A Study on the Reduction Strategies of Stack Effect in High-rise Residential Buildings

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ABSTRACT

The stack effect in high-rise buildings in winter causes many problems such as difficulty in opening or closing doors, infiltration, energy loss, noise in lobby floor and fire protection. The main purpose of this study is to analyze the feature of stack effect in high-rise residential buildings and investigate the effect of reduction strategies with network simulation method. The simulation has been conducted for 2 high-rise buildings under the construction which have 36, 37 stories above the ground level and 2 basement stories respectively by CONTAMW.

In this paper, the results of pressure difference, the location of the neutral plane and air-flow between spaces for analyzed cases will be presented. Further, the control method to minimize the stack effect will be discussed.

Keywords: stack effect, airflow, high-rise residential building, CONTAMW, simulation

1. INSTRUCTION

Recently, the residential buildings are becoming higher and more luxurious due to the increase of urban population and betterment of quality of life in Korea. In urban renewal projects, tearing down low-rise buildings and re-constructing as high-rise buildings can afford to supply more green space and can be secured the urban environment in healthy. Furthermore, high-rise buildings have many benefits in terms of efficiency and environment-friendliness such as centralizing facilities to maximize convenience of the residents. For this reason, high-rise residential building is popular in advanced countries where renewal projects are actively undertaken.

However, high-rise buildings arouse a series of new problems such as stack effect. A high-rise building inevitably contains a lofty vertical shaft, and stack effect occurs because of pressure difference between the inside and outside. The temperature difference between inside and outside of buildings causes a difference in air density, which leads to pressure difference and arouse air-flow. Especially, the stack effect become conspicuous in winter according to the temperature gap between interior and exterior of building widens. Compared to office buildings, residential buildings usually have a larger number of openings, in other words, the air-tightness of exterior skin is relatively inferior. Also, the probability is high that some openings are likely to be open at any time. Thus residential buildings are more subject to the stack effect.

To reduce the stack effect, building envelope needs to be tighten to minimize infiltration of outside air. Another way is to install a wind-screening room at the entrance of the ground floor and the basement, which helps to distribute pressure at the entrance. As a more progressive solution, the
architectural strategies such as partitioning a vertical shaft and mechanical solution such as cooling shaft space and pressurizing the vertical shaft space to discourage infiltration of outside air should be considered.

Researches on the stack effect have begun in the North American since 1960s. Tamura and Wilson (1967) measured a pressure distribution in high-rise office buildings and they examined the effect of an airtightness of exterior wall and architectural elements of the interior on air flow through the numerical simulation. Tamblyn (1993), Lovatt (1994) reported influence of the stack effect on opening and closing an elevator, and ventilation system performance. Hayakawa and Togari (1988) suggested a modified TDC(Thermal Draft Coefficient) as target office buildings. In Korea, the issue of the stack effect has begun to attract attention from 2000s as a number of high-rise buildings constructed. Researches on the stack effect mostly depend upon field research and network simulations, and the topic were restricted to the architectural solutions in most cases.

Based on the previous researches, in this study, the impacts of the stack effect of a high-rise building will be analyzed through network simulation method. Moreover the reduction strategies of stack effect such as enhancement of air-tightness of building envelopes and doors or cooling vertical shaft spaces will be analyzed.

2. SIMULATION OUTLINE

2.1 Building Description

The analyzed building is high-rise residential building located at A-san city in Korea, that is under construction. As shown in Figure 1(a), the analyzed building is consists of two residential buildings (building A: two-story underground, 36-story high; building B: two-story underground, 37-story high) and a utility complex that connects the two buildings. The analyzed building is arranged in a typical composition of a large-scale high-rise residential complex. As for building A, three units surround each core respectively. In building B, five households are arranged around the center core for each floor. Both buildings have separate elevators for general use and emergency use and there is no shuttle elevator. The elevator shaft is in one unit from bottom to the top of the building, therefore a probability of stack effect is fairly high. Heating is expected during the winter in elevator halls, which further aggravates the stack effect.

2.2 Simulation Outline

The network simulation method was used to examine the stack effect of a high-rise building in this

Figure 1. Building Layout and Floor Plan
study. Because the stack effect is hard to generate through an actual experiment, and the analysis should be examined at the early design stage. A network simulation tool such as CONTAMW is suitable to analyze for a subject with numerous analyzing nodes as like analysis model in this study. As a result of CONTAMW, the air features (pressure distribution, temperature, etc) and quantity of airflow at multiple nodes will be suggested. In CONTAMW, the properties of airflow on each node and among nodes are defined as follows.

The air flow rate from zone \( i \) to zone \( j \) is function of the pressure difference along the flow path.

\[
F_{j,i} = f(P_j - P_i)
\]  
(2.1)

The mass of air \( m_i \) [kg] in zone \( i \) is given by the ideal gas law.

\[
m_i = \rho_i V_i = \frac{P_i V_i}{RT_i}
\]  
(2.2)

where, \( V_i \) is zone volume [\( m^3 \)]; \( P_i \) is zone pressure [Pa]; \( T_i \) is zone temperature [K]; and \( R \) is gas constant for air, 287.055 [J/kg \( \cdot \) K]

For a transient solution the principle of conservation of mass states that

\[
\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\partial \rho_i}{\partial t} = \sum_j F_{j,i} + F_i
\]  
(2.3)

where, \( m_i \) is mass of air in zone \( i \) [kg]; \( F_{j,i} \) is airflow rate [kg/s] between zones \( j \) and zone \( i \); and \( F_i \) is non-flow processes that could add or remove significant quantities of air form the zone.

Table 1 illustrates conditions for simulation modeling. The underground parking lot was considered as outdoor, only core sections were included in the modeling for underground level. Atmospheric pressure of the ground-floor level was considered as base and variance is accordingly applied to height of analyzed node. Each residential unit, hall and corridor were regarded as a single zone. An elevator shaft and a stairwell, which are vertical airflow paths, were modeled as independent zones for each floor, and each zone was vertically connected.

Table 1. Conditions for Simulation Modeling

<table>
<thead>
<tr>
<th>Category</th>
<th>Modeling Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underground parking lot</td>
<td>Considered as outdoor air</td>
</tr>
<tr>
<td>Underground levels</td>
<td>Modeling only core sections</td>
</tr>
<tr>
<td>Stairwell</td>
<td>Modeling each story as one node. Vertical connection of nodes</td>
</tr>
<tr>
<td>Elevator shaft</td>
<td>Modeling each story as one node. Vertical connection of nodes</td>
</tr>
<tr>
<td>Hall</td>
<td>Modeling as a single zone</td>
</tr>
<tr>
<td>Residential unit</td>
<td>Modeling as a single zone</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>Atmospheric pressure on the first floor is set as a base and the variance due to height is considered.</td>
</tr>
<tr>
<td>Temperature setting</td>
<td>Interior (household units, hall): 22°C; Outdoor air: -9.4°C (lowest winter time average temperature of the area) Cooling temperature for a shaft is set above a dew point (shaft temperature/humidity is set at 22°C; 35% as a initial condition)</td>
</tr>
</tbody>
</table>
Table 2. Simulation Cases

<table>
<thead>
<tr>
<th>Cases</th>
<th>Classification</th>
<th>Reduction Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Basic design</td>
<td>-</td>
</tr>
<tr>
<td>Case 2</td>
<td>Minimal strategy</td>
<td>Installation of a wind-screening room in the lobby and underground level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Building A: Reinforcing air-tightness of doors to emergency stairwell in the whole building, additional division of an elevator hall in the lobby, installing a wind-screening room on the roof level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Building A &amp; B: Installing a revolving front door in the lobby</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Building B: Additional division of an elevator hall on the lobby, standard and upper levels</td>
</tr>
<tr>
<td>Case 3</td>
<td>Architectural measures</td>
<td>-Building A: Reinforcing air-tightness of doors to emergency stairwell in the whole building, additional division of an elevator hall in the lobby, installing a wind-screening room on the roof level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Building A &amp; B: Installing a revolving front door in the lobby</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Building B: Additional division of an elevator hall on the lobby, standard and upper levels</td>
</tr>
<tr>
<td>Case 4</td>
<td>Basic design with cooling</td>
<td>Cooling temperature: 6℃</td>
</tr>
<tr>
<td></td>
<td>the elevator shaft and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>stairwell</td>
<td></td>
</tr>
<tr>
<td>Case 5</td>
<td>Basic design with cooling</td>
<td>Cooling temperature: 6℃</td>
</tr>
<tr>
<td></td>
<td>the elevator shaft only</td>
<td></td>
</tr>
</tbody>
</table>

The interior temperature was set at 22℃. For outdoor temperature, lowest winter period average temperature of A-san city was applied. Shaft cooling temperature was set above a dew point about 6℃, the dew-point temperature was calculated on the condition that the interior temperature and humidity was set at 22℃, 35% respectively. Building A and B are connected by Building C for working as a corridor space and community space. To examine interaction among the three buildings, the three buildings were modeled simultaneously.

Table 2 lists simulation cases. In case 1, the stack effect for a basic design was analyzed. In case 2, the effect of minimal reduction strategy such as installing a wind-screening room in the lobby and underground level was investigated. In case 3, when more architectural measures such as installing a revolving door in the lobby and underground level, enhancing air-tightness in each stairwell entrance and partitioning elevator halls were taken, the reduction effect was reviewed. For case 4 and 5, a mechanical method was adopted to reduce the stack effect, the shaft space (elevator hall, stairwell) is cooled to minimize a temperature discrepancy between the exterior and interior. By doing so, the outdoor air which inflows into indoors through shaft space will be diminished remarkably. For case 4, the cooling temperature for shaft space (elevator and stairwell) was set at the lowest point without dew condensing. For case 5, to minimize problems derived from cooling the whole shaft space, only elevator shaft was cooled.

3. SIMULATION RESULT

This chapter presents the results of network simulation under the above mentioned conditions. The results focus on the pressure difference at main elements and overall air flow of the analyzed building.

3.1 Basic Design (Case 1, Fig. 2)

No particular measure is applied to reduce the stack effect in Case 1. Figure 2 shows the result of the simulation. In comparison with the allowable pressure standard for entrances (elevator door: 25Pa, and general doors: 50Pa), the pressure on doors of the lobby floor, top floor, elevator and stairwells are kept within the standard. However, the pressure applied to the entrance door of each residential unit is rather significant. Especially, for residential units located in the lower levels and upper levels, the stack effect might bring difficulties in opening and shutting the entrance doors. Thus, it is recommended to take appropriate measures to minimize stack effect.
3.2 Minimal Strategy (Case 2, Fig. 3)

Installing a wind-screening room in the lobby and underground level contributed to decrease the pressure difference at the lobby entrance. The pressure distribution of the lobby floor (Fig. 7) shows that after installing a wind-screening room, the pressure decreased by half. However, other nodes in buildings are hardly influenced, as results, the volume of airflow is almost same (Fig. 9).
Figure 5. Cooling Elevator Shaft and Stairwells (Case 4)

Figure 6. Cooling Elevator Shaft (Case 5)

Figure 7. Pressure Distribution between Basic Design and Minimal Strategy
3.3 Architectural Measures (Case 3, Fig. 4)

For building A, the pressure in the underground level and the lobby substantially decreased. However, due to improved air-tightness of building B, more air flowed into the less protected building A, which causes a pressure increase on the upper floors. For building B, the pressure decreased generally. However, the biased division of the elevator hall led to significant variance in air pressure for each residential unit (Fig. 8).

3.4 Basic design + Cooling Elevator Shaft and Stairwell (Case 4, Fig. 5)

The vertical shaft space was cooled to 6°C. Both building A and B showed decrease of pressure by approximately half compared to the basic design. In comparison with a case of architectural measures (Case 3), the pressure dropped by more than half in building A. While, in case of building B, the pressure somewhat increased for units where pressure was measured. However, in general, the pressure evenly decreased for the residential units.

3.5 Basic Design + Cooling Elevator Shaft (Case 5, Figure 6)

Cooling the whole shaft space is ideal to minimize stack effect. However, in reality, it can occur additional problems such as thermal comfort and increase of heating load, thus it is critical to find an optimal point. Taking feasibility into consideration, a case where only elevator shaft is cooled was analyzed. The pressure on elevator doors is decreased substantially, yet the pressure on the entrance to a stairwell relatively increased. The temperature discrepancy between elevator shaft and stairwell led to increased volume of airflow to the stairwells.

3.6 Overall air-mass flow

Figure 9 illustrates the overall air-mass flow of the analyzed building in this study. By examining the amount of air infiltration, the degree of stack effect reduction could be compared among analyzed cases. Case 2 shows little variance of the air-mass flow compared to the basic design(Case 1). This means that wind-screening room is not efficient in reducing stack effect on the whole. In Case 3, the airflow reduced by 42% compared to the basic design in building B, however, the effect was negligible for the building A. As to the Case 4, where whole vertical shaft space is cooled, the airflow decreased evenly in both buildings. The stack effect reduction was most outstanding with all conditions(air pressure applied on the main elements of the building, air mass flow, pressure distribution) in Case 4. In case 5, where only the elevator shaft is cooled, still showed superior
performance to the architectural measures.

4. CONCLUSIONS

In this paper, the properties of the stack effect have been examined through a network simulation upon a high-rise residential building. Following outcomes were derived from examining architectural, mechanical methods to minimize the stack effect.

1) The basic design without reduction strategies could be problematic because of high pressure on the entrance doors of residential units located on the lower and upper levels.
2) By installing a wind-screening room on the underground level and the lobby, the amount of airflow and pressure decreased for the entrance on the same levels. However, other nodes are hardly affected. Thus the effect is evaluated to be rather negligible.
3) Analysis of architectural measures revealed that the pressure on the underground and the lobby level for building A substantially decreased, however, due to the reinforced air-tightness of building B, the amount of air infiltration for building A unchanged. On the upper levels of building B, the air pressure slightly increased. Also, uneven distribution of pressure was observed due to biased division of an elevator hall.
4) As to the mechanical method of cooling a shaft, pressure was evenly decreased by about half compared to the basic design. Furthermore, the problem of uneven distribution of pressure was relieved. This mechanical method was the most efficient for reducing the stack effect among the analyzed cases.

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