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Rapid identification of multiple constantly-released contaminant sources in indoor environments with unknown release time

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ABSTRACT

The sudden release of airborne hazardous contaminants in an indoor environment can potentially lead to severe disasters, such as the spread of toxic gases, fire, and explosion. To prevent and mitigate these disasters it is critical to rapidly and accurately identify the characteristics of the contaminant sources. Although remarkable achievements have been made in identifying a single indoor contaminant source in recent years, the issues related to multiple contaminant sources are still challenging. This study presents a method for identifying the exact locations, emission rates, and release time of multiple indoor contaminant sources simultaneously released at constant rates, by considering sensor thresholds and measurement errors. The method uses a two-stage procedure for rapid source identification. Before the release of contaminants, only a limited number of time-consuming computational fluid dynamics (CFD) simulations need to be conducted. After the release of contaminants, the method can be executed in real-time. Through case studies in a three-dimensional office the method was numerically demonstrated and validated, and the results show that the method is effective and feasible. The effects of sensor threshold, measurement error and total sampling time on the source identification performance were analysed, and the limitations and applicability of the method were also discussed.

1. Introduction

Indoor environments in modern society are persistently threatened by a huge variety of airborne hazardous contaminants, such as toxic, inflammable, or explosive chemicals, harmful microbes, and radioactive substances [1–4]. The sudden release of these contaminants, accidentally or intentionally, can potentially result in exposure to toxic gases, fire, explosion, epidemic, or radiation. All these incidents would lead to significant casualties and property losses if no effective response measures were taken. In recent years, several tragic incidents, such as the Tokyo subway sarin attack, severe acute respiratory syndrome outbreak and the Fukushima nuclear leak, have aroused the concern of indoor environmental safety. To prevent and mitigate disasters due to the sudden release of hazardous contaminants, it is critical to promptly and accurately identify the characteristics of the contaminant sources, such as locations, emission rates, and release time. Source identification is an important premise for developing effective response measures, such as source elimination, dilution ventilation, air purification, evacuation, and shelter-in-place [5,6].

With known locations and emission rates of contaminant sources, the transient distribution of a contaminant can be well predicted using a dispersion model. However, in most practical applications the information on contaminant sources is incomplete or unknown, and needs to be identified using the sensor measurements of the airflow and concentration fields. This type of identification constitutes an inverse problem, which has been widely studied for several decades in the fields of heat transfer [7–9], groundwater contamination [10,11], soil pollution [12,13], and atmospheric constituent transport [14–16].

Due to increasing concern about indoor environmental safety, research on identifying indoor contaminant sources has developed rapidly in recent years. The methods available for identifying indoor contaminant sources can be roughly categorised as backward and forward methods, as shown in Table 1. To date, most backward and forward methods have shown their applicability in identifying a single indoor contaminant source [17–40]. In contrast, very few studies have discussed the scenarios involving multiple indoor contaminant sources, which are frequent and common in real-world applications [18,38]. In

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Table 1
Major methods for identifying indoor contaminant source.

Category	Principle	Typical methods	Reference
Backward methods	Contaminant dispersion models are solved inversely to obtain source characteristics, using sensor measurements of concentration at a given time point as initial conditions.	Quasi-reversibility method	Zhang and Chen [17], Liu et al. [18,19]
		Pseudo-reversibility method	Zhang and Chen [20]
		Tikhonov regularization method	Zhang et al. [21]
		Probability-based inverse method	Liu and Zhai [22–24], Zhai and Liu [25], Zhai et al. [26], Wang et al. [27]
		Lagrangian-reversibility model	Zhang et al. [28]
Forward methods	Contaminant dispersion models are solved directly, and typically a two-stage procedure is performed for quick identification. In the first stage, before contaminant release, the time-consuming simulations of contaminant dispersion are conducted. In the second stage, after contaminant release, source characteristics are identified quickly by finding the best match between the simulated and measured concentrations over a given time period.	Bayesian probability method	Sohn et al. [29], Sreedharan et al. [30–32], Tagade et al., [33]
		Artificial neural network method	Vukovic and Srebric [34], Vukovic et al., [35], Bastani et al. [36]
		Spatial flow impact factor method	Wang et al. [37]
		Optimization methods based on a limited number of CFD simulations	Cai et al. [38–40]

residential or working environments, chemical contaminants are ubiquitous and continuously emitted from building materials, furniture, and equipment. In emergency situations related to earthquakes, blasts or impacts, hazardous chemicals may simultaneously escape from many leakage points. During an epidemic outbreak, many infected people may be found in hospital or other buildings. In terrorist attacks, chemical or biological agents may be deliberately released from many locations. Therefore, research on identifying multiple indoor contaminant sources is of great practical significance.

For identifying multiple indoor contaminant sources, a major challenge to the backward methods is how to ensure the uniqueness of the identification results. When multiple contaminant sources are released, different combinations of sources may result in the same or close sensor measurements at a given time point. In other words, different causes may lead to the same outcome. Because the backward methods use the same outcome (sensor measurements at a given time point) as the initial condition, it is difficult to differentiate various possible causes. Besides, the backward methods would require a significant reduction in computing time for solving inverse computational fluid dynamics (CFD) models. This potentially limits their application in real-time source identification.

As shown in Table 1, forward methods use sensor measurements during a given time period, rather than at a single moment, as inputs. In indoor environments, it is quite rare that different release scenarios will produce the same or close sensor measurements at all time points. Therefore forward methods are more promising for finding a unique solution. In addition, the two-stage procedure of the forward methods (see Table 1) also makes real-time source identification possible. A major constraint of the forward methods is that most of these methods only work well using a fast contaminant transport model, such as a multi-zone model, because a large number of simulations are usually required before a release incident to cover all possible scenarios. The multi-zone model generally assumes a uniform contaminant distribution in one zone [41,42]. Therefore the forward methods using the multi-zone model cannot identify the exact locations of contaminant sources in each zone or room.

In a previous study we presented a theoretical model for quickly identifying the exact locations and emission rates of multiple constant contaminant sources indoors, using ideal sensors [38]. By using an analytical expression of indoor contaminant dispersion, the theoretical model only requires a limited number of CFD simulations. Because CFD simulations can provide detailed information of contaminant dispersion, the exact locations of contaminant sources can be identified by the theoretical model. The major constraint of this model is that it cannot work by using real sensors, mainly because the model cannot work when there is no response of sensors due to sensor thresholds. In real-world situations, the use of real sensors will make the problem of source identification much more difficult, primarily due to three issues: (1) no response of sensors due to sensor thresholds; (2) inevitable measurement errors; and (3) unknown release time of contaminant. This research aims to fill the gap by developing a more sophisticated method that can promptly identify the locations, emission rates, and release time of multiple indoor contaminant sources simultaneously released at constant rates, by considering the sensor threshold and measurement errors.

2. Major assumptions

The source identification problem is specified by introducing the following assumptions.

Assumption 1. **The contaminant is dispersed as a passive gas in steady indoor airflow**. The passive gas refers to the gaseous contaminant that is present in sufficiently low concentration that the effects of its dispersion on the indoor airflow field and air density can be neglected.

Assumption 2. **The number of potential sources is limited and their locations are known**. The current work does not attempt to