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RESEARCH AND DEVELOPMENT OF A HOME USE VAV AIR-CONDITIONING SYSTEM

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ABSTRACT

For the ducted central VAV (variable-air-volume) air-conditioning system, which is regarded as the air-conditioning system of the next generation in the present Japanese market, a new method for controlling air volume has been developed, and the details are reported here. For conventionally controlled central air conditioning, it is necessary to provide detailed duct design and complicated testing to adjust air volume. The new method of controlling air volume, however, allows us to maintain the balance of the air volume in each duct, even if the flow resistance in each duct route is diversified. This method enables us to reduce the power consumption of the indoor fan by 50%.

This report describes an algorithm for the new air volume control method and reports the results of analysis and experiments with regard to the effects.

INTRODUCTION

The demand for air-conditioning equipment in Japan has been increasing year by year, and it has become more popular to install equipment in each room instead of having one unit for each house. The need for energy saving has stimulated the trend toward higher thermal insulation and greater airtightness in houses. Improvement of indoor air quality is another goal. All these trends have stimulated the development of the central VAV (variable-air-volume) air-conditioning system.

Until recently in Japan, conventionally controlled central VAV air-conditioning systems have been used mainly in office or factory buildings. When such a system is adapted for houses, the major problem is control of the air volume. This report describes the basic control logic and the effects of the new method of controlling air volume, which has two favorable features. One is the realization of constant air volume. The other is the reduction in power consumption of the indoor fan by rather simple means.

CONTROL LOGIC

The following functions are considered necessary for air volume control:

1. Precise control of the air volume for each room and automated adjustment of air volume distribution.
2. Optimum air pressure at the fan outlet in accordance with the thermal load, without mechanical loss and noise resulting from excessive air pressure at the fan outlet.
3. Simplification of the design and installation of ductwork with the application of standard duct units (for example, flexible ducts).

In order to satisfy these necessary functions, the newly developed air volume control method is structured with the logic described below. In short, after the installation of the ductwork, the flow resistance of each duct route is checked in the test operation. In normal air volume control, test operation data are utilized to ensure the necessary air volume for each duct route with minimum power consumption of the indoor fan. As shown in Figure 1, this system consists mainly of functional components, such as the proportional drive VAV damper unit in each duct route. The air volume sensor and the supply air pressure sensor are provided inside the indoor unit of the air-conditioning system.

The new air volume control method proposed in this paper is derived from the following sections, including the test operation and the actual control of air volume.

Method of Test Operation

In order to determine the characteristics of the airflow resistance in each duct branch, the test is conducted after the installation of the ductwork. This test operation has the

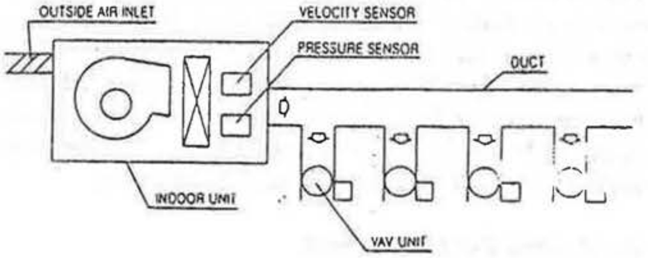

Figure 1 System model.

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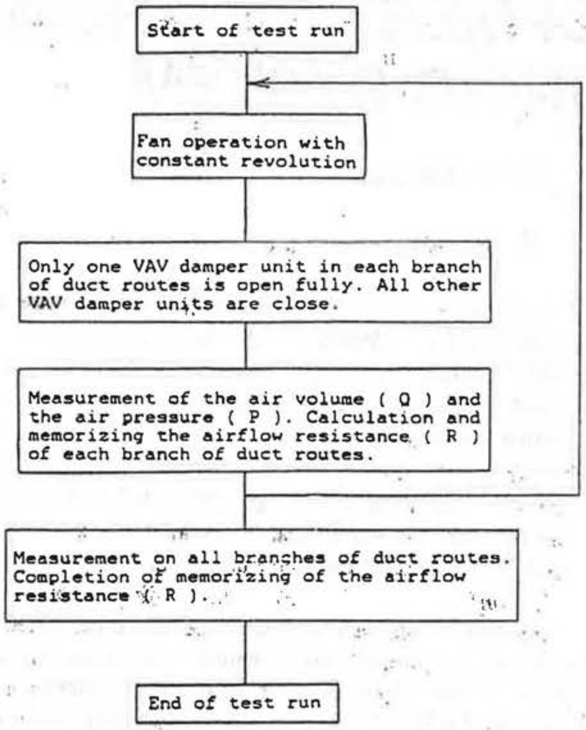

Figure 2 *General flow chart of test run.*

effect of system initializing. Figure 2 shows a general flow chart of the test operation. In order to learn the airflow resistance of each duct branch for the unit, air flows through a specific duct branch while all other VAV damper units are completely closed. The air volume (*Q*) and air pressure of the fan outlet (*P*) are measured.

Because the airflow discussed in this paper is fully developed turbulent flow, it is assumed that the following relation is within the range of this study:

$$P = R \cdot Q^2 \ (R = \text{resistance coefficient}).$$

Each duct branch is subjected in turn to the above measurement. The fixed resistance coefficient (except for the VAV damper unit itself), which is composed of the friction loss and the structural resistance of each duct route branch, is obtained. Further, if the value of the resistance coefficient of the VAV damper unit is defined as the function of the blade aperture angle, and the relation between these two factors is connected linearly, the relation of the airflow resistance of each duct branch and aperture angle of the VAV damper units can be calculated.

Air Volume Control Method

By using the air volume control during actual operation of the air-conditioning system, the blade aperture angle of the VAV damper unit of each duct branch is determined instantly, the minimum air pressure of the fan outlet is gained, and the required air volume at each room (each duct route) is satisfied. This is based on the resistance coefficient obtained during the test.

The general flow chart of the air volume control method is shown in Figure 3.

1. *Determination of the required air volume (Qi) for each room:* The required air volume at each duct branch is determined by the difference between the room temperature and the set temperature.

2. *Calculation of the necessary air pressure at the fan outlet for each duct branch:* The necessary air pressure at the fan outlet (P_i) for each duct branch with the VAV damper unit fully opened is calculated by using the required air volume (Q_i) in each room with the following equation:

$$P_i = R_{oi} \cdot Q_i^2$$

where

R_{oi} = fixed resistance value of each duct branch,
Q_i = required air volume in each room.

3. *Maximum air pressure of fan outlet (P_{max}) and selection of the specific duct branch:* The specific duct branch with the maximum air pressure at the fan outlet is selected by calculating the necessary air pressure at the fan outlet (P_i) of each duct branch, as shown above.

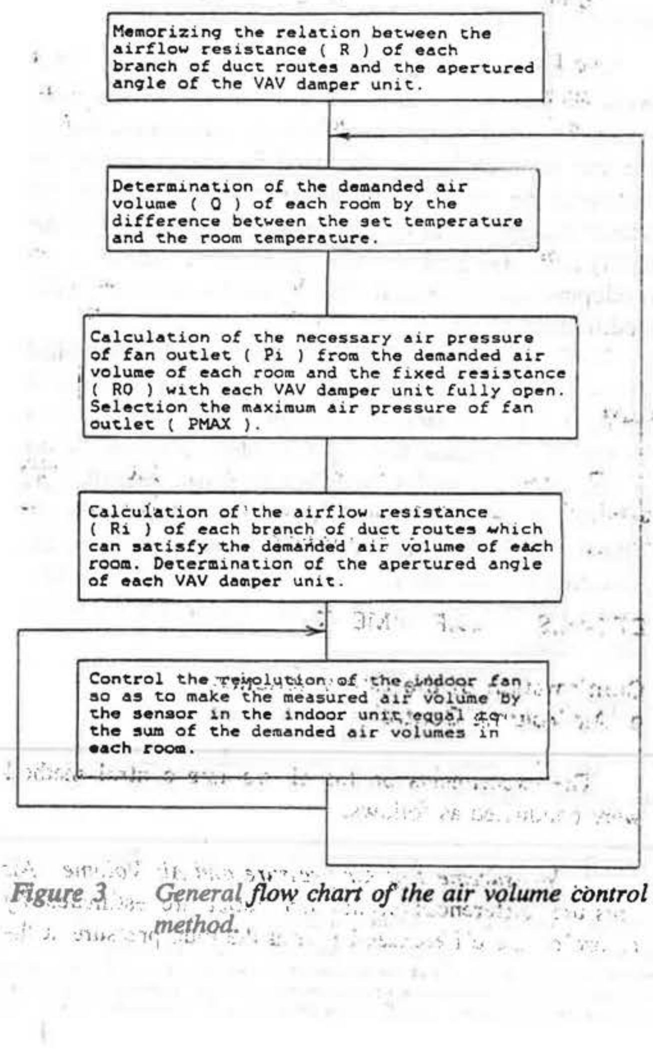

Figure 3 *General flow chart of the air volume control method.*

4. *Calculation of resistance of each duct branch:* The resistance coefficient (R_i) of each duct branch, which can provide the required air volume in each room, is calculated by using the maximum air pressure at the fan outlet (P_{max}):

$$R_i = P_{max} / Q_i^2 .$$

5. *Determination of the blade aperture angle of each VAV damper unit:* The blade aperture angle of the respective VAV damper unit, which can satisfy the resistance (R_i) of each duct branch, is determined.

6. *Control of the air volume:* The revolution of the fan is controlled to equalize the air volume measured with the sum of the required air volume of each room by using the airflow rate sensor inside the indoor unit of the air-conditioning system.

EXPERIMENTAL APPARATUS

Test House

The house has a floor space of 34 m^2 and consists of six rooms with a unit space of 4.86 m^2. A 400-by-600-mm louver is provided at the bottom of the door in each room. (There is no return duct.)

Test Equipment and System Structure

Two kinds of systems were tested. One is the branch duct system, shown in Figure 4, and the other is the main duct combined system (not shown). The rated capacity of the air-conditioning system fan in the figure is 200 W, and the fan capacity is controlled by an inverter.

The diameter of each branch duct is 150 mm. The diameter of the main duct is 250 mm. These are flexible ducts and a commercially available air measurement chamber. A circular diffuser is used at the outlet in each room.

VAV Damper Unit

The VAV damper unit has a diameter of 150 mm with an elliptical blade having an overall length of 300 mm. The proportional control method is employed.

DETAILS OF EXPERIMENT

Confirmation of the Characteristics of Air Volume Control

The experiments on the air volume control method were conducted as follows:

1. *Measurement of Air Pressure and Air Volume.* Air pressure differences at the fan outlet are estimated by recording the differences between the total pressure at the outlet duct of the indoor unit and the pressure around the inlet duct in the room. In order to measure the air volume of each duct branch, a straight duct of the same diameter as the flexible ducts, with a rectifying grid at the inlet, is installed in each duct branch. Airflow speed at the center of the straight duct is measured at a point 8D (eight times the diameter) below the grid using a hot wire anemometer. The average airflow speed is calculated as the developed turbulent flow, and the air volume of each duct branch is obtained as a result. The total air volume of the indoor unit is defined as the sum of the air volumes of all duct branches.

2. *Determination of the Required Air Volume.* The maximum air volume of each duct branch is specified to be 250 m^3/h and the minimum air volume is 50 m^3/h in this experiment. The required air volume for each duct branch is calculated by using six random values of air volume between the minimum and the maximum.

3. *Confirmation of the Reduction Effect of the Power Consumption of the Indoor Fan.* The maximum rated air volume for each duct branch (Q_{max}) is specified to be 200 m^3/h, since the indoor unit of this experiment is smaller than that of the air volume control method experiment, and the minimum rated air volume (Q_{min}) is to be 50 m^3/h. The required air volume for each duct branch is obtained by using six random values of air volume between Q_{max} and Q_{min}. The power consumption of the indoor fan is determined as the arithmetic mean of 10 measurements of the input power of the fan inverter; each required air volume is satisfied in each experiment. Experiments on the two control methods, as shown below, were carried out using 20 sets of required air volume (Q_i) groups for each operational zone (one to six zones). In addition, the

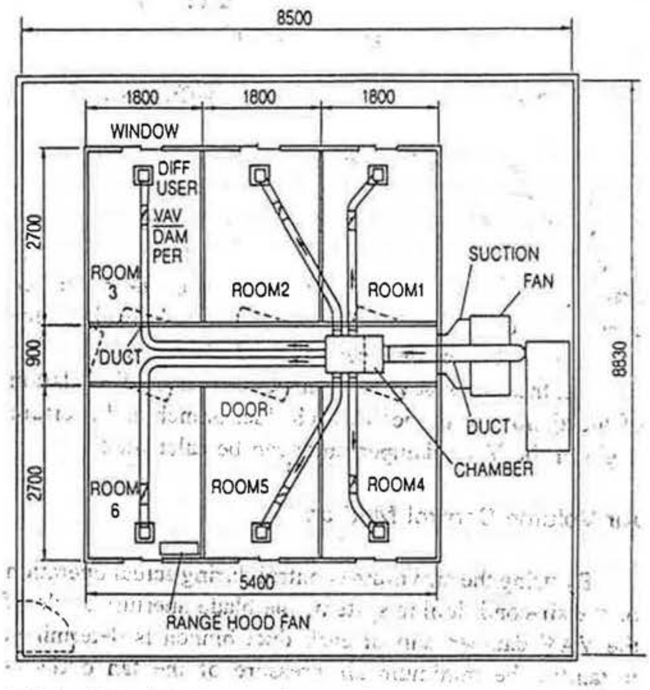

Figure 4 The branch duct method.

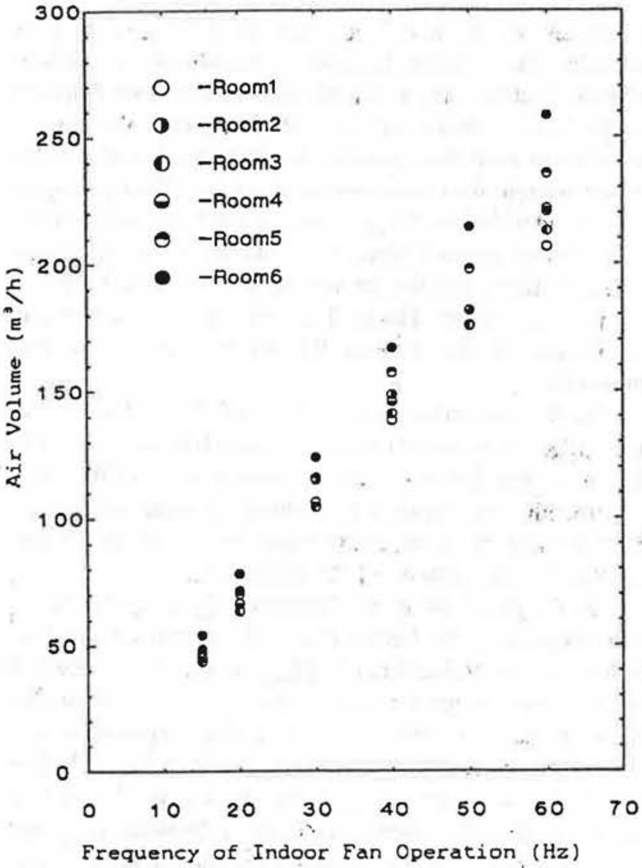

Figure 5 *The results of the branch duct method (no control).*

selection of the operational zone has been determined at random.

Constant Control of Air Pressure at Fan Outlet

It is necessary to determine beforehand the actual operating air pressure at the fan outlet for the constant control method. In this experiment, the minimum difference of the air pressure between the inlet and outlet of the fan was measured. This air pressure gave the maximum rated air volume (Q_{max}) in all the duct branches by controlling the fan revolution with the VAV damper unit of each duct fully open, as shown in Figure 1. Since the operating air pressure difference (P_{SET} = 170 Pa) was obtained as a result, this was taken as the operating air pressure at the fan outlet with the constant control method. Fan revolution was controlled with the inverter so as to make the measured air pressure difference at the fan outlet equal to the operating air pressure at the fan outlet (P_{SET} = 170 Pa). The blade aperture angle of each VAV damper unit was also controlled so that the measured air volume of each duct branch satisfied each required air volume as mentioned above.

RESULTS OF EXPERIMENT

Difference of Airflow Resistance of Each Duct Branch

In order to clarify differences in the airflow resistance among duct branches, the airflow volumes were measured without control of the blade aperture angle of the VAV damper unit by the branch duct pattern shown in Figure 4 and the main duct combined pattern. Results are shown in Figure 5. The horizontal axis indicates the operating frequency of the fan inverter, and the vertical axis shows the air volume of each duct branch. The figure shows that there is a difference in the resistance of each branch.

Results of the Air Volume Control Method (Experiment 1)

Results of the experiment with regard to the efficiency of the method based on this control logic are shown in Figure 6. The horizontal axis in this figure indicates the required air volume of each of six rooms, while the vertical axis represents the actual measured air volume. Symbols show the air volumes of the different rooms. As explained above, the required air volume is obtained by repeating 20 times the six sets of random values of air volume. The figure shows that each measured air volume is in accord with a corresponding required air volume within a range of deviation of 10% and that the air volume control method functions effectively.

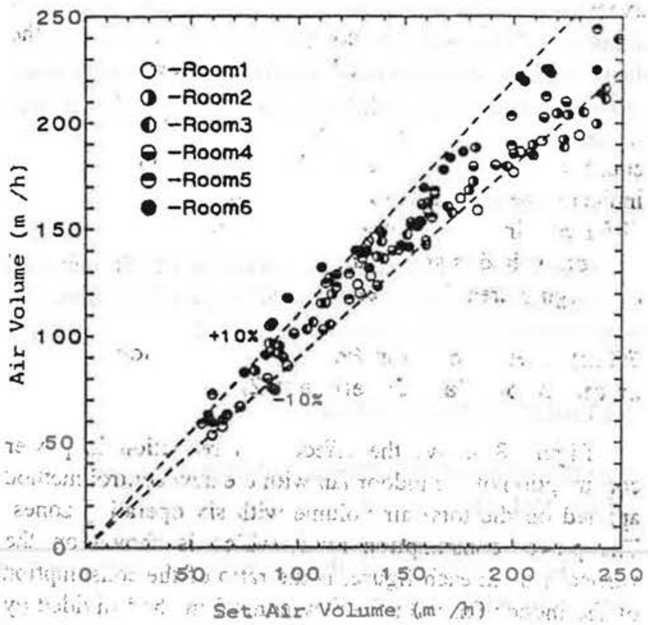

Figure 6 *The results of the branch duct method (by the air volume control method).*

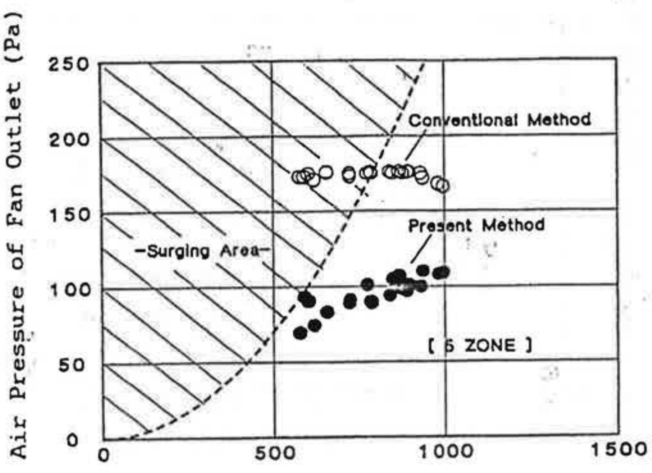

Figure 7 *The operating point of the fan.*

Differences of Operating Air Pressure

Figure 7 indicates the operating point of the fan, based on the relation between total air volume and the difference in air pressure at the fan outlet, when this control method and the conventional method (constant air pressure at the fan outlet) were carried out. The purpose is to clarify the difference between these two methods. Figure 7 shows the case with six operating zones.

As is apparent, the operating point (indicated by a ○) of the control method with constant air pressure at the fan outlet is fixed at about 170 Pa. A difference in the air pressure at the fan outlet cannot be observed through experiments regardless of the change in the total air volume. With the new control method, however, the experimental point (indicated by a ●) operates with a small air pressure difference at the fan outlet (70 to 110 Pa), so that a reduction of the power consumption of the indoor fan could be expected. The hatched section in the figure indicates the surging area of the indoor fan. Generally, the difference in air pressure at the fan outlet with this new control method is small, and the possibility of operation in the surging area decreases relatively.

Effect of Reduction in Power Consumption of the Indoor Fan (Experiment 2)

Figure 8 shows the effect of a reduction in power consumption of the indoor fan with the new control method applied on the total air volume with six operating zones. The power consumption ratio, which is shown on the vertical axis in each figure, is the ratio of the consumption of the indoor fan with the new control method divided by that of the constant-control method. Experimental points of the power consumption ratio in Figure 8 correspond to the groups of required air volume in each duct branch. The values indicated in this figure represent the averages of 20 experimental points of the power consumption ratio versus the number of operating zones. These figures show that power consumption with this new control method can be reduced by 50% from that of the constant control method.

The figures also show that the consumption ratio increases gradually according to the number of operating zones. Study of family life patterns leads to the expectation that the number of operating zones will be small in a home. This air volume control system is considered the best for home use because the larger reduction in power consumption of the indoor fan is achieved with a smaller number of operating zones.

DISCUSSION

A method based on the duct structure, as explained above, was used to compare the power consumption of the constant control method of air pressure at the fan outlet with the new control method.

Analytical Model and Method

In this analysis, the duct structure shown in Figure 1 is expressed as shown in Figure 9. Analytical conditions are the same as in the experiments. The maximum rated air volume for each duct branch (Q_{max}) is 200 m^3/h and the minimum air volume (Q_{min}) is 50 m^3/h. The required air volume for each branch (Q_i) was obtained by generating six random numbers between Q_{max} and Q_{min}. Analysis of both control methods was carried out with 50 groups of the required air volume (Q_i) for each operating zone (1-6). In addition, the selection of the operating zone was determined by generating random numbers. Analysis was made using the circuit network method, and the calculation was based on the Newton-Raphson method.

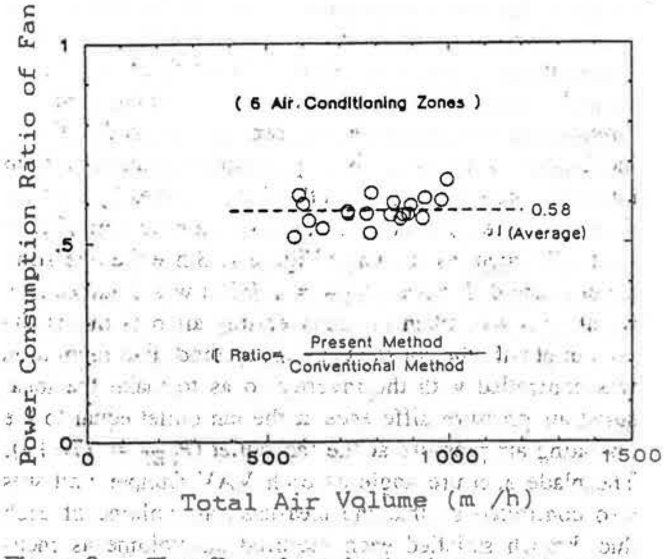

Figure 8 *The effect of a reduction in power consumption.*

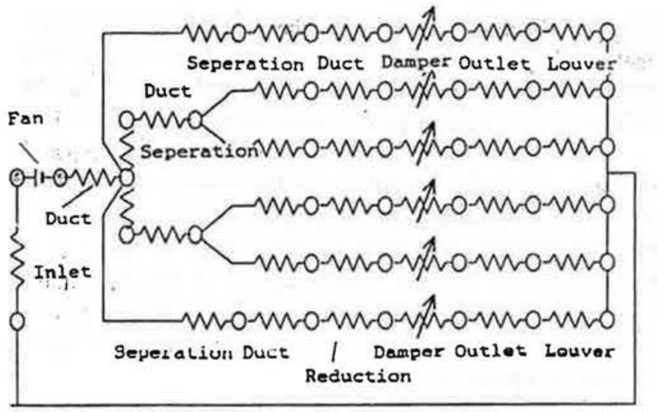

Figure 9 *Analytical model.*

The power consumption ratio was determined by using the following method for the analysis. The power consumption is proportional to the product of the total air volume and the total loss. Therefore, it is proportional to the total loss at the constant air volume. As explained previously, the required air volume for each duct branch (Q_i) in the analysis was determined by generating the same six random numbers for both control methods. Therefore, the air volume for all sets of random numbers is the same for both control methods. Consequently, if the pressure differences (dP_1, dP_2) between the inlet and outlet of the indoor fan are calculated for both control methods, the power consumption ratio can be estimated as the ratio of the pressure differences and can be ascertained by using the following equation:

$$\text{Power consumption ratio} = dP_2/dP_1.$$

Results of Analysis

Figure 10 shows the arithmetic means of the analytical results of the power consumption ratio versus the number of operating zones and comparison between them and their experimental values. In the figure, O indicates the experimental values and ● the calculated values. The trend of proportional increase of power consumption in accord with the number of operating zones is the same for both control methods, and the values are identical with three to six operating zones. When a small number of zones (one or two) are studied, however, there is a remarkable difference—that is, the calculated values of the power consumption ratio are much smaller than the measured values. This is presumed to occur because the analysis took only the ratio of pressure difference between the inlet and outlet of the fan into account, as mentioned above.

Next examined was how much the extent of differences in airflow resistance in each duct branch would affect the reduction in power consumption of the indoor fan. It has been a common procedure in the planning, design, and installation of ductwork to adjust the airflow resistance of each branch in order to get a balance of air volumes in each branch. From considerations in the previous paragraph, however, this procedure may not always be necessary when the control method proposed here is employed.

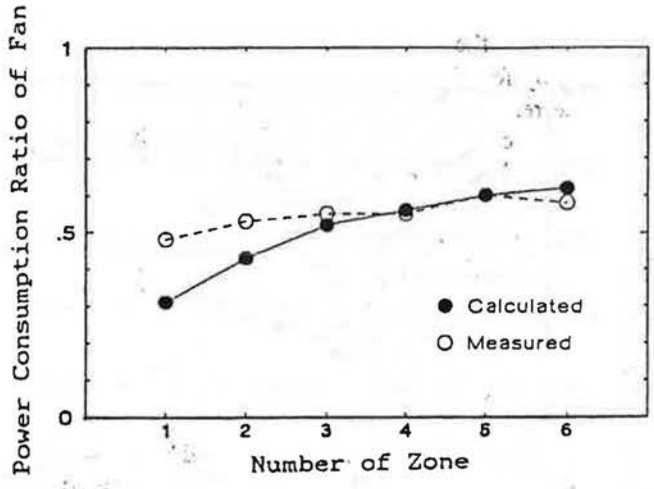

Figure 10 *Number of operating zones and power consumption.*

The fixed part of the airflow resistance, which consists of the friction loss and structural resistance in each duct branch, is changed intentionally in the duct structure analysis model, as shown in Figure 10, to study how much it affects the reduction in power consumption. Figure 11 shows the arithmetic means of power consumption ratio versus the number of operating zones, where the parameter is the resistance ratio that indicates the extent of the deviation of resistance in each duct branch. "Resistance ratio" means the ratio of the maximum value (R_{max}) and the minimum value (R_{min}). (This means R_{min}/R_{max} of the fixed resistance coefficient, R_i, of each duct branch.) In this case, the fixed resistance coefficient (R_i) for the remaining

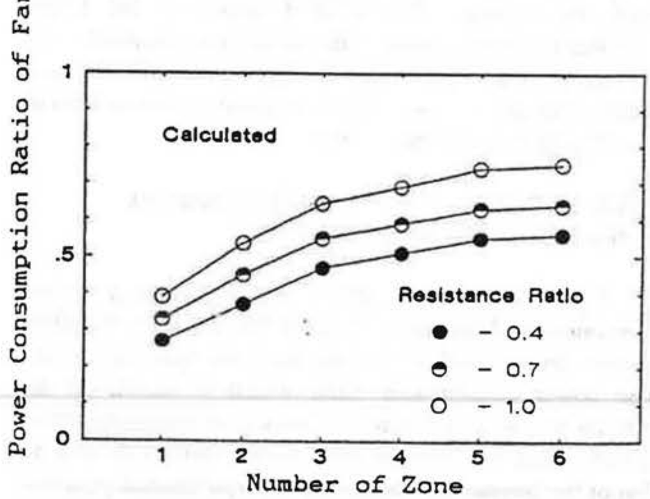

Figure 11 *Airflow resistance ratio and power consumption.*

four routes of the branch duct is set at a value divided internally by four between R_{max} and R_{min}. As a result, the larger the resistance ratio (the value of 0 to 1), the larger the deviation of airflow resistance of each duct branch, and R_i becomes identical when $R_r = 1$. Figure 11 shows that the trend of proportional increase with the number of operating zones is not dependent on the resistance ratio. There is, however, an apparent tendency of increased power consumption in accord with the increase in the resistance ratio.

CONCLUSION

The following conclusions are obtained by the study of the new air volume control method presented in this paper.

1. It is confirmed that each measured air volume is in accord with a corresponding required air volume within the range of deviation of 10% and that the air volume control method functions effectively.

2. It is confirmed that the power consumption of the indoor fan can be reduced with this control method by 50% from that of the method of constant control of air pressure at the fan outlet.

3. It has been learned that the trend of proportional increase in the number of operating zones is independent of the resistance ratio. There is, however, an apparent tendency of increased power consumption in accord with an increase in the resistance ratio.

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