Simplified Prediction Method of Stack-Induced Pressure Distribution in High-rise Residential Buildings

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Abstract
This paper presents a simple prediction strategy for estimating the pressure distribution in high-rise residential buildings, using key parameters that affect the magnitude and distribution of stack pressure. The strategy is composed of two procedures: first, the stack pressure is predicted from parameters such as the height of the elevator shaft, the location of the neutral pressure level for each shaft, and the interior temperature of each shaft. Then, the pressure distribution of each floor is calculated using the equivalent leakage areas of the exterior and interior walls, by which finally the pressure difference across the exterior walls can be estimated. To verify the feasibility of this strategy, the predicted pressure differences across exterior walls were compared to measured data of a high-rise residential building with multiple elevator zoning. The results show that this strategy can predict pressure distribution quickly with satisfactory results for both the architectural designer and HVAC engineer.

Keywords: stack effect; pressure distribution; high-rise; residential building

1. Introduction
Numerous high-quality residential buildings of over 30 stories are being planned in Korea, and problems due to stack pressure differences are becoming an issue. These residential buildings are similar to tower shaped-office buildings in various aspects; they generally have a central core, elevator shafts and stairwells, are surrounded by corridors, and have 4 to 7 residential units on each floor. During the cold season, severe problems are experienced in high-rise buildings due to the stack effect, which are problems associated with pressure differences. These stack-induced excessive pressure difference problems were found to occur mainly around the core area as shown in a previous field study (Jo et al. 2007). Stack effect problems associated with pressure difference are common in countries of Northeast Asia which have severe cold weather marked by an indoor-outdoor temperature difference of over 30°C. Therefore, HVAC engineers and architects need to understand the pressure difference across the internal partitions of high-rise residential buildings in order to minimize the potential problems caused by the stack effect. It is also crucial that the pressure differences across exterior walls be considered in high-rise buildings, as they affect the heating load from infiltration and adequate ventilation planning. Stack pressure differences have often been used as a major variable in previous infiltration calculation models (Liddament 1986, Lyberg 1997), though they are limited in the case of low-rise buildings. The use of network models such as COMIS (Feustel 1990) and CONTAM (Dols et al. 2002) is an effective way to evaluate the pressure distribution in high-rise buildings, but this requires accurate data for the many leakage variables and can only be employed by a small number of experts. Based on the observation results from field measurements and simulations, this paper presents a simple prediction strategy for pressure distribution that may be used to quickly predict stack-induced pressure differences in the early design stages for heating load calculations and ventilation planning.

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2. Simplified Prediction Approach

To predict the stack-induced pressure distribution for a building, the magnitude of the total pressure difference over the entire building must first be determined, and the proportion of pressure differences across the exterior wall and interior separations must then be calculated. Since high-rise buildings have various vertical airflow routes and complicated interior floor plans, the following simplifications were adopted in this study.

(1) Simplifications in wind and equipment effects

Generally, wind pressure affects the airflow routes in the case of high-rise buildings. However, the effect of wind pressures is instantaneous, unlike stack pressure which is sustained over a long period. Sometimes, the effect of wind pressure is combined with the effect of stack pressures in a procedure called superposition (Walker 1993). This study focuses on stack pressure during the winter season when indoor-outdoor temperature differences are considerable, and the effect of wind pressure is excluded. In high-rise buildings in Korea, each residential unit has a separate heat recovery ventilator because the exterior walls are airtight and a minimal amount of ventilation is supplied to the indoor corridor zones to provide a balanced pressure. Therefore, the effect of ventilation equipment is excluded in this study.

(2) Simplifications in the shape of the building

Simplification in vertical shafts

The vertical airflow routes in a high-rise building consist of elevator shafts, stairwells, and various mechanical shafts. As shown in the field measurements and airflow simulations of previous studies, the main vertical airflow routes that have the most significant effect on the pressure distribution of each floor are the passenger elevator shafts, which are connected to each serving floor. The emergency elevator shaft or stairwells, which are inevitably included in high-rise buildings, are also highly vulnerable to stack pressure difference problems, and the building code usually requires that they are connected to all floors and that vertical airflow routes are thereby created. However, additional partitions and vestibules can be installed to increase the airtightness of these shafts, in order to reduce excessive pressure differences. Also, these shafts are rarely used in daily routines, and therefore do not have a significant impact on the airflow of the entire building. Therefore, this study focuses only on the significance of the heights of passenger elevator shafts in predicting the pressure distribution of a building.

Simplification in typical floor plans

Stack-induced pressure differences are proportioned over building elements according to the structure of the building and the leakage area of each building element. An effective means of reflecting this proportion is the Thermal Draft Coefficient (TDC), which is defined by ASHRAE (2001) as the sum of the top and bottom pressure differences across the exterior walls divided by the total theoretical pressure differences, and which has been discussed in detail by Tamura (1967, 1994). Hayakawa (1989) indicated that the proportions of pressure differences will be similar if the typical floor plans are similar, and interpreted the TDC as the proportion of pressure difference supported by the exterior walls. Examining the typical floor plans of high-rise residential buildings in Korea, each floor can be simplified so that it is separated by a first partition formed by the exterior walls, a second partition formed by the entrance and the wall between the residential unit and the corridor, and a third partition formed by the elevator door and the wall of the elevator shaft. In this study, the equivalent leakage area of the exterior walls and the equivalent leakage area of interior separations were used to determine the pressure difference across the exterior walls of each floor. In Fig.2., the typical floor plan can be simplified by three boundary lines; the first line consisting of exterior walls, the second line consisting of resident entrance doors and the wall between corridors and residences, and the third consisting of elevator shafts and core walls.

3. Data Gathering for Stack Pressure Prediction

To predict the pressure distribution in high-rise buildings, it is necessary to analyze the key parameters influencing the pressure distribution and to define the precise values for these parameters, which is the main source of the stack effect. Based on the characteristic of the pressure profile derived from field measurements and computer simulation analysis in the previous study (Jo et al. 2007), the required key information consists of the inside and outside temperature differences, the height of the building, the location of the NPL (neutral plane level), the height of the vertical compartment, and the ratio of the airtightness of the exterior walls and interior partitions which is derived by TDC. Therefore, we have gathered data for key parameters by carrying out field measurements and network simulation in high-rise residential buildings.

(1) Locations of the NPL

While leakage openings in the exterior walls of a building are not always distributed uniformly from the
bottom to the top, the in-flow always equals the outflow. If the openings at the lower part of a building were larger than those at the higher part, and therefore a smaller resistance to flow is imposed, the pressure difference across the bottom would be less than that across the top. This would be equivalent to a shift of the inside pressure line to the right and a lowering of the NPL. Because of the non-uniform leakage area of a building, however, the location of the NPL can be estimated by equating the flows through the two parts of the leakage areas. The location of the NPL ($h$) can be expressed by

$$h = \frac{H}{1 + (A_1/A_2)^2 T/To}$$

where $A_1$ and $A_2$ are the lower and higher leakage areas, $T_1$ and $T_2$ are the outdoor and indoor absolute temperatures, and $H$ is a building height. The density of the air that flows inward and outward of the building is not identical due to temperature differences, and this is included in this equation. The influence of the density difference, however, is so negligible that the location of the NPL can be derived from the ratio of the opening area above and below the NPL. However, it is still difficult to define all the possible openings on the airflow path and measuring the area of these openings is beyond consideration.

In this research, high-rise residential buildings with more than 30 stories were reviewed and field measurements and network simulation analysis were carried out. Since the levels that has no air flow between the shaft and adjacent rooms are similar to the height of neutral zone has been defined on the exterior wall, this is also called NPL in this paper. The results are shown in Fig.3. and Fig.4., and are categorized according to vertical compartment type, single zone type and two zone type. In the buildings with a single zone, the NPL was averagely located at 39% of the elevator shaft height. In two zone type buildings, it was located at 63% for the low-rise elevator shaft and 64% for the high-rise elevator shaft. All the NPL locations are summarized in Table 1.

(2) Heights of Vertical Compartments

There are many components of high-rise buildings that play a main role as a vertical airflow path such as elevator shafts, stairwells, and shafts that accommodate mechanical equipment. Because shafts for passenger elevators occupy most of the area allocated to vertical shafts and they are the most frequently used shafts, they are generally the most influential components contributing to pressure distribution in high-rise buildings. Moreover, if elevator shafts are vertically compartmentalized, i.e. by low-rise and high-rise elevators, there is a discontinuous point in the pressure profile at the top and bottom of each shaft; thus, it is essential to know the height of the shafts in order to predict pressure distribution in buildings. In this research, we have defined this parameter as the height of the vertical compartment (S) and it is included in the key factors, which is used when vertical pressure distribution is predicted.

Typical shaft-zoning types in high-rise residential buildings are shown in Table 2., as well as the height of the vertical compartment for each type which is required for predicting pressure profile. In buildings with two-zone type, for example, height of the low-rise elevator shaft ($S_{low}$) and high-rise elevator shaft ($S_{high}$) are the key factors.

(3) Airtightness of exterior walls and interior separations

Since most of the stories in high-rise buildings have identical floor plans, with the exception of basement floors and the ground floor, the overall pressure difference between vertical shafts and the exterior...
is distributed to elements on the airflow path based on the airtightness of each element. Therefore, the pressure profile of each floor can be derived if $TDC(\gamma)$ or $ITDC$(Internal Thermal Draft Coefficient, the expression of the ratio of the airtightness of internal compartments and exterior walls), is known. Based on the previous study, pressure differences acting on interior compartments are drawn from ITDC and the overall pressure difference on each floor. The sum of the pressure difference on the interior compartments on the $i^{th}$ floor can be derived by $\Delta P_{ST,i}$ (stack pressure difference on $i^{th}$ floor) multiplied by ITDC. Field measurements and computer simulations were conducted to define the ITDC value in high-rise residential buildings, and TDC values of 0.31~0.40 are used in this study, which can be converted to ITDC values of 0.60~0.69 in Table 3. The stack pressure difference on the $i^{th}$ floor $\Delta P_{ST,i}$, shown in Fig.5., can be drawn from the theoretical equation. TDC, which is a proportion of the pressure difference covered by the overall exterior walls, can be calculated by using equivalent leakage areas. TDC and ITDC provide the total pressure difference operated on interior partitions, and this is defined as the internal stack pressure difference on the $i^{th}$ floor $\Delta P_{TP}$, which is expressed in equations (2) and (3).

$$\Delta P_{ST,i} = (1 - \gamma_i) \times \Delta P_{ST,i} \quad (2)$$
$$\Delta P_{TP,i} = ITDC_i \times \Delta P_{ST,i} \quad (3)$$

4. Prediction of Stack-induced Pressure Distribution

The prediction strategy is composed of the following two procedures, and the key parameters are as follows in each step:

1. Predicting the vertical stack pressure distribution: the height of each elevator shaft ($h_{low}$, $h_{high}$), the location of the neutral pressure level for each shaft, ($h_{NPL,low}$, $h_{NPL,high}$), and the outdoor and interior temperatures of each shaft ($t_o$, $t_s$).

2. Predicting the horizontal stack pressure distribution: the equivalent leakage areas in exterior walls ($A_w$) and interior partitions including the vertical shafts ($A_e$).

To easily show the strategy for predicting the buoyancy-induced pressure distribution, a model building was selected, with which the strategy may be demonstrated. The key parameters for the model building are given in Table 4. Here, the location of the NPLs and ratio of equivalent leakage areas are based on measurement data of 15 high-rise residential buildings of over 30 stories, while the other values are based on the design conditions of the model building.

(1) Predicting the vertical stack pressure distribution

To predict stack-induced pressure distribution over a building, the magnitude of maximum pressure difference must be calculated for each floor by first assuming the position of the neutral pressure level. The main parameters affecting the stack-induced pressure difference are the building height, the indoor-outdoor temperature difference, and the height of the neutral pressure level, which may differ depending on the proportion of openings on the upper and lower parts of a building. The building height is closely related to the height of the vertical shafts within the building and, as shown in a previous study (Jo et al. 2007), because the main airflow within a building depends on the
heights of the passenger elevator shafts, the heights of the vertical zoning of such shafts must be considered. The vertical distance from the neutral pressure level of each passenger elevator shaft, along with the indoor-outdoor temperature difference, are used to complete the basic calculation equation, and consequently, the vertical stack pressure distribution may be predicted by determining the magnitude of the stack-induced pressure difference for each floor. The "prediction of vertical stack pressure distribution" follows the process shown below, and the results are shown in Fig.6.e.

1) Draw a line with a slope representing the absolute pressure ($P_{\text{outside}}$) for the outdoor temperature (ref. Fig.6.a).
   - Outdoor temperature, $t_o$: -12°C

2) Mark the position of the estimated neutral pressure level for each elevator shaft on the absolute pressure line (ref. Fig.6.b).
   - Position of the NPL for the upper level elevator shaft, $h_{\text{NPL,high}}$: 64 % of building height
   - Position of the NPL for the lower level elevator shaft, $h_{\text{NPL,low}}$: 32 % of building height

3) Mark the height of each passenger elevator shaft on the vertical axis, and draw parallel horizontal lines (ref. Fig.6.c).
   - Height of the upper level elevator shaft (equal to building height), $S_{\text{high}}$: 210 m
   - Height of the lower level elevator shaft, $S_{\text{low}}$: 105 m

4) For each elevator shaft, draw a line that passes the neutral pressure level of the corresponding shaft, with a slope representing the absolute pressure ($P_{\text{low-rise elevator}}$ or $P_{\text{high-rise elevator}}$) for the temperature inside the shaft (ref. Fig.6.d).
   - Temperature inside the elevator shafts (equal to the indoor temperature), $t_s$: 22°C

(2) Predicting the horizontal stack pressure distribution
As discussed in the previous section, a model building is used and the procedure of predicting the horizontal stack pressure distribution is demonstrated in this section. First, the pressure distribution across the exterior wall and indoors is predicted by utilizing the TDC, which represents the proportion of pressure difference for the exterior wall. The pressure difference across the exterior wall may then be calculated by multiplying the pressure difference for each floor, obtained by predicting the vertical stack pressure distribution. In the same manner, the pressure distributions across specific interior separations may

### Table 4. Parameters for the Model Building

| Parameter                        | Symbol | Value          |
|----------------------------------|--------|----------------|
| Outdoor temperature              | $t_o$  | -12°C          |
| Indoor temperature               | $t_s$  | 22°C           |
| Location of NPL (two zone type)  | $h_{\text{NPL,high}}$ | 64 % (best estimate) |
|                                  | $h_{\text{NPL,low}}$ | 32 % (best estimate) |
| Height of elevator shaft (two zone type)   | $S_{\text{high}}$ | 210 m            |
|                                  | $S_{\text{low}}$ | 105 m            |
| Ratio of equivalent leakage areas | $A_e/A_w$ | 0.67~0.82 (best estimate: 0.73) |

![Diagram for the first step](image1)

![Diagram for the second step](image2)

![Diagram for the third step](image3)

![Diagram for the forth step](image4)

![Predicted results](image5)

Fig.6. Diagrams for the Prediction Procedure of Stack Pressure Distribution and the Predicted Results
The "prediction of horizontal stack pressure distribution" follows the process shown below, and the results are shown in Fig.6.e.

1) Calculate the TDC using the equivalent leakage area of the interior separations \( A_e \) and the equivalent leakage area of the exterior wall \( A_w \).

- \( \frac{A_e}{A_w} : 0.67 \sim 0.82 \) (best estimate: 0.73), and \( \gamma_i : 0.31 \sim 0.40 \) (best estimate: 0.35)

2) Multiply the TDC to the stack pressure difference for each floor \( \Delta P_{ST,i} \) to obtain the pressure difference across the exterior wall \( \Delta P_{w,i} \).

- \( \Delta P_{ST,i} = 3460 \times \left[ \frac{1}{(t_o+273)} - \frac{1}{(t_s+273)} \right] \times \Delta Z_i \)
- \( \Delta P_{w,i} = \Delta P_{ST,i} \times \gamma_i \)

5. Field Verification of the Prediction Method

To show the applicability of the prediction strategy for the stack-induced pressure difference, the strategy is applied to a case study for which field measurements were obtained in a previous study, so that the prediction results may be compared with the measurement results. The field measurements were carried out at dawn during winter season and on the day with stable weather condition to minimize other influences such as wind, elevator use by occupants, and opening of doors. We have measured the absolute pressure at 6 points (elevator shaft, corridor, occupied area, emergency elevator shaft, vestibules and ambient) simultaneously on each floor from the top floor to the bottom successively. To compensate the change of absolute pressure as time goes, we have measured the top, the middle, and the bottom point of each shaft and the ambient in advance. The pressure was measured at the floor surface. Based on the measured data, the key parameters for the verification building are expressed in Table 5.

The vertical pressure profile in the objective building was predicted and the overall process is shown in Fig.7. For the purpose of validation, prediction results and field measurement results are plotted in the nomograph in Fig.8.a.

Based on the vertical pressure profile, the horizontal pressure distribution was then derived and the results are plotted in Fig.8.b. Fig.8. shows the stack-induced pressure differences, which represent the pressure difference between the exterior and the interior of the vertical elevator shaft. It can be seen that the stack-induced pressure differences are the same for most of the floors, with the exception of the upper levels and the 54th floor (the transfer floor). Also, as the results sufficiently reflect the change in absolute pressure at each vertical separation area, the airflow at each floor can easily be determined. The reason for the discrepancy in the results of the upper levels is believed to be caused by the difficulty, and hence inaccuracy, in measuring the airflow of the upper levels during the field measurement. Furthermore, the reason

Table 5. Parameters for the Verification Building

| Parameter                  | Symbol | Value    |
|----------------------------|--------|----------|
| Outdoor temperature        | \( t_o \) | -6°C     |
| Indoor temperature         | \( t_s \) | 22°C     |
| Location of NPL (multiple zone type) | \( h_{NPL,high} \) | 60 %  |
|                            | \( h_{NPL,middle} \) | 44 %  |
|                            | \( h_{NPL,low} \) | 21 %  |
| Height of elevator shaft   | \( S_{high} \) | 247 m   |
| (multiple zone type)       | \( S_{middle} \) | 184 m   |
|                            | \( S_{low} \) | 53 m    |
| Ratio of equivalent leakage areas | \( A_e/A_w \) | 0.80 (best estimate: 0.80) |
for the discrepancy in the results for the 54th floor is that the upper and lower elevator shafts meet on the same floor and create airflow routes that are difficult to account for when using the prediction strategy of this study. However, the elevator shaft of the typical high-rise residential building, which yields the height of the main vertical zone, is usually a single zone type or a two zone type without a transfer floor. Therefore, by using the prediction strategy of stack pressure distribution presented in this study, the stack-induced pressure difference may effectively be obtained for all typical floors of the building.

6. Conclusions

This paper presents a simple prediction strategy for estimating the pressure distribution in high-rise residential buildings to be utilized in the early planning stages. The strategy comprises two main procedures: first, the "prediction of the vertical stack pressure distribution," in which the pressure difference over the entire building is determined, and second, the "prediction of the horizontal stack pressure distribution," in which the pressure difference across the exterior wall for each floor is calculated from the stack pressure difference obtained from the first procedure. In calculating the magnitude of the pressure difference over the entire building and on each floor, such parameters as the height of the elevator shaft, the location of the neutral pressure level for each shaft, and the indoor-outdoor temperature difference were considered. Next, in calculating the pressure distribution on each floor, the leakage area of the exterior wall was utilized, as well as the equivalent leakage area of the interior walls, which includes the airtightness of the shafts. Using these procedures, the stack-induced pressure difference across the exterior walls can be estimated. In this paper, the procedure of predicting the stack-induced pressure difference across exterior walls in high-rise residential buildings assumes that the typical floor plan is uniform and that the temperature of all indoor zones are kept constant. Therefore, it may not be applied to buildings with non-uniform floor plans or many zones with different indoor temperatures. Also, further research is necessary to provide reliable data on the equivalent leakage areas of exterior walls and interior separations and the locations of neutral pressure levels for various elevator shafts in various kinds of buildings, for a more accurate prediction of pressure distribution.

Fig. 8. Pressure Distribution Comparisons of Predicted Results and Measured Results

a) vertical stack pressure distribution comparison of predicted results and measured ones

b) horizontal stack pressure distribution comparison of predicted results and measured ones
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