Numerical Simulation of the Air-Conditioning Environment in a Computer Room

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ABSTRACT

This paper describes the development of software for simulating the air-conditioning environment in a computer room. This software uses a finite volume method combined with a rectangular structured mesh system and a k-ε two-equation model for turbulence. Some special modeling techniques are also used. This software has two purposes: (1) to optimize the layout of a computer room, thus minimizing the electric power used for air conditioning, and (2) to reproduce the situation in which an accident is caused by an air-conditioning problem and to assist in an investigation of the problem. Measurements and simulation tests on the flow and temperature distribution in computer rooms confirm the accuracy and usefulness of this simulator.

INTRODUCTION

This paper investigates a technique for simulating the air-conditioning environment in computer rooms. Air conditioning in computer rooms is unique in the fact that high-power heat sources, such as mainframe computers and high-power air conditioners, are set in relatively small rooms. Therefore, heat entering from outside is not as important as with conventional rooms. But air in the room may become extremely hot when the balance between the heat generation of the computer and the cooling power of the air conditioner is lost. Then the computer may have problems because computers are sensitive to environmental conditions. Therefore, suitable control of the environment is required, and accuracy is important in an environmental simulation.

In this investigation, we made software to simulate the environment in computer rooms. This software can quickly simulate the wind velocity, temperature, and humidity in computer rooms using workstation-class computers. There are two important aspects of this simulation software. First, the simulator can assist in developing an optional computer room layout that minimizes electric power usage and reduces air

conditioning. Second, if an accident is caused by the air conditioning in a computer room, this simulator can reproduce the situation in which the accident occurred. Some accidents are caused by extraordinarily high temperatures or high humidity. The simulator can assist in investigating the causes of the accident and in taking measures against it.

This paper first explains the calculation method used in the simulator. Then results of simulation are compared with results of measurements in a computer room to verify the accuracy of the calculation. Next, an example of a problem in a computer room is shown. Finally, measures to solve the problem are investigated using this simulator.

CALCULATING METHOD

In this investigation, the Navier-Stokes equation, the continuous equation, the energy equation, and the mass transfer equation are discretized using the finite volume method (Patanker 1980) after which the air velocity, temperature, and humidity in the computer room can be obtained. The k-ε two-equation model is adopted for the calculation of turbulence. The rectangular structured mesh system is adopted because objects in computer rooms are represented by rectangular boxes in almost all cases. Co-located mesh systems (Farhanieh et al. 1993) in which velocity components along each x, y, z axis (u, v, w), pressure, temperature, and humidity are located together at the center point of the control volume were adopted instead of staggered mesh systems.

An example of a computer room is shown in Figure 1. A number of supports are set on the concrete floor and tiles are set on the supports. This layer of tiles is called the "free-access floor," and computers and air conditioners are set on it.

Many rooms for mainframe computers are under-floor cooled—air conditioners blow cooled air into the space under the free access floor and computers take in the air directly from the space under the floor. The space under the free-access floor also is used for the wiring and piping. Using this under-floor
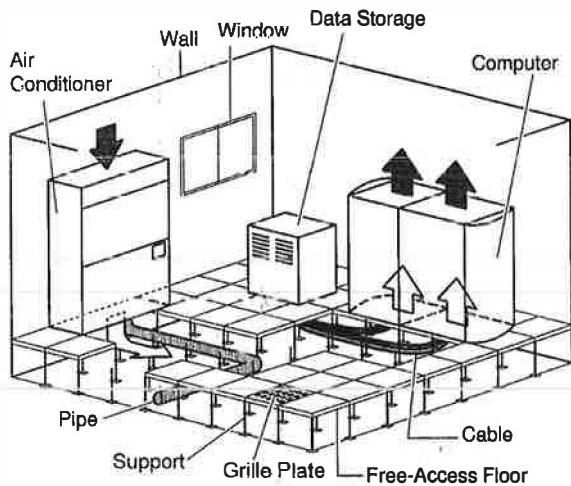
Figure 1 *Model of a computer room.*

cooling system, cool air can be carried to the computers without overcooling the room air. If the air conditioners blow the air above the floor, the wind velocity and temperature are too uncomfortable for computer operators because mainframe computers require air with a huge flow rate and an extra low temperature. Accurate simulation of flow and heat transfer under the free-access floor is important because the cooled air is supplied through this space.

The supports under the free-access floor are modeled as the uniform flow resistance because obtaining the exact mesh on each support would require a large mesh size and an enormously long calculation time. The body force due to the flow resistance of the supports is given below (JSME, 1986).

$$F_x = 0.959 \frac{\pi d}{4S^2 - \pi d^2} \left(\frac{4S^2 - \pi d^2}{\pi dS} \right)^{0.4} Re_x^{-0.2} \rho u^2 \quad (1)$$

$$Re_z = \frac{4S^2 - \pi d^2}{\pi d} \frac{u}{w}$$

$$F_z = 0.092 \frac{\pi d}{4S^2 - \pi d^2} Re_z^{-0.2} \rho w^2 \quad (2)$$

$$Re_z = \frac{4S^2 - \pi d^2}{\pi d} \frac{w}{v}$$

where

F_x = horizontal component of the resistance force,
F_z = vertical component of resistance force,
d = diameter of a support,
S = distance between supports,
u = horizontal component of air velocity,
w = vertical component of air velocity,
Re = Reynolds number.

The wind blowing through the cables set under the free-access floor is ignored. Therefore, the cables are regarded as a solid. Although the wind through the cables can be counted

in the same way as the supports under the free-access floor, we assume a solid model to save the labor of inputting data for simulation. Through the simulations and experiments on some computer rooms, it has been confirmed that the solid model does not cause any serious problems with the accuracy of the simulation.

Under the free-access floor, there are some pipes that carry water or coolant. These cylindrical pipes are modeled as square rods because a cylinder is difficult to accurately model in a rectangular mesh system. Each side of a square rod equals half the diameter of the cylindrical pipe. Thus, using this model makes their flow resistances equal.

There are also some air vents (grille plates) set in the free-access floor. A grille plate is a tile with many holes that allows cool air to flow through into the space above the free-access floor. This flow of cool air keeps the room from becoming too hot for the computer operators.

The equipment takes in the cool air from under the free-access floor and blows the heated air out the top. The exhaust air temperature is calculated by the following equation.

$$T_{out} = T_{in} + Q/(\rho Cp \cdot V) \quad (3)$$

where

T_{out} = exhaust air temperature,
T_{in} = inflow air temperature,
Q = heat generation rate,
Cp = specific heat,
V = the flow rate.

Some equipment has more than one outlet, and each outlet may have a different flow rate and temperature.

Sometimes a computer has several outlets for heat and airflow, but the catalog explains the total heat generation and airflow. Thus, heat generation might be concentrated in a small area and the exhaust air might become very hot. Therefore, a detailed investigation of the flow rate and temperature at each computer outlet is required for an accurate simulation.

An air conditioner takes in the air from the top and blows cooled air into the space under the free-access floor. The flow rate, temperature, and maximum cooling power can be specified. If the power required to cool the room air to the temperature set is lower than the maximum cooling power of the air conditioner, the temperature at the outlet will equal the temperature desired. On the other hand, if the power required is greater than the air conditioner's maximum power, the temperature at the outlet will be higher than the temperature desired.

RESULTS AND DISCUSSION

Comparing Simulated and Measured Data

An example of a computer room is shown in Figure 2. Although the actual room is larger than that shown in the figure, we partitioned the actual room into an area of this size, using polyethylene curtains, for our experiment. The space
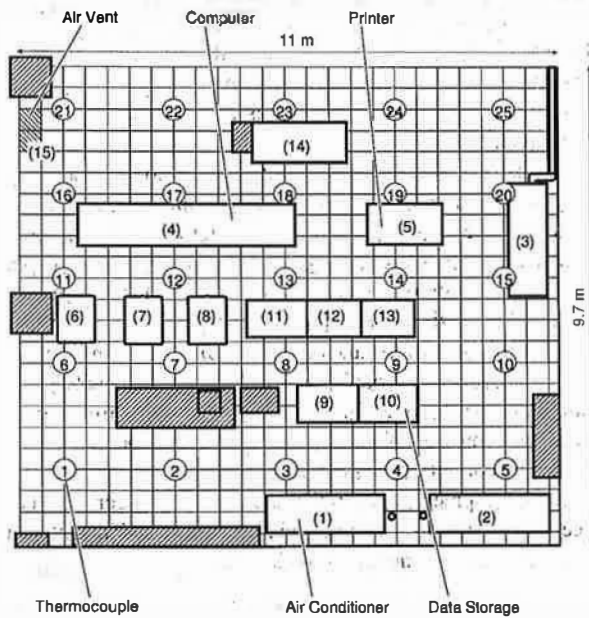
Figure 2 Example of computer room layout.

Figure 3 Vertical arrangement of thermocouples.

TABLE 1
Flow Rate, Power, and Intake Temperature of Equipment

No.	V (m³/min)	Q (kW)	T_in (°C)
(1)	220	—	—
(2)	0	—	—
(3)	220	—	—
(4-1)	49	4.1	22
(4-2)	8	0.3	22
(4-3)	32	1.3	22
(4-4)	51	9.7	22
(4-5)	9	1.4	22
(4-6)	40	3.5	22
(4-7)	7	0.9	22
(5)	20	4	20
(6)	30	3	room air
(7)	30	3	room air
(8)	30	3	room air
(9)	18	2	24
(10)	18	2	24
(11)	18	2	24
(12)	10	0.5	24
(13)	10	0.5	22
(14)	10	1	20
(15)	51	—	20

under the free-access floor was also partitioned by cardboard. There are three air conditioners, Nos. 1 to 3, but No. 2 was not used because two air conditioners are enough for this area. There were large computers and their power unit, Nos. 4 to 8, and there were also disk units and printer, Nos. 9 to 14. No. 15 was an air vent in the free-access floor.

Thermocouples were arranged in the room for the measurement of room temperature. One hundred thermocouples were hung from the ceiling at 25 points in the room, circled numbers 1 to 25 in Figure 2. At each point there were four thermocouples arranged in a vertical line. The vertical thermocouple arrangement is shown in Figure 3.

The airflow, heat generated, and intake air temperature of the computers, other equipment, and air conditioners in the test computer room are given for the simulation in Table 1. All the equipment, Nos. 1 to 14, is shown in Figure 2.

The input data for the computer unit ((4) in Figure 2) are divided into seven parts to represent the distribution of temperature and velocity of the exhaust air, which are very important for accurate simulation. Figure 4 shows the air outlets of the computer unit. The airflow rate and heat generation values are given for each outlet because those values differ between each outlet. The temperature and velocity are treated as uniform within an outlet because the distribution of temperature and velocity in one outlet is negligible compared with the required accuracy. Other equipment has plural air outlets, but only the averaged values are shown in Table 1.

Our simulation was carried out only in the space above the free-access floor. Only the flow rate is given for the air conditioners because they take in the air from the space above the
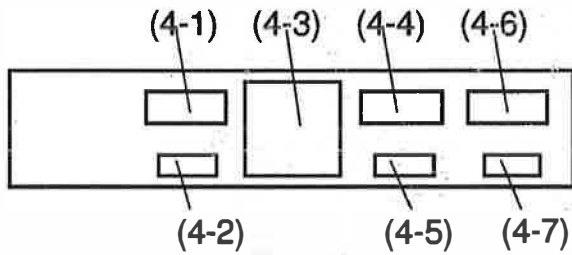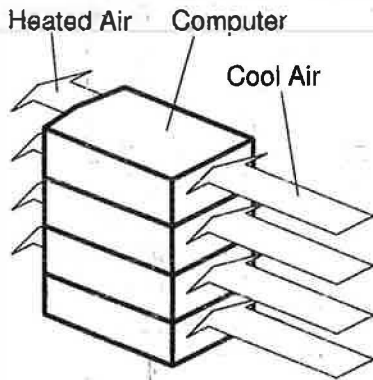
Figure 4 Air outlets of the computer

Figure 5 Model of computers 6 - 8.

Figure 6 Calculating mesh system (1).

free-access floor. On the other hand, the flow rate, heat generation, and air temperature at the intake are given for the under-floor-cooled computers and other equipment (Nos. 4, 5, and 8 to 14).

Flow rate and heat generation are given for computers 6 to 8. A model of those computers is shown in Figure 5. It takes in room air at the back side and blows out heated air from the front side. It is partitioned into several vertical units, and each unit has its own air intake and outlet. The temperature of the exhaust air was calculated by adding the temperature difference in the unit to the air temperature at the air intake for each unit. The purpose of this modeling was to calculate an accurate temperature distribution at the front side (exhaust) when the temperature may vary for each unit at the back side. Such a model was required because the temperature of the room air near the ceiling was higher than that near the floor due to natural convection.

The flow rates, heat generation, and intake air temperatures of the computers and other equipment were measured on the actual machines because correct input data were important for an accurate simulation.

The flow and temperature distribution simulation was carried out using a simulation mesh of $101 \times 64 \times 27 = 174,528$ nodes that is shown in Figure 6. We tried to carry out this simulation with such relatively coarse mesh because our purpose is to build software for practical simulation with the least computational resources so that system engineers can predict
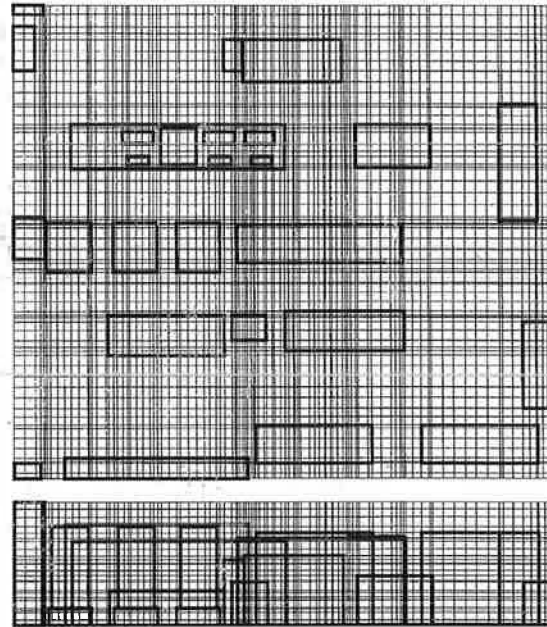
the air-conditioning environment of the rooms while installing the computers. Thus, the simulation result with the least mesh size representing the computer room was compared with the result of measurement.

The simulation calculation took 770 minutes using a 100 MHz workstation computer with RISC CPU. The temperature distribution of the room air is shown in Figure 7. The simulation results are shown by the solid line, and the measured results are shown by the black dots. The measured results and simulation results are about the same for the most part. The accuracy of the temperature data measured by the thermocouples is examined by a mercury thermometer. The error of the temperature data is less than 0.5 °C, and the error of the location of the thermocouples is less than 5 cm. These results confirmed that this simulator has an acceptable level of accuracy.

An Example of Trouble and Measure

Another example of a computer room is shown in Figure 8. In this room, there are ten air conditioners and one large computer in a corner. The power, flow rate, and air temperature set for the equipment are listed in Table 2. As shown in the table, the total amount of cooling power of the air conditioners is 500 kW, which is greater than the heat generation of the computer.

A simulation of the airflow and temperature distribution was carried out using a mesh of $43 \times 54 \times 18 = 41,796$ nodes, which is shown in Figure 9. The simulation calculation took 54 minutes per case, using a 100 MHz workstation computer with RISC CPU. The flow vector and temperature distribution at a
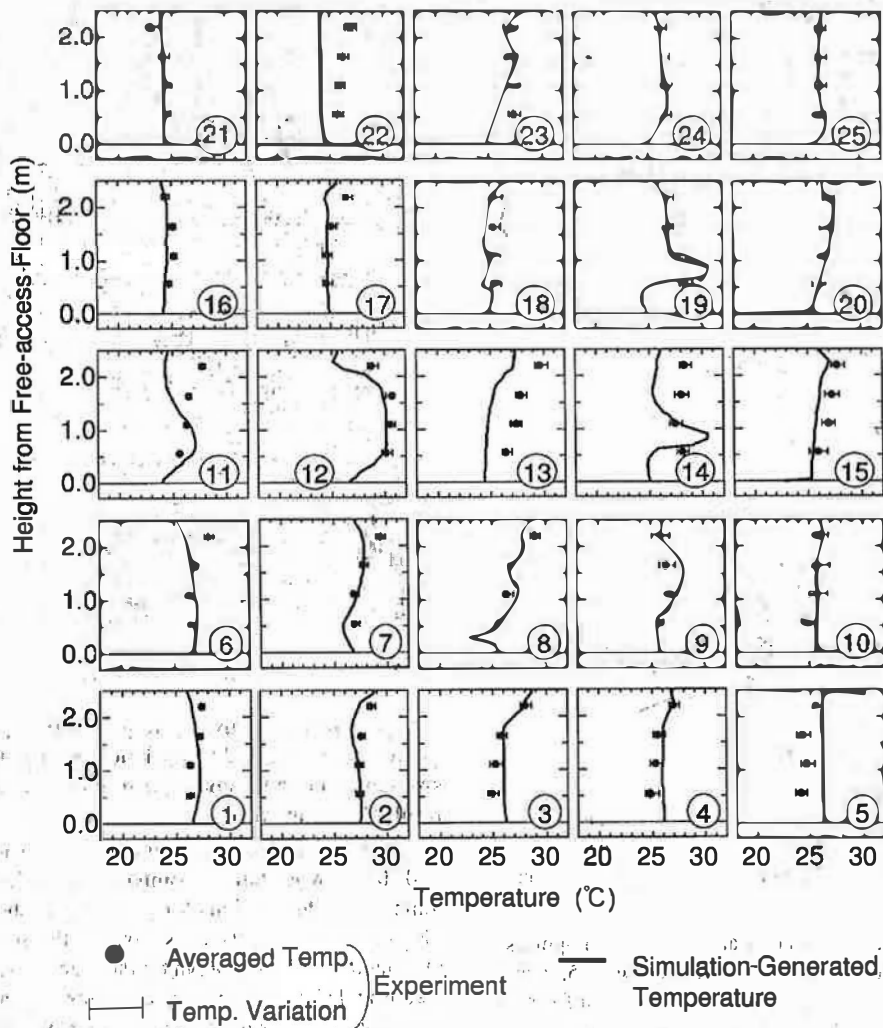
Figure 7. Computer room temperature distribution.

height of 2.5 m are shown in Figure 10. Most of the exhaust from the computer is going to air conditioners Nos. 5 and 6 because the computer is near those units.

The flow vector and temperature distribution at a height of −0.3 m (under floor) is shown in Figure 10. The temperature of the air under the free-access floor is hotter than the desired temperature because air conditioners Nos. 5 and 6 cannot cool the air sufficiently. Thus, the computer takes in air that is hotter than desired. The temperature of the air at the intakes and outlets of the air conditioners and computer is shown in Table 3. Air conditioners Nos. 5 and 6 are cooling air at their maximum power, while the other air conditioners are cooling air at much less than their maximum power. Generally, the intake air temperature for mainframe computers with under-floor cooling must be kept under their specified temperature. Otherwise,

the computer may have trouble. The following conditions may result:

• The temperature difference in the computer may be greater than that in the air conditioners.

• The computer may be located in a corner of the room.

The rise in temperature difference in the computer, as shown in Table 2, is about 20 °C, and each air conditioner can cool the air 10 °C at maximum power. Therefore, the air conditioners cannot cool the air to the desired temperature if the exhaust from the computer enters the air conditioners directly.

Although the power of computers has been increasing recently, the flow rate has been kept low so as to keep the noise down. Therefore, the risk of trouble is increasing.
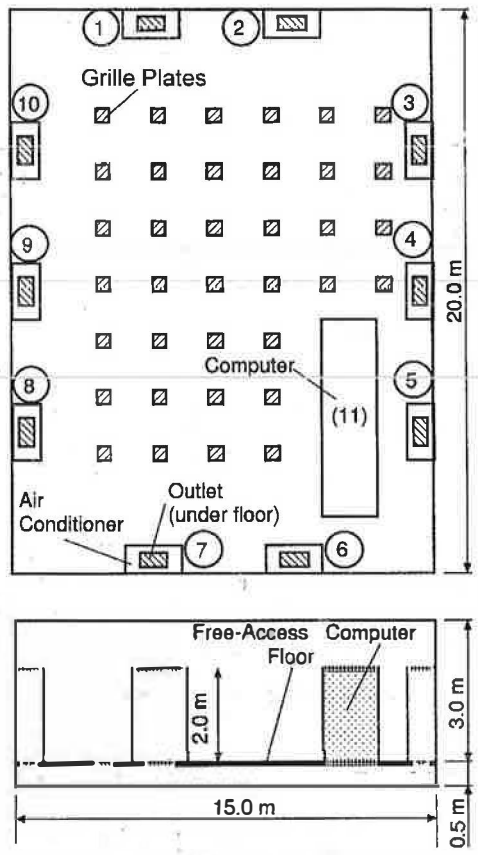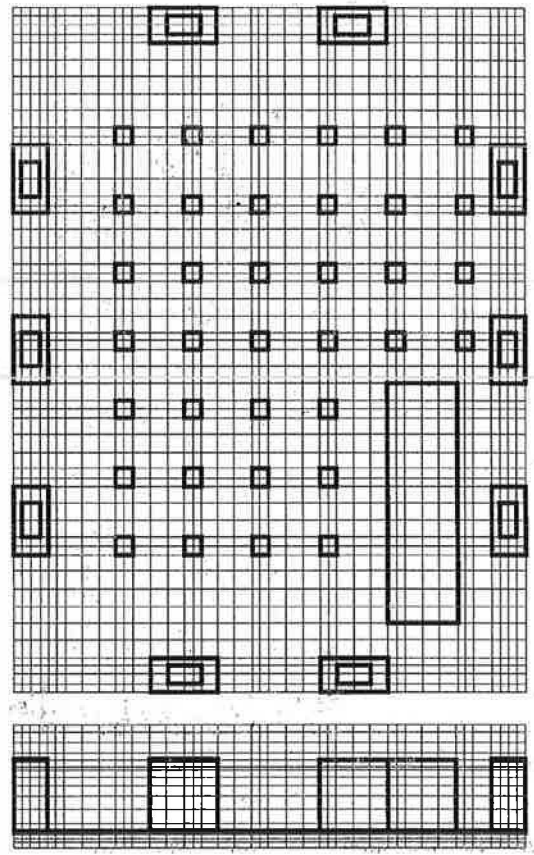
Figure 8   Example of computer room layout.

Figure 9   Calculating mesh system (2).

TABLE 2
Flow Rate, Power, Outlet Temperature, and Temperature Difference of Equipment

No.		V (m³/min)	Q (kW)	T_{out} (°C)	ΔT (°C)
(1)-(10)	Air Con.	250 × 10	50 × 10	20.0	10
(11)	Computer	600	230	—	20

An additional condition that may cause an air-conditioning problem is when the computer owners set their machines near a wall because they want to reserve the center space.

Next, we will discuss measures to deal with this air-conditioning problem. In order to make the air temperature low under the free-access floor, the intake air temperature of an air conditioner must be low enough. However, if the exhaust temperature from a computer is too high, the exhaust air must be mixed with cooler room air between the outlet of the computer and the intake of the air conditioner.

The first measure is to move the computer to the center of the room, the point farthest from all air conditioners. Then, the exhaust from the computer will disperse equally toward all the air conditioners, resulting in the temperature at the intake of

the air conditioners becoming low. But this case is an idealized one. In reality, computers cannot be moved as we like because there are other machines in the room. Moreover, moving a mainframe computer involves installation by professionals. Thus, we look for other less expensive measures.

The second measure is to move grille plates. The purpose is to concentrate grille plates between the computer and air conditioners Nos. 5 and 6, thus thinning the exhaust air with air from under the free-access floor. The new arrangement of grille plates is shown in Figure 11.

The flow vector and temperature distribution at a height of 2.5 m is shown in Figure 12. The exhaust from the computer is spread over the room, and the air temperature near the right bottom corner becomes lower.

The flow vector and temperature distribution at a height of –0.3 m are shown in Figure 12. The computer's exhaust is thinned, and the load on air conditioners Nos. 5 and 6 becomes lower. Thus, the temperature of the air supplied to the computer decreased to a level that met the specifications of the computer.

The temperature of the air at the intake and the outlet of the air conditioners and the computer is shown in Table 4. The cooling load is shared by all the air conditioners, and the outlet
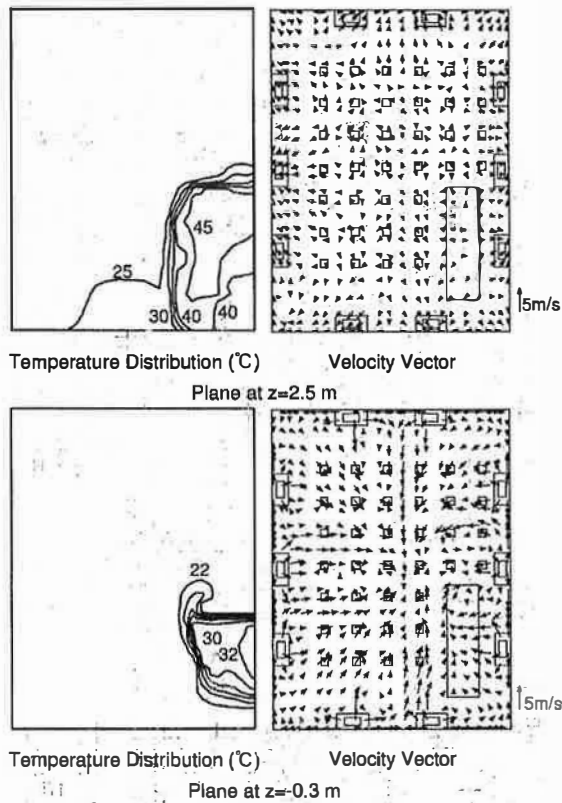
Temperature Distribution (°C)   Velocity Vector

Plane at z=2.5 m

Temperature Distribution (°C)   Velocity Vector

Plane at z=-0.3 m

Figure 10 *Simulations results (original layout).*

TABLE 3
Intake and Outlet Air Temperature (Original)

No.	T_{in}	T_{out}
(1)	20.3	20.0
(2)	20.2	20.0
(3)	20.1	20.0
(4)	28.8	20.0
(5)	42.8	32.4
(6)	32.5	21.8
(7)	25.7	20.0
(8)	22.6	20.0
(9)	20.8	20.0
(10)	20.4	20.0
(11)	25.9	45.8

air temperature of air conditioners Nos. 5 and 6 becomes lower than in the original case.

CONCLUSIONS

Simulation software for predicting the air-conditioning environment in computer rooms has been developed. The following conclusions are based on the measurement and
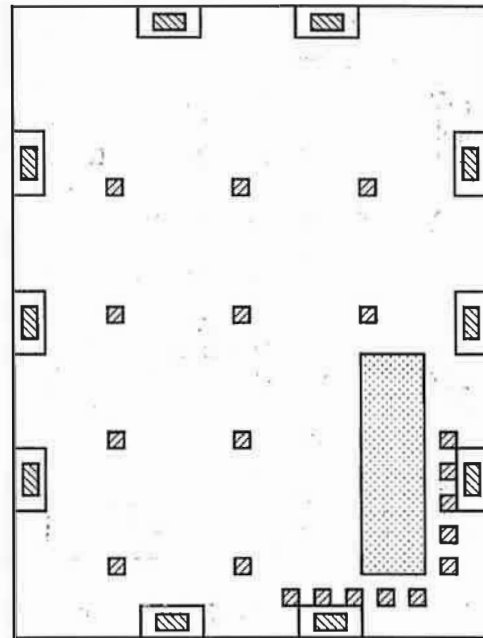

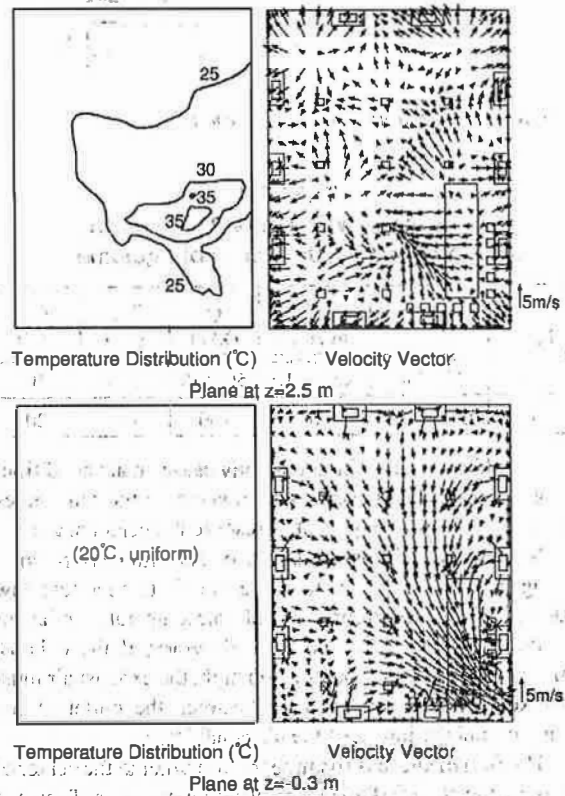**Figure 11** *Rearranged grille plate layout.*

Temperature Distribution (°C)   Velocity Vector

Plane at z=2.5 m

(20°C, uniform)

Temperature Distribution (°C)   Velocity Vector

Plane at z=-0.3 m

Figure 12 *Simulation results (rearranged layout).*

TABLE 4
Intake and Outlet Air Temperature (Rearranged)

No.	T_{in}	T_{out}
(1)	23.7	20.0
(2)	24.4	20.0
(3)	25.3	20.0
(4)	27.7	20.0
(5)	20.7	20.0
(6)	21.3	20.0
(7)	22.3	20.0
(8)	23.1	20.0
(9)	24.2	20.0
(10)	23.5	20.0
(11)	20.0	38.8

simulation of the airflow and temperature distribution in computer rooms.

1. Flow and temperature distribution in computer rooms can be simulated with sufficient accuracy using this simulator.

2. When an accident occurs due to an air-conditioning problem, this simulator can assist in the investigation of the cause of the accident and can help develop measures to counter a reoccurrence of the problem.

REFERENCES

Farhanieh, B., L. Davidson, and B. Sunden. 1993. Employment of second-moment closure for calculation of turbulent recirculating flows in complex geometries with collocated variable arrangement. *International Journal for Numerical Method in Fluids*, 16: 525-544.

JSME. 1986. *JSME Data Book: Heat Transfer*, 4th ed., p. 255. Tokyo: Maruzen Publishing.

Patanker, S.V. 1980. *Numerical heat transfer and fluid flow*. New York: McGrawHill.