

Effects of Parameters Affecting Ventilation Performance of a Vertical Shaft

Hwataik Han¹ and Chulyong Shin² and Chang-In Baek³

¹Professor, Kookmin University, Seoul, Korea, hhan@kookmin.ac.kr

²Graduate student, Kookmin University, Seoul, Korea, seasondragon@naver.com

³Chief executive officer, Invent-ENG, Seoul, Korea, cibaek@invent-eng.co.kr

ABSTRACT: It is frequently reported that kitchen exhaust hoods do not function properly in high-rise apartment buildings. The uneven pressure distributions in a vertical shaft can cause hood fans to extract insufficient airflows depending on the floor level. It is important to investigate the pressure and airflow characteristics in a vertical shaft in order to understand overall building ventilation performance. There are various system parameters affecting the pressure distributions in a shaft, such as building height, shaft size, fan characteristics, concurrent hood fan usage, shaft bottom inlet condition, outdoor temperature, and etc. It is the objective of the present study to investigate the effects of these parameters on pressure distributions and overall ventilation performance of a building. A computer program has been developed by implementing the principles of fluid dynamics in a vertical air column with horizontal branches. Simulation results have been obtained in a 25-story apartment building according to the method of experimental design for various parameter combinations. Analysis of variance has been conducted to investigate correlations between parameters. The results show that the pressure deviation based on -4mmAq has a strong correlation with the maximum pressure in the shaft. It indicates the possibility of using the pressure deviation as a single objective parameter which represents both the maximum value and the standard deviation of the pressure distribution in the shaft. The roof fan rpm and the inlet damper opening can be used as operation parameters, and the pressure at the top-most level and the outside temperature can be used as sensing parameters.

Keywords: Vertical shaft, Ventilation, Design of experiment, Exhaust, Simulation

NOMENCLATURE

d	Shaft diameter [mm]
Q	Airflow rate [CMH]
P	Static pressure [mmAq]
ΔP	Pressure loss [mmAq]
T	Temperature [$^{\circ}\text{C}$]
u	Usage rate [%]
ω	Fan inverter frequency [Hz]
ξ	Shaft inlet loss coefficient

σ	Standard deviation
Subscript	
E	Exhaust
N	Number of floors
i	Floor index
fr	Friction
fo	Form
jo	Joint

1. INTRODUCTION

Recently, concerns about indoor air quality have increased since the buildings are constructed more and more air-tight. There are various indoor air pollutants such as carbon dioxide from human body and volatile organic compounds from building structure. Effluents generated in cooking processes contribute greatly to indoor air pollution among various indoor contaminant sources. The role of kitchen exhaust is important as a means of local ventilation of high-concentration contaminants in kitchen area. But many users are reluctant to use kitchen exhaust hoods because of unsatisfactory exhaust performance and unwanted noise. The unsatisfactory performance is due to insufficient airflow rates generated by exhaust fans. The problem of kitchen ventilation should be attacked as a ventilation system as a whole including vertical shafts and building air-tightness, but not as an individual mechanical hood component.

Many literatures can be found on ventilation in high-rise buildings with vertical shafts but not many on pressure simulations or airflow experiments along vertical shafts. Murakami et al.[1] analyzed the pressure distributions in a vertical shaft numerically depending on the system parameters. They provided comprehensive results on pressure distributions but did not address methods to control the pressure distributions in vertical shafts. Kwon and Ahn[2] investigated experimentally to improve exhaust performance of kitchen hood by controlling pressure distributions in a shaft using roof fans and on-off dampers at each floor.

The purpose of this study is to analyze the correlations of parameters affecting the pressure distributions in a vertical shaft in order to propose a pressure control methodology for overall ventilation performance of a building. Numerical simulations have been conducted using the method of experimental design in order to

reduce the number of cases by the combinations of various system parameters. The objective functions and sensing parameters are proposed based on the correlation results.

2. THEORY

2.1 Pressure Distribution Model

The pressure characteristics in a vertical shaft should be understood first of all in order to derive related system parameters and to develop control methods. The pressure distributions vary depending on various conditions such as outdoor temperature, hood usage, fan characteristics, duct size, and etc. Figure 1 shows a typical pressure distribution profile in case concurrent hood operating units are located at lower floor levels. The maximum static pressure appears in the midst of hood operating family units and the minimum pressure appears at the top-most floor by roof fan suction. The roof fan characteristics contribute a great deal to determine the minimum pressure at the top-most level and the bottom inlet pressure loss coefficient contributes to determine the pressure at the first level.

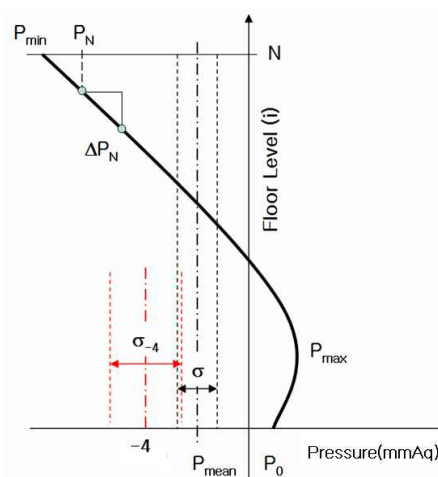


Figure 1: Schematic pressure distribution in a vertical shaft.

The maximum pressure should be maintained within a specific value in order to ensure minimum hood exhaust at each

floor. Meanwhile, the minimum pressure should not be too low to conserve fan power consumption as well as accompanying problems such as unwanted air exhaust or leak noise. Therefore, an ideal distribution might be a more or less uniform pressure distribution at a slightly negative value.

2.2 System Parameters

System parameters affecting the pressure distribution in a shaft include shaft diameter (d), concurrent hood usage rate (u), roof fan performance (ω), outdoor temperature (T_{out}) and shaft inlet pressure loss coefficient (ξ). Among the parameters, the shaft diameter is a parameter determined during a design stage. The concurrent hood usage rate and the outdoor temperature are conditions that can not be controlled but are provided as given conditions. The roof fan performance and the shaft inlet coefficient can be operation parameters for pressure control in the shaft. The parameters are grouped and their relations are expressed in Figure 2.

The control objective is to minimize the maximum static pressure and the deviation of pressure distribution in the shaft. The derived parameters are resultants of the pressure distribution along the shaft, such as a mean, a standard deviation, a maximum and a minimum of pressures. The outdoor temperature and the pressure at the top-most floor can be considered as sensing parameters for control purposes.

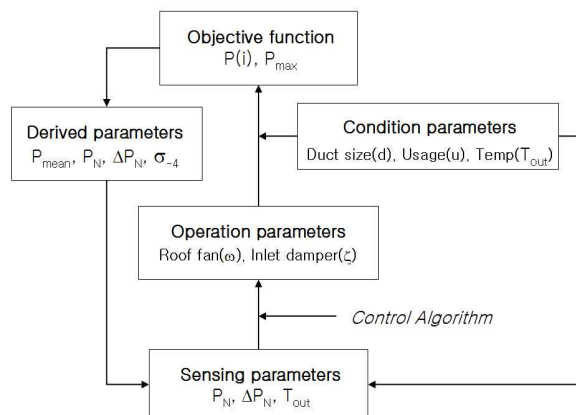


Figure 2: Parameters related to the pressure control in a vertical shaft.

2.3 Analysis Program

A numerical node is placed at each floor to derive governing equations for pressure distributions along a vertical shaft as is shown in Figure 3. From the mass conservation, the outlet flow from a node can be expressed by the sum of the inlet flow and the kitchen exhaust from each floor unit.

$$Q_{i+1} = Q_i + Q_{E,i} \quad (1)$$

The pressure at each floor can be calculated by considering buoyancy due to temperature difference, friction loss by shaft wall, joint loss at a junction, and form loss depending on shaft form.

$$P_{i+1} = P_i + \Delta P_B - (\Delta P_{fr} + \Delta P_{fo} + \Delta P_{jo}) \quad (2)$$

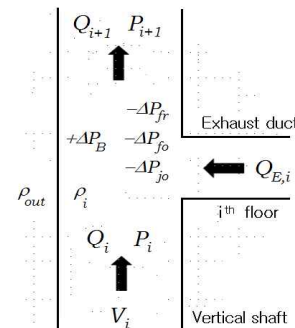


Figure 3: Schematic diagram for explaining balance equation in each floor.

Heat balance equation can be also derived for each node. The details of the governing equations and related coefficients are not provided here, but can be found in Murakami et al.[1]

A numerical program has been developed by incorporating the governing equations. It is divided into two parts, a vertical shaft and an exhaust duct at each floor unit. The static pressure and airflow rate at each node is calculated from the bottom-most floor to the top-most floor by assuming a pressure condition at the bottom inlet of shaft. The resultant airflow rate at the top-most floor is

compared with the airflow rate by P-Q curve of the roof fan. Based on the difference in the airflow rates, the inlet airflow rate is modified with a relaxation factor. This procedure is repeated until convergence. Similarly, the static pressure at each floor unit is analyzed with an assumed exhaust airflow rate as an initial guess. The airflow rate calculated from P-Q curve of the kitchen fan is compared with the initially assumed airflow rate. Calculations are repeated until convergence. This procedure is expressed by Figure 4.

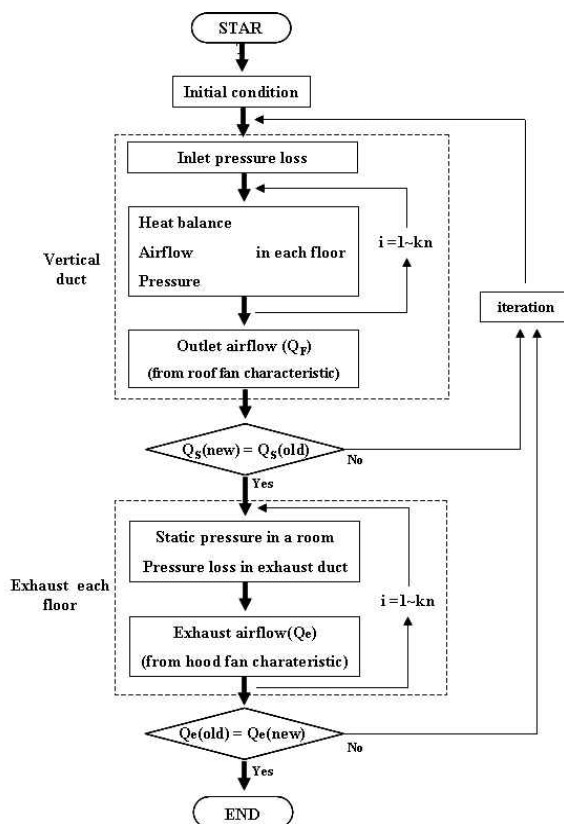


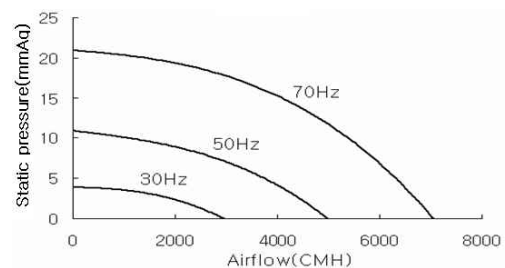
Figure 4: Flow chart of numerical analysis program.

2.4 Design of Experiment

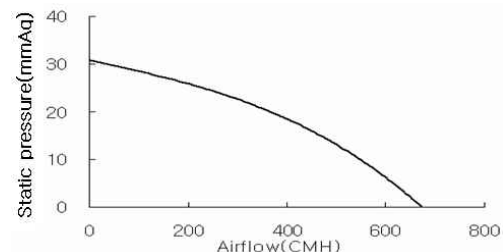
The apartment considered in the present study is a 25-story building. The vertical shaft is a dry type in circular shape. The exhaust duct diameter is 150mm. Figure 5 shows P-Q curves for the fans used. Concurrent hood usage units are assumed to be located serially at the lower part of the building starting from the first floor. This case is the worst case that static pressure can

be the largest in the vertical shaft. For example, 32% of usage rate means the units on 1-8 floors out of 25 are operating kitchen hoods at the same time.

The system parameters and their levels are given in Table 1. There are five parameters and three levels for each parameter. Complete parametric analysis requires simulations of 3^5 cases in theory. By Taguchi method, 27 cases are chosen for the present study. The design of experiment is a method that can gain information with reduced number of simulations using relevant principles [2]. From the results of parametric analysis, parameters have been grouped to analyze correlations between parameters.



(a) Roof fan



(b) Exhaust hood fan

Figure 5: Fan characteristic curves.

Table I: Levels of parameters

Parameter		Level
A	Shaft diameter (mm)	450, 550, 650
B	Concurrent hood usage rate (%)	32, 40, 48
C	Roof fan inverter freq (Hz)	30, 50, 70
D	Outdoor temperature (°C)	0, 15, 30
E	Shaft inlet loss coefficient	1, 10, 100

3. RESULTS AND DISCUSSION

3.1 Verification

In order to verify the program developed, the simulation results are compared with the results by Murakami et al.[1] It is the case of 25-story building with a square shaft of 600×600 mm. The concurrent hood usage rate is 32%, and the outdoor temperature is 0°C . Simulations are executed with and without buoyancy for the inlet pressure loss coefficient of 1. The results are in good agreement with their results as are shown in Figure 6.

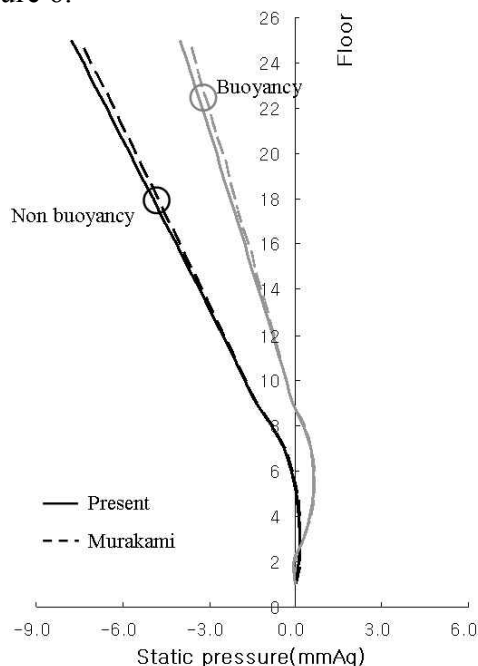


Figure 6: Verification of simulation results.

3.2 Effect of parameters

Figure 7 shows the effect of shaft diameter on pressure distributions. As the diameter increases, friction loss decreases in a duct, and maximum pressure decreases slightly. Pressure distributions are smoother for larger diameters especially around the concurrent usage floor units.

The concurrent hood usage rate determines the number of family units using exhaust hood starting from the first floor simultaneously. As can be seen in Figure 8, maximum pressure increases as the usage rate increases. Fan speed exhibits large influence on the pressure distribution in the

shaft especially the minimum pressure at the top. A high speed fan can reduce the maximum pressure but can cause excessive pressure drop in the shaft, which can cause air leakage and noise generation.

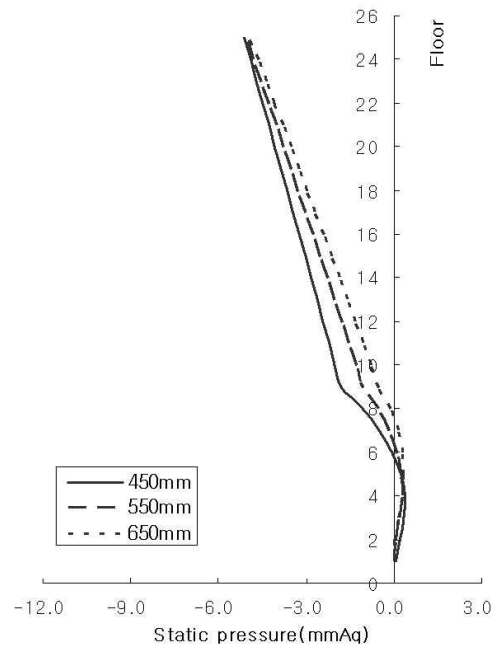


Figure 7: Effect of shaft diameter on pressure distribution in the shaft.

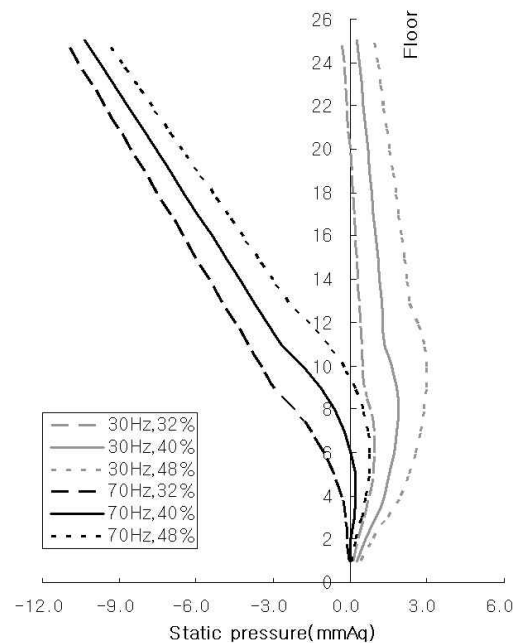


Figure 8: Effects of concurrent usage rate and roof fan characteristics.

Figure 9 shows the effect of shaft inlet loss coefficient for summer and winter conditions. In general, there is a larger positive slope in winter than in summer due to stack effects. However, because of the fan suction at the roof, the pressure profiles change their slopes in the negative direction by the same amount for both summer and winter. Therefore, it is interesting to notice that the magnitude of the slope is smaller in winter than in summer as is shown in the figure.

The inlet damper coefficient affects significantly in summer but not in winter. The pressure curves tend to move parallel to the right direction as the inlet damper coefficient increases in summer. Roughly speaking, the coefficient of 10 indicates the area contraction ratio of 30%, and 100 indicates contraction ratio of 10%.

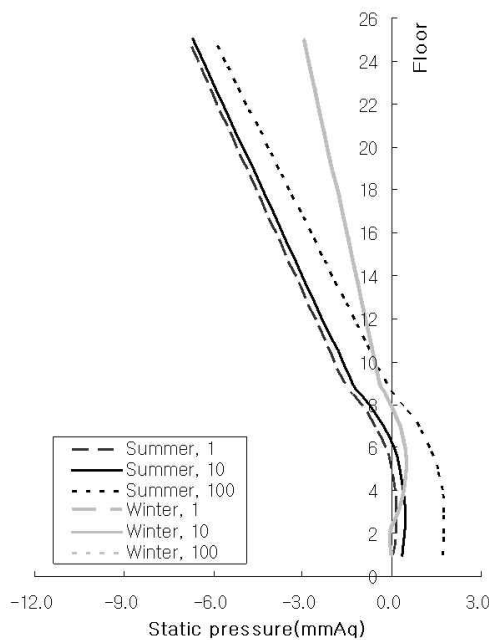


Figure 9: Effects of inlet pressure loss coefficient for winter and summer conditions.

3.3 Correlations between parameters

As mentioned earlier, the pressure in the shaft should not be high, but also it should not be too low. Therefore, the maximum pressure should be minimized and the

standard deviation of pressures should be also minimized.

The correlations of the standard deviations with the maximum, minimum and mean values are analyzed. As is shown in Figure 10, any of them does not exhibit any correlations with the standard deviation based on the mean pressure. However, the deviation based on the pressure of -3mmAq or -4mmAq shows evident correlation with the maximum pressure in the shaft. It can be noticed in Figure 11. Therefore, this parameter can be used as an objective parameter to express both characteristics of maximum pressure and deviation of pressures in a shaft.

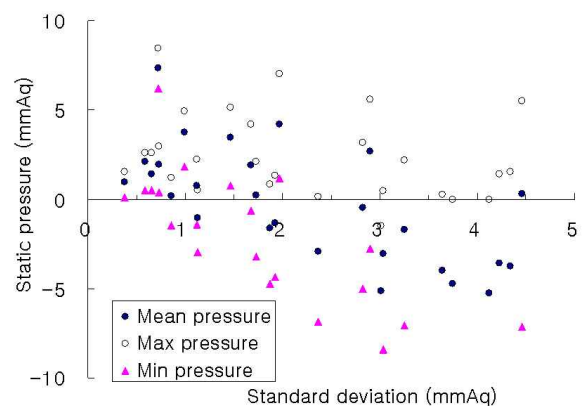


Figure 10: Correlations of static pressures with standard deviation of pressure.

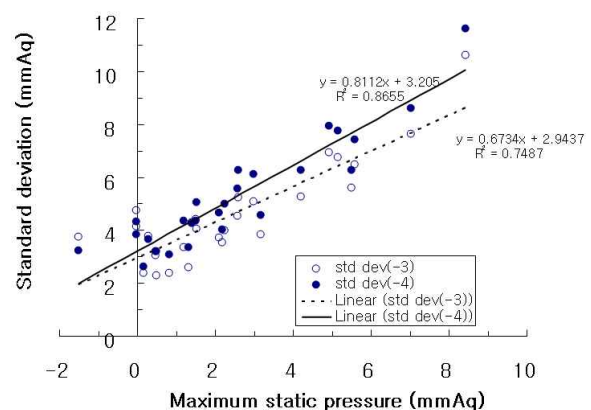


Figure 11: Correlations of maximum pressure with the pressure deviations at -3 and -4mmAq.

Maximum pressure and its location change as the concurrent hood usage pattern changes. In a practical sense, it is impossible to locate the maximum pressure point or to monitor the concurrent usage rate. Outdoor temperature and pressure at the top-most floor and/or pressure gradient in the shaft can be used as sensing variables to control an objective parameter. From the correlation results, outdoor temperature is quite independent from the static pressure of top-most floor. But there is a correlation to a certain degree between the pressure and the pressure gradient at the top-most floor as is shown in Figure 12. The pressure gradient of the top-most floor can be omitted from sensing parameters by this reasoning. Equation (4) expresses a correlation between the sensing parameters and the object parameter, i.e. the pressure deviation based on -4mmAq.

$$\sigma_{-4} = 5.93 + 0.31P_N + 0.0331T_{out} \quad (4)$$

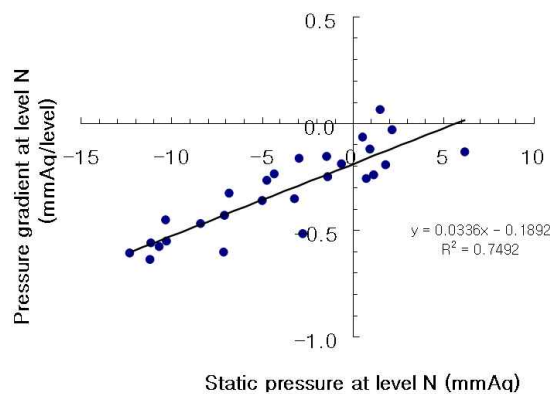


Figure 12: Correlation with pressure gradient and static pressure at the top-most floor

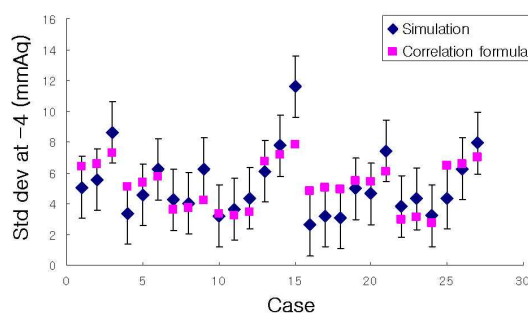


Figure 13: Comparison with the simulation data for pressure control

The pressure deviation based on -4mmAq can be reproduced with the sensing parameters using the correlation equation as is shown in Figure 13.

The objective function should be minimized using the operating parameters; i.e. fan speed and inlet pressure coefficient, for the given sensing parameters; i.e. outdoor temperature and the pressure at the top-most level. Control algorithm can be written accordingly. In summary, the fan speed and the inlet damper are adjusted based on the outdoor temperature and the static pressure in the shaft, so that the pressure deviation based on -4mmAq should be minimized.

4. CONCLUSIONS

This study investigated the effects of five parameters on the pressure distributions in a vertical shaft and the correlations between parameters. As shaft diameter and roof fan speed increases, the maximum pressure in a vertical shaft decreases. Overall pressure distribution in the shaft increases as concurrent usage rate and inlet pressure loss coefficient increase. The effect of inlet pressure loss coefficient is large in summer, and is almost negligible in winter.

A control algorithm for minimizing the maximum pressure only can create excessive pressure drop in the shaft, which can cause energy loss and flow noise as well as uneven exhaust performance between floors.

The pressure deviation based on -4mmAq shows a strong correlation with the maximum pressure in the shaft. It provides a possibility of using this pressure deviation as a sole objective function to control the pressure distributions in a vertical shaft to minimize both the maximum pressure and pressure deviations in the shaft.

Further researches are required to investigate detailed control algorithms for pressure distribution in a vertical shaft.

REFERENCES

- [1] Murakami, S., Yoshno, H., Mizutani, K., Akabayashi, S., and Hasegawa, K., 1990, Ventilating Performance of Vertical Exhaust Duct in a Multi-story House, SHASE.
- [2] Kwon, Y. I. and Ahn, J. H., 2007, Intelligent Exhaust Control System used in High Riser for elevating Exhaust Efficiency of Toilet and Cooking Place, Proceedings of SAREK '07 Summer Annual Conference, pp. 565-571.
- [3] Taguchi, G., 1987, System of Experimental design, UNIPUB.
- [4] Nakazato, H., Kawazaki, K., Hiraguri, N., and Ohtaki, N., 1993, Design of Experiment Text for Production Management, JUSE Press, Japan.