REAL-TIME DETERMINATION OF INDOOR CONTAMINANT SOURCE LOCATION AND STRENGTH, PART II: WITH TWO SENSORS

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ABSTRACT

In the preceding companion paper (Part I), a method with one sensor that could identify the indoor contaminant source location and strength in short time was presented. On the basis of further theoretical study, a method with two sensors is presented in this paper to identify contaminant source with higher accuracy. This paper demonstrates how to use the method with two sensors to find the location of contaminant source in a three-dimensional room. In addition, the accuracy of two types of methods was compared. The correctness probability, which are used to evaluate the accuracy of source locating, of the method with two sensors and the method with one sensor are 83.3% and 94.8% respectively. The results show that the method with two sensors works better for locating contaminant source than that with one sensor. In practice, the method with two sensors may be more applicable for the situations where the accuracy of source identification is crucial while the costs of sensors are not of great concern.

KEYWORDS

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

INTRODUCTION

In Part I of this companion papers, we presents a method with one sensor (Method I for short) to identify the contaminant source location and strength in real time. The results of case study show that Method I could identify the contaminant source locations with acceptable accuracy. Although the identifications of source strength are not very accurate, the predictions and actual values are in the same order of magnitude (Cai et al, 2007). One major purpose of the above study is to explore whether we could identify the contaminant source with minimum sensors. If the answer is positive, the costs of sensors will be saved significantly, so that the technique of source identification will be more applicable for the situations where the costs of sensors are of great concern.

Fortunately, we get the positive answer. Nevertheless, problems are still far from settled. Let us consider another kind of situations where the accuracy of source identification is crucial while the costs of sensors are not of great concern. Under such circumstances, it may be of significance to explore the problem that whether we can improve the accuracy of identification with more sensors. This paper aims to presents a new method with two sensors (Method II for short) to improve the accuracy of Method I. For the purpose of demonstration and comparison, this new method will be applied to the identical room presented in the previous paper (Part I).

METHODOLOGY

The premises of present method are same with that of Method I. They are briefly summarized in the following,

1. Indoor airflow is known and is in steady state;

2. Only one point source is released at a steady rate in the room;

3. The sensors employed can measure the contamant under any conditions;

4. The release and the measurements take place simultaneously.

Suppose that two sensors are placed in the room at points β_1 and β_2. Unknowns to the problem include location α^* and strength S^* of the source CS^*.

The overall framework of Method II is divided into two stages just as Method I.

In the pre-event stage, we divide the room into N control volumes and form a set $A = \{\alpha_1, \alpha_2, \cdots, \alpha_N\}$ with their centers, construct a vector $\vec{X}(\tau)$ composed of index $X(\alpha_i, \tau)$ which represents the closeness degree between α_i and α^*, run CFD

simulations to get the concentration of contaminant at points β_1 and β_2 for every possible scenarios, and store the simulations in the database for next stage. As discribed in Part I, this stage is not time-critical and not difficult to achieve by virtue of fast personal computers and inexpensive data storage devices.

In the second stage, we solve the vector $\vec{X}(\tau)$ with the simulations stored in the database and the measurements from the two sensors, and find the closest point α_k to α^* in the set A using the vector $\vec{X}(\tau)$. As discussed in Part I, this stage is mathematically simple and can be executed in real time during a release event.

Although the premises and overall framework of Method II is similar to that of Method I, Method II is distinct from Method I in one important feature, that is, the specific form of index $X(\alpha_i,\tau)$. In order to make full use of the measurements from two sensors and improve the accuracy of identification, we should develop a new index in this paper. In the following, we will present how to derive this new index.

First, we redefine the "similarity characteristic" index as follows,

$$SC_2(\alpha_i,\tau) = \log\left(\frac{\int_0^\tau C^*(\beta_1,t)\mathrm{d}t \times \int_0^\tau C_i(\beta_2,t)\mathrm{d}t}{\int_0^\tau C^*(\beta_2,t)\mathrm{d}t \times \int_0^\tau C_i(\beta_1,t)\mathrm{d}t}\right) \qquad (1)$$

where $SC_2(\alpha_i,\tau)$ is a non-dimensional parameter, which indicates the similarity characteristic of α_i and α^* at time τ; $C^*(\beta_1,t)$ and $C^*(\beta_2,t)$ are the measurements from two sensors at time t, and at point β_1 and β_2, respectively, when the unknown source CS^* is released in the room; $C_i(\beta_1,t)$ and $C_i(\beta_2,t)$ are the contaminant concentrations at time t, and at point β_1 and β_2, respectively, when the source CS is released at point α_i and with steady strength S, which are obtained by simulations and stored in the database; and the subscript "2" represents that two sensors are employed.

Since 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 $\alpha_k \rightarrow \alpha^*$, we get

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

From Eqs. (1) and (2), we obtain that $SC_2(\alpha_k,\tau) \rightarrow \log 1 = 0$ as $\alpha_k \rightarrow \alpha^*$, in other words,

the variation curve of $SC_1(\alpha_k,\tau)$ with τ approaches a horizontal line $f(\tau) = 0$.

Based on $SC_2(\alpha_i,\tau)$, we rewritten the "absolute similarity" index in the following,

$$ASD_2(\alpha_i,\tau) = \left\{\int_0^\tau |SC_2(\alpha_i,t)|\mathrm{d}t \Big/ \tau\right\}^{-1} \qquad (3)$$

where $ASD_2(\alpha_i,\tau)$ is a non-dimensional parameter while $ASD_1(\alpha_i,\tau)$ in Part I is dimensional.

From the Eq. (3), we can see that $ASD_2(\alpha_i,\tau)$ is characterized by the following properties:

1) $ASD_2(\alpha_i,\tau) \geq 0$;

2) The more the curve of $g(\tau) = SC_2(\alpha_i,\tau)$ approaches the horizontal line $f(\tau) = 0$, the greater the value of $ASD_2(\alpha_i,\tau)$;

3) As $\alpha_k \rightarrow \alpha^*$, $ASD_2(\alpha_k,\tau) \rightarrow \infty$.

According to $ASD_2(\alpha_i,\tau)$, the "relative similarity" inex is given further,

$$MGS_2(\alpha_i,\tau) = ASD_2(\alpha_i,\tau) \Big/ \sum_{i=1}^N ASD_2(\alpha_i,\tau) \qquad (4)$$

where $MGS_2(\alpha_i,\tau)$ is a non-dimensional index and has major properties as follows:

1) $0 \leq MGS_2(\alpha_i,\tau) \leq 1$;

2) $\sum_{i=1}^N MGS_2(\alpha_i,\tau) = 1$;

3) As $\alpha_k \rightarrow \alpha^*$, $MGS_2(\alpha_k,\tau) \rightarrow 1$.

With the above properties, $MGS_2(\alpha_i,\tau)$ is employed here to represent the closeness degree between α_i and α^*. As there are N control volumes, we construct a vector as,

$$\vec{MGS}_2(\tau) = [MGS_2(\alpha_1,\tau), MGS_2(\alpha_2,\tau),\cdots, \\ MGS_2(\alpha_N,\tau)]^T \qquad (5)$$

In the above vector, the value of each element represents the probability or menbership 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 $\vec{MGS}_2(\tau)$, then the contaminant source location could be identified.

After we have clarified how to locate the contaminant source with Method II and the major differences between two methods, it is nessecary to determine whether Method II can locate source with higher accuracy than Method I. Therefore, an evaluation system is needed. The "correctness probability" index η and corresponding evaluation standard, which are proposed in Part I, will be adopted in the next section for the purpose of comparison between two methods.

Based on the identification of source location, we move on to discuss how to find its strength further. In this paper, we still use the method presented in the Part I to identify the source strength, although this method needs to be improved. Despite this, if source locating is more accuracte with Method II, we can also identify the strength of source more accurately. For example, if the source locating is proved to be wrong with Method I, we could hardly solve the source strength with high accuracy. However, if the souce locating is right with Method II, the solution of strength may be easier and more accurate.

CASE STUDY

In the following, we apply Method II to the room, which is identical with that presented in Part I, for the purpose of demonstration and comparison.

Case description

The room is 5 m long(X), 3m high(Y) and 5m wide (Z) as shown in Fig. 1. Details of it can be referred to that in Part I.
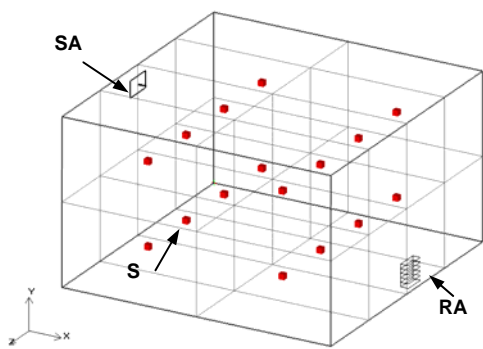

Figure 1 Schematic of the room (SA—supply air diffuser, RA—return air grill, S—Contaminant source locations to be identified）

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 determined. These unknown locations correspond with the volume centers one by one, that is $\alpha_i = \alpha_i^* (i=1,2,\ldots,16)$. Two sensor are placed at the point β_1, X, Y, Z = 1.25, 2.2, 1.25 m, and β_2, X, Y, Z = 3.75, 2.2, 3.25

m. The plan of unknown sources, sensors, and control volumes are shown in Figure 2 in which sources and zones at lower level in Y direction are labeled in the bracket.
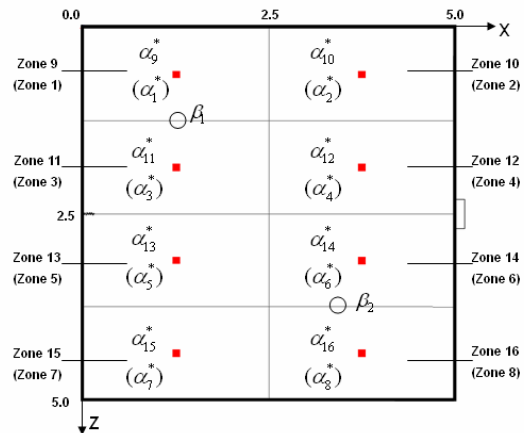

Figure 2 Plan of the locations of sources and two sensors, and the volumes

Results and discussion

Since two kinds of methods presented in this companion papers decouple the pre-event simulations from source identification during the event stage, we can quickly obtain the results with Method II, and need not re-execute the time-consuming pre-event stage of the simulations. The decoupled nature of these methods together with the "correctness probility" index also allow easy and quick evaluation of alternative identification methods and sampling plans without repeating the computationally intensive CFD simulations.

In the preceding paper (Part I), we solved the concentration field of contaminant by Airpak (Fluent Inc. 2001) in order to obtain the measures from the sensor during the event. 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 this study, what we only need to do is to read the samples of $C_i^*(\beta_1,t)$ and $C_i^*(\beta_2,t)$ with a constant time step 1s from the solved concentration field.

By calculating $\vec{MGS}_2(\tau)$, we identify the source locations quickly in the second stage. Table 1 summarizes the results of the identifications by two methods. The sampling duration of sensors was $\tau = 30s$, that is, the sampling of sensor ended after 30s from the release. From Table 1, it is shown that Method II is more accurate than Method I for source locating. In this case, all the sixteen locations are identified correctly by virtue of the new method, which improves the accuracy of source locating by

properly taking advantage of the measurements from two sensors. By the evaluation method presented in the previous companion paper, we got the correctness probability of Method II is 94.8%. Since the correctness probability of method I is 83.3%. A comparison between Method II and Method I shows that the improvement is quite obvious.

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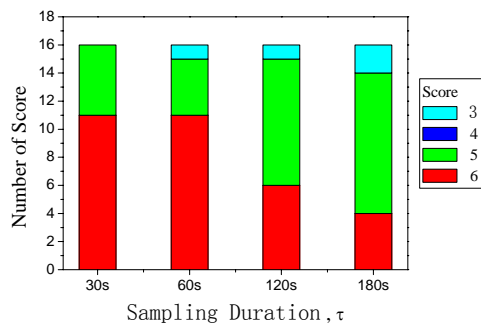

Figure 3. Locating results with different sampling duration τ using the method with two sensors

Moreover, since all the sixteen locations are identified correctly by Method II while only thirteen locations by Method I, the identification of strength may be more accurate by Method II.

CONCLUSION

Based on the previous companion paper (Part I), this paper presented a new method with two sensors for identifying source location and strength in real time. Method II proposed in this paper inherit the advantages of Method I and make full use of the measurements from two sensors. By applying Method II to the room identical with that presented in Part I, the following conclusions could be drawn,

1. Method II could be more accurate than Method I for source locating. As a result, Method II may be an alternative way for improving the accuracy of the identification of source strength.

2. Method II also has the nature that the accuracy of source locating decreases with the increase of sampling duration.

3. Method II may be more applicable for the situations where the accuracy of source identification is crucial while the costs of sensors are not very important.

The decoupled nature of the methods proposed in this series (Parts I and II) together with the evlaution standard similar to the grading method of shooting competition also allow easy and quick evaluation of alternative identification methods and sampling plans without repeating the computationally intensive CFD simulations. It could be helpful for us to further study the improvement of identification methods and the optimization of sensors layout in the future.

ACKNOWLEDGEMENT

REFERENCES

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Table 1 Comparison of the contaminant source identifications by two methods

| NO. | METHOD WITH ONE SENSOR | | | | METHOD WITH TWO SENSORS | | | |
| | $MGS_1(\alpha_i, 30)$ | | DETERMINATION OF LOCATION | | $MGS_2(\alpha_i, 30)$ | | DETERMINATION OF LOCATION | |
	VALUE	RANKING	RIGHT? （Y/N）	MARK	VALUE	RANKING	RIGHT? （Y/N）	MARK
1	0.33	1	Y	5	0.69	1	Y	6
2	0.58	1	Y	6	0.78	1	Y	6
3	0.26	2	N	3	0.68	1	Y	6
4	0.05	3	N	1	0.24	1	Y	5
5	0.40	1	Y	5	0.71	1	Y	6
6	0.73	1	Y	6	0.30	1	Y	5
7	0.59	1	Y	6	0.66	1	Y	6
8	0.85	1	Y	6	0.60	1	Y	6
9	0.16	2	N	3	0.46	1	Y	5
10	0.43	1	Y	5	0.75	1	Y	6
11	0.41	1	Y	5	0.42	1	Y	5
12	0.77	1	Y	6	0.83	1	Y	6
13	0.52	1	Y	6	0.84	1	Y	6
14	0.69	1	Y	6	0.82	1	Y	6
15	0.16	1	Y	5	0.36	1	Y	5
16	0.82	1	Y	6	0.77	1	Y	6
	Correctness probability η (%)			83.3	Correctness probability η (%)			94.8