Development of a Ventilation Performance Prediction Equation for Korean Multi-Family Housing Units Using Airflow Analysis

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Abstract
In this study, using an indoor airflow analysis model established for housing units, a computer simulation was conducted to investigate the indoor-to-outdoor and room-to-room ventilation performance in multi-housing. In the computer simulation, actual measured ventilation performance data were used as the input conditions for the airflow analysis program COMIS, in which a network model for indoor airflow analysis was employed. A prediction model was developed to evaluate the ventilation performance of multi-family housing based on multiple regression analysis with the data obtained in the computer simulation.

Keywords: multi-family housing; airflow analysis; ventilation performance; COMIS

1. Introduction
1.1 Purpose of the Study
During the past few decades, a large number of high-rise residential buildings have been constructed in Korea. Recently, in residential buildings, various symptoms related to problems of indoor air quality (IAQ) were reported. These problems resulted from the low air change rate and the use of building materials that emitted chemical gases. During the design stage, it is necessary to utilize a prediction model to analyze the air change rates of multi-housing units.

Many researchers developed ventilation methods. Fitzgerald and Woods studied a room ventilated with multiple vents and tried to determine the position of neutral buoyancy. Li and Delsante developed numerical solutions for calculating natural ventilation flow rates in a building having two openings. However, these models are very difficult for the designer who is not an expert in ventilation. Additionally, these studies did not deal with high-rise multi-family housing buildings over 15 floors.

The purpose of this study is to develop a basic equation model to analyze ventilation performance in multi-housing units. Based on a field survey and measurement data from multi-housing units in Seoul and newly developed towns, ventilation performance was analyzed using COMIS, an airflow analysis program, using network models.

In addition, with consideration given to interactions between related variables, multiple regression analysis was employed on simulation results. The prediction equation of ventilation performance was presented using the simulation results shown in Fig.1.

1.2 Scope of the Study
There are many factors that affect ventilation performance in a building (e.g. building type, tightness of windows and ventilation systems, etc.). Since it is hardly possible to use all of the factors in the simulation, this study concentrates on the 20-floor reinforced concrete structure of a 106 m² multi-housing unit. They are the most common housing types in Korea. The wind velocity and temperature difference between the indoors and outdoors were considered. The airflow paths connecting nodes were windows, main entrance door, exhaust fans for kitchen and bathroom, rooftop exhaust fans, staircases, exhaust ducts, and inside doors.

2. Computer Simulation for Analysis
2.1 COMIS Program for Airflow Analysis
(1) Application of Program
In this study, the Ilsibat COMIS version 2.1, which was developed as a part of the Annex 23 study of AIVC, is used. The program is capable of simulating the following elements.
- Determine wind pressure coefficient (Cₚ) data through a wind tunnel test
- Analysis of cracks and gaps, openings (entrance doors, windows and doors), staircases, exhaust ports, kitchen range hoods, as well as mechanical ventilation systems
- Consideration of vertical airflow in an opening
- Consideration of turbulent flow effect from a single wall opening
• Estimation of both airflow rate and pollutant transmission rate through the entrance door, windows and doors as well as other openings

(2) Verification of the Program

A direct method of employing comparative analysis of the measurements and operations of the simulation on an actual domestic multi-housing unit as an object was also used to verify the propriety of the COMIS program used in this study (Fig.1.).

First, there is an error rate of about ±10% in the airflow rate of the whole building based on Viktor Dorer's program propriety verification result. It reports that the errors are caused by a difference in outside weather conditions. Simulation is carried, and the measured value is compared with a predicted value. After inputting the measurements of the ventilation rates and various input data, which are as close as possible to the actual multi-housing unit in this study, verification is carried out along with the indirect comparison method. Measurement was conducted five times on the 1st, 11th and 20th floors at three multi-housing units. Outdoor temperature during the measurement period was 19.7-23.5°C (assumption of 20°C), indoor temperature was 23.1-25.2°C (assumption of 25°C), the staircase was 18.2-18.9°C (assumption of 18.5°C), and wind velocity 0.2-0.7m/s (assumption of 0.5m/s). The tracer gas (decay method using CO2 gas) method was used for the measurement.

Part of the input conditions during the simulation came from construction field measurement results. The predicted values tend to be smaller than the measured values in the lower floor section. The opposite tendency is seen in the higher floor section based on the analysis results.

The differences between predicted and measured average values are shown to be relatively small, ranging from -0.54% (1st floor) to +8.42% (20th floor), as shown in Fig.2.

2.2 Model House and Simulation Conditions

(1) Model House for Simulation

A multi-housing unit identical to the one shown in Fig.3., which is based on the existing result of the design tendency in Korea, is selected as a standard analysis model house. Concrete design conditions are shown in Table 1. The model house is assumed to be in Seoul, Korea. This unit is connected to the elevator hall and the staircase. The elevator shaft and stair shaft are connected to each floor. Air can move between the unit and the shafts through air leakages.

(2) Simulation Variable

Based on the construction field measurement results and ASHRAE standard 90.1-1989, the various variables that affect indoor airflow of the multi-housing unit and each simulation scope are established as shown in Tables 2. and 3. The variables are also chosen considering the characteristics and the adaptabilities of multi-housing units in Korea.
3. Influence of Each Variable on Ventilation Performance

3.1 Outdoor Wind Velocity

Air leakage area per floor area is assumed to be 2.0 cm²/m², and the indoor/outdoor temperature difference is assumed to be 25°C. The simulation was carried out based on the assumption that there is no stack effect from the staircase or vertical exhaust duct within the building. The outside wind velocity varies within 2 m/s to 8 m/s.

The air change rate between the floors is very small when the wind speed is 2 m/s, which is close to the annual average wind velocity (2.5 m/s) of Seoul. When the wind velocity increases, the air change rate in high floors is very large compared to the rate in low floors.

3.2 Stack Effect

Air leakage area per floor area is assumed to be 2.0 cm²/m². The wind velocity was 0.0 m/s.

The indoor, outdoor and staircase temperatures are 25°C, 0°C, and 15°C, respectively. The air tightness in each floor is assumed to be identical in the simulation. Therefore, the airflow in the vertical ducts was produced by the temperature difference only.

The air change rate for each floor is shown in Fig. 4. The neutral zone was produced on the 11th floor. For housing units below the 11th floor, air was introduced through leakages of the window. In contrast, airflow for housing units above the 11th floor came from shafts. The air change rate increased according to the temperature difference. The middle floors (10th and 11th floor) have a very low air change rate, and the low and high floors have a high air change rate. These values are not actual air change rates for the floor unit. The differences exist not because of the outside air but rather because after the fresh outside airflows into the living room, it becomes mixed and flows to each room again. This means that the total air change rate of a unit cannot be described as an actual representative air change rate for each room.

3.3 Wind Velocity and Stack Effect

The stack effect from a staircase that occurs under conditions in which the indoor temperature is 25°C, the...
staircase 15°C, the outside air 0°C, and the air leakage area 2.0 cm²/m² is analyzed. Indoor air change rate of a multi-housing unit based on the change of outside wind velocity is estimated.

The air change rate of the middle floor is the least (W-S=0.0 in Fig.5.) when only the stack effect applies. However, when the wind velocity (W-S) is increased, the air change rate of the lower floor section decreases and the air change rate of the high floor section increases significantly, as shown in Fig.5.

3.4 Ventilation Performance of Building Envelope Air Tightness

By assuming that the indoor temperature is 25°C, the staircase 15°C, and the outside air 0°C, the changes in indoor air change rates by floor based on the air leakage area per floor area of multi-family housing units are examined. The result shows that the difference in air change rate decrease is largely based on air leakage area change. Therefore, air tightness of the building envelope or the consideration of effectively strengthening the air leakage area per floor area will significantly reduce the air-change rate difference by floor.

3.5 Ventilation Performance of Bathroom Exhaust

Most domestic multi-housing units have natural exhaust fans installed in the rooftop part of vertical exhaust ducts; these ducts are connected with bathrooms. In this study, the exhaust flow rate of rooftop non-electric natural exhaust fans is artificially changed so that the simulation estimates their effects. The size of a vertical exhaust duct, which is based on the simulation result, is shown to have little effect on the whole ventilation rate.

As shown in Fig.6., the case of R-V=0.1 (airflow rate is 0.1 m³/min) has a 300×300mm duct and R-V=0.3 (airflow rate is 0.3 m³/min) has a 400 mm×400 mm duct. However, it is also true that the air change rate of the high floors of the unit is rapidly increased by the increasing airflow rate of the rooftop exhaust fan. The effect of the rooftop exhaust fan is significant in the 14th-20th floors section.

3.6 Ventilation Performance Based on Kitchen Exhaust Fan

The indoor air change rate based on the operation of the kitchen exhaust fan changes as shown in Fig.7. In the graph DF=0.1 indicates the airflow rate when a capacity of 6.0 m³/min exhaust fan was operated for one minute. The air change rates for the lower floors are significantly increased by increasing the airflow.
rate of the exhaust fan. However, the effect of the kitchen exhaust fan is small in the upper part of the building.

3.7 Ventilation Performance Based on Air Tightness of Interior Entrance Door

Assuming the air leakage area difference per floor area of the interior entrance door to be airflow resistance, the air leakage area per floor area of the entrance door was changed from 1.0 to 4.0 cm²/m². The result shows an air change rate increase of approximately 3.73%, which is the average of the low floors section (approximately 4.44%), the middle floors section (approximately 1.83%), and the high floors section (approximately 4.96%).

4. Ventilation Performance Prediction Model of Multi-Family Housing Unit

4.1 Design of Prediction Model and Establishment of Variables

Using both field measurements and existing surveys on the actual multi-housing unit, we selected the independent variables thought to be important to predict the ventilation performance. In addition, a multi-regression analysis was carried out by the stepwise input method of variables. After that, using the selected variables, the ventilation performance prediction model for the multi-family housing unit was produced.

4.2 Ventilation Performance Prediction Model Using Multi-Regression Analysis

The airflow variable that has a high relationship with ventilation performance is applied in establishing the recurrence model. The correlations between the variables have to be analyzed to identify the linear or nonlinear relationship between variables. The SAS 6.12 program was used to examine the correlation between the dependent variable and each independent variable.

| Independent Variable | Parameter Estimate | Standard Error | Sig. T |
|----------------------|--------------------|----------------|--------|
| A1                   | 0.283              | 0.0025         | 0.0001 |
| A2                   | 0.449              | 0.0163         | 0.0001 |
| A3                   | 1.642              | 0.0129         | 0.0001 |
| A4                   | 0.013              | 0.0596         | 0.0001 |
| A5                   | 0.062              | 0.0013         | 0.0001 |
| A6                   | 0.017              | 0.0149         | 0.0001 |
| A7                   | -0.040             | 0.0082         | 0.0451 |
| M1                   | -0.040             | 0.0070         | 0.0001 |
| M2                   | -0.288             | 0.0219         | 0.0001 |
| M3                   | 0.013              | 0.0014         | 0.0001 |
| M4                   | -0.006             | 0.0012         | 0.0001 |
| M5                   | 0.001              | 0.0002         | 0.0001 |
| M6                   | 0.061              | 0.0186         | 0.0014 |

\[ R^2 = 0.9963 \]

Standard variables and mathematical variables that are established as independent variables are shown in Table 5.

4.3 Correlation between Independent Variable and Dependent Variable

The correlation between each independent variable and air-change rate was examined. An example (1st floor) of correlations regarding air change rate and each independent variable is shown in Table 6. The significance rate of almost all variables, both standard and mathematical, is 0.0001, which is below the significance level of less than 0.01 (explanation ability is more than 99%). Additionally, the crystallization coefficient R2 is 0.9963, which is very significant.

4.4 Correlation between Mutual Independent Variables

To identify the existing linear or nonlinear relationship between variables, the correlation between the mutual independent variables is analyzed. Variables

| Independent Variable | Composition of Variable |
|----------------------|-------------------------|
| A1                   | Wind Rate of Kitchen Exhaust Fan |
| A2                   | Wind Rate of Bathroom Exhaust Fan |
| A3                   | Available Air Leakage Area of Building Envelope |
| A4                   | Wind Rate of Rooftop Exhaust Fan |
| A5                   | Staircase Stack Effect |
| A6                   | Outside Wind Velocity |
| A7                   | Airflow Resistance of Inside Entrance Door |
| M1                   | Available Air Leakage Area × Wind Velocity |
| M2                   | Wind Velocity/(Kitchen Exhaust Fan + Bathroom Exhaust Fan + Rooftop Exhaust Fan + Stack Effect + Wind Velocity) |
| M3                   | Kitchen Exhaust Fan × Bathroom Exhaust Fan 3 |
| M4                   | Available Air Leakage Area4 |
| M5                   | (Bathroom Exhaust Fan × Available Air Leakage Area × Stack Effect × Outside Wind Velocity)/(Kitchen Exhaust Fan + 1) |
| M6                   | I/EXP(A3×A6) |

Table 5. Standard Variables and Mathematical Variables Established as Independent Variables

Table 6. Correlation between Independent and Dependent Variables (Example of 1st Floor)
4.5 Ventilation Performance Prediction Model

Figs. 8. and 9. are examples of remaining difference analysis on the recurrence model. The remaining difference in the case of the applied multi-recurrence model by standard variable is shown in Fig. 8. (crystallization coefficient $R^2 = 0.9720$). The result of mathematically inputting the variable group into the first result to decrease the remaining difference is shown in Fig. 9., which has the most exact prediction result ($R^2 = 0.9962$).

The prediction equation estimated by the multi-recurrence analysis is equation (1). The final ventilation performance prediction model of the unit for each floor of the multi-housing unit is equation (2). Both the coefficients and the constants by floors of equation (2) are shown in Table 8.

$$Y_n = a_n A_1 + b_n A_2 + c_n A_3 + d_n A_4 + e_n A_5 + f_n A_6$$
$$+ g_n A_7 + h_n A_8 + i_n A_9 + j_n A_{10} + k_n A_{11} + l_n A_{12} + \text{const}_n$$

$$V_n = A_1 A_2 \left( \frac{a_n}{A_1} + \frac{b_n}{A_2} + \frac{c_n}{A_3} + \frac{d_n}{A_4} + \frac{e_n}{A_5} + \frac{f_n}{A_6} \right)$$
$$+ A_1 A_2 \left( \frac{g_n}{A_7} + \frac{h_n}{A_8} + \frac{i_n}{A_9} + \frac{j_n}{A_{10}} + \frac{k_n}{A_{11}} + \frac{l_n}{A_{12}} \right) + \text{const}_n \exp(A_1 \times A_2)$$

5. Conclusion

The purpose of this study was to develop a prediction model for analyzing ventilation performance in multi-housing units. A computer simulation was used to analyze ventilation performance. Using the simulation results, the prediction equation of ventilation performance was presented in the study. The results of the study are as follows:

1. The air change rate of each room is different from the total air change rate of the household unit. More specifically, the air change rate of the living room, which has the most exposure to the outdoors, is more than two times per hour. Since most of the rooms face the living room, most of the airflow of each room comes from the living room. In addition, the ventilation rate of each room is highly influenced by the airflow rate from the living room. Thus, independent ventilation control is required to maintain the proper ventilation rate in each room.

2. The network analysis method applied in this study calculates the indoor/outdoor airflow rate

with a more than ±0.5 correlation coefficient are shown in Table 7.

| Ind. Var. | A2 | A3 | A5 | A6 | M1 | M2 | M3 | M4 | M5 |
|-----------|----|----|----|----|----|----|----|----|----|
| A2        | -  | -  | -  | -  | -  | -  | -  | -  | 0.594 |
| A3        | -  | -  | -  | -  | -  | -  | -  | -  | 0.791 |
| A5        | -  | -  | -  | -  | -  | -  | -  | -  | 0.569 |
| A6        | -  | -  | -  | -  | -  | -  | -  | -  | 0.862 |
| M1        | -  | -  | -  | -  | -  | -  | -  | -  | 0.753 |
| M2        | -  | -  | -  | -  | -  | -  | -  | -  | 0.920 |
| M3        | -  | -  | -  | -  | -  | -  | -  | -  | 0.939 |
| M4        | -  | -  | -  | -  | -  | -  | -  | -  | 0.346 |
| M5        | -  | -  | -  | -  | -  | -  | -  | -  | 0.335 |

Table 8. Correlation between the Mutual Independent Variables (Example of 1st Floor)
between the flow paths of each room within the unit. The average error between the prediction value and the measured value is less than 8.4%. The developed model can be applied as a more effective method to calculate the airflow rate of the general multi-family housing unit.

(3) The study result of the ventilation performance prediction model of the multi-family housing unit can be usefully applied to ventilation design. Based on reliable prediction results, it is possible to quantitatively estimate air change rate based on outside wind velocity, staircase stack effect, air leakage area of the building envelope, flow resistance of indoor air (entrance door, etc), bathroom and kitchen exhaust fan, as well as rooftop exhaust fan with vertical exhaust duct.

(4) Among the driving forces of airflow that produce ventilation in the multi-family housing unit, the air leakage area is the largest factor with a contribution rate of approximately ±35%.

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