

# A New 3D Thermal Environment Visualization System for Improved Air Conditioning Comfort

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## Keywords

Environmental measurement data, CFD analysis, visualization, air conditioning control

Conventionally uniform air-temperature profiles have been made using sensors installed on a wall or pillar. But recently, there has been interest in air conditioning methods that provide both comfort and energy savings by dealing with the uneven distribution of people and heat-generating equipment. This kind of advanced air conditioning control requires a detailed understanding of the indoor thermal environment, which wall- or pillar-mounted sensors cannot provide. As a solution, we have developed a thermal environment visualization technology and a system for profiling the thermal environment of a room in detail.

## 1. Introduction

In the past, air conditioning control was generally used to give a room a uniform air-temperature profile. With the diversification of office space in recent years, the air conditioning load, such as persons and heat-generating equipment, is more unevenly distributed. At the same time, to achieve the CO<sub>2</sub> reduction targets set by the “Energy Basic Plan”<sup>1</sup> of the Ministry of Economy, Trade and Industry, air conditioning, which accounts for more than 40 % of the energy consumption in office buildings,<sup>2</sup> must be more energy-efficient. For these reasons, an air conditioning control method known variously as task/ambient air conditioning or personalized air conditioning has received attention. This method balances comfort and energy savings by proactively distributing the temperature in the room.<sup>3</sup> In order to achieve this kind of air conditioning control, it is necessary to have a detailed grasp of the temperature distribution in the room, preferably utilizing three-dimensional temperature data.

Therefore, we have devised an air conditioning control technology using three-dimensional temperature data obtained by combining various environmental data mea-

surement units and a spatial temperature distribution analysis unit as shown in figure 1. The new technology is now feasible.

Section 2 describes the three-dimensional temperature distribution visualization system built by this study for understanding the detailed spatial temperature distribution in a room. The system was implemented in our air conditioning laboratory, and at the time when the system was developed we studied the possibility of reducing the engineering load required for configuring the temperature distribution model, as well as improving the accuracy of analysis. The results of our study of these matters are given in section 3.

In addition, in order to put the new system into practical service in spite of the time required for computational fluid dynamics (CFD)\* analysis, we propose a method of continuously alternating indoor environment data measurement intervals and CFD analysis intervals. The control system was used with this method in an actual environment, the results of which are described as an example in section 4.

## 2. Configuring the New 3D Thermal Environment Visualization System

In order to understand the detailed temperature distribution in a room, we built a three-dimensional temperature-distribution visualization system that utilizes CFD analysis. Figure 2 shows a conceptual diagram.

In the past, CFD analysis was generally used in the design of buildings and air conditioning systems to predict the indoor temperature distribution during building use, but in this study it was utilized for air conditioning control. To control air conditioning, it is necessary for CFD analysis to predict indoor conditions, which change constantly. In an actual office, the movements or equipment ON/OFF states of heat generators such as people or PCs should be obtained, but these are hard to predict.

Furthermore, in order to make more accurate predictions, it was important to set conditions of boundaries such as the walls that separate the analysis area, and it was necessary to build a wall model with complex parameters to reproduce the heat flows from neighboring rooms or from the outdoor air.

Instead, our system uses, in addition to data related to the air conditioning (supply air temperature and volume), data from environmental measurements, including surface temperature data for the walls, ceiling, and floor, and occupant detection data (the number of people and their position). By inputting the constantly changing indoor environmental measurements as the boundary conditions for the CFD analysis, it was possible to obtain and visualize the spatial temperature distribution and other data that reflected the changing conditions in the room. Also, since we used actual measurements, it was not necessary to set complicated parameters for reproducing the heat flows from neighboring rooms or outdoor air. Consequently the engineering workload for constructing the wall model was reduced. For our indoor environmental measurement data, we used infrared array sensors to measure surface temperature and to detect occupants.<sup>4</sup>

\*A method of using computer software to simulate fluid flow and heat transfer.

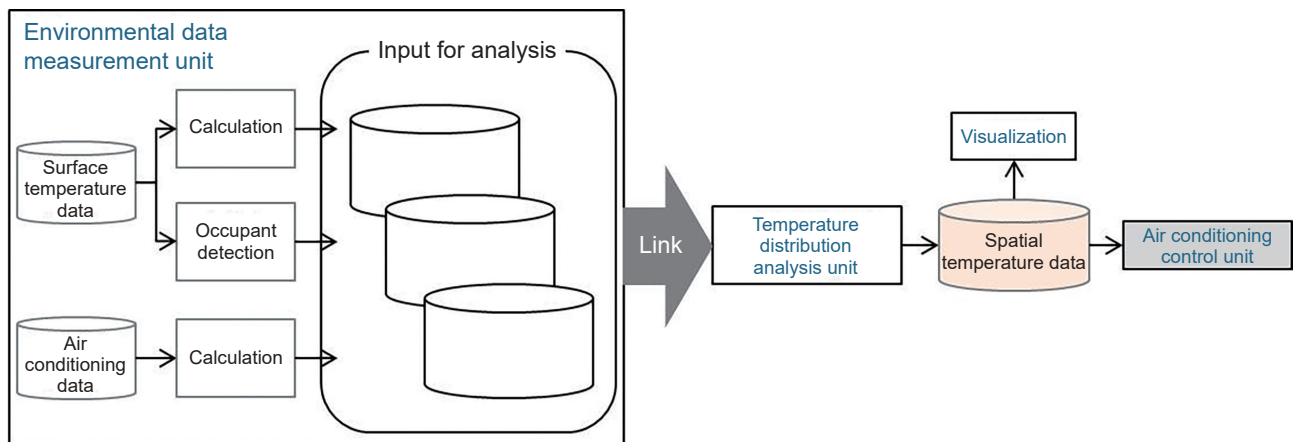


Fig. 1. Conceptual diagram of air conditioning control combining measurement and analysis

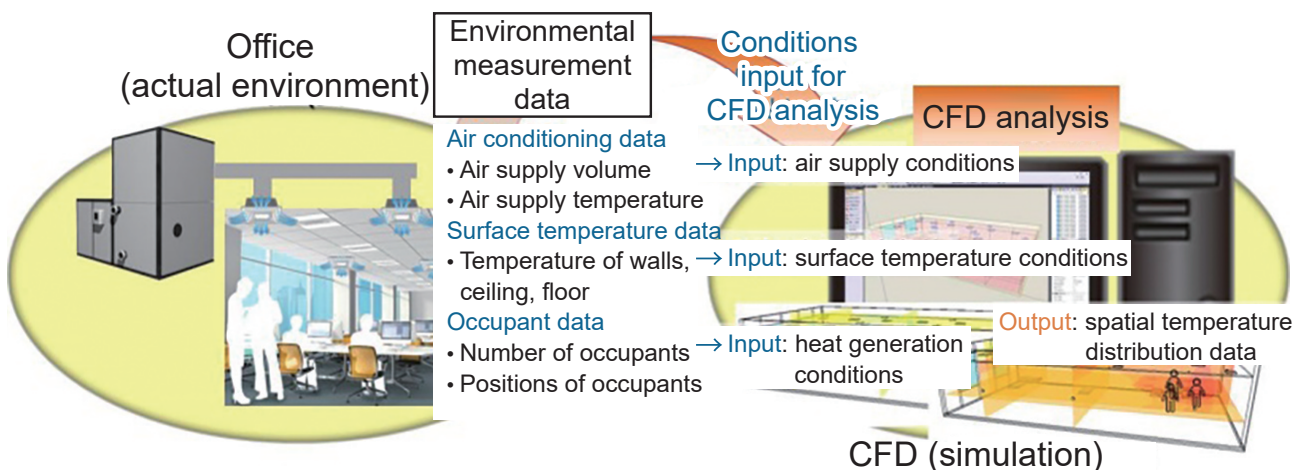


Fig. 2. Conceptual diagram of 3D thermal environment visualization system

### 3. Application Example and Verification of the New 3D Thermal Environment Visualization System

#### 3.1 Overview of Verification

In a room where desks and people were placed, experiments were conducted that imitated the movements of people during working hours and the specific air conditioning environment. We obtained the input conditions (supply air conditions, surface temperature conditions, heat generation conditions) used in the verification of the system and the indoor environmental measurement data corresponding to the output results (spatial temperatures). The CFD analysis was carried out using the environmental measurements (as boundary conditions) as input conditions in order to output three-dimensional temperature distribution data. The accuracy of this system was verified by comparing the results of analysis with the corresponding spatial temperature measurements. Furthermore, in order to verify the effectiveness of our method of using environmental measurements directly as boundary conditions, we compared the results of the method with that of the conventional method (wall modeling) using detailed parameters.

#### 3.2 System Application Environment

The system was applied in our air conditioning laboratory (see figure 3), which simulates an office.

The size of the room was  $15 \times 8 \times 3$  m, and as shown in figure 4, chambers simulating the outdoor air and neighboring rooms were installed around it. By controlling the temperature of each chamber, the desired environment could be reproduced. Central air conditioning was provided by an AHU using a variable air volume (VAV) system with 12 air inlets and 12 air outlets. Since there is only one AHU, the supply air temperature was equal at all air inlets. One VAV was installed for every two air inlets, so the air velocity of two neighboring air inlets was equal.

#### 3.3 Experimental Conditions

In the laboratory, air conditioning control was executed for a scenario of deskwork and meetings in a summer office environment. Measurement of the environmental data took into account the movements and presence or absence of people. The spatial temperature distribution was measured using thermocouples installed at points A, B, and C in figure 5, and it was then compared with the

results of the CFD analysis.

The time schedule for the experiment is shown in figure 6. The time schedule was set for two-hour operation scenarios, including 30 minutes for startup of the air conditioning before work (period 1), 30 minutes for deskwork after employees arrive at the office (period 2), 30 minutes for meeting attendance in the conference area (period 3), and 30 minutes for deskwork after the meeting (period 4). Temperature settings were  $26^\circ\text{C}$  for room temperature,  $30^\circ\text{C}$  for outdoor temperature (the outdoor air chamber), and  $26^\circ\text{C}$  for the air temperature of the neighboring room (the neighboring chamber).



Fig. 3. Air conditioning laboratory

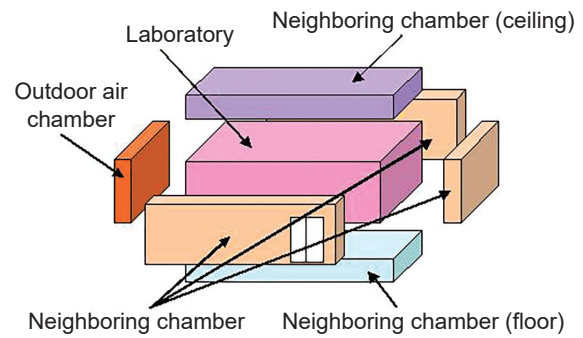


Fig. 4. Air conditioning laboratory overview

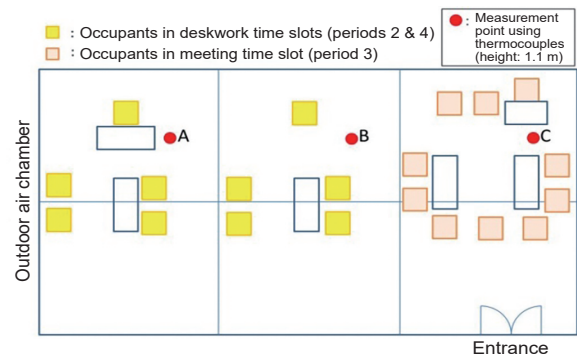


Fig. 5. Temperature measurement points in the experiment

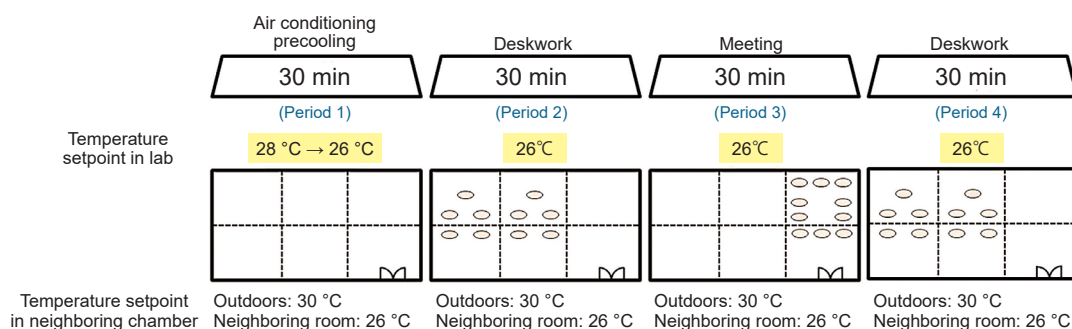


Fig. 6. Time schedule for experiment

### 3.4 Conditions for CFD Analysis and Case Settings

Figure 7 shows the room model used for the CFD analysis. Table 1 shows the conditions for the CFD analysis.

In order to verify the effectiveness of direct use of environmental measurements as boundary conditions, and to compare that method with the conventional wall model with detailed parameters, two versions of the room model were used with different methods of setting the surface temperature of the walls, ceiling, and floor (used as boundary conditions). We compared the results of the CFD analysis in each case (detailed parameters and sensor measurements) with the results from actual spatial temperature measurements.

#### 3.4.1 Wall Model Case with Detailed Parameter Settings (the Detailed Parameter Case)

This is a conventional wall model in which parameters such as the density, specific heat, heat conductivity, and heat transfer coefficient of the wall material are set in detail. The accuracy of the wall model was improved by adjusting the parameters based on the results of actual measurement, and we carried out our analysis using the relatively high-precision wall model constructed by that method. After setting the temperature of the outdoor air or the neighboring room, the surface temperature of the room was calculated based on the conduction heat, so the temperature settings for the outdoor air and the neighboring room, as well as the parameter settings of the wall model, affected the results of analysis.

#### 3.4.2 Wall Model Case with Surface Temperature Measurements Using Infrared Array Sensors (the Sensor Measurement Case)

In our new wall model, the surface temperature of the walls was directly set by the surface temperature measurements taken by infrared array sensors. Therefore, in addition to the fact that the measured temperature conformed to the actual situation, there was no need for complicated configuration of parameter settings or actual measurements in order to construct the wall model, so the model could be easily built.

### 3.5 Verification Results

In this section we report the visualized temperature distribution data obtained from the CFD analysis of the two cases and the results of comparing the CFD analysis to the actual measurements.

#### 3.5.1 Comparison of the Spatial Temperature Distribution in the Two Cases

Figures 8 and 9, and figures 10 and 11, show the temperature distribution map at a height of 1.1 m for each wall model case in the deskwork time slot (period 2) and the meeting time slot (period 3). Refer to 3.3, “Experimental Conditions,” for the time slot of each period.

In both cases, the deskwork time slot generally shows 25–26 °C, while the meeting time slot has a temperature rise to almost 26–27 °C. Similar trends in temperature distribution and temperature change are observed for both

cases. Accordingly, we found that the same temperature distribution results and temperature change trend results can be obtained by the detailed parameter case and by the case of data measured by infrared array sensors.

#### 3.5.2 Comparison of Measurement Data and Analysis Results of Indoor Temperature Change

Figures 12, 13, and 14 compare the results of the CFD analysis (for each case) and of actual temperature measurement at points A, B, and C shown in figure 5. The CFD analyses and the actual measurements show the same temperature change trends at the three points.

The maximum error between the CFD analysis and the actual measurement at point A in the deskwork time slot (period 2) was 0.6 °C for the detailed parameter case and 0.2 °C for the sensor measurement case. At point B it was 0.8 °C for the detailed parameter case and 0.9 °C for the measurement case, and at point C it was 0.2 °C for the detailed parameter case and 0.2 °C for the measurement case.

Also, the maximum error between the CFD analyses and the actual measurement at point A in the meeting time slot (period 3) was 1.1 °C for the detailed parameter case and 0.7 °C for the measurement case. At point B it was 1.3 °C for the detailed parameter case and 0.8 °C for the measurement case, and at point C it was 1.4 °C for the detailed parameter case and 1.1 °C for the measurement case. For all the time slots, the accuracy of the temperature in the measurement case at points A, B, and C was equal to or better than that of the detailed parameter case.

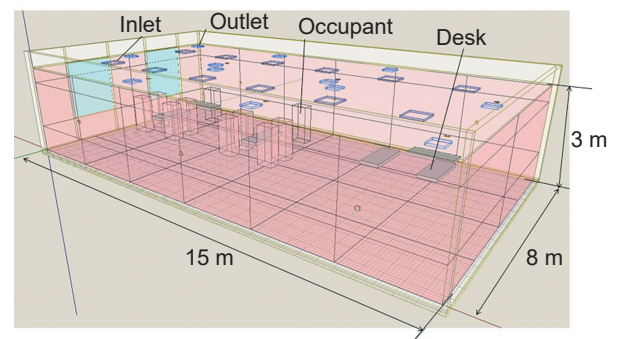


Fig. 7. CFD model of the air conditioning laboratory

Table 1. CFD analysis conditions

		Detailed parameter case	Sensor measurement case
Type of analysis		Unsteady analysis	
Boundary conditions	Inlet	Automatic input of supply air temperature and air volume measurements	
	Outlet	Natural outflow	
	Wall surface temperature	Calculated with detailed parameters and temperature data from neighboring chambers	Automatic input of data from infrared array sensors
	Air temperature of neighboring chambers	Manual input of measurements	
Heat generation	Person	Automatic input of data from infrared array sensors	
Number of mesh elements		Approx. 400,000	

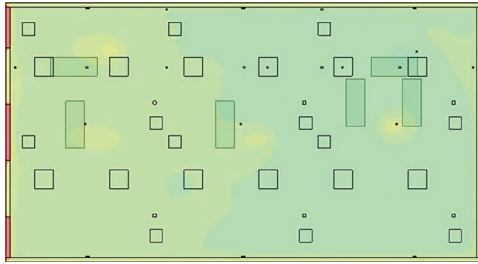
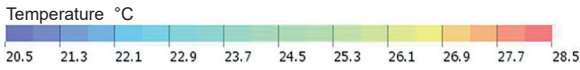


Fig. 8. Deskwork time slot (detailed parameter case)

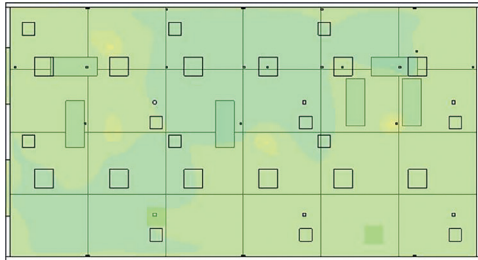


Fig. 9. Deskwork time slot (measurement case)

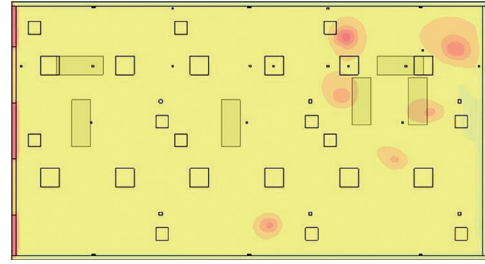


Fig. 10. Meeting time slot (detailed parameter case)

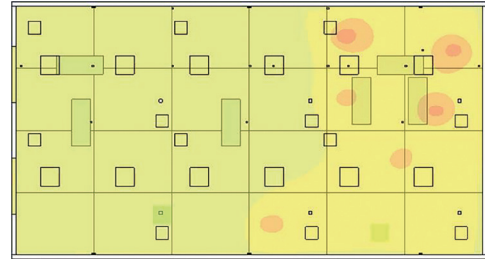


Fig. 11. Meeting time slot (measurement case)

Consequently, our system allows us to calculate the predicted mean vote (PMV) thermal comfort index (the predicted average vote for feeling hot or cool), which depends upon temperature and five other elements (humidity, radiant temperature, air velocity, amount of clothing, amount of activity) as described in ISO 7730. Therefore, it can be used for air conditioning control that takes comfort into consideration.

We confirmed that it is possible to understand the temperature distribution in a room, including the moment-by-moment changes in an office situation, using the system we constructed. Analysis of the experiment showed that the measurement case, which used infrared array sensors, gave the same results as, or better results than the detailed parameter case, and the latter additionally has the disadvantage of requiring complex parameter settings. We also found that the use of data from infrared array sensors eliminates the need for complicated parameter settings and the measurements required for setting them, significantly reducing the engineering load for building the wall model.

With this system, it is possible to understand details of the thermal environment that cannot be obtained by sensors on walls and columns. In order to consider comfort, it is necessary to examine the environmental conditions, including the humidity, airflow velocity, radiant temperature, etc. By utilizing the thermal environment data that we obtained, it is possible to achieve air conditioning control that balances comfort and energy savings and is responsive to the presence or absence of people and other factors in the thermal environment.

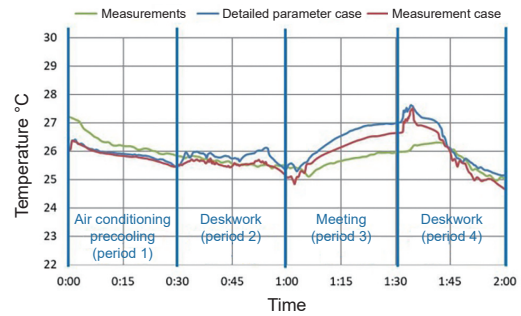


Fig. 12. Comparison of actual measurements and CFD analysis results at point A

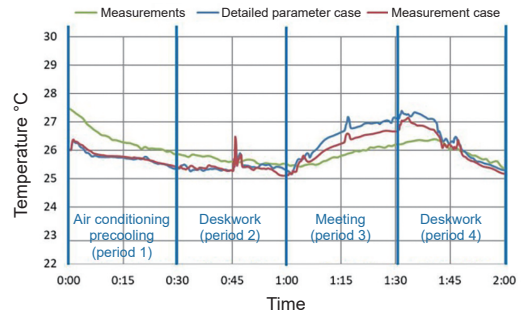


Fig. 13. Comparison of actual measurements and CFD analysis results at point B

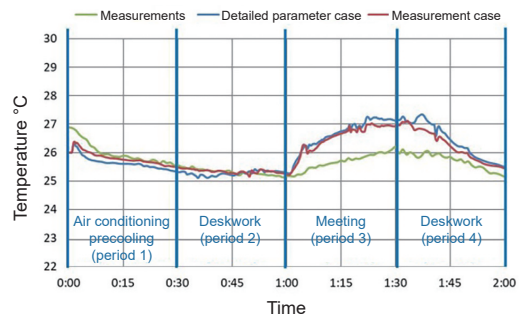


Fig. 14. Comparison of actual measurements and CFD analysis results at point C

## 4. Application Example in Actual Environment

In order to utilize this system for the air conditioning control, it is necessary to obtain it in time to synchronize it with the air conditioning control cycle, the temperature change cycle in the room, etc. However, the large amount of time required for CFD analysis presents a problem. In consideration of this problem, we describe below the results of the application of our system in a real environment.

The experiment was carried out in an Azbil Corporation exhibition booth as shown in figure 15. The size of the booth was  $14 \times 10 \times 10$  m and the number of mesh elements was about 600,000. Data was measured by infrared array sensors installed in the booth and served as continuous boundary conditions for the CFD analysis.

As shown in figure 16 (a), when measuring and analyzing data collected for a certain fixed period, it takes time to obtain the results of the analysis. Therefore, on this occasion, the measurement period was divided into small segments as shown in figure 16 (b), and consequently the time required for one analysis was reduced proportionally. By continuously executing measurement and analysis alternately for short periods of time, we were able to continuously display the results of the analysis of fixed short intervals, rather than measuring and analyzing a mass of data for a single fixed period.

At this stage, we have only tried to display the results, but in the future we will evaluate the accuracy of the analysis, the time required for calculation, and the timing for display, and further investigate the practical use of this method of air conditioning control.

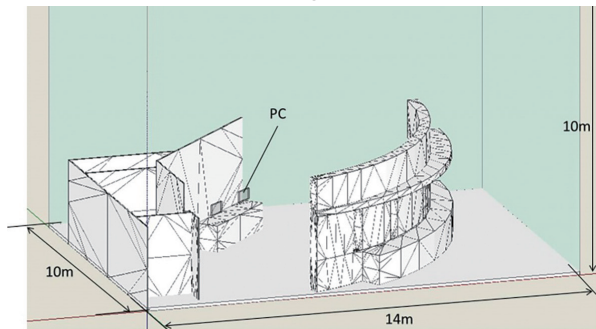


Fig. 15. CFD model for the exhibition booth

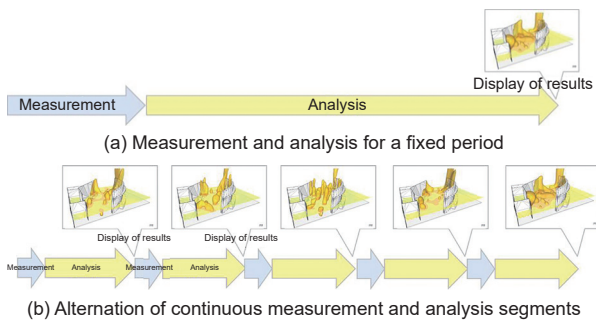


Fig. 16. Proposal for practical use in air conditioning control

## 5. Conclusions

With the aim of utilizing three-dimensional spatial thermal data obtained by CFD analysis to achieve the type of air conditioning control that has received attention in recent years for balancing comfort and energy savings, we developed a three-dimensional thermal environment visualization system that combines indoor environment measurement data and CFD analysis. We installed the system in an air conditioning laboratory and analyzed the data on surface temperature and data on occupants detected by infrared array sensors in conjunction with CFD analysis. We found that the accuracy of analysis using our wall model, which uses sensor measurements, was equal or higher than that of the conventional wall model whose parameters are adjusted in detail, and moreover the engineering load for building our wall model is lower. Also, as reported in the example above, the method we propose for the practical use of the system that we have developed has been employed in an actual environment.

In the future, our goals are to automatically monitor the spatial thermal environmental data obtained by our three-dimensional thermal environment visualization system, and to use that data to automate air conditioning control.

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