PREDICTION OF BUOYANCY-INDUCED PRESSURE DIFFERENCE ACROSS EXTERIOR WALLS OF HIGH-RISE RESIDENTIAL BUILDINGS

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ABSTRACT

It is very important to estimate the stack pressure difference across exterior walls for understanding the energy impacts of infiltration and ventilation in high-rise buildings, because stack pressure is likely to significantly affect energy load and is sustained over a long period. 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, Residential building, High-rise

INTRODUCTION

Numerous high-class residential buildings of over 30 stories are being planned in Korea, and problems due to stack pressure differences are becoming an issue. It is crucial that the pressure differences across exterior walls be considered in these buildings, as they affect the heating load from infiltration and adequate ventilation planning. Stack pressure differences have been used often 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 CONTAMW (Dols et al. 2002) is effective, but it requires accurate data for many airtightness variables and may only be employed by a few number of experts. Based on the observation results from field measurements and simulations (Jo 2005), this paper presents a simple prediction strategy for pressure distribution that may be used to quickly predict buoyancy-induced pressure differences in the early design stages for heating load calculations and ventilation planning.

SIMPLIFIED PREDICTION APPROACH

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

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 (e. g., Walker 1993). This study focuses on stack pressure during the winter season when indoor-outdoor temperature differences are great, and excludes the effect of wind pressure. In high-rise buildings in Korea, the each residential unit has a separate heat recovery ventilator on the grounds that the exterior walls are airtight, and a minimal amount of ventilation is supplied to the indoor corridor zones to provide a balanced pressure. Therefore, this study excludes the effect of ventilation equipment.

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 (Jo 2005), the main vertical airflow routes with 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, as building code requirements usually force them to be connected to all floors and create vertical airflow routes. However, additional partitions and vestibules are installed to increase their airtightness as measures against excessive pressure differences. Also, these shafts are rarely used in daily routines, so that they do not render a great impact on the airflow of the entire building. Therefore, this study focuses only on the heights of passenger elevator shafts in predicting the pressure distribution of a building.

Simplification in typical floor plans

Buoyancy-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 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. Looking at the typical floor plans of high-rise residential buildings in Korea, each floor can be simplified to be separated by a first partition formed by the exterior walls, a second partition formed by the entrance and 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.

PREDICTION OF BUOYANCY-INDUCED PRESSURE DIFFERENCE

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 ($h_{NPL,low}$, $h_{NPL,high}$), 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 readily show the strategy of predicting 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 1. Here, the location of NPLs and ratio of equivalent leakage areas are based on measurement data of 15 high-rise residential buildings of over 30 stories (Jo 2005), and the other values are based on the design conditions of the model building.

TABLE 1 Parameters for the model building

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

Predicting the Vertical Stack Pressure Distribution

To predict buoyancy-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 buoyancy-induced pressure difference are the building height, the indoor-outdoor temperature difference, and also 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 previous study (Jo 2005) has shown that 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 buoyancy-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. 1.

(1) Draw a line with a slope representing the absolute pressure ($P_{outside}$) for the outdoor temperature (see Fig. 1 a).

- Outdoor temperature, t_o : -12℃

(2) Mark the position of the estimated neutral pressure level for each elevator shaft on the absolute pressure line (see Fig. 1 b).

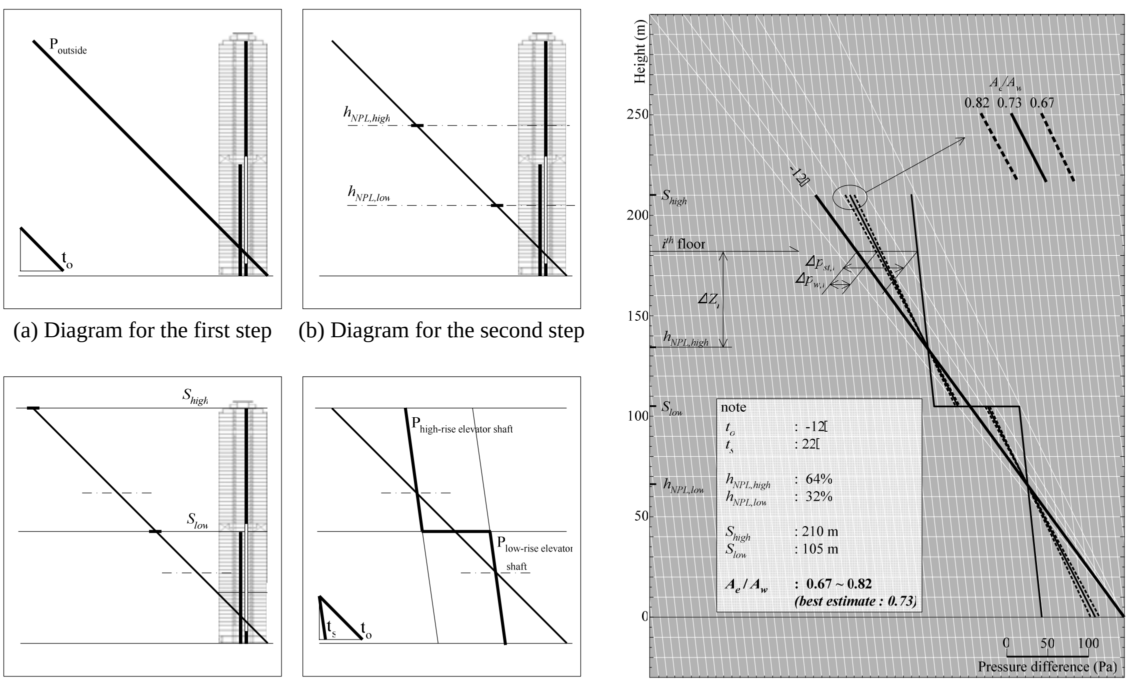
- Position of the NPL for the upper level elevator shaft, $h_{NPL,high}$: 64 % of building height
- Position of the NPL for the lower level elevator shaft, $h_{NPL,low}$: 32 % of building height

(3) Mark the height of each passenger elevator shaft on the vertical axis, and draw parallel horizontal lines (see Fig. 1 c).

- Height of the upper level elevator shaft (equal to building height), S_{high} : 210 m
- Height of the lower level elevator shaft, S_{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 ($P_{low\text{-}rise\ elevator}$, $P_{high\text{-}rise\ elevator}$) for the temperature inside the shaft (see Fig. 1 d).

- Temperature inside the elevator shafts (equal to the indoor temperature), t_s : 22℃



(a) Diagram for the first step (b) Diagram for the second step

(c) Diagram for the third step (d) Diagram for the forth step

(e) Predicted results

Figure 1: Diagrams for the prediction procedure of stack pressure distribution and the predicted results

Predicting the Horizontal Stack Pressure Distribution

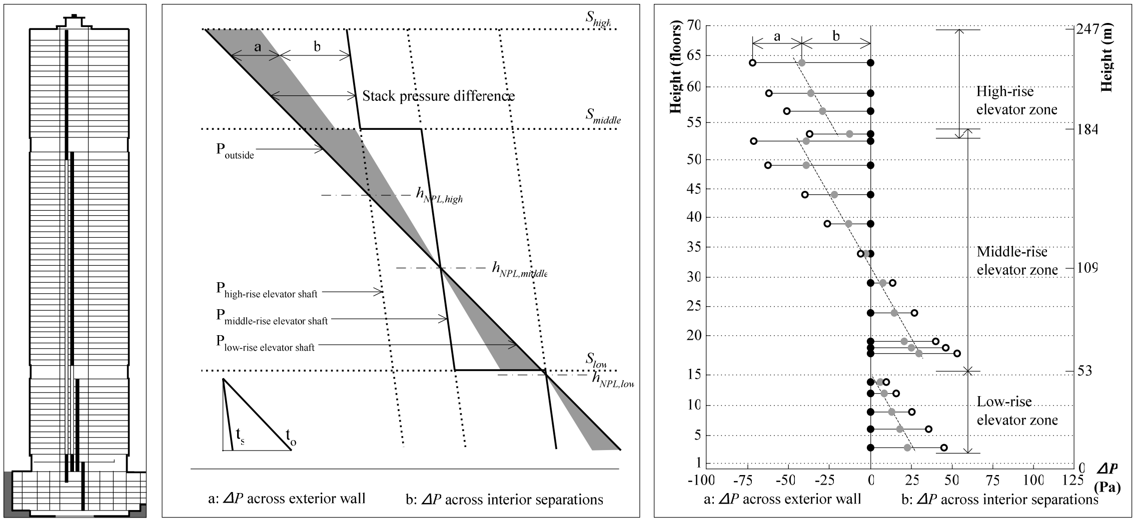
As in the previous section, a model building is used and the procedure of predicting the horizontal stack pressure distribution is demonstrated in this section. First, the pressure distribution across the exterior wall and indoors is predicted by utilizing the TDC, which represents the proportion of pressure difference for the exterior wall. Then, the pressure difference across the exterior wall may be calculated by multiplying the pressure difference for each floor, obtained in predicting the vertical stack pressure distribution. In the same manner, the pressure distributions across specific interior separations may be calculated also, by using the equivalent leakage areas for the specific interior separations. The "prediction of horizontal stack pressure distribution" follows the process shown below, and the results are shown in Fig. 1 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).
   - A_e/A_w : 0.67 ~ 0.82 (best estimate: 0.73), and Υ_i : 0.31 ~ 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 ($\Delta P_{w,i}$). ΔZ_i is a vertical distance from the neutral pressure level of each passenger elevator shaft to ith floor (see Fig. 1 e).
   - $\Delta P_{st,i} = 3460 \times [1/(t_o+273) - 1/(t_s+273)] \times \Delta Z_i$
   - $\Delta P_{w,i} = \Delta P_{st,i} \times \Upsilon_i$

VERIFICATION OF THE PREDICTION STRATEGY

To show the applicability of the prediction strategy for buoyancy-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. Figure 2 shows that the buoyancy-induced pressure differences, which represent the pressure difference between the outdoors and inside the vertical elevator shaft, are the same for most of the floors except for the upper levels and the 54th floor (the transfer floor). Also, as the results well reflect the change in absolute pressure at each vertical separation area, the airflow at each floor may easily be determined. The reason for the discrepancy in the results of the upper levels is regarded to lie in the difficulty, and hence inaccuracy, in measuring the airflow of the upper levels during the field measurement, and the reason for the discrepancy in the results for the 54th floor is because the upper and lower elevator shafts meet on the same floor and create airflow routes that are difficult to account for 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, so that by using the prediction strategy of stack pressure distribution presented in this study, the buoyancy-induced pressure difference may effectively be obtained for all typical floors of the building.



(a) Section (b) Predicted data (c) Measured data

Figure 2: Pressure distribution comparisons of predicted results and measured results

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 is composed of two main procedures: first, "prediction of the vertical stack pressure distribution," in which the pressure difference over the entire building is determined, and second, "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 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 buoyancy-induced pressure difference across the exterior walls can be estimated.

Limitations

In this paper, the procedure of predicting the buoyancy-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 that supplies 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.

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