REAL-TIME DETERMINATION OF INDOOR CONTAMINANT SOURCE LOCATION AND STRENGTH, PART I: WITH ONE SENSOR

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ABSTRACT

In case contaminants are released in occupied rooms, it is necessary to determine the contaminant source location and strength rapidly so that prompt response measures can be taken to protect indoor occupants. This paper presents a new method with one sensor to identify the contaminant source location and strength. It completes the time-consuming computational fluid dynamics (CFD) simulations before the release event, and finds the source in real time during the event. In addition, an index called "correctness probability" for evaluating the accuracy of this method is proposed. This paper demonstrates how to use the method in a three-dimensional room. The method could identify the contaminant source locations with quite high accuracy but not very accurate for strength. The results also show that this method is characterized by quick response and low cost.

KEYWORDS

Contaminant source, Identification method, Computational fluid dynamics (CFD), Sensor, Indoor environment

INTRODUCTION

The Sever Acute Respiratory Syndrome (SARS) epidemic, which affected the whole world in 2003, together with the recent occurrence of chemical and biological terrorism, have been increasingly threat against the health and security of indoor occupants. Under this background, people are paying more and more attentions to response measures to avoid or reduce the influence of suddenly released contaminant when emergency occurs. The determination of contaminant source location and strength in real time is crucial for developing the prompt response measues. It could also be of great importance for mitigating the disaster and protecting occupants.

If the contaminant source location and strength are known, the solving of indoor contaminant concentration field is a typical direct problem. Thus, if the indoor concentration field is known, the solving of contaminant source location and strength is an inverse problem. Although much research has been devoted to inverse problems in heat transfer, groundwater transport, and atmospheric constituent transport, only a little work has, to our knowledge, been published on the determination of indoor contaminant source.

Several researchers have studied the above problem regarding the contaminant releases in a multi-room building. Sohn et al. (2002) used Bayesian probability model to identify the contaminant source in a five-room building. Arvelo et al. (2002) employed the genetic algorithm to interpret the computed data to locate the sources in a building with nine offices and a hallway. In the above studies, multi-zonal model was used to calculate the airflow and contaminant transport. Since the multi-zone model can only provide some macroscopic information about the contaminant transport, it cannot be used for accurate identification of location and strength, which was proved by Chen (2005). She presented an approach to roughly identify comtaminant source, which is similar to multi-zone model. The accuracy of this approach is undesirable for some applications. In addition, the method requires a lot of sensors to identify the source, and thus the practical application of it may be limited when we consider the costs of sensors.

In order to identify contaminant source more accurately, Computational Fluid Dynamics (CFD) simulations are used instead of zonal model. Zhang and Chen (2006) studied this probem by solving the inverse CFD model directly. Their results show that the method could identify the contaminant source location but not very accurate for strength. Since the above method requires to execute a computationally intensive inverse CFD model during a release event, it may be time-consuming and too slow for online and real-time identification.

From the above reviews, we come to the following understandings: 1) it is necessary to employ CFD modeling if more accurate and detailed information about airflow and contaminant transport is needed; 2) the method with less sensors may have more advantages in case that the costs of sensors is a critical fator; 3) since the proper reponse measures should be taken promptly to ensure the security of indoor occupants, it is of great importance to develop a quick and accurate method for real-time identification.

Based on the above understandings, we explored two new methods which could identify the contaminant source location and strength in real time with the sensor measurments during a release event and the CFD simulations before it. Considering the length of paper, we organize this paper into two parts. In Part I, a new method with one sensor is presented, and is demonstrated in a three-dimensional room. Moreover, an index called "correctness probability" is proposed to scale the accuracy of the identification method, which may be used to determine optimal tradeoffs, such as benefits and costs, between different methods, and guide sensor deployment, etc. In Part II, a new method with two sensors will be presented and demonstrated. Furthermore, comparison of the two methods will be summarized in Part II.

METHODOLOGY

Premises of this study

For simplicity, the premises of this paper are defined as follows:

1. Indoor airflow is known and is in steady state;
2. Only one contaminant source is released in the room, which is a point source and released at a steady rate;
3. Only one sensor is placed in the room, which can measure the comtaminant in the air accurately whether its concentration is very high or extremely low;
4. The contaminant release and the sensor measurements take place simultaneously.

Method for determining the location of indoor contaminant source

Suppose there is one sensor placed in the room at point β. Unknowns to the problem include location α^* and strength S^* of the source CS^*. The method is divided into two stages. First, in the pre-event or simulation stage, main steps include the following,

1. Divide the room into N control volumes, the center of each control volume forms a set $A=\{\alpha_1,\alpha_2,\cdots,\alpha_N\}$;
2. Define an index to represent the closeness degree between α_i and α^* and denote it as $X(\alpha_i,\tau)$. As there are N control volumes, we construct a vector as,

$$\vec{X}(\tau)=[X(\alpha_1,\tau),X(\alpha_2,\tau),\cdots,X(\alpha_N,\tau)]^T;$$

3. Run CFD simulations to get the concentration of contaminant at point β. Each simulation repensents a release scenario in which the source location is a_i and strength is a constant S. Finally, store the set of simulations in a database for next stage.

The resulting database of simulations consist of N scenarios. Because this stage is not time-critical, a large database of simulations is not difficult to develop with the advances of fast personal computers and inexpensive data storage devices.

In the second stage, during a release event, main steps of source identification are described as follows,

4. With the CFD simulations and the data from the sensor, we solve the vector $\vec{X}(\tau)$;
5. Using $\vec{X}(\tau)$, find the closest point α_k to α^* in the set A. Then the mission is accomplished.

The second stage of the method is mathematically simple and can be executed in real time as data stream in from sensor during a release event.

According to the above description of the method, the proper index $X(\alpha_i,\tau)$ is a key to solve the problem. Now, we will present how to deduce the specific form of $X(\alpha_i,\tau)$.

First, an index called "similarity characteristic" is defined as:

$$SC_1(\alpha_i,\tau)=\log\left(\int_0^\tau C^*(\beta,t)\mathrm{d}t\Big/\int_0^\tau C_i(\beta,t)\mathrm{d}t\right) \qquad (1)$$

where $SC_1(\alpha_i,\tau)$ is a non-dimensional parameter, which indicates the similarity characteristic of α_i and α^* at time τ, $C^*(\beta,t)$ is the measurement from sensor at point β and time t when the unknown source CS^* is released in the room, $C_i(\beta,t)$ is the contaminant concentration at point β and time t when the source CS is released at point α_i with steady strength S, which is obtained by simulation and stored in the database; and the subscript "1" represents that only one sensor is in use.

When the indoor flow field is known, the equation of contaminant transport is a liner equation, where Superposition Theorem can be applied. Thus if S^* and S are constant, when $\alpha_k\to\alpha^*$, we get

$$\frac{\int_0^\tau C^*(\beta,t)\mathrm{d}t}{\int_0^\tau C_k(\beta,t)\mathrm{d}t} \to \frac{S^*}{S} \tag{2}$$

According to eq.(1) and eq.(2), we know that $SC_1(\alpha_k,\tau) \to \lg(S^*/S)$, that is, the variation curve of $SC_1(\alpha_k,\tau)$ with τ approaches a horizontal line. From $SC_1(\alpha_i,\tau)$, another index can be defined,

$$ASD_1(\alpha_i,\tau) = \left\{ \int_0^\tau \frac{\left|\mathrm{d}[SC_1(\alpha_i,t)]\right|}{\mathrm{d}t}\mathrm{d}t \Big/ \tau \right\}^{-1} \tag{3}$$

where $ASD_1(\alpha_i,\tau)$ is called “absolute similarity”, it is a dimensional parameter.

From the eq.(3), we can see that $ASD_1(\alpha_i,\tau)$ has the following properties:

1) $ASD_1(\alpha_i,\tau) \geq 0$;

2) The more the curve of $SC_1(\alpha_i,\tau)$ approaches a horizontal line, the greater value of $ASD_1(\alpha_i,\tau)$;

3) As $\alpha_k \to \alpha^*$, $ASD_1(\alpha_k,\tau) \to \infty$.

According to $ASD_1(\alpha_i,\tau)$, a new index is defined further:

$$MGS_1(\alpha_i,\tau) = ASD_1(\alpha_i,\tau) \Big/ \sum_{i=1}^{N} ASD_1(\alpha_i,\tau) \tag{4}$$

where $MGS_1(\alpha_i,\tau)$ is referred to as “relative similarity”. Eq. (4) shows that $MGS_1(\alpha_i,\tau)$ is a non-dimensional index and possesses the following properties:

1) $0 \leq MGS_1(\alpha_i,\tau) \leq 1$;

2) $\sum_{i=1}^{N} MGS_1(\alpha_i,\tau) = 1$;

3) As $\alpha_k \to \alpha^*$, $MGS_1(\alpha_k,\tau) \to 1$.

With the above properties, $MGS_1(\alpha_i,\tau)$ is employed here to represent the closeness degree between α_i and α^*. As there are N control volumes, we construct a vector as,

$$\begin{aligned}\overrightarrow{MGS_1}(\tau) = [&MGS_1(\alpha_1,\tau), MGS_1(\alpha_2,\tau), \cdots, \\ &MGS_1(\alpha_N,\tau)]^T\end{aligned} \tag{5}$$

In the vector $\overrightarrow{MGS_1}(\tau)$, the value of each element represents the probability or membership grade of which α^* is at point α_i. The larger the diffferences between these elements, the easier and more accurate the identification will be, vice versa. If we find the center α_k which is corresponding to the biggest element in $\overrightarrow{MGS_1}(\tau)$, then the contaminant source location could be identified.

Next, let us discuss how to evaluate the accuracy of the identification method further. Sort the elements in $\overrightarrow{MGS_1}(\tau)$ in descending order from max to min. Suppose that $\alpha_k \to \alpha^*$, if the greater value of $MGS_1(\alpha_k,\tau)$, or more toward the front of its ranking, the more accurate the determination will be. To evaluate the accuracy of the identifications, we imitate the grading method of shooting competition as shown in Table 1.

Table 1 Standard for evaluating the accuracy of identifications

RANKING	$MGS_1(\alpha_i,\tau)$	**MARK**
No.1	⩾0.5	6
	<0.5	5
No.2	⩾0.3	4
	<0.3	3
No.3	⩾0.1	2
	<0.1	1
Others	--	0

When the ranking of $MGS_1(\alpha_k,\tau)$ is No.1 in the sequence and $MGS_1(\alpha_k,\tau) \geq 0.5$, we consider this judgement hits the bull's-eye and gets a mark of 6; the score of judgement declines with the decrease in the value or ranking of $MGS_1(\alpha_k,\tau)$; when the ranking of $MGS_1(\alpha_k,\tau)$ is No.4, or even behind, in the sequence, we consider this judgement is off target and gets a mark of 0.

When we identified N contaminant source locations, the total mark of the judgements, Z, can be solved. Then, the probability of correctness for the identifications of N times is defined as:

$$\eta = \frac{Z}{6 \times N} \times 100\% \tag{6}$$

where η indicates the accuracy of the identifications quantitatively and provides a basis for evaluating the effect of the identifications.

Method for determining the strength of indoor contaminant source

Based on the identification of source location, we discuss how to find its strength further. Suppose $\alpha_k \to \alpha^*$, then the time-averaged value of $SC_1(\alpha_i,\tau)$ is defined as:

$$\overline{SC_1}(\alpha_k,\tau)=\frac{\int_0^{\tau} SC_1(\alpha_k,t)\mathrm{d}t}{\tau} \tag{7}$$

According to eq.(1) and eq.(2), the unknown strength is given by:

$$S^* \approx S\times 10^{\overline{SC_1}(\alpha_k,\tau)} \tag{8}$$

CASE STUDY

In the following, we demonstrate how to use the method to identify contaminant source in a three-dimensional room.

Case description

The room is 5 m long(X), 3m high(Y) and 5m wide (Z) (see Fig. 1).

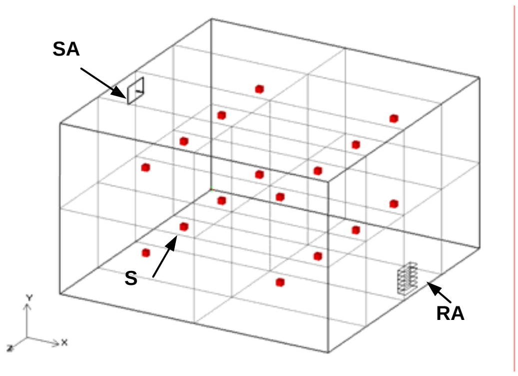

Figure 1 Schematic of the room (SA—supply air diffuser, RA—return air grill, S—Contaminant source locations to be identified)

The room is divided into 16 volumes; X and Y directions are divided into two equal parts, while direction Z is divided into 4 equal parts. The centers of various volumes construct the set $A=\{\alpha_1,\alpha_2,\cdots,\alpha_{16}\}$. Sixteen possible locations of source are set up in the example (see Fig. 1), which constuct the set $A^*=\{\alpha_1^*,\alpha_2^*,\cdots,\alpha_{16}^*\}$ to be determinated. These unknown locations correspond with the volume centers one by one, that is $\alpha_i=\alpha_i^*(i=1,2,\ldots,16)$. One sensor is located at the point β_1, X, Y, Z = 1.25, 2.2, 1.25 m. The plan of the locations of unknown source and sensor, and the volumes are shown in Figure 2 in which sources and zones at lower level in Y direction are labeled in the bracket.

Numerical procedure

The CFD method (Patankar 1980, Launder and Spalding, 1974) is employed in this article to simulate airflow and contaminant transport. The commercial software Airpak2.0 (Fluent Inc. 2001) is used as the simulation tool. To account for the turbulent flow in a room, a zero-equation turbulence model (Chen and Xu, 1998) was used in this case, which adapts the algebraic equation of eddy viscosity directly in the near-wall region. The Reynolds Averaged Navier-Stokes (RANS) equations were discretised by the finite volume method (FVM) and the coupling between velocity and pressure was solved by the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm （Patankar, 1980）. The pressure equation is solved using the body force weighted scheme, and all the other equations are solved using a first-order scheme. The adopted time step is 0.5 s.

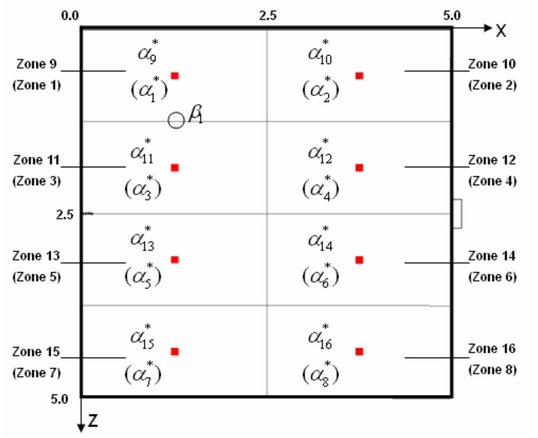

Figure 2 Plan of the locations of sources and sensor, and the volumes

Results and discussion

In the pre-event stage, the contaminant source was placed at the center of each volume, $\alpha_i(i=1,2,\cdots,16)$, and released in steady strength $S=0.1$ g/s. Base on the pre-calculted airflow field, sixteen simulations of contaminant transport were numerically calculated by Airpak. The samples of $C_i(\beta_1,t),(i=1,2,\cdots,16)$ were stored in database with a constant time step, 1 s.

This study used Airpak to obtain the measurements from sensor during the contaminant release event. Although these data can only be obtained by sensor in practical, it is appropriate to use CFD modeling here to generate these data for demonstration purpose. In each simulation, the contaminant source to be identified was placed at the locations, $\alpha_i^*(i=1,2,\cdots,16)$, and released in steady strength, $S^*=0.01$ g/s. In a similar manner, The samples of $C_i^*(\beta_1,t),(i=1,2,\cdots,16)$ with a constant time step, 1 s, were obtained by CFD simulations.

In the second stage, we identify the contaminant source locations and strength by calculating $\overrightarrow{MGS_1}(\tau)$ and $\overline{SC_1}(\alpha_k,\tau)$ as shown in Table 2. The sampling duration of sensor was assumed to be $\tau = 30\text{s}$, that is, the sampling of sensor ended after 30s from the release. This stage can be executed very quickly, even more quickly than the rate at which new measurement are likely to arrive from sensor at next second. Among the 16 locations to be identified, 13 are identified correctly. By the evaluation method presented in the "Methodology" section, we got the probability of correctness $\eta = 83.3\%$. The results show that the method proposed could locate the source with quite high accuracy in real time. The strength was identified further based on the determinated location. It is seen that the predictions are not very accurate, and the maximum of ralative errors approaches 129.62%. Nevertheless, the predictions and actual values are in the same order of magnitude.

The reason why the identification of contaminant source location and strength are with very different accuracy may be that the present indices varied with the location and strength at different degrees. The results also indicate that the location of contaminant source may be found easier. In order to determinate the source strength with higher accuracy, several indices or joint indices may be necessary for identifying the different parameters in the future.

Figure 3 shows the influence of sensor sampling duration τ on locating different sources. The probability of correctness η decreases with the increase of sampling duration as shown in Figure 3. This indicates that it is possible for us to identify the soure with high accuracy after short time from the release.

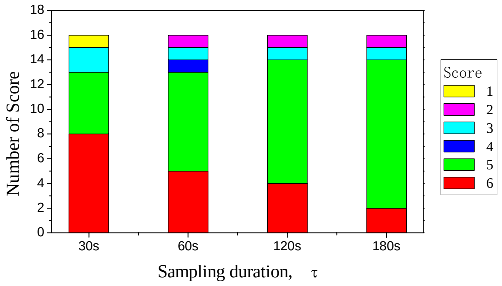

Figure 3. Locating results with different sampling duration τ

CONCLUSION

This paper presented a new method with one sensor for identifying contaminant source location and strength in real time. The method divides the identification into two parts. The pre-event stage completes the time-consuming tasks and stores the results into a database. The second stage is mathematically simple and can be executed in real time as data stream in from sensor during a release event. By applying the method to contaminant transport in a three-dimensional room, the following conclusions could be drawn,

1. The present method could identify the contaminant source locations with high accuracy. Although the identifications of source strength are not very accurate, the predictions and actual values are in the same order of magnitude.
2. The accuracy of source locating decreases with the increase of sampling duration. This nature of the proposed method also allows quick identifaction of contaminant source.
3. Since only one sensor is required theoretically, this method is also characterized by low cost. It may be desirable in case that the cost of sensors is a critical restriction.

For demonstration purpose, this study used CFD simulations to represent the measurements from sensor during the release event. In future work, real measurements may be used to further validate the reliability of the method. Moreover, the uncertainties of environment parameters have been omitted for simplicity, which should be covered in the future.

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Table 2 Summarization and evaluation of contaminant source identifications (one sensor)

NO. OF SOURCE	$MGS_1(\alpha_i, 30)$		**DETERMINATION OF LOCATION**		**DETERMINATION OF STRENGTH**		
	VALUE	**RANKING**	**RIGHT ?（Y/N）**	**MARK**	$\overline{SC}_1(\alpha_k, 30)$	**RESULT,** g/s	**RELATIVE ERROR,%**
1	0.33	1	Y	5	-0.670	0.02136	113.56
2	0.58	1	Y	6	-1.001	0.00998	-0.18
3	0.26	2	N	3	-0.639	0.02296	129.62
4	0.05	3	N	1	-2.445	0.00036	-96.41
5	0.40	1	Y	5	-0.670	0.02139	113.95
6	0.73	1	Y	6	-0.968	0.01077	7.66
7	0.59	1	Y	6	-0.910	0.01230	22.99
8	0.85	1	Y	6	-0.999	0.01001	0.13
9	0.16	2	N	3	-1.334	0.00463	-53.68
10	0.43	1	Y	5	-1.218	0.00605	-39.50
11	0.41	1	Y	5	-1.311	0.00489	-51.11
12	0.77	1	Y	6	-1.029	0.00935	-6.49
13	0.52	1	Y	6	-1.029	0.00935	-6.48
14	0.69	1	Y	6	-1.038	0.00917	-8.34
15	0.16	1	Y	5	-1.628	0.00235	-76.47
16	0.82	1	Y	6	-1.212	0.00614	-38.56
Correctness probability, η (%)					83.3		