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AIR FLOW RATE VARIATION OF HVAC CAUSED BY STACK EFFECT AND OPENING A WINDOW

by S. Hayakawa, S. Togari

Kajima Institute of Construction Technology
No. 19-1, Tobitakyu 2 Chome, Chofu-shi, Tokyo-182, JAPAN
Cable Address: KAJIMAINST TOKYO CHOFU
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Summary

Unopenable fixed windows have been widely used in high-rise buildings ever built in Japan because of their relatively low cost, excellent quality in water tightness and danger prevention. Good controllability or stability of HVAC system is also obtained adopting this type of windows.

The energy crisis, together with the occupants' desire for free contact with outdoor air, has made a chance to recognize its demerits; Japanese climate enables us to maintain rooms in considerably good conditions for several months in spring and autumn without operating cooling or forced ventilation system, only if there are some openings of adequate area at the outside walls. Opening the windows in high-rise buildings, however, has many demerits. One of them is that to open windows in winter causes air flow rate variation of HVAC due to stack effect.

In this paper the computer simulation results on this problem are reported with some cases of HVAC systems.

Key Words: Computer simulation ; Tall building ; Stack effect ; Openable window ; HVAC system ; Pressure distribution

※ Senior Reseach Engineer of Kajima Institute of Construction Technology, Kajima Corporation
※※ Reserch Engineer of Kajima Institute of Construction Technology, Kajima Corporation

I. INTRODUCTION

The authors have made a study on the feasibility of the natural ventilation in high-rise building, as a result of which it has been shown that room air condition will be kept comfortable by natural ventilation in calm weather, only if effective area of openable window is 0.7% or more of the typical floor area[1].

What variation of pressure and air flow rate will be caused by opening the window in winter when it is strictly prohibited, however, must be also studied.

So, the authors have developed a new computer program by which air flows for all possible paths in a building like ducts, shafts, orifices and cracks are calculated simultaneously and immediately. Computer simulation using this program has been repeated as a clue to explain how opening the window influences the pressure and air flow rate of HVAC.

Many studies on the stack effect have been made in Canada and U.S.A. these ten years. Especially the reports written by G.T. TAMURA, A.G. WILSON[2] and R.E. BARRETT[3] show many important data and informations.

In these reports, however, leakage area of exterior wall is calculated equally all over the wall, so there is no partially big opening like a window in the example building. And as to the HVAC system, though the performance of fans is considered, they do not take into consideration the detailed pressure loss or air flow rate calculation of ducts, especially at the joint or branch points of ducts.

So, they do not always present the sufficient data for the subject studied in this paper.

The special features of this simulation are;

1) The example building has the popular HVAC system and duct layouts designed by equal friction method. And pressure loss and air flow rate in

the ducts including joint and branch points are calculated in detail.

2) In order to study the relation between stack effect and HVAC system, both Individual HVAC System and Central HVAC System are examined.

3) To examine the influence of the opening place, air flow rate variation is calculated when a window is opened in a large room or in a small room.

4) The relation between the area of opening window and pressure or air flow rate variation is also studied.

II. DEVELOPMENT OF THE PROGRAM

The authors have developed a computer program by which air flows for all possible paths in a building including duct network are calculated. This program uses iterative method and at the first step of calculation pressures at each point in the building and ducts are assumed. Fig. 1 shows the block diagram of the program.

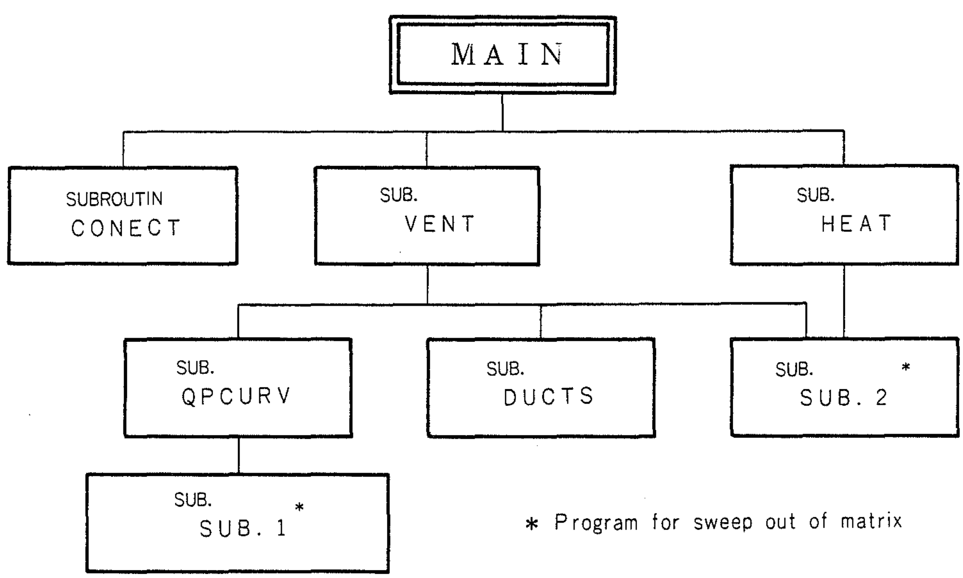


Fig. 1 Block Diagram of the Computer Program

SUBROUTINE CONNECT makes the matrix showing the connective state of every node and branch using 1, 0, -1.

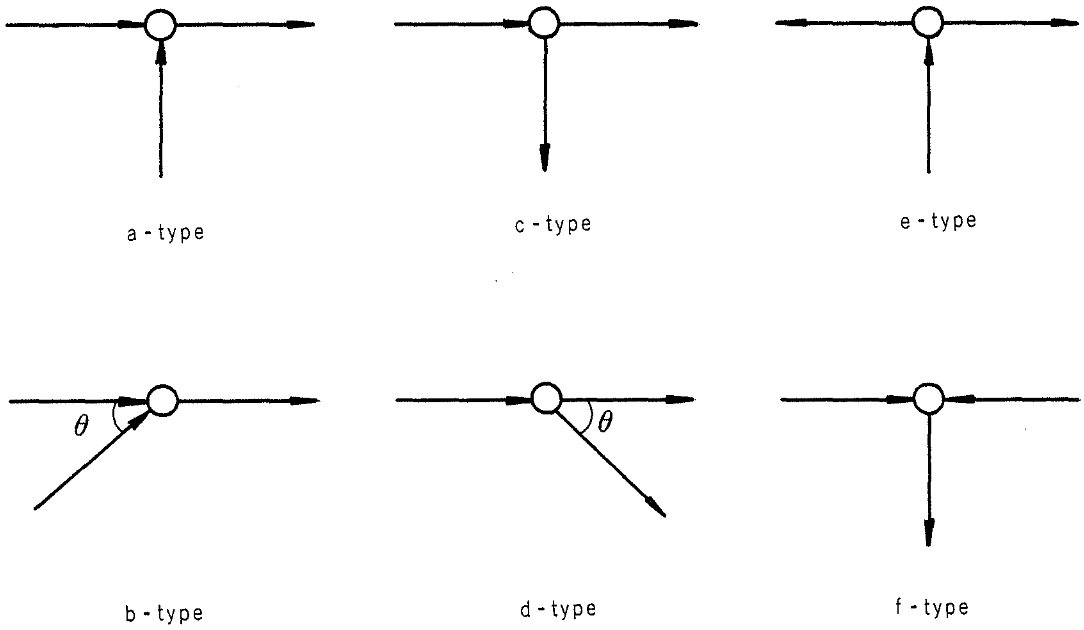
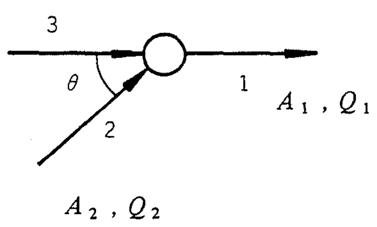


Fig. 2 Joint and Branch Types Considered in the Program

SUBROUTINE QPCURV gives the performance curves equation by the least square method. By this curve an operating point is selected.

SUBROUTINE DUCTS calculates the flow resistance at the joint or branch point of the duct. The paterns of joint and branch prepared in the program are 6 types shown at Fig. 2. Pressure loss equations are reffered to the reports of the JASME[4) and Gardel's equation.

For example, at the b-type.



A_i : Area of duct i (m^2)

Q_i : Air flow rate at duct i

m : A_1 / A_2

ζ : Coefficient of friction loss

Fig. 2-2 ζ of the b-type

$$\zeta_{31} = (1.62 - 0.37\cos\theta)\frac{Q_2}{Q_1} - (0.79 + 1.23\,m\cos\theta + 0.28\,m\sin\theta)\left(\frac{Q_2}{Q_1}\right)^2$$

with limited conditions in case $m = 1 \quad 45° < \theta < 135°$

$m \fallingdotseq 1 \quad \theta = 45°,\ 60°$

$$\Delta P_{31} = \zeta_{31} \bullet \frac{\gamma}{2g}\left(\frac{Q_1}{A_1}\right)^2$$

$$\zeta_{21} = -1 + (3.7 - 0.46\cos\theta)\frac{Q_2}{Q_1} + (m^2 - 2 - 1.02\,m\cos 0.9\theta - 0.36\,m\sin 0.9\theta)\left(\frac{Q_2}{Q_1}\right)^2$$

without limited conditions

$$\Delta P_{21} = \zeta_{21} \bullet \frac{\gamma}{2g}\left(\frac{Q_1}{A_1}\right)^2$$

SUBROUTINE VENT calculates the air flow rate of each branch with equation $Q = A\Delta P^{\frac{1}{n}}$, SUBROUTINE QPCURV and DUCTS.

SUBROUTINE HEAT calculates the node temperature when heat products exists in the node. But it does not consider heat transmission through the wall or heat storage.

Required input data of air flow paths are effective area αA and coefficient n in the next equation.

$$Q = \alpha A \Delta P^{\frac{1}{n}}$$

III. EXAMPLE BUILDING

The example building is 30 stories. Its height above ground is 119 m to the roof. The internal dimensions of a typical floor are 24 x 48 m and a 3.8 m height between floors. A stairway, elevators and various services are located at both sides of the building. This plan is most convienient to the natural ventilation [1] and able to provide a sure escape route in case of fire. Fig. 3 shows a half of typical floor. It is symmetric with respect to the ℄ axis. Based on the assumption of no wind, air flow rate is calculated in this half area.

For analysis, it is convenient to devide a building into multi-story zones based on the design of both the building and the HVAC-system.
Fig. 4 shows the zones of the building with the individual HVAC system and the building with the central HVAC system is shown in Fig. 5. In the later case, the building is divided into a total of 20 spaces consisting of 5 occupied zones, 1 shaft and 14 nodes of air ducts. Elevator shafts and a stairway are also combined into one composite shaft.

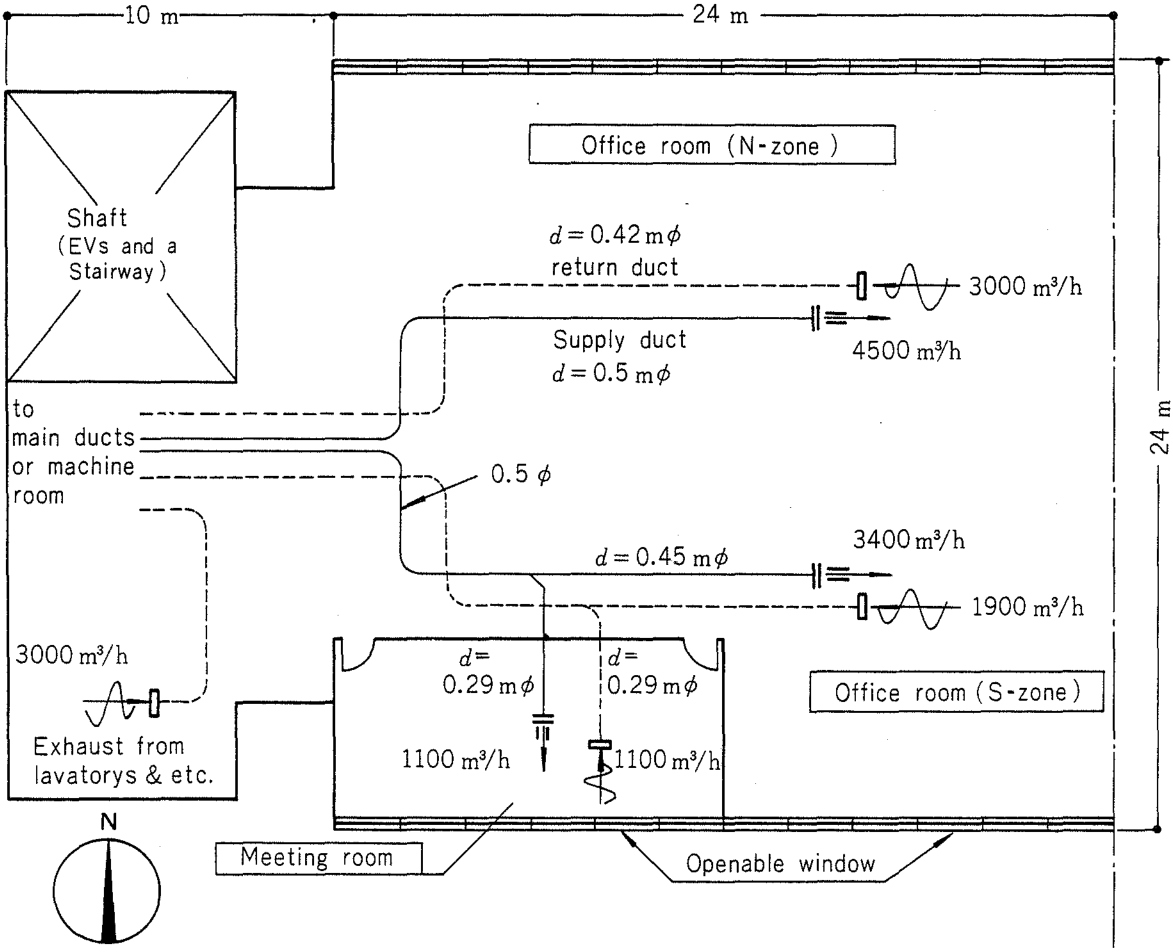


Fig. 3 Typical Floor Plan and Duct Network of the the Example Building

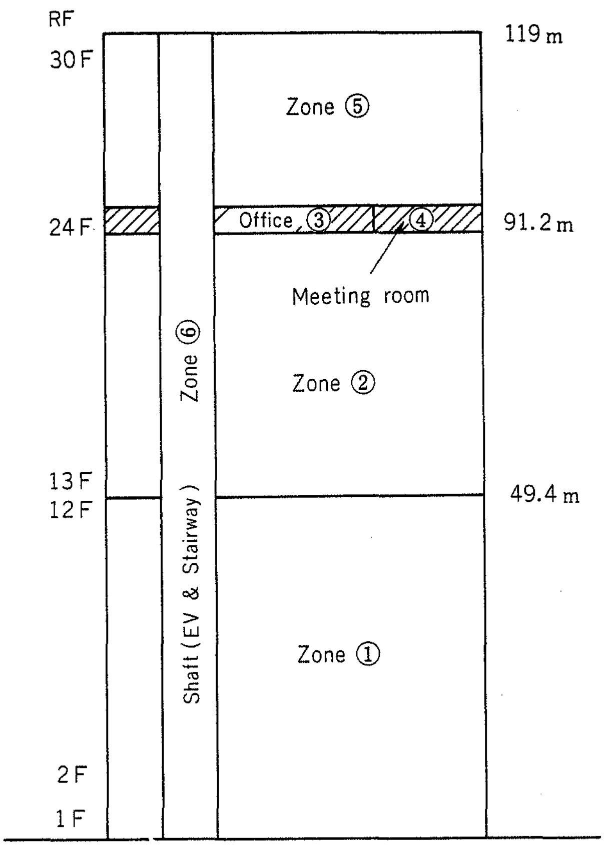


Fig. 4 Example Building with the Individual HVAC System and Its Zones

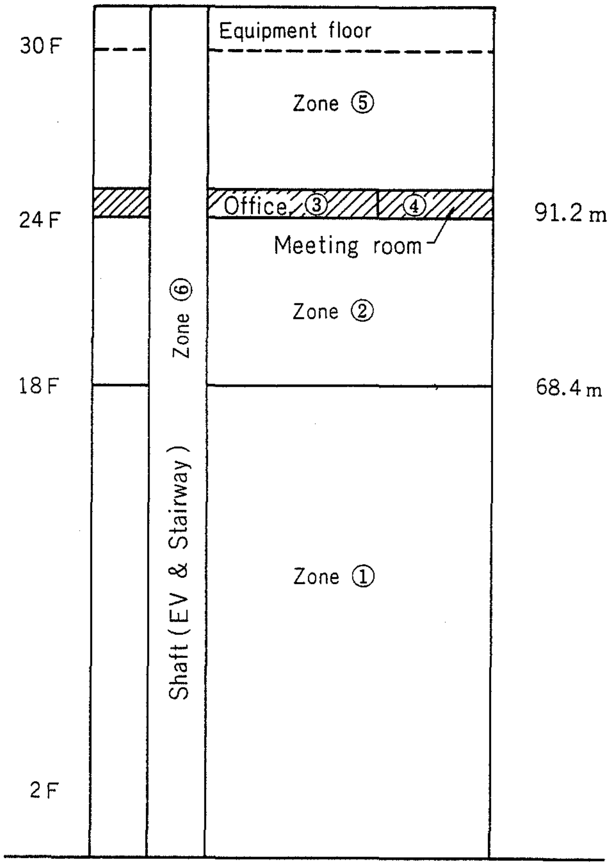


Fig. 5 Example Building with the Central HVAC System and Its Zones

The 24th story is an example floor and a window is opened in a small room or in a large room.

IV. BUILDING CHARACTERISTICS ALONG AIR-FLOW PATHS

1. Air leakage characteristic of the exterior wall is assumed as follows.

$$Q = 0.22A\,\Delta P^{\frac{1}{1.26}} \qquad (1)$$

where A : outside wall area (m^2)

Q : air leakage (m^3/h)

By the equation (1), Q=0.06 cfm/f^2 is got when ΔP is 0.3 inches of water pressure differential.
So, this is a rather tight wall.

2. Elevator door and stairway door peripheral crack area

2EV shafts	door closed 2 x 0.045 m^2/1 door
1 stairway shaft	door closed 1 x 0.018 m^2/1 door
	Total 0.108 m^2/1 floor

At the ground floor, 1 EV door opens and its effective area is 0.5 m^2.

3. Leakage area for interior doors: 0.018 m^2 (0.2 ft^2) per door.

4. Entrance door is kept open by 4.0 m^2.

5. Leakage area of shaft wall at the roof top is 0.1 m^2.

6. Effective area of an opening window

The openable window is a type of flaps hinged bottom. And the dimensions of unit window are 0.6 m (H) x 1 m (W). Flow coefficient of this window is about 0.5. So the maximum effective area of the opened window is 0.5 x (0.6 x 1) = 0.3 m^2. Therefore the calculation is made in the region of 0.0 ~ 0.3 m^2, but in some cases air flow rate and pressure are calculated at 0.8 m^2 and 1.6 m^2, too.

The values described above are reffered to the papers written by G. T. TAMURA and R. E. BARRETT.

V. HVAC-SYSTEM CHARACTERISTICS

Fig. 3 shows duct layouts at the typical floor. They are all round ducts and the connection angles at the joint or branch are all 45°. They are designed by equal friction method (0.1 mmAq/1.0 m).

The coefficient of pressure loss at inlets or outlets of the room is decided so that the pressure may be lost by about 3 mmAq. As to the air handling unit, pressure loss is about 40 mmAq. Even if the duct layout is decided by any design method, air flow rates in the ducts will not become the design value, when fan systems are on. Especially the central HVAC system has a such tendency. After the first simulation with closed window case, therefore, the coefficients of friction loss are slightly added or subtracted so that they may get near to design values.

Supply air volume to the typical floor is 9000 m^3/h, which consists of 6000 m^3/h return air and 3000 m^3/h exhaust (= fresh air volume). The air change rate is about 6 times. Duct system consists of 3 lineages. They are two duct systems of HVAC for a north zone and a south zone of the floor and

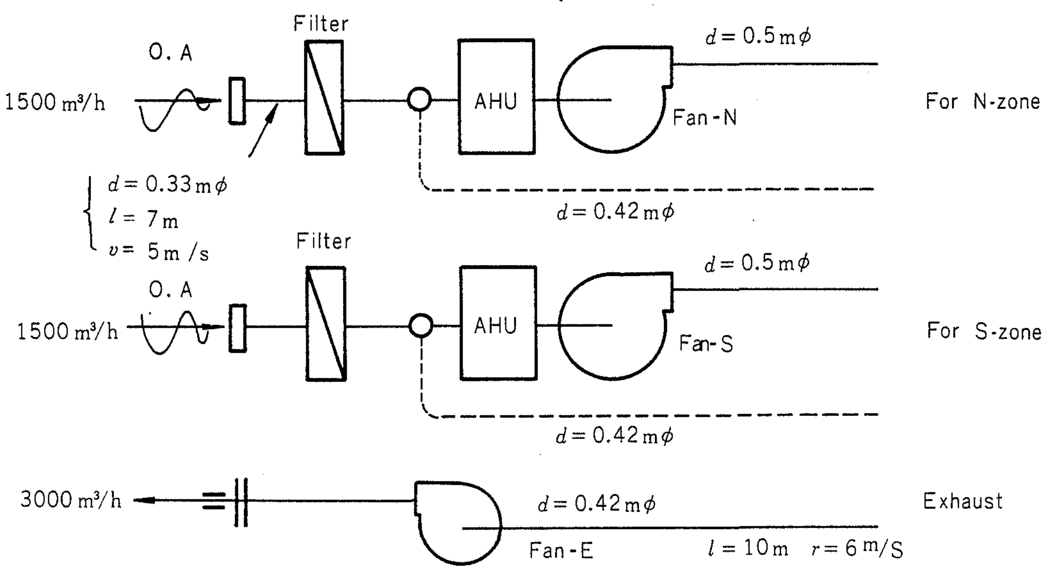


Fig. 6 Duct Network around Fans and Air Handling Units of the Individual HVAC System

a duct for exhaust. In case of the individual HVAC system, Fan-N, Fan-S and Fan-E are equipped as shown in Fig. 6. Inlet and exhaust openings are in the exterior wall of this floor. In case of the central HVAC system, as shown in Fig. 7, main ducts from the equipment floor are connected. Fan-N', Fan-S' and Fan-E' located at the 30th floor serve the zones on and above 18th floor.

Fig. 8-1, -2 show the performance curves of every fans.

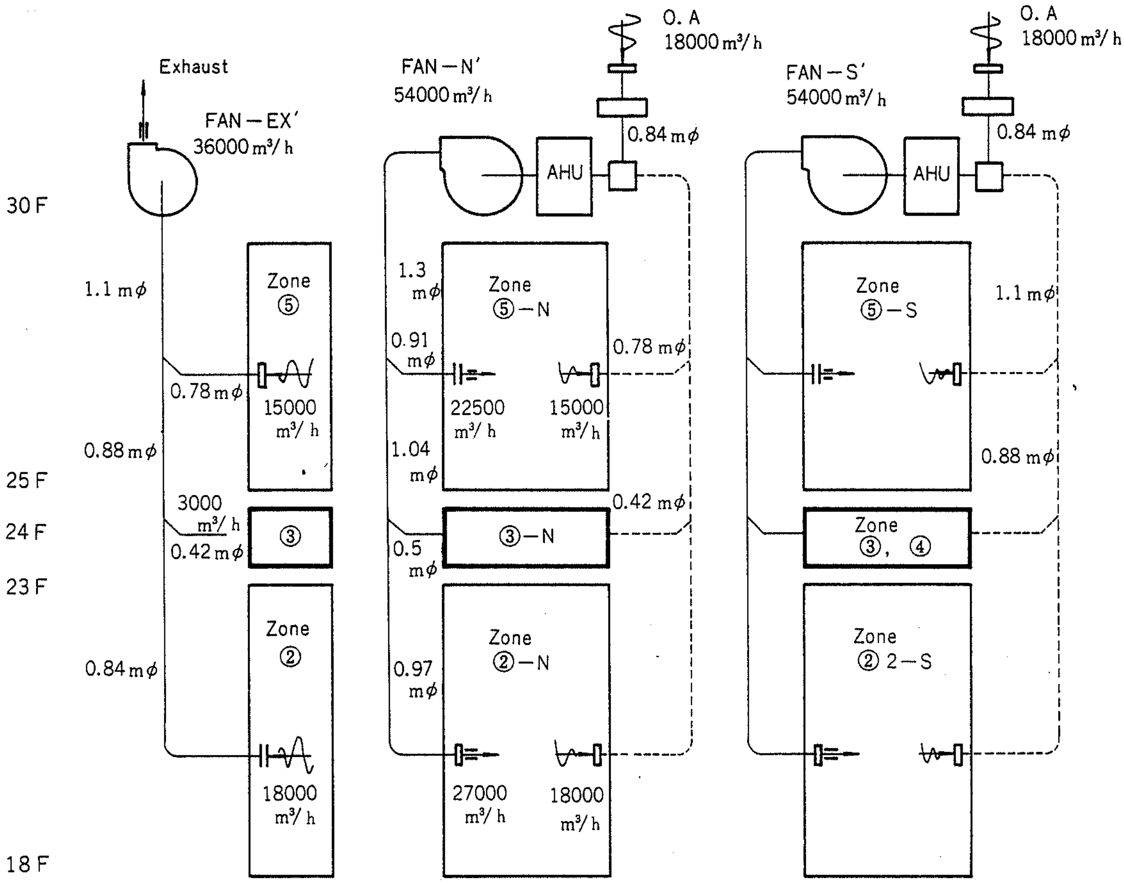


Fig. 7 Duct Networks of the Central HVAC System

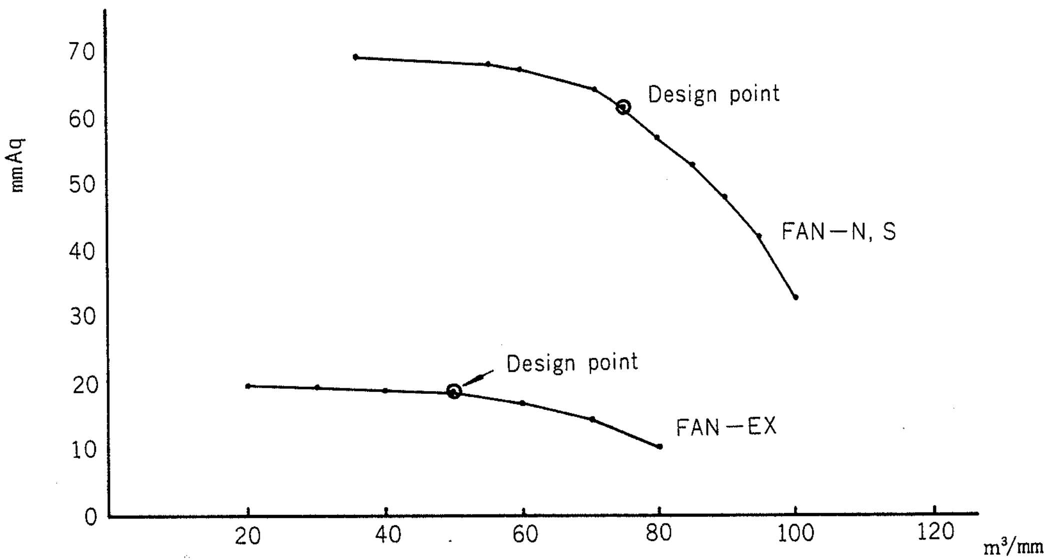


Fig. 8-1 Performance Curves of Fans Used at the Individual HVAC System

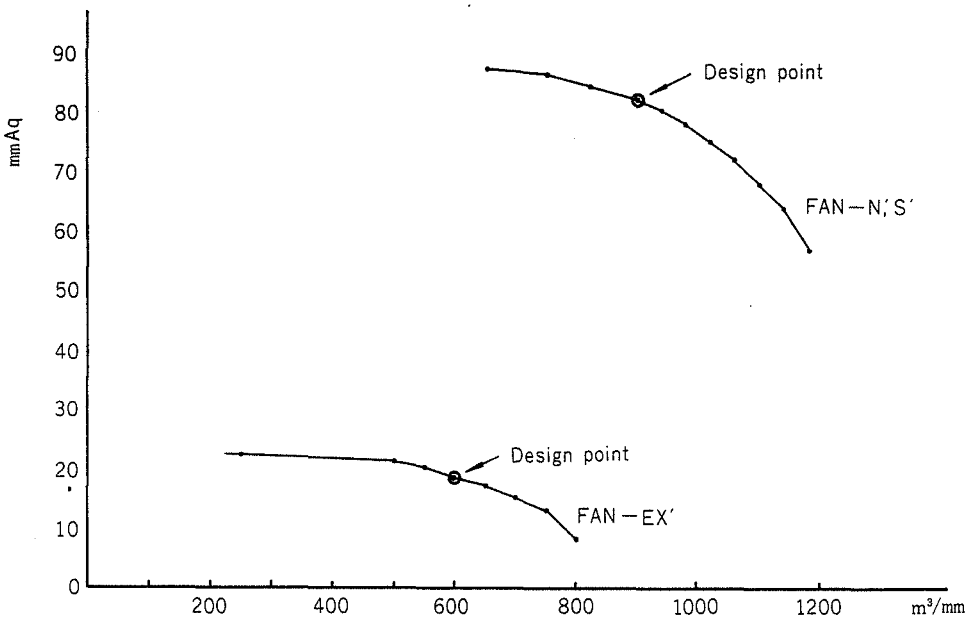


Fig. 8-2 Performance Curves of Fans Used at the Central HVAC System

VI. CASES EXAMINED

Factors for the cases examined are HVAC system, the place where window is opened and effective area of the opened window. Table 1 shows the cases examined. In all cases, temperature in the building is 22°C (72°F) and outdoor temperature is 0°C (32°F). Wind effect is not taken into consideration.

Table 1 Cases Examined

System / Place	Individual HVAC System	Central HVAC System
Meeting room's window	αA = 0.05, 0.10, 0.20, 0.3, 0.40, 0.80, 1.60	αA = 0.025, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35
Office room's window	αA = 0.05, 0.10, 0.20, 0.3, 0.40, 0.80, 1.60	αA = 0.05, 0.10, 0.20, 0.30

αA = effective area of the opened window (m^2)

VII. RESULTS OF ANALYSIS FOR EXAMPLE BUILDING

(1) Individual HVAC System

CASE-1 - opening a window in the meeting room -

Fig. 9 and 10 show ΔP and air flow rate variation at the example floor caused by opening the meeting room's window. According to those figures, the pressure difference between the meeting room and outdoor decreases rapidly as the opening's area increases.

Therefore, this pressure difference becomes to be taken across the interior wall between the office and the meeting room. When opening area of window becomes over 0.4 m^2, pressure differences among every node and zone attain equilibrium. So, the leakage rate of leak air through the opened window, air flow rates through the cracks in the building and in the ducts become constant.

Supply air volume to the meeting room increases by 53% of design value, while return air decreases by 42% of that.

Supply air to the south zone of office room decreases by 580 m^3/h (design value: 3400 m^3/h), which is equal to the amount of increase of supply air volume for the meeting room.

N-zone duct system and exhaust air volume are scarcely influenced.

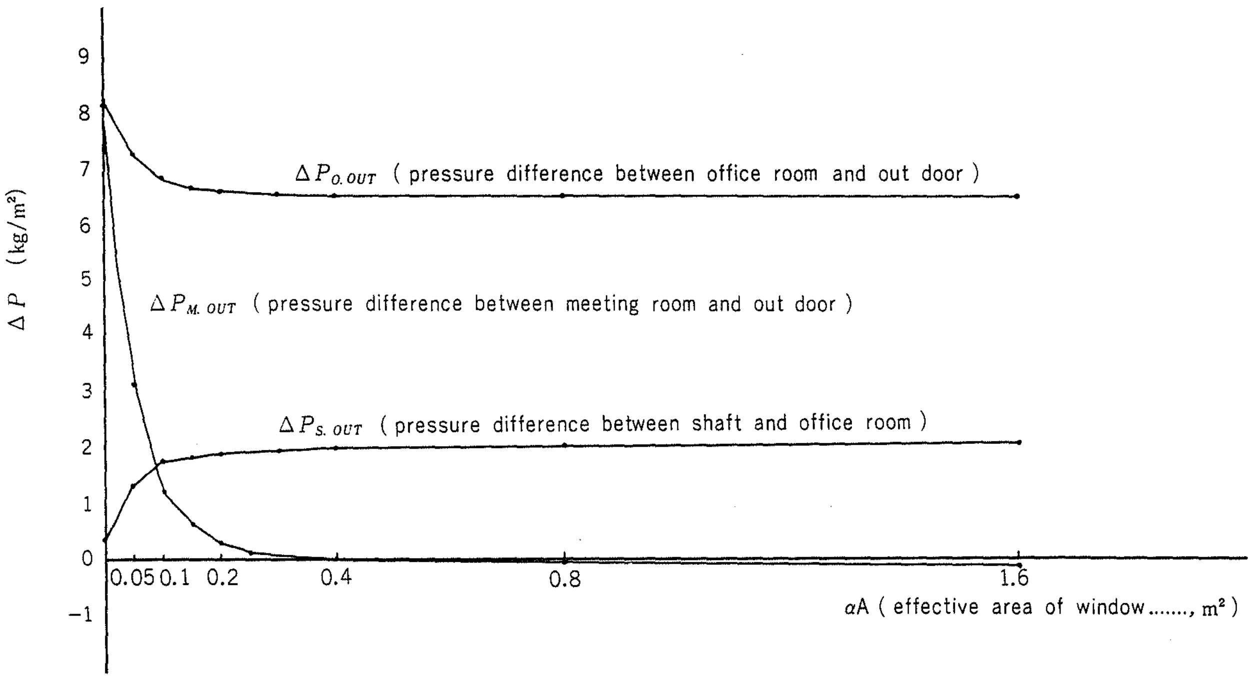


Fig. 9 ΔP Variation Caused by Opening the Meeting Room's Window at the Individual HVAC System

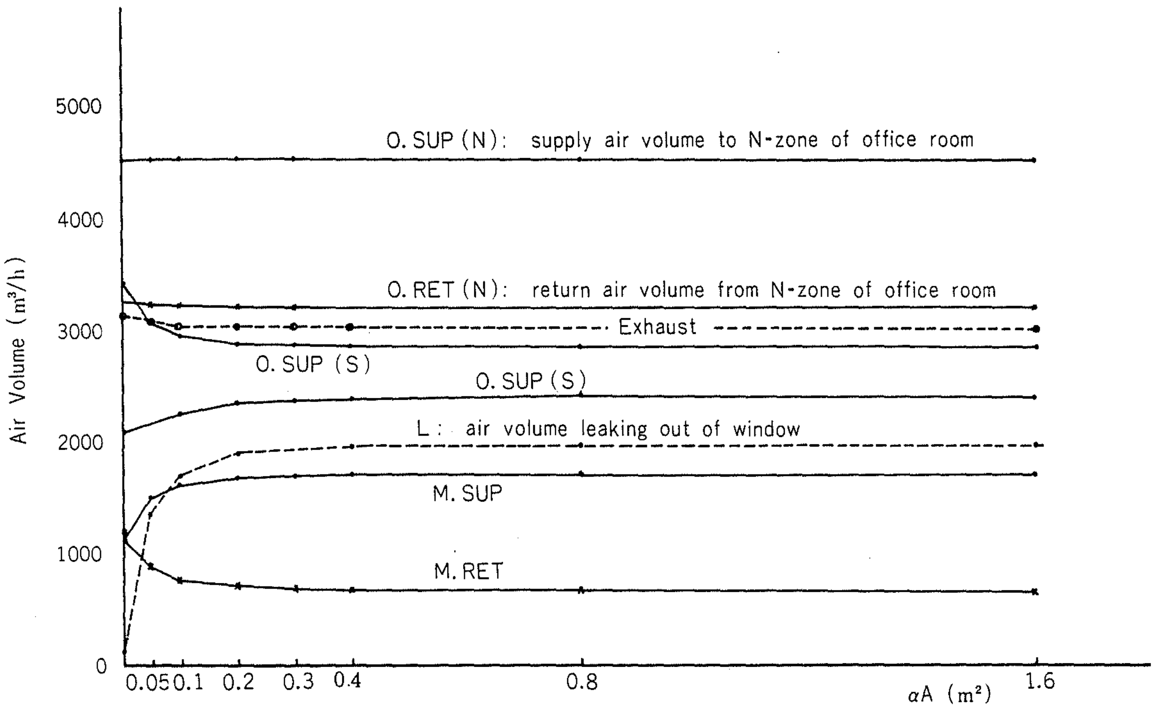


Fig. 10 Air Flow Rate Variation Caused by Opening the Meeting Room's Window at the Individual HVAC System

CASE-2 - opening a office room's window -

Fig. 11 and 12 show ΔP and air flow rate variation at the example floor caused by office room's window's being opened. Pressure difference across the outside wall decreases more slowly than that of the former case. It is a distinctive feature that there is scarcely pressure difference across the interior wall, and the pressure on the outside wall shifts on the shaft wall. Leak air volume out of the window is about 2.5 times of that in the former case. This difference occurs because there is no pressure buffer zone between the shaft and the office room.

(2) Central HVAC System

CASE-3 - opening a meeting room's window -

Fig. 13 shows ΔP and air flow rate variation caused by opening the meeting room's window. Comparing with the Case 1, every air flow rate varies more widely. At the joint point of the return ducts serving the meeting room and office room (S-zone), air flow rate of each duct varies very delicately, because coefficient of pressure loss of a branch duct from the meeting room becomes less than 0.0. Generally speaking, in the region of certain ratio of the main duct's air volume to the branch duct's air volume, pressure loss coefficient easily become under zero.

So, the return air volume of the meeting room does not decrease smoothly. It affects the leak air volume, too. It may happen that the air flows out of the inlet of a return duct inversely. In this case, the duct system for the N zone of the office room is not influenced.

CASE-4 - opening a office room's window -

The variation of ΔP and air flow rate are shown in Fig. 14. Pressure of the office room becomes lower than that of the meeting room. As the office room is connected with the shaft wall almost directly, the pressure of this room is easily affected by stack effect like in case-2.

Leak air volume out of the opened window increases rapidly. Supply and return air serving the office room, therefore, vary most widely in all cases.

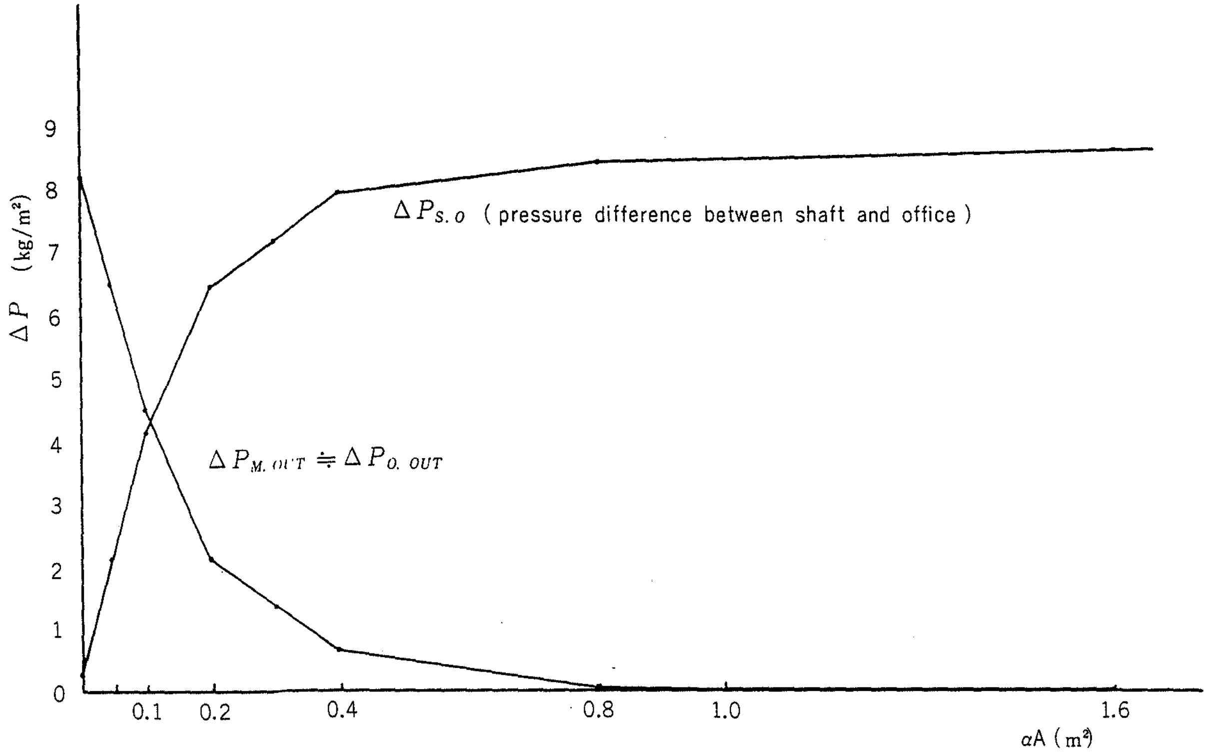


Fig. 11 ΔP Variation Caused by Opening the Office Room's Window at the Individual HVAC System

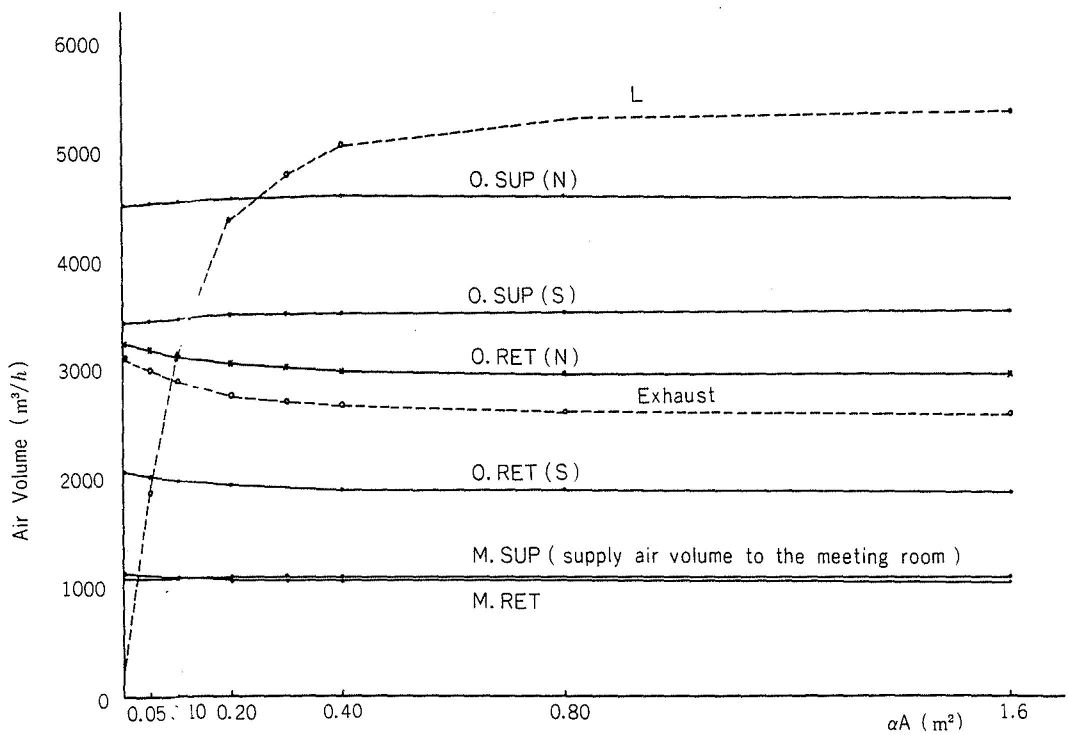


Fig. 12 Air Flow Rate Variation Caused by Opening the Office Room's Window at the Individual HVAC System

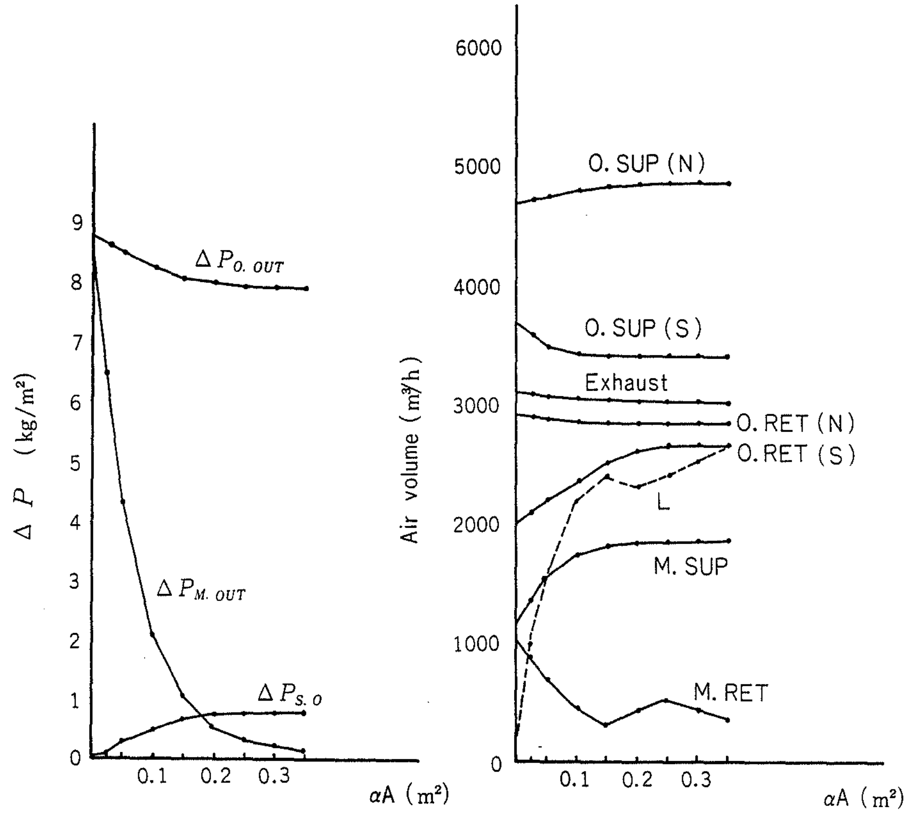


Fig. 13 ΔP & Air Flow Rate Variation Caused by Opening the Meeting Room's Window at the Central HVAC System

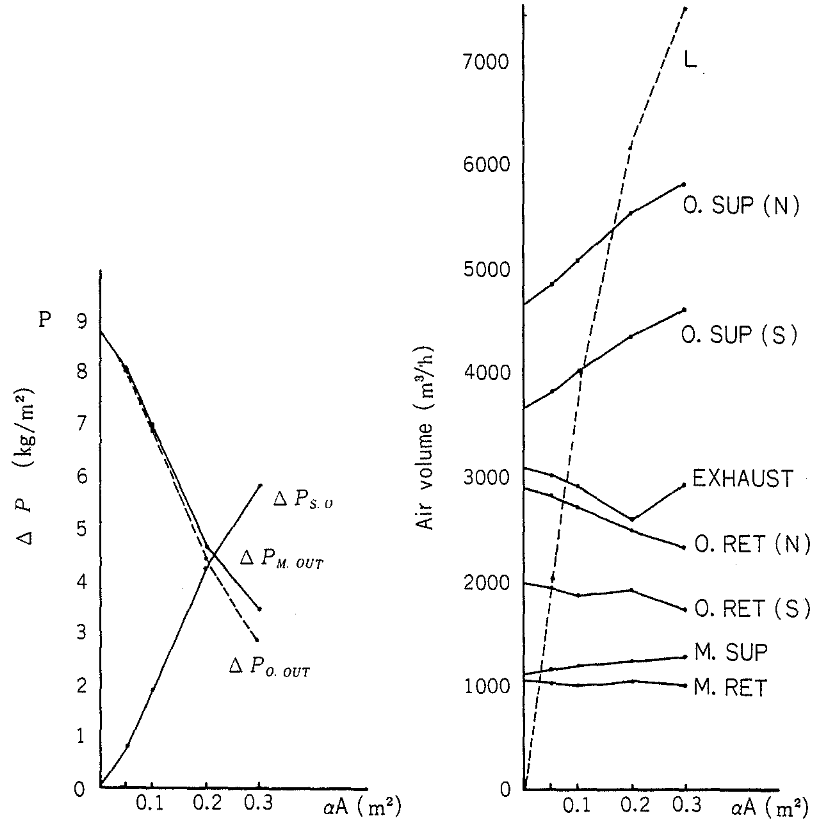


Fig. 14 ΔP & Air Flow Rate Variation Caused by Opening the Office Room's Window at the Central HVAC System

And about a half of leak air volume is supplied through the crack of the shaft wall and meeting room's door.

VIII. CONCLUSION

1. HVAC SYSTEM

(1) Variation of Air Flow Volume

Table 2 shows variations of air flow rate in ducts in all cases, in which effective area of the opened window is 0.3 m^2. Table 3 shows variations of outdoor air volume which are taken in by fans.

Table 2 Air Flow Rate Variation Caused by Opening a Window (αA = 0.3 m^2)

			Normal Condition	Meeting room's window open	Office room's window open
Individual HVAC System	Meeting room	Supply	1080 m^3/h	+53 %	+ 1 %
		Return	1140	-42	- 7
	Office room	Supply	7840	- 7	+ 2
		Return	5270	+ 4	- 6
		Exhaust	3070	- 3	-14
	Leakage through the window		-	(1900 m^3/h)	(4730 m^3/h)
Central HVAC System	Meeting room	Supply	1100	+65 %	+15 %
		Return	1040	-59	- 6
	Office room	Supply	8250	- 2	+25
		Return	4840	+12	-17
		Exhaust	3050	- 2	- 5
	Leakage through the window		-	(2480 m^3/h)	(7400 m^3/h)

Table 3 Variations of O. A Intake through Fans Caused by Opening a Window (αA = 0.3)

		Normal condition	Meeting room's window open		Office room's window open	
Individual HVAC System	N-zone	1140 m³/h	1210 m³/h	+ 6 %	1440 m³/h	+26 %
	S-zone	1190	1340	+13	1470	+24
	Total	2330	2550	+ 9	2910	+25
Central HVAC System	N-zone	17950	17890	0	18140	+ 1
	S-zone	17960	18020	0	18240	+ 2
	Total	35910	35910	0	36280	+ 1

From these tables, some features of both systems are as follows.

a. In all cases, though air flow rate varies at each path, the fan driving points scarcely move. This reason is that at the individual HVAC system, the decrease of return air volume causes the increase of 0. A intake by fans, and at the central HVAC system the flow variations of the examined floor are compensated by variations of the supply, return and exhaust air of other floors.

The total supply air volume for the examined floor does not change at the individual HVAC. While, it increases by 6% (in case of opening the meeting room's window) ~ 24% (in case of opening the office room's window) at the central HVAC system.

b. At the individual HVAC, air flow rate in every path becomes constant when opened area is over 0.3 ~ 0.8 m^2. While, at the central HVAC, it does not become constant, but continues to vary as the opened area increases. For example, the amount of leakage through the opened window at the central HVAC is about 1.3 ~ 1.5 times of the amount at the individual HVAC.

(2) Variation of Pressure Difference

Table 4 Variation of Pressure Differentials Caused by Opening a Window

		Normal condition	Meeting room's window open	Office room's window open
Individual HVAC System	ΔP_{SO}	kg/m² 0.25	kg/m² 1.93	kg/m² 7.02
	ΔP_{OM}	0.12	6.39	0.00
Central HVAC System	ΔP_{SO}	0.01	0.80	5.75
	ΔP_{OM}	0.00	7.59	-0.61

where

P_{OUT} : pressure of out door

P_O : pressure of the office room

P_M : pressure of the meeting room

P_S : pressure in the shaft

ΔP_{SO} : pressure difference between the shaft and the office room ($= P_S - P_O$)

ΔP_{OM} : pressure difference between the office and the meeting room ($= P_O - P_M$)

$\Delta P_{O \bullet OUT} = P_O - P_{OUT}$

$\Delta P_{M \bullet OUT} = P_M - P_{OUT}$

Variations of pressure difference in all cases examined, in which the opening area is 0.3 m^2, are shown at Table 4. For both kinds of the HVAC system, no remarkable difference was found. However, ΔP_{SO} is somewhat larger at the individual HVAC than at the central HVAC.

$$\Delta P_{SO}(I) > \Delta P_{SO}(C)$$

And ΔP_{OM} is somewhat smaller at the individual HVAC than at the central HVAC.

$$\Delta P_{OM}(I) < \Delta P_{OM}(C)$$

These are explained as follows: in the individual HVAC system room pressures and flow rates of all paths become constant more rapidly than they do in the central HVAC system. Thus, amount of $\Delta P_{O \bullet OUT}$ (I) variation is larger than amount of $\Delta P_{O \bullet OUT}$ (c) variation.

$\Delta P_{SO} \fallingdotseq$ amount of $\Delta P_{O \bullet OUT}$ variation because there is no pressure buffer zone between office and shaft.

By these equation and inequalities,

$$\Delta P_{SO}(I) > \Delta P_{SO}(C)$$

Then,

$$\Delta P_{OM} = \Delta P_{O \bullet OUT} - \Delta P_{M \bullet OUT}$$

$$\Delta P_{M \bullet OUT}(C) \fallingdotseq \Delta P_{M \bullet OUT}(I)$$

$$\Delta P_{O \bullet OUT}(C) > \Delta P_{O \bullet OUT}(I)$$

$$\therefore \Delta P_{OM}(I) < \Delta P_{OM}(C)$$

2. Rooms with Opened Window

(1) Variation of Pressure Difference

When a window is opened in a large office room, inner pressure of every room on that floor drops at the same rate. So, there are no large pressure differences across the interior walls and doors. But the ΔP_{SO} becomes rapidly large because there is no pressure buffer zone between the office room and shafts.

While, in case of the small meeting room, the pressure on the exterior wall shifts to act on the interior wall.

Therefore, when an openable window is adapted to a tall-building, one must know how to release the pressure.

In this simulation model, the problem will be easily solved by putting a small opening of grill shape on the interior door.

(2) Variation of Air Flow Volume

When a window is opened in the small meeting room, supply air rate of this room increases and return air rate decreases.

Consequently, supply air rate decreases and return air increases respectively in the adjacent office room. But, in case of opening a window in the office room, air flow rates of the ducts change at the same tendency in both rooms. This phenomenon can be explained through the same way as in the above case.

Opening the window in a small room causes the pressure drop of the examined room, but opening the window in a large room causes the pressure drop of the total floor.

(3) Leakage Through the Opened Window

The amount of leakage in the office room is about 2.5 to 3 times of that of the meeting room. It reaches about 7410 m^3/hr with the central HVAC system.

As there is no pressure buffer zone between the shaft and the office room, a large amount of air flows into the office through cracks around doors of elevators and stairways.

To prevent this phenomenon, elevator shafts and stairway shafts should be isolated from the occupied zone.

Generally speaking, the central HVAC system is thought more disadvantageous than the individual HVAC system owing to the buoyancy in the vertical duct. But in this simulation the air flow rate variation is affected by the scale and complexity of the duct layout. In other words, the stability of air flow rate balance in the ducts or a building owes to how the values of variation are made up for.

The authors conclude from the simulation described above that if the individual HVAC system is equipped and if at a small room the window is opened, there will be no serious problem. And the individual HVAC system should be equipped in high-rise buildings.

To study air flow rate variation of HVAC caused by stack effect, the air flow calculation considering the flow resistance at joint or branch duct is necessary.

Especially, at the complex duct layout like central HVAC system, delicate pressure variation at a joint of duct affects the other air flow rates considerably.

But for the program including this calculation, it is not so easy to arrive at an acceptable solution. Therefore, it requires mathematical technique or ideas for convergency.

The error ϵ in this simulation is as follows.

CASE 1, CASE 2	$= 0.0005$		at all zones and nodes
CASE 3, CASE 4	$= 0.0005$	$(\alpha A \leqq 0.1)$	
	$= 0.01$	$(\alpha A \leqq 0.2)$	
	$= 0.02$	$(\alpha A \leqq 0.35)$	

where at one node

$$\epsilon = \frac{|\Delta G|}{Gi\,(or Go)}$$

Gi : sum. of entering air quantities

Go : sum. of leaving air quantities

$\Delta G = Gi - Go$

- o This program is run on HITAC M-180 (equivalent to IBM 370-168)
- o CPU TIME: in case of the individual HVAC system, 5 sec/a case
  : in case of the central HVAC system, 15 sec/a case
- o Numbers of steps: 1400
- o Language: Fortran

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