VENTILATION SYSTEM PERFORMANCE

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VENTILATION SYSTEM PERFORMANCE OF VERTICAL EXHAUST COMMON-DUCT IN A MULTI-STORY HOUSE

SHUZO MURAKAMI
KUNIO MIZUTANI*

Institute of Industrial Science
University of Tokyo
5-7-1 Roppongi, Minato-ku
Tokyo 106
Japan

HIROSHI YOSHINO

Department of Architecture
Faculty of Engineering
Tohoku University
Sendai 980
Japan

SHIN-ICHI AKABAYASHI

Department of Architecture
Faculty of Engineering
Niigata University
8050 Igarashi-Ninomachi
Niigata 950-21
Japan

KOU HASEGAWA

Technical Research Laboratory
Mitsui Construction Co., Ltd.
518-1 Komaki, Nagareyama-shi
Chiba 270-01
Japan

*Contract researcher from Sanken Setsubi Kogyo Co., Ltd.

SYNOPSIS

Ventilation performance of a vertical exhaust common-duct installed in a multi-story house was analysed using model experiment and computer simulation. Pressure losses at the flow junctions in the vertical common-duct were investigated using the model experiment. The pressure distributions along the vertical common-duct in three different multi-story houses of 5, 15 and 25 stories, respectively, were calculated by the computer simulation. The results are as follows:

(1) The pressure losses in the converging flow at the junctions in the vertical common-duct were expressed by approximate equations with two ratios, namely, the ratios of the velocity of airflow and the sectional area of the vertical common-duct to those values of the branch duct.

(2) The pressure loss in the converging flow at the junction through the vertical common-duct was positive in the case of the T-type junction. But the pressure loss in the case of the elbow-type junction was negative, which means that the elbow-type junction increases the pressure in the common-duct and may cause a reverse flow from the vertical common-duct to the apartments, especially those in the upper stories. Therefore, the T-type junction should be used in order to prevent such reverse flow.

(3) It is possible to keep the difference between the static pressure in the common-duct and the outside pressure small by controlling the rotational speed of the exhaust fan mounted at the top of the vertical common-duct.

List of symbols

A_1	:Sectional area of a vertical exhaust common-duct	[m^2]
A_2	:Sectional area of a branch duct	[m^2]
d_e	:Equivalent diameter of a rectangular duct	[m]
V_1	:Velocity of airflow through a common-duct before a junction	[m/s]
V_2	:Velocity of airflow through a branch duct	[m/s]
V_3	:Velocity of airflow through a common-duct after a junction	[m/s]
Q_1	:Volume of airflow through a common-duct before a junction	[m^3/h]
Q_2	:Volume of airflow through a branch duct	[m^3/h]
Q_3	:Volume of airflow through a common-duct after a junction	[m^3/h]
ζ_{13}	:Pressure loss coefficient in converging flow through a common-duct with a single junction	
ζ_{23}	:Pressure loss coefficient in converging flow from a branch duct to a common-duct with a single junction	
ζ_{13}'	:Pressure loss coefficient in converging flow through a common-duct with double junctions	
ζ_{23}'	:Pressure loss coefficient in converging flow from a branch duct to a common-duct with double junctions	
λ_s	:Friction loss coefficient through a common-duct	
ζ_e	:Pressure loss coefficient due to a elbow-type junction	
ζ_f	:Pressure loss coefficient due to a leg of the angle appeared inside of a common-duct	
ζ_{ex}	:Pressure loss coefficient of the outlet at the top of the common-duct	
ζ_{in}	:Pressure loss coefficient of the inlet at the bottom of the common-duct	
ΔP_r	:Pressure loss from the outside to the inside of an apartment through the envelop	[Pa]
ΔP_{df}	:Pressure loss from the inside of an apartment to the end of the branch duct connecting with a common-duct	[Pa]
Re	:Reynolds number of a common-duct	
P_s	:Static pressure (A difference from the atmospheric pressure)	[Pa]
P_1	:Total pressure in a common-duct before a junction	[Pa]
P_2	:Total pressure in a branch duct before a junction	[Pa]
P_3	:Total pressure in the common-duct after a junction	[Pa]
ΔP_{13}	:Total pressure loss in converging flow through a common-duct	[Pa]
ΔP_{23}	:Total pressure loss in converging flow from a branch duct to a common-duct	[Pa]
ν	:Coefficient of kinematic viscosity	[m^2/sec]
ρ	:Air density	[kg/m^3]

1. INTRODUCTION

The center-core-type apartment, which has a kitchen, a bath, a lavatory, and a laundry in the center area of the floor plan, is a popular type of multi-story apartment house in Japan from the viewpoints of daylighting and natural ventilation for the living room and bedrooms. Many types of mechanical systems have been employed for ventilation of this center-core area. Presently, a mechanical ventilation system with a horizontal duct installed in each apartment (individual ventilation system) is used in many multi-story houses. Prior to the use of this type of system, a mechanical ventilation system with a vertical exhaust common-duct connected with the branch ducts from apartments was popular. The reasons why this latter ventilation system became unpopular are as follows:

1) Unstability of exhausted air volume, which leads to the possibility of a reverse flow of odors from the vertical common-duct to individual apartments.

2) Disadvantages in building construction, including time needed for construction, and maintenance of the vertical common-duct.

3) Difficulty in dealing with occupants' complaints of noise from other apartments and reverse flow from the vertical common-duct.

4) Problems from the viewpoint of fire protection.

However, the ventilation system with this vertical exhaust common-duct has some advantages as follows:

1) Horizontal ducts are not needed, which eliminates the necessity of installing such ducts through beams.

2) Low ceilings necessary for concealing such horizontal ducts, are not needed in the case of the individual ventilation system.

3) The ventilation system with the vertical exhaust common-duct is relatively uninfluenced by outdoor wind pressure. On the hand, the individual ventilation system with a horizontal duct is easily influenced by outdoor wind pressure, because the exhaust air outlet of the horizontal duct is installed on the outer wall.

High-rise apartment houses with more than 25 stories are now common in the center of large cities. When the individual ventilation system with a horizontal duct is installed, some of the following problems are encountered;

1) A large capacity fan should be installed to overcome strong wind pressure on exhaust from the air outlet of the horizontal duct.

2) If such a large capacity fan is installed, there is a possibility of negative high indoor pressure, which leads to troubles such as difficulty in opening doors and noise due to air infiltration.

3) The height of beams can not be reduced because the horizontal ducts pass through these beams.

On the other hand, high performance household equipment and control systems have been rapidly developed in recent years. Nowadays, there is a possibility that the defects of the ventilation system with the vertical common-duct can be overcome by means of such kind of household equipment and control systems.

The most important point for design of the ventilation system with the vertical common-duct is how to prevent reverse flow. The reverse flow from the common-duct to apartments may occur when the static pressure in the common-duct rises to a level higher than that of an apartment due to the stack effect and the converging flow effect. There is a possibility that the rise of static pressure may be prevented by taking into consideration the type of flow junction, the sectional area of the common-duct, the performance of the exhaust fan mounted at the top of the common-duct and the performance of the individual exhaust fan (kitchen fan) in an apartment. However, there is little data available on pressure loss in converging flow at the junction.

In this study, firstly, the pressure loss coefficient of converging flow at the junction is investigated by use of an experimental model. Secondly, a computer program for calculating the pressure distribution along the vertical common-duct and airflow volume through the vertical common-duct and the branch duct is developed by use of a network model. Thirdly, the pressure distribution and airflow volume is calculated in many cases with different combinations of parameters: the type of junction, the number of stories, the roof fan performance, the internal heat gain from cooking stoves, the sectional area of the vertical common-duct, and the pressure loss coefficient of the inlet installed at the bottom of the vertical common-duct. Lastly, ways of designing a ventilation system employing with a vertical exhaust common-duct are recommended.

2. MODEL EXPERIMENT FOR PRESSURE LOSS IN CONVERGING FLOW

2.1 Description of the Experiment

(1) Model used for the experiment

Figures 1 and 2 show the experimental model used. The model incorporated a vertical exhaust common-duct of four stories, assumed to be part of such a duct of a high-rise apartment house with 14 stories. The sectional area of the vertical common-duct was 0.5 meter by 0.5 meter. The model of vertical common-duct was horizontally situated for the experiment. No experiment regarding the stack effect was conducted. Figure 3 shows the two types of junctions employed. The elbow-type junction was popular for the common-duct from the viewpoints of fire protection and making upward airflow. The branch duct connected to the common-duct from each apartment had three different sectional areas. Types of roof fans and kitchen fans commonly used for actual high-rise apartment houses were employed. The chambers were connected with the top and the bottom of the common-duct. In some cases of actual common-ducts, the legs of angles for connecting the parts of the common-ducts are inside the common-duct. But such legs were not employed in our model. The pressure loss coefficient of such legs, which was used for computer calculation, was measured in other experiments.

(2) Measurement methods

The points at which static pressure on the inside surface of the common-duct were selected every 75 mm along the center line of each side of the common-duct. The volume of intake airflow from the bottom of the common-duct was estimated by measuring the velocity of airflow at the center of the intake air duct, which was connected to the intake air chamber. The relation between the velocity of airflow and the airflow volume was investigated by measuring the profile of airflow velocity in the intake air duct.

The volume of exhaust airflow from a branch duct was estimated by measuring the velocity of airflow at the center of a branch duct connected with a kitchen fan. The relation between the velocity of airflow and the airflow volume measured by an orifice plate was also investigated.

The rotational speed of the roof fan could be changed by an inverter. The airflow volume of the kitchen fan was changed by a damper installed in the branch duct.

The pressure difference between each point on the inner surface of the common-duct and reference point A in the common-duct was measured by a capacitance manometer. The pressure difference between reference point A and the atmosphere was also measured. For the expression of measurement results, the static pressure on the inner surface of the common-duct was indicated as the difference between such pressure and the atmospheric pressure.

2.2 Friction Loss Coefficient

(1) Friction loss of the common-duct

The friction loss of the common-duct was estimated by measuring the pressure loss between point A and point B as shown in Fig. 1 under the condition without branch ducts. It was estimated that the friction loss factor varied from 0.017 to 0.032, depending on the Reynolds number.

(2) Pressure loss due to an elbow-type junction

The pressure loss due to an elbow-type junction was estimated by subtracting the friction loss of the common-duct from the pressure loss between point A and point B as shown in Fig. 1 under the condition with elbow-type junctions. It was estimated that the pressure loss coefficient due to the elbow-type junction was 0.135 - 0.200, which depended on the diameter of the branch duct.

2.3 Pressure loss of flow junctions

There were six types of flow junctions employed as shown in Fig. 3. The point at which pressure was measured in the branch duct was 40 cm from the connection of the branch duct with the common-duct.

The total pressure loss in the converging flow at the junction through the vertical common-duct (ΔP_{13}) was estimated by subtracting the pressure loss due to the elbow-type junction and the friction loss of the common-duct, from the total pressure loss between point A and point B. The total pressure loss in the converging flow at the junction from the branch duct to the common-duct (ΔP_{23}) was estimated by subtracting the total pressure loss from point C to the end of the branch duct and the friction loss from the end of the branch duct to point B, from the total pressure loss between point C and point B.

(1) Static pressure distribution along the common-duct

Figures 4 and 5 show the static pressure distribution along the vertical common-duct with T-type junctions and elbow-type junctions, respectively, which were installed at the first to third floor levels. For T-type junctions, in all three cases with different rotational speeds of the roof fan, the static pressure decreases around the flow junctions and becomes lower in upper floor levels.

In the case of the elbow-type junction, the static pressure decreases just before flow convergence and increases after flow convergence. The static pressure in upper floor levels is greater than that in lower floor levels in the case of low airflow volume of a roof fan. On the contrary, in the case of high air volume of a roof fan, the static pressure in upper floor levels is smaller.

This difference corresponds with which is larger, the total of the friction loss in the common-duct and the pressure loss due to the elbow-type junctions, or the static pressure rise due to flow convergence.

(2) Pressure loss coefficient in converging flow in the case in which only one branch duct is connected

Figure 6 shows the pressure loss coefficient in the converging flow at the junction from the branch duct to the common-duct (ζ_{23}), which is expressed by the function of only the velocity ratio of airflow, V_2/V_3.

Figure 7 shows the pressure loss coefficient in the converging flow at the junction through the common-duct (ζ_{13}). The ζ_{13} of the

T-type junction is roughly proportional to the velocity ratio of airflow, V_2/V_3, and the slope of the line depends on the sectional area of the branch duct. The ζ_{13} of the elbow-type junction is negative in the range of the velocity ratio of airflow, V_2/V_3, being more than 2.0, and depends on the cross-sectional area of the branch duct.

(3) Pressure loss coefficient of converging flow in the case of two adjacent branch ducts connected with the common duct

The converging flow may influence the pressure loss in the converging flow at the adjacent downward junction. Figure 8 shows the measurement results of the pressure loss coefficient in converging flow at the downward junction through the common-duct (ζ_{13}'). In the case of the T-type junction, the marks plotted can be divided into three groups. The pressure loss in converging flow from the branch duct to the common-duct was not influenced by the adjacent upward junction and is equal to the case in which there is only one branch duct.

2.4 Approximate Equations of the Pressure Loss Coefficient in Converging Flow

In order to calculate the pressure losses at the junctions for the network model, the approximate equations of the pressure loss coefficient depending on the velocity ratio of airflow were formulated based on the relationships as shown in Figs. 6 - 8 using the least square method. The results are shown in Table 1. The ζ_{13} is expressed as the function of both the velocity ratio of airflow and the cross-sectional area ratio.

3. VALIDATION OF CALCULATION MODEL

3.1 Calculation Method

Input data for the calculation are as follows:

1) Type of a flow junction
2) Fan performance curve
3) Indoor and outdoor temperatures
4) Internal heat gain from a cooking stove

The airflow volume through each branch duct from the kitchen fan and that from outdoors taken in to the bottom of the common-duct are initially given. Secondly, the static pressure is calculated for each junction along the common-duct from the bottom to the top. If the relation between the pressure difference in front of and behind the roof fan mounted on the top of the common-duct and the exhaust airflow volume through the roof fan dose not fall on the performance curve of the roof fan employed, the airflow volume taken in from the bottom of the common-duct is revised and the same calculation is repeated. If the relation between the two values falls just on the fan curve, then the pressure difference in front of and behind the kitchen fan is calculated for each apartment. If the relation between the pressure difference and the airflow volume through the branch duct initially assumed dose not fall on the performance curve of the kitchen fan, the airflow volume is revised and the calculation is repeated from the first stage. If the relation between the two values falls just on the fan curve, the iterative calculation finally yields the static pressures at all the nodes and the airflow volumes through all the branches between nodes.

3.2 Comparison Between Measurements and Calculations

Figures 4 and 5 include the calculation results of pressure distribution, which are shown by solid lines. The pressure distribution around the flow junctions as shown by calculation and that based on measurement were different, because, in the case of calculation, the pressure change due to flow convergence occurs just at the flow junction. The calculation showed that the static pressure along the common-duct decreases in upper floor levels in the case of the T-type junction and increases in upper floor levels in the case of the elbow-type junction. It can be said that the characteristics of the calculated pressure distribution totally correspond to the measurement results.

4. CALCULATION OF PRESSURE DISTRIBUTION AND AIRFLOW VOLUME

4.1 Parameters for Calculation

Three different multi-story houses, which had 5, 15 and 25 stories, respectively, were used for calculation models. The vertical exhaust common-duct was of two different sizes as shown in Table 2. The pressure loss coefficients of flow junctions and duct fittings are also included in Table 2. The seven combinations for operating conditions of the kitchen fans installed in apartments were assumed on the basis of the data in Ref. 1. The type of junctions, internal heat gain from the cooking stove, kitchen fan performance and pressure loss coefficient of the air inlet at the bottom of the common-duct had two different values for parameters. As to the roof fan type, calculations were performed for fans with and without rotational speed control. The performance curves of the roof fan are shown in Figure 9. Figure 10 shows the performance curve of the kitchen fan. There was 1344 combinations of calculation conditions.

4.2 Calculation Results

In this paper, calculation results are reported for two cases: one is that in which kitchen fans are used in some lower level apartments, and the other is that in which such fans are not used.

(1) Cases without rotational speed control of the roof fan

Figures 11 and 12 show the pressure distribution along the vertical common-duct calculated for three different multi-story apartment buildings with 5, 15 and 25 stories, which have the common-duct sizes of 600 mm by 600 mm and 600 mm by 1000 mm.

In the cases without operation of kitchen fans, the static pressure strongly depends on both the pressure loss coefficient of the air inlets at the bottom of the common-duct and the size of the common-duct. When the pressure loss coefficient changes from 1.0 to 10.0, the static pressure at the bottom of the common-duct decreases from around 0 Pa to -20 ∿ -40 Pa, depending on the number of stories. The static pressure at the top of the common-duct is -70 ∿ -80 Pa in the case of the duct size of 600 mm by 600 mm and -45 ∿-55 Pa in the case of the duct size of 600 mm by 1000 mm.

The pressure distribution is clearly different between the T-type junction and the elbow-type junction in the case of the 25 story apartment house. In the case of the T-type junction, the increase of the static pressure in upper floor levels is small, because the pressure loss at the junction offsets the pressure rise due to the stack effect. On the other hand, in the case of the elbow-type junction, the pressure loss at the junction is negative, which means that the static pressure increases at the junction. Therefore, the static pressure at the seventh floor level reaches 30 Pa due to both the pressure rise in converging flow and the stack effect. In these case, the effect of the ζ_{in} on the pressure distribution was small.

Figure 15(a) shows the airflow volumes at the top and the bottom of the common-duct and the airflow volumes from the branch ducts calculated for eight cases. The airflow volumes from the branch ducts are 520 m^3/h and 500 m^3/h in the cases of the elbow-type junction and the T-type junction, respectively. The reverse flow from the bottom of the common-duct to outdoors occurs in some cases with the duct size of 600 mm by 600 mm. But in cases with the duct size of 600 mm by 1000 mm, there is no such reverse flow.

(2) <u>Cases with rotational speed control of the roof fan</u>

In order to keep the static pressure in the common-duct small for any combinations of operating conditions of kitchen fans, it is assumed that the rotation speed of the roof fan can be controlled to maintain the static pressure at the top of the common-duct at a constant. Figures 13 and 14 show the pressure distribution calculated for the two cases with duct sizes of 600 mm by 600 mm and 600 mm by 1000 mm, respectively, under the condition that the static pressure at the top of the common-duct is constant at -30 Pa. Figure 15(b) shows the airflow volumes calculated for the same conditions. When an apartment house had 25 stories, the duct size was 600 mm by 1000 mm, and the flow junction was the T-type, the static pressure in the common-duct is 0 ∿-30 Pa, regardless of any combinations of operating conditions of kitchen fans with and without heat gain. But in the case with the duct size of 600 mm by 600 mm and the elbow-type junction, the static pressure is 30 Pa at the maximum near the ninth floor, which leads to the possibility of reverse flow from the exhaust vertical common-duct to the apartment through the branch duct.

5. CONCLUSIONS

5.1 Pressure Loss Coefficient for Converging flow

1) The pressure loss coefficients for converging flow, which depended on the velocity ratio of airflow, could be expressed by several approximate equations.

2) In the case with the elbow-type junction, the value of pressure loss at the flow junction in the common-duct was negative where the velocity ratio of airflow was more than 2, which means that the static pressure rises at the flow junction.

3) Computer calculation using the network model with approximate equations of pressure loss coefficients for converging flow gave reasonable results of pressure distribution in the common-duct and of airflow volumes, which totally corresponded to the results of measurement.

5.2 Recommendations for the Vertical Exhaust Common-Duct Design

1) The T-type junction is desirable for the connection of individual ducts to the vertical common-duct. If the elbow-type junction is used, the static pressure in the common-duct increases in upper floor levels leading to the possibility of reverse flow from the common-duct to the apartment through the branch duct.

2) When the T-junction is employed, if the optimum combination of duct size and performance of the roof fan is selected, it is possible to keep the static pressure at a relatively low level by controlling the static pressure at the top of the common-duct using a inverter for the roof fan control.

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Table 1 Approximate equations for pressure loss coefficient in converging flow

	Equations	
Elbows ζ_{13}	$\zeta_{13} = C_1 R^3 + C_2 R^2 + C_3 R + C_4$ $R = \{6.93 (A_2/A_1) + 0.510\} (V_2/V_3)$	
	Single elbow	$C_1 = 1.56\times10^{-3}$ $C_2 = -1.50\times10^{-2}$ $C_3 = 1.67\times10^{-1}$ $C_4 = 5.90\times10^{-3}$
	Double elbows	$C_1 = -3.25\times10^{-3}$ $C_2 = -1.34\times10^{-2}$ $C_3 = 2.54\times10^{-2}$ $C_4 = 1.05\times10^{-2}$
Tees ζ_{13}	$\zeta_{13} = C_1 \{C_2 (V_2/V_3) + C_3$ $C_1 = 1.48 \log (A_2/A_1) + 2.70$	
	Single tee	$C_2 = 1.40\times10^{-1}$ $C_3 = 0.0$
	Double tees	$C_2 = 8.16\times10^{-2}$ $C_3 = 0.0$ $(V_2/V_3 \leqq 1.77)$
		$C_2 = 2.34\times10^{-1}$ $C_3 = -2.69\times10^{-1}$ $(1.77 < V_2/V_3 \leqq 3.82)$
		$C_2 = 3.24\times10^{-2}$ $C_3 = 5.00\times10^{-1}$ $(3.82 < V_2/V_3)$
ζ_{23}	$\zeta_{23} = 0.967 (V_2/V_3)^2 - 0.195 (V_2/V_3) - 1.20$	

Note: $\zeta_{13} = \Delta P_{13} / \{\rho/2\} \cdot V_3^2$
$\zeta_{23} = \Delta P_{23} / \{\rho/2\} \cdot V_3^2$

Table 2 Values assumed for calculation

λ_s	$\lambda_s = 10^{-0.232 \log Re - 0.463}$	
Duct size[mm]	600× 600	600× 100
D_e [m]	0.60	0.75
ζ_e	0.127	0.016
ζ_T	1.09	0.73
$\zeta_{13}, \zeta_{23}, \zeta_{13}', \zeta_{23}'$	See Table 1	
ζ_{ex}	$\zeta_{ex} = 1.24$	
ΔP_r	$\Delta P_r = 2.18\times10^{-3} Q_2^{1.54}$	
ΔP_{dT}	$\Delta P_{dT} = 5,94\times10^{-4} Q_2^{1.9}$	

Note: $R_e = V_1 d_e / \nu$

Table 3 Parameters for calculation

Number of stories	5 , 10 , 15						
Common duct size	600 × 600 600 × 1000[mm]						
Number of floor levels of kitchen fans operated	0	1 lower level	1 middl level	1 highest level	N lower level	N-1,for higher levels and 1,for lower level	N randomly situated
Type of junction	Tee(150 ϕ) Elbow(150 ϕ)						
Internal heat gain from a cooking stove	0kw(0 kcal/h) 1.744kw(1500kcal/h)						
Roof fan	With or without rotational speed control(Fig.9)						
Kitchen fan	High speed operated or Low sped operated(Fig.10)						
ζ_{in}	$\zeta_{in} = 1.0$ $\zeta_{in} = 10.0$						
Total number of the combination : 1344							

Note: N=3,6,and 8 when the number of story is 5,15,and 25 respectively

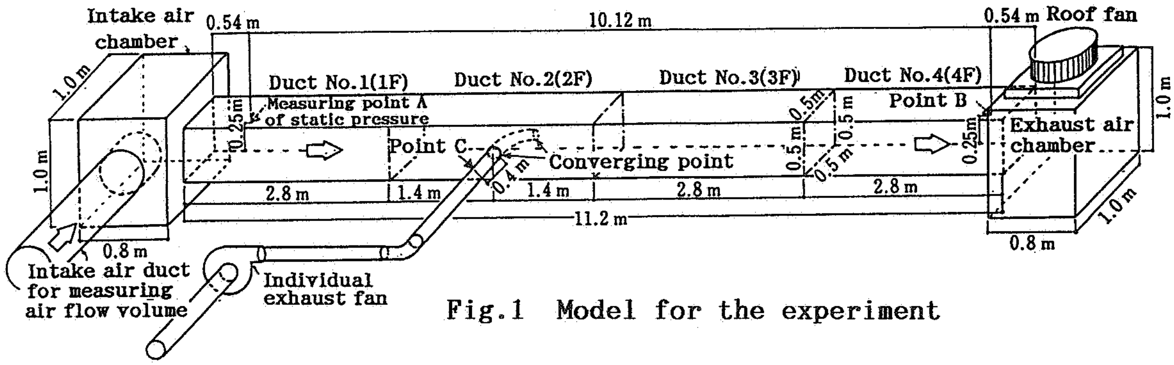


Fig.1 Model for the experiment

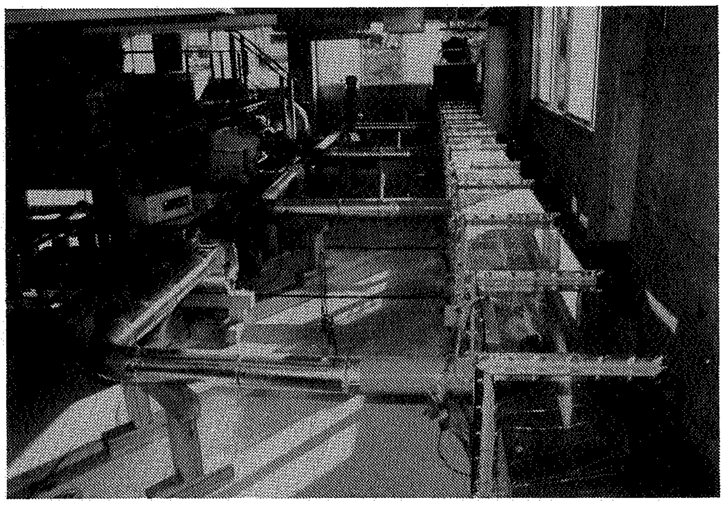
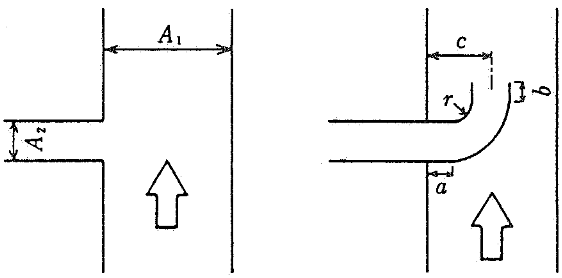


Fig.2 View of test facility



Branch duct size (mm)	Sectional area ratio (A_1/A_2)
ϕ100	0.03
ϕ150	0.07
ϕ250	0.20

(a) T-type junction

Branch duct size (mm)	Dimension (mm) r	a	b	c	Sectional area ratio (A_1/A_2)
ϕ100	50	150	50	250	0.03
ϕ150	75	100	75	250	0.07
ϕ250	125	0	0	250	0.20

(b) Elbow-type junction

Fig.3 Details of flow junctions

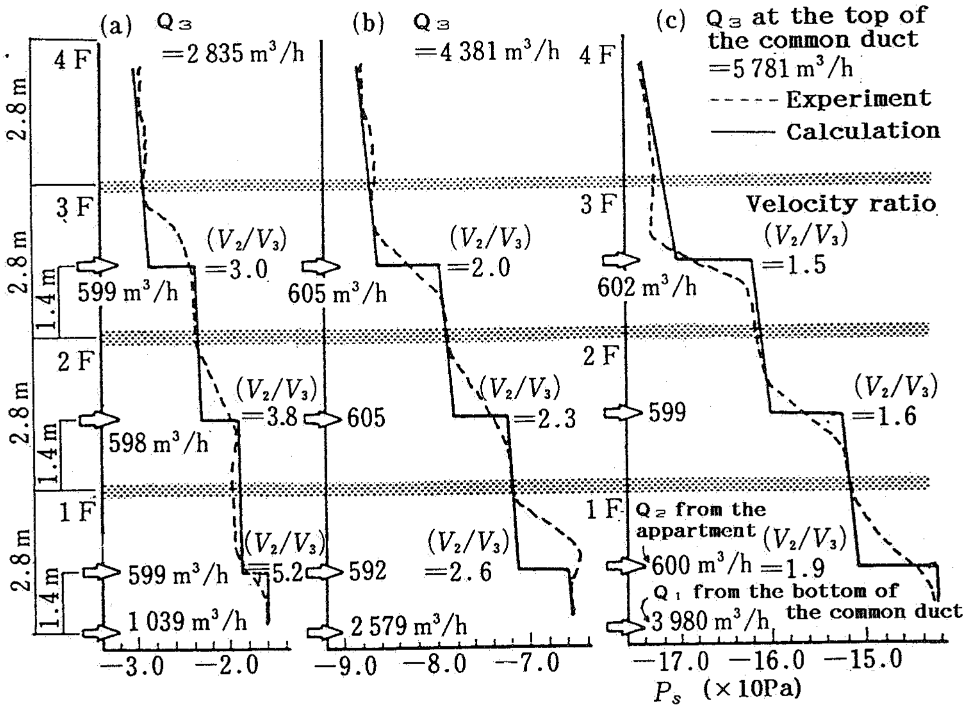


Fig.4 Pressure distribution along the common duct in the case of T-type junction with the duct diameter of 150mm

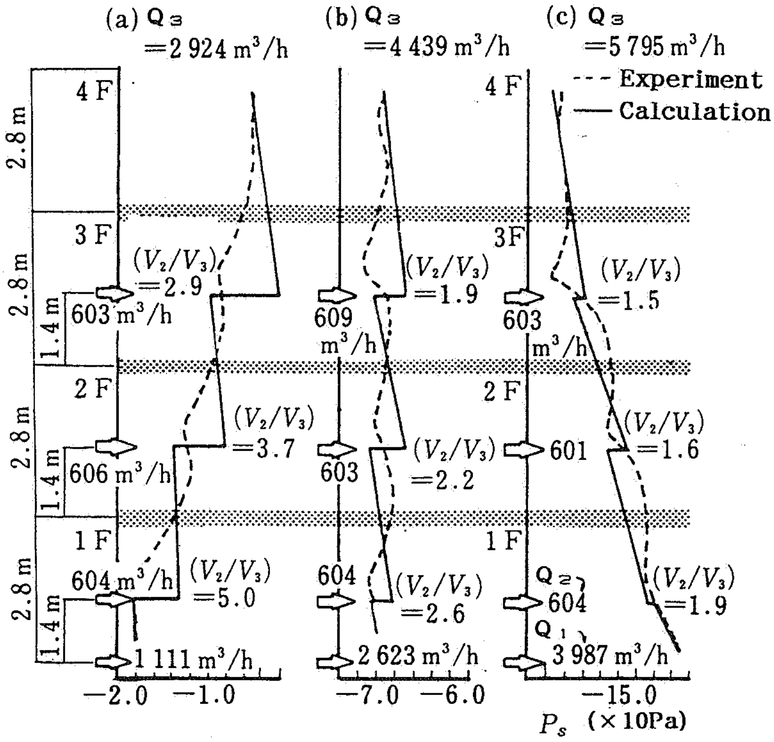


Fig.5 Pressure distribution along the common-duct in the case of elbow-type junctions with the duct diameter of 150mm

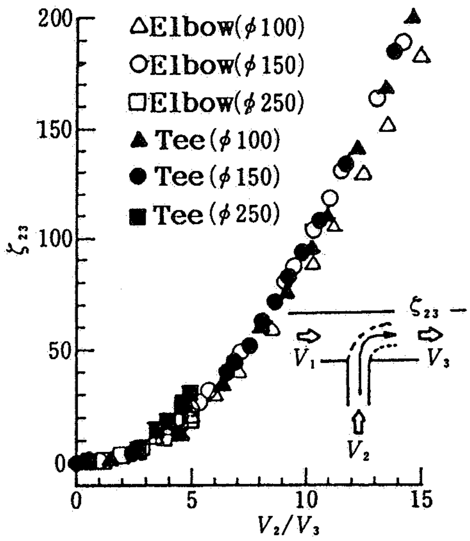


Fig.6 Pressure loss coefficient in converging flow from a branch duct to a common-duct

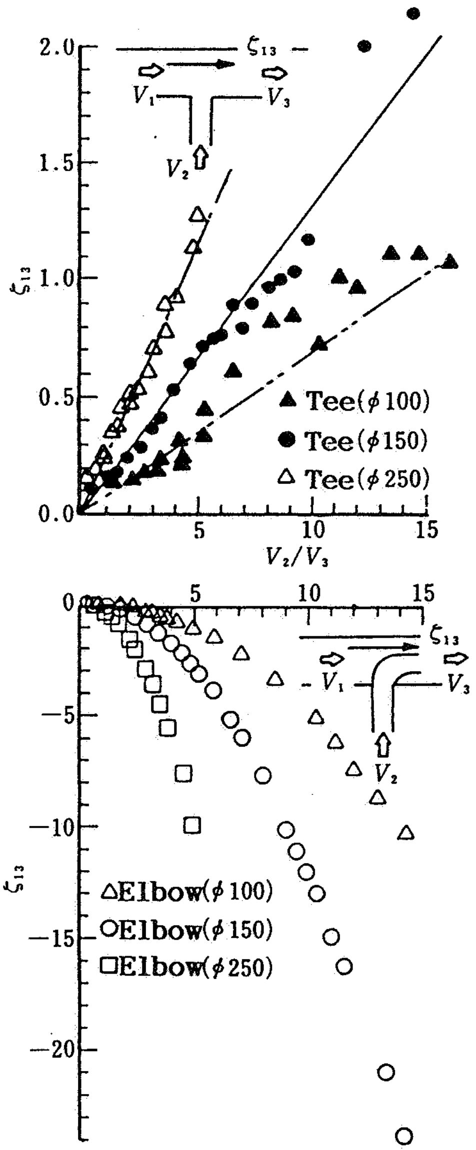


Fig.7 Pressure loss coefficient in converging flow through a common-duct

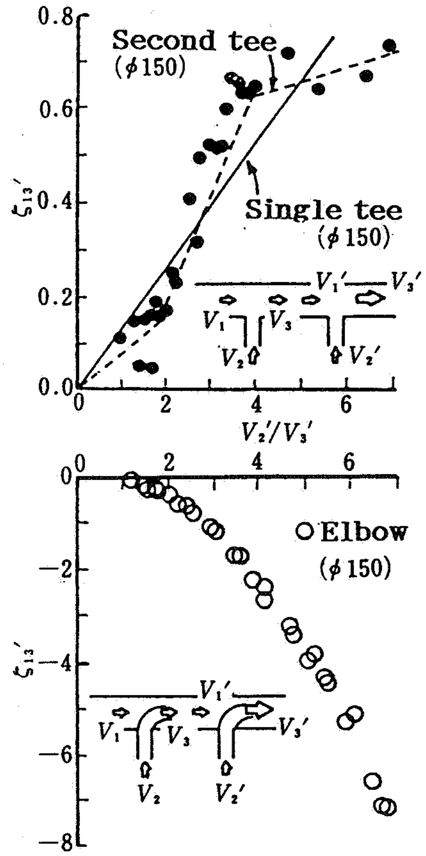


Fig.8 Pressure loss coefficient in converging flow at the second junction through the common-duct with double junctions

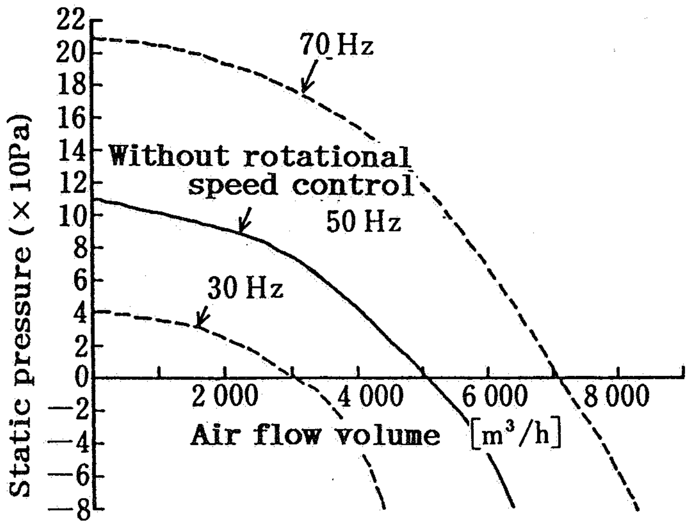


Fig.9 Performance curve of a roof fan

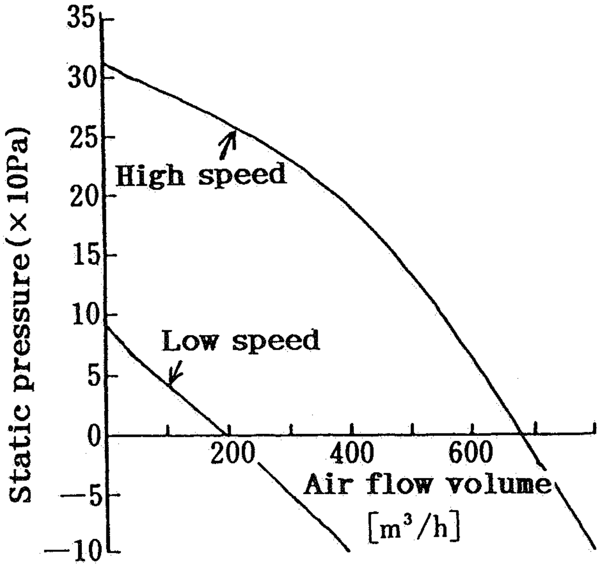


Fig.10 Performance curve of a kitchen fan

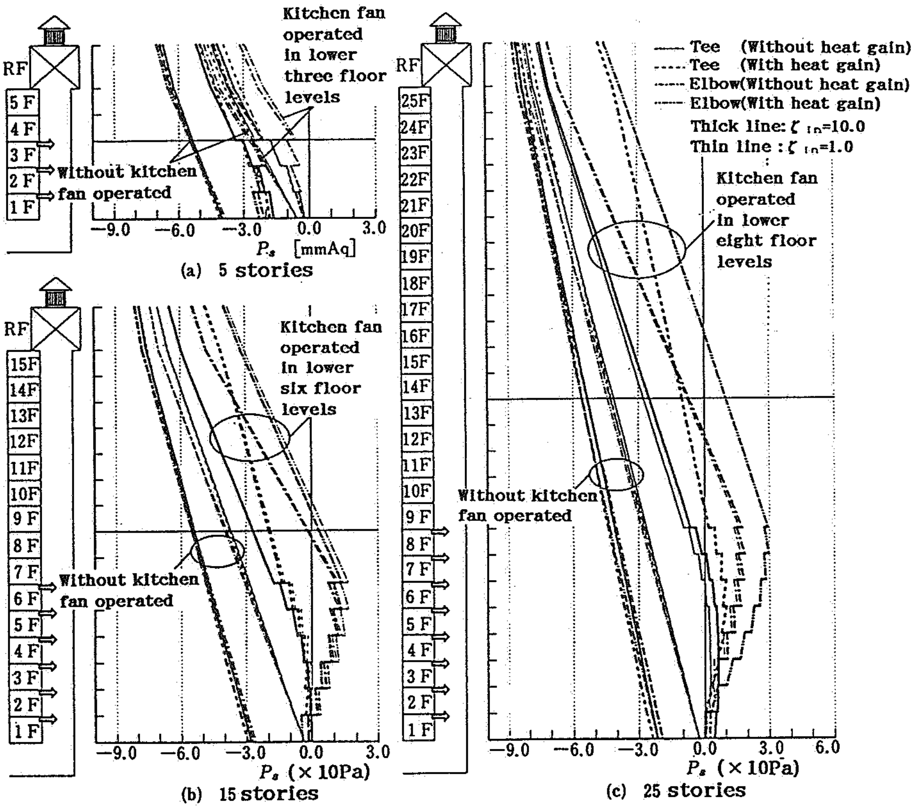


Fig.11 Static pressure distribution (Duct size:600 ×600, without rotational speed control)

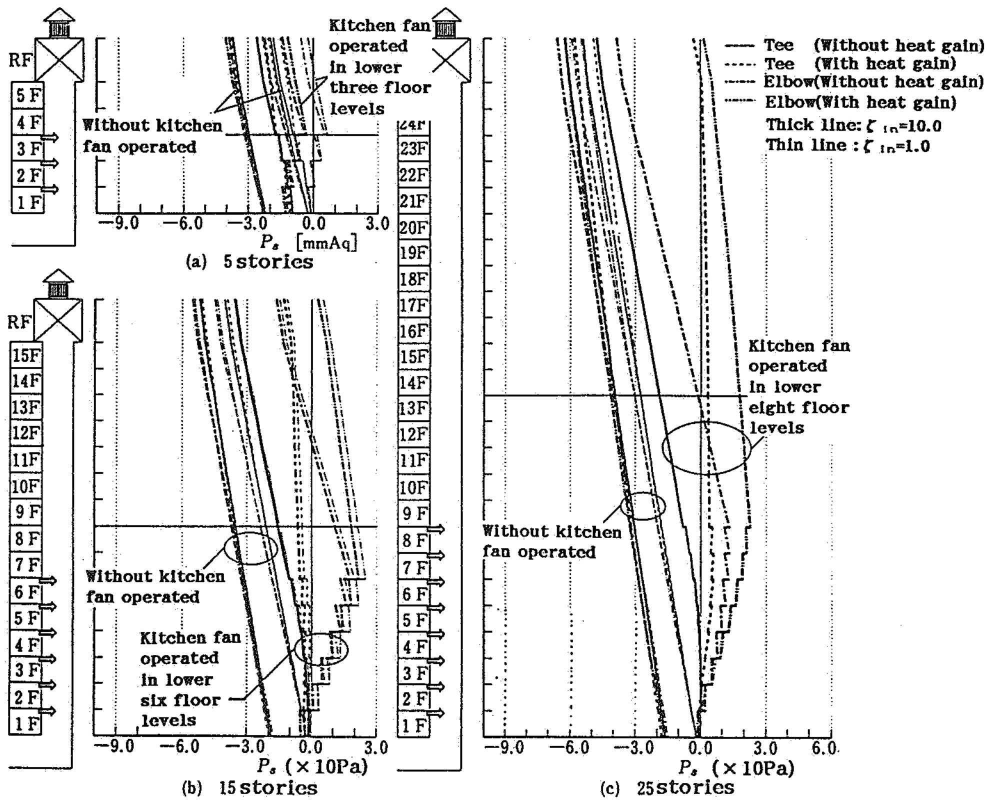


Fig.12 Static pressure distribution (Duct size:600 ×1000, without rotational speed control)

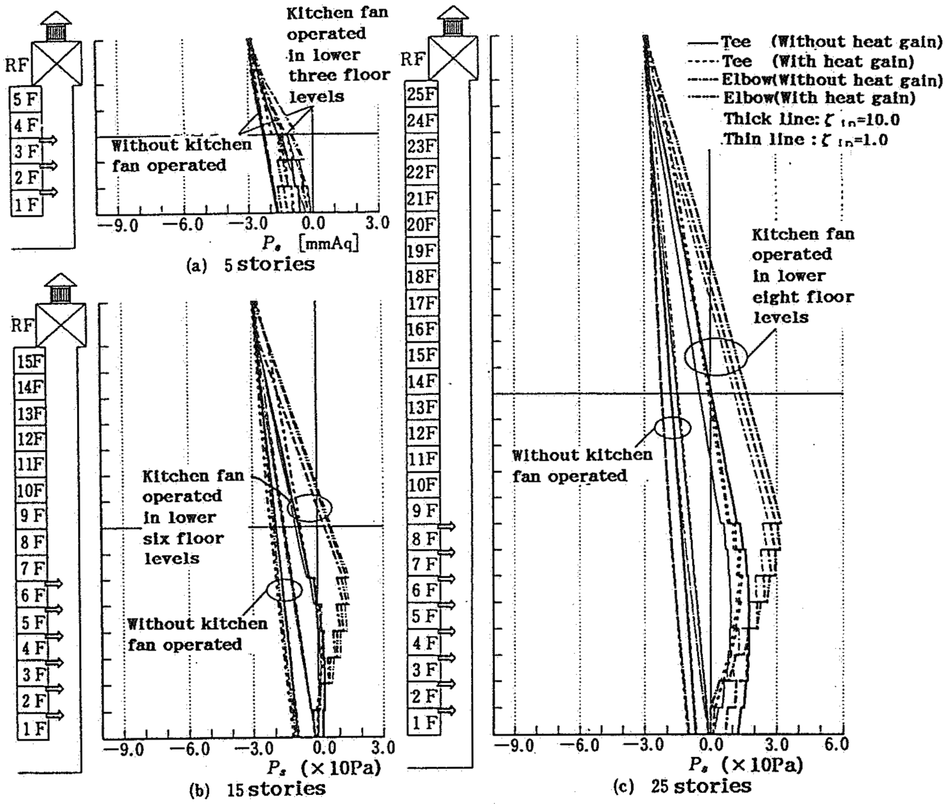


Fig.13 Static pressure distribution (Duct size:600 × 600, with rotational speed control)

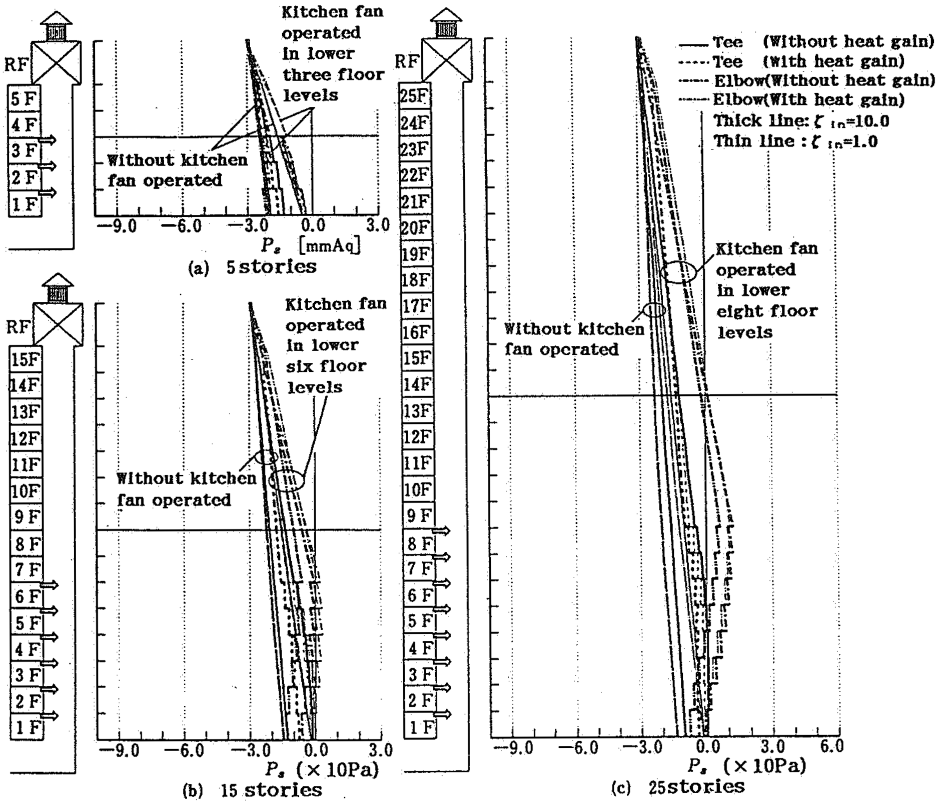


Fig.14 Static pressure distribution (duct size:600 × 1000, with rotational speed control)

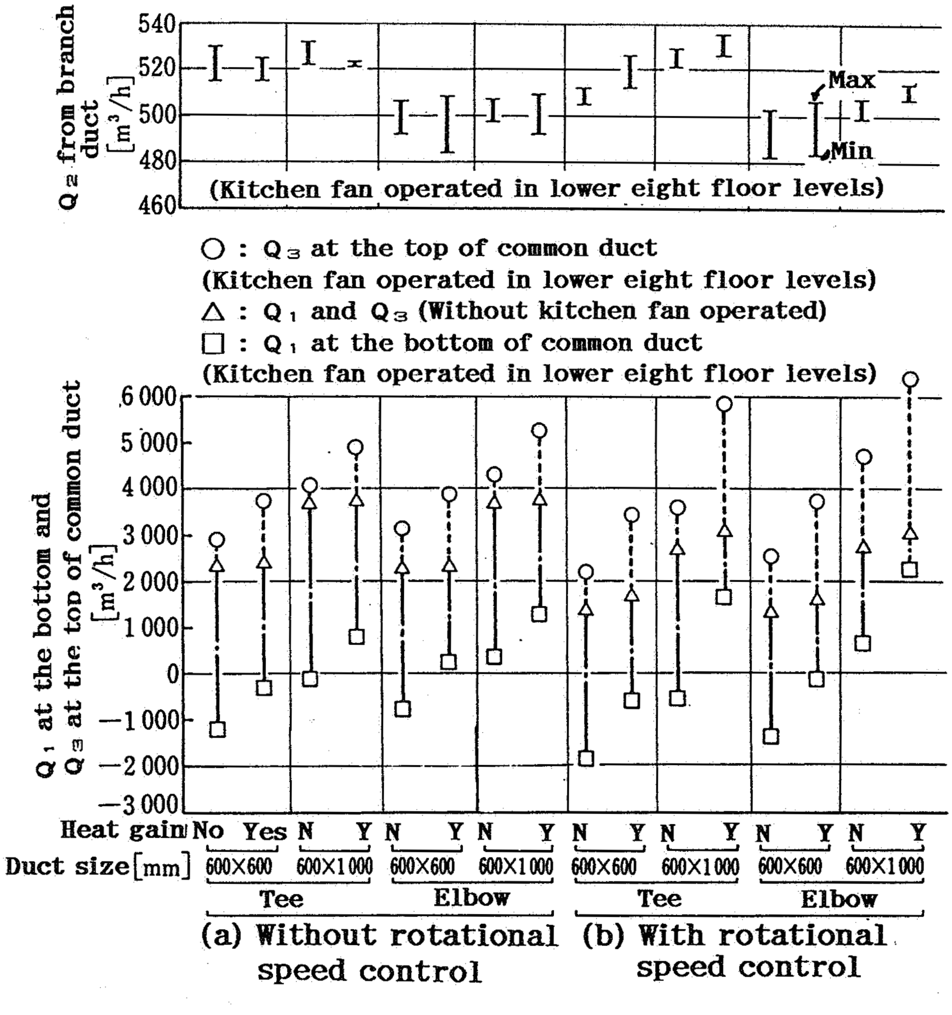


Fig.15 Exhaust air volumes in case of the apartment house with 25 stories