncertainties of estimated results is small when the turn-on time is assumed between the correct value and the moment when sensors first detect the measured concentrations. However, when the turn-on time is assumed far earlier than the correct value, the errors and the uncertainties of the estimated result are large.

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