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Recent Progress on the Multi-Chamber Airflow Measurement System

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ABSTRACT

Research into the measurement method for multi-chamber airflow is important because of the limitations and errors inherent in the conventional single-chamber method. The fundamental theory for this measurement and several application examples by the author have been published. The theory is based on the general tracer gas dispersion model in a multi-chamber system called the thermal network state equation, which is also applicable to a heat transfer system. Estimation of the airflows in a multi-chamber system is considered as a type of system identification of the state equation model, and two calculation procedures have been deduced from the least-squares method. Several field measurements and tests for verification have shown the practicality, accuracy, and also defects of the measurement system. In this paper some improvements of these defects and verification of the field measurement are described.

INTRODUCTION

An earlier theoretical model for measuring multi-chamber airflow in a building can be found in Sinden (1978). Sinden formulated an equation system describing gas concentration decays after the gas ceases to be released in chambers and outlined eigenvalue characteristics in the equation system. Honma (1975) tried to estimate airflow rates using the least-squares method based on equations that give the rate of change in gas concentration, but the method was inadequate in coupling for all the chambers. In this type of measurement, there are more airflow paths than there are chambers. Therefore, Grimsrud *et al.* (1979) used multiple gases when taking measurements. Due to limitations on gas concentration analyzers, however, a maximum of six chambers can currently be handled. The author established a measurement method using a single gas based on his thermal network model (Okuyama 1978, 1987). This mathematical model describes general dispersion systems and was developed from the idea of modeling for solar collectors that is described in the appendix of a Solar Energy Laboratory report (UW 1972). Axley (1989) has also developed a gas dispersion model using a similar, though more complex, procedure with the finite element method. By contrast, the author uses a simple and general nodal equation. The system identification theory as proposed by the author (Okuyama 1983, 1984a, 1990) was derived and reformulated from the essence of the least-squares method, which the author was motivated to study by a paper (Pryor and Winn 1982) concerning passive solar house. This theory has been applied in measuring not only air infiltration in buildings (Okuyama 1985) but also thermal performance in buildings (Okuyama 1984b, 1986). In the present paper, the development of hardware and improvement of the theory are described with reference to sample applications.

PROGRESS OF SYSTEM IDENTIFICATION THEORY

The thermal network model studied by the author also has relevance with respect to the spatial dimensions and shapes of the diffusion and transfer system to be handled and serves as a general model for lumped parameter systems involving spatial finite difference and finite-element method models. This generalized model is mathematically expressed as a state equation. In our gas diffusion or dispersion system, the airflow rate and room volume are handled as parameters. One of the features of this measuring method is to view the obtaining of these parameters as a system identification process. As the method used for identification, the author has proposed both recursive and batch systems using the principle of least squares.

This method, however, idealizes complex diffusion phenomena as a simple mathematical model. Thus, some difference between the actual phenomena and the mathematical model is inevitable. For example, gas concentration in a room is assumed to diffuse instantly and uniformly, and vacant spaces in a wall or above a ceiling are frequently ignored. In addition, the measuring instrument available for use may not allow the actual phenomena to be measured accurately. For example, it takes at least one minute to

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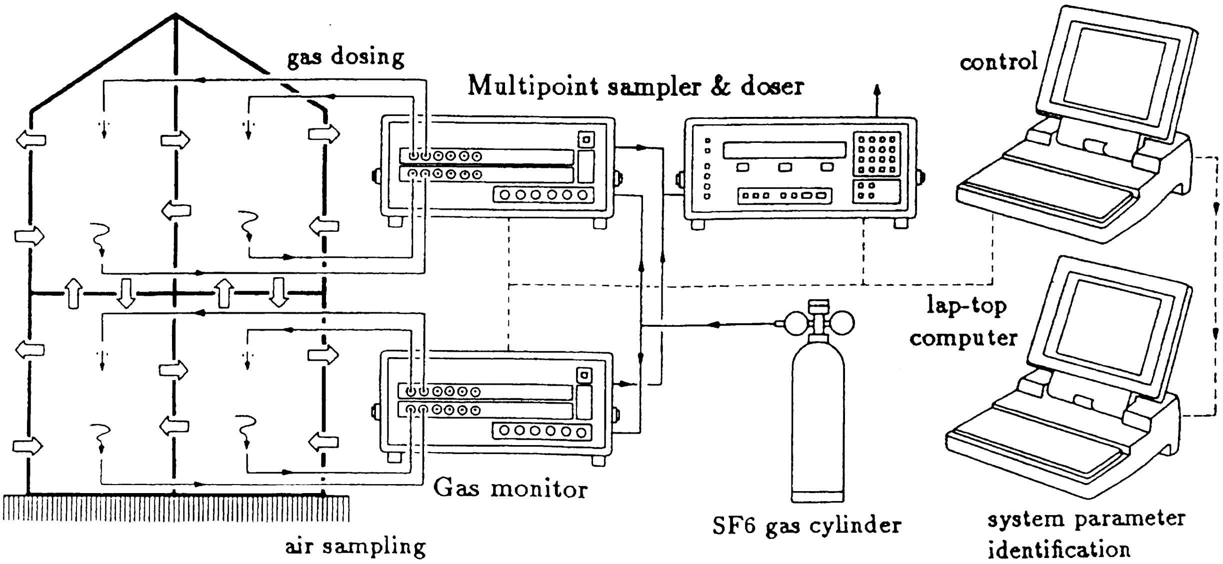


Figure 1 *Diagram of multi-chamber airflow measurement system.*

measure gas concentration in one place, so an error may occur in obtaining continuous, simultaneous, multi-point measurements.

Due to the many errors described so far, some of the airflow rates identified may appear as a negative value. A negative diffusion conductance is generally illogical except for the case in which aconductive diffusion system is changed to a lumped parameter by means of a finite-element method, but the illogicality has been avoided by regarding a negative airflow rate as one in the reverse direction. However, the optimized identification result itself should be made non-negative. In other words, it is desirable to incorporate non-negative constraint conditions into the process of optimizing the identification. This situation is similar to the constraint conditions for the law of conservation of mass (continuous condition). Fortunately, however, this constraint is not a condition of inequality like the non-negative condition and is expressed by a linear equation condition of a system of homogeneous linear equations. Therefore, this constraint can be substantially incorporated into the measurement equation to be identified.

On the other hand, to incorporate a condition of inequality into the process of optimizing the identification, a method such as linear programming, using the Kuhn-Tucker theorem, must be added, as is intuitively clear. In addition, the process of optimization is complicated by iterative calculations. Referring to the book by Lawson and Hansen (1974) on the non-negative least-squares method, this study improves the author's past batch identification so that non-negative constraint conditions can be incorporated.

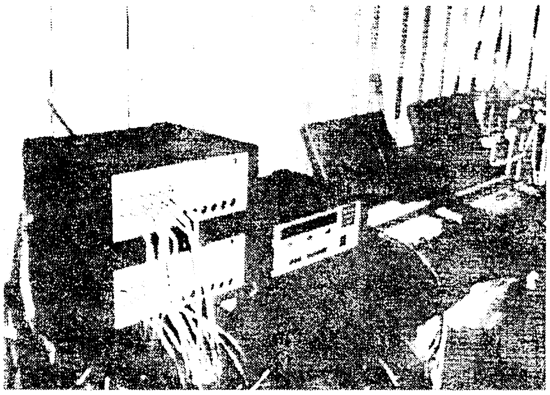


Figure 2 *Photo of the new measurement system.*

DEVELOPMENT OF MEASURING INSTRUMENTS

The old measurement system uses carbon dioxide gas as a tracer while the new measurement system uses sulfur hexafluoride as the tracer. This is due to the flow-rate limit of the gas injection unit. The new system uses a ready-made hardware. Two units are used to inject gas and sample air from each room. This new system can measure a maximum of 11 rooms (open air excluded) instead of 9 rooms as in the old system. The gas concentration of each room is measured with multi-gas monitors, which are all controlled by lap-top computers. The control program was developed using high-tech BASIC language that allows interrupt control. The gas concentration and injection flow rates in all rooms were measured at one-minute intervals, transmitted to the lap-top

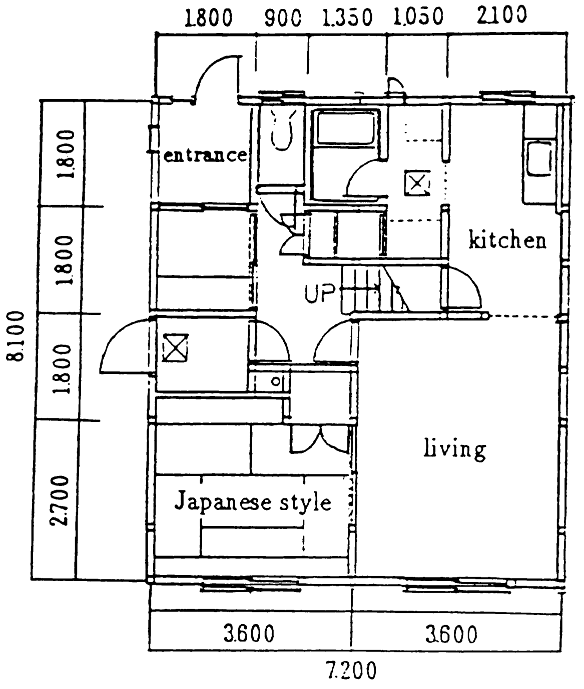


Figure 3 *First (ground) floor.*

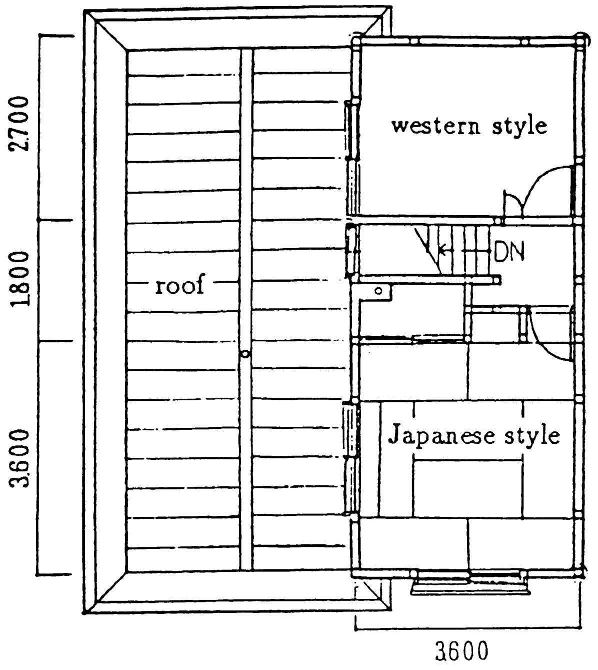


Figure 4 *Second-floor plan.*

computer, and processed with a sequential identification program. The number of personal computers decreased from three to two. This, together with other compact devices, downsized the whole system, making it more suitable to application in the field. The measuring system is shown in Figures 1 and 2.

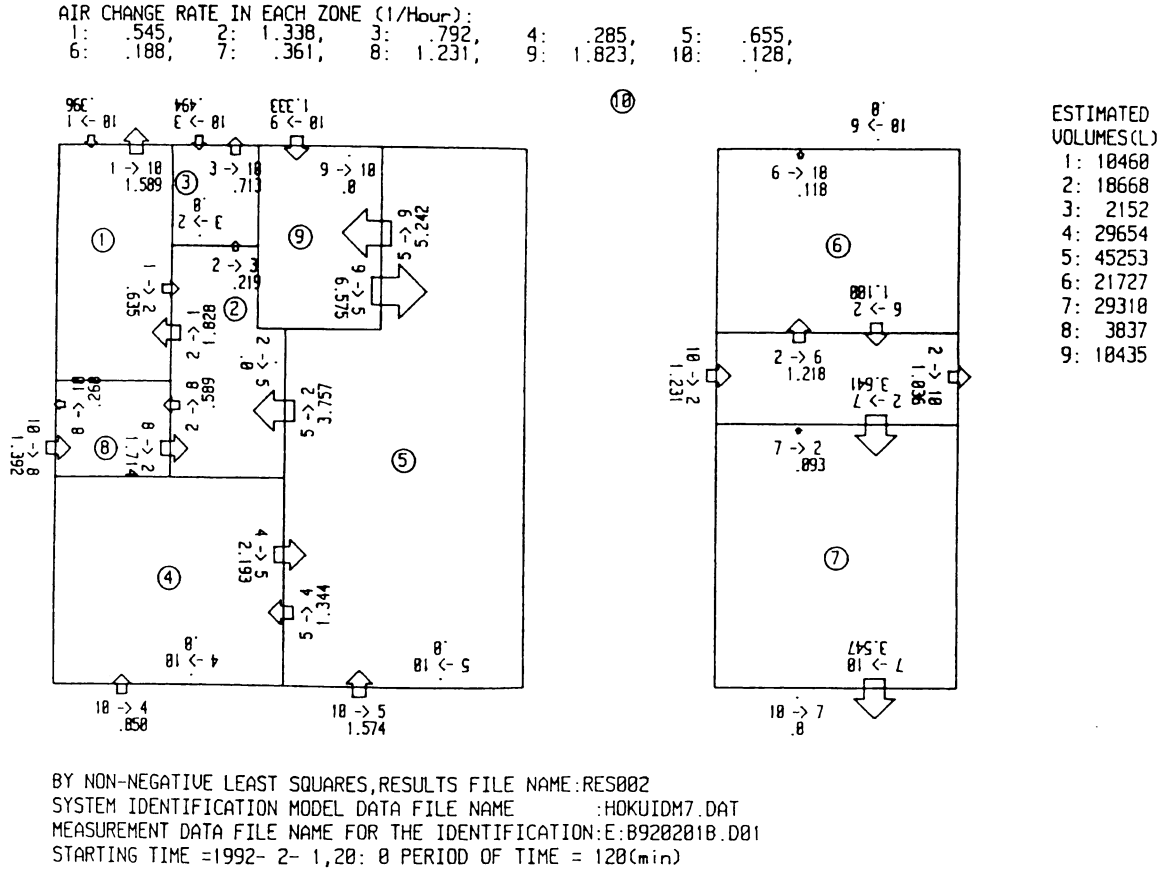
APPLICATION EXAMPLE

The measurements were taken in a two-story wooden house in Sapporo City. Figures 3 and 4 show the floor plans of the house. The first (ground) floor is 7.2 (m) from east to west and 8.1 (m) from north to south; the second floor is 3.6 (m) from east to west and 8.1 (m) from north to south. The total floor space is 87.48 (m^2) and the height is 7.6 (m). The interior of the house was considered as nine rooms for the identification model shown in Figure 5. For example, Room No. 1 was the entrance, and Room No. 5 included the kitchen and living room although regarded as one room. Room No.2 was the staircase, where the sum of the first-floor and the second-floor staircases was regarded as one room. Rooms 4 and 7 were Japanese-style rooms, the others were western-style rooms. Room No. 10 means open air.

Tracer-gas injection for identification is the means of excitation for the measured building; the change in gas concentration in each room is the response to this excitation. According to the identification principle, the excitation and response need not be regular ; it is only necessary that adequate variation can be secured either in time and between rooms. However, an easy-to-control periodic excitation is usually applied. If excitation frequency is too high, it is difficult to obtain a sufficient variation of response. If too low, excitation frequency takes a lot of time before identifiability is achieved, which invalidates the assumption of time invariability of estimated parameters. As a result, gas was injected at a two-hour cycle. The air in rooms was agitated and sampled in the same way as in Okuyama (1985). For the identification model, the injection gas concentrations were assumed to be known parameters. Thirty-four parameters for airflow rates to be identified exist in the relationship of room geometrical connection. The room volumes can be also identified.

The experimental results for February 1, 1992, will be described below. Figure 6 shows gas injection room No. 9, and Figure 7 shows the change in gas concentration. This is a part of the graph during 360 minutes beginning at 11:02 on February 1. The actual experiment ended at 6:45 on February 2, 1992, after a measurement duration of about 20 hours. Figure 5 shows the result of a batch identification with non-negative constraint conditions using values measured up to two hours from the start of the experiment. Under each arrow indicating the airflow rate, the room numbers at windward and leeward and the airflow rate (L/s) are output. In Figure 5, the air change rate in each room appears at the upper area. No. 10 indicates the air change rate for the whole house.

Next, the accuracies of the new batch identification with non-negative constraint and the old batch identification were compared, although this comparison was made using the



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AIR CHANGE RATE IN EACH ZONE (1/Hour):
 1:   .545,    2:  1.338,    3:   .792,    4:   .285,    5:   .655,
 6:   .188,    7:   .361,    8:  1.231,    9:  1.823,   10:   .128,
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ESTIMATED
VOLUMES(L)
 1: 10460
 2: 10660
 3:  2152
 4: 29654
 5: 45253
 6: 21727
 7: 29310
 8:  3837
 9: 10435
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BY NON-NEGATIVE LEAST SQUARES,RESULTS FILE NAME:RES002
SYSTEM IDENTIFICATION MODEL DATA FILE NAME         :HOKUIDM7.DAT
MEASUREMENT DATA FILE NAME FOR THE IDENTIFICATION:E:B920201B.D01
STARTING TIME =1992- 2- 1,20: 0 PERIOD OF TIME = 120(min)
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Figure 5 *Result of batch identification with non-negative constraints.*

data by old measurement system. In Figure 8, the symbol lozenge indicates the air change rate in the whole house at a constant tracer gas supply method that has been adopted as the proper solution for use as a reference. For this reference, the results of both batch identification methods were compared on various days, in various time zones, and under indoor-outdoor temperature differences. The results indicate that new batch identification more closely approximates the correct solution. Under old batch identification, negative airflows are considered as flow in the reverse direction, rather than as zero, so that the air change rate seems to become greater.

The temporal variation of air change rate of the whole house was also investigated. Although it may seem suitable to apply the successive identification to this analysis, the author has found that method does not give better precision than the batch identification. Therefore, the successive identification is now used only as a check of the proper system operation in real-time observation. Figure 9 indicates the results by batch identification every two hours. Factors affecting air change rate of the in-out temperature difference are plotted as well as the wind velocity. The trends of these three types of plots show that the air change rate depends more on temperature difference than wind velocity.

CONCLUSION

As one application of the thermal network system identification theory, the progress of the newly developed multi-chamber airflow measurement system has been described. The measurement system was made more compact to facilitate various field measurements. The number of rooms that can be handled was increased from 9 to 11. A non-negative least-squares method was incorporated to allow a non-negative inequality constraint condition to be added to the airflow rate to be identified. One application example was presented to indicate the improved accuracy of the new method.

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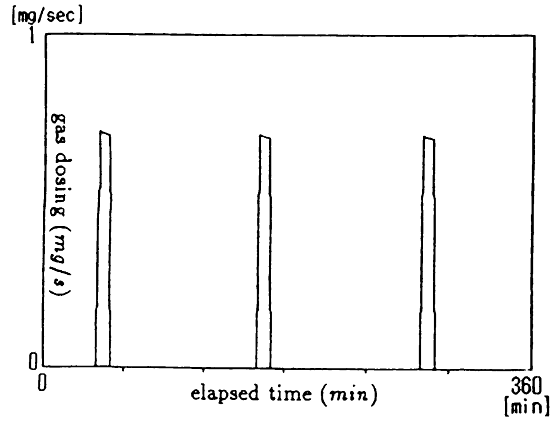

Figure 6 *Gas injection into Room No.9.*

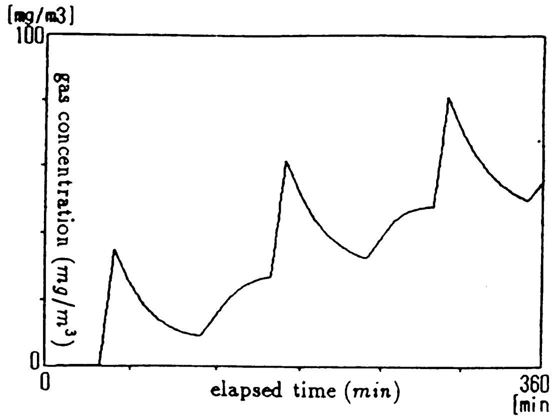

Figure 7 *Gas concentration change in Room No.9.*

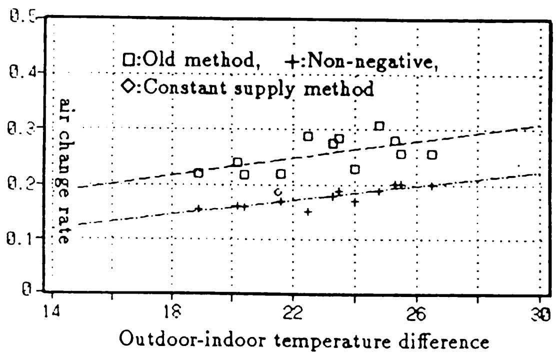

Figure 8 *Comparing the accuracies of the new and old batch indentification.*

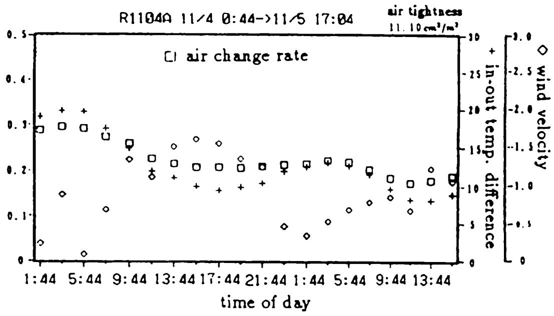

Figure 9 *Variation of air change rate with some factors.*

the Research Institute of the Hokkaido Electric Power Company for giving him the opportunity to do the experiments and permission to present the paper.

POSTSCRIPT

The author readily considers any proposal for performance testing or competition on this measurement method. This paper is revised and improved from the paper that appeared in the *Transactions of Annual Meeting of SHASEJ*, pp. 1089-1092 (October 1991).

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DISCUSSION

Howard Goodfellow, Goodfellow Consultants Inc., Toronto Canada: What is the time lag for the measuring equipment and what is the error in obtaining time-continuous multi-point measurement?

Okuyama: There are several time lags in the measurement process: the travel time of the sampled air to the analyzer through the tube and the gas concentration measurement itself, etc. We considered the time lags and prevented it from having ill effects on accuracy as much as possible in both data treatment and devices. To obtain every one-minute multi-point simultaneous gas concentration datum, we adopted linear interpolation approximation. All these causes of error can be evaluated using equation residual analysis, which is included in my system identification theory. However, the essential solution for this problem would be given by the improvement or development of hardware, for example, a decentralized gas release and monitoring system in which these devices are placed in each room.

Francis Allard, Thermal Engineering Research Center of National Institute of Applied Science, Lyon France: (1) Could you comment on your "generalized diffusion system model" ? As far as I know, the leading parameter is transport and not diffusion.

(2) What is the standard deviation of your measurements and evaluation of airflow rates?

Okuyama: (1) The direct translation from Japanese may have caused your misunderstanding, so it should be corrected. The meaning of the Japanese term "diffusion" includes transportation and dispersion. In my thermal network model, generalized conductance c_{ij} is defined representing all kinds of transfer forms, such as advection, conduction, radiation, or convection. My model is a unified framework for all kinds of spatial discretized models, such as FEM, FDM, or CVM.

(2) The standard deviations are diagonal elements of the co-variance matrix calculated by the error propagation law from the measurement equation residual expectation matrix. The major causes of error are measurement errors following Gaussian distribution and disagreement with real phenomenon. Please see my published papers for details.