Characteristics of Revolving Door Use as a Countermeasure to the Stack Effect in Buildings

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Abstract
Efficient control of ventilation and cooling/heating systems in buildings is integral to making adjustments to indoor environments and to minimizing energy use. In high-rise buildings, however, the stack effect is generated through vertical shafts in the buildings, and the air flow due to the stack effect greatly affects the efficiency of air-conditioning systems used for ventilation, cooling, and heating. Therefore, attenuating the stack effect in high-rise buildings is a critical aspect of HVAC operations as well as a solution for direct problems related to the stack effect, such as high-velocity draft, high-level noise in the buildings, and so on.

In general, as a method to attenuate the stack effect in high-rise buildings, revolving doors are installed at the lobby entrance. However, while this method may be effective on the floors where revolving doors are applied, the efficiency is very low when considering the entire building due to the existence of many air flow paths and the fact that revolving doors applied to only part of a building can control only a portion of the air flow. Numerical simulation analysis was performed in this study to quantitatively examine the stack effect attenuation characteristics of revolving doors on both a partial building level and for the entire building. In addition, the effects of building height and airtightness on the performance of the building envelope were considered.

Keywords: stack effect; revolving door; stack effect attenuation; numerical simulation; high-rise buildings

1. Introduction
Skyscrapers are currently being competitively constructed throughout Asia. As cities are becoming Manhattanized, the possibility of the stack effect in these new high-rise buildings inevitably increases. At the same time, the magnitude of problems created by the stack effect continues to grow. Problems generated by the stack effect in skyscrapers can mainly be divided into problems related to habitability and problems related to the performance of disaster prevention. The problems related to habitability, such as the occurrence of high-velocity drafts and high-level noise in buildings, the incorrect operation and operational inability of doors, difficulty in controlling indoor cooling/heating environments, and so on, have been recognized as major problems resulting from the stack effect.

The diffusion of poisonous gases from a fire is one of the concerns related to disaster prevention. If a fire were to break out in a building, it would be difficult to control the diffusion of poisonous gases because the air flow from the stack effect accelerates the diffusion in the building. Another concern is the spread of viruses, as, for example, severe acute respiratory syndrome (SARS) was shown to have spread through the stack effect in Amoy Garden, Hong Kong, in May 2003. Accordingly, minimizing the occurrence of such problems by effectively controlling the stack effect in skyscrapers is currently a problem that is being addressed by many researchers.

The early researches on the stack effect were largely related to the performance of disaster prevention and the efficiency of energy in buildings. At that time, most of the researches considered the characteristics of pressure distribution by the stack effect in buildings and on the relationship between the stack effect and the airtightness performance of buildings. As a representative example, Tamura studied the relations between the air leakage area of the envelope, internal partitions, and the horizontal pressure distribution of the building. Through field measurements, he found that the internal partitions of an office building were less airtight than the building envelope. Tamura also measured the amount of air leakage of the building envelope and other components of office buildings and presented airtightness performance data of each component of the buildings studied. Klote
reported the results of a study on smoke management considering the stack effect\(^1\).  

Researches have recently begun to analyze the effect that building components and external environmental conditions have on the stack effect in buildings\(^2\). For example, Maatouk investigated the effect that outdoor wind conditions have on the characteristics of the stack effect generated in a high-rise apartment\(^{15-16}\). Yu examined the effect that the plane shape and the window area ratio in the ground floor of a building have on the stack effect\(^1\). Koo studied the effect that architectural components of a high-rise residential building have on the occurrence of stack effect characteristics\(^1\).  

Meanwhile, to study means to actively control stack effect problems, Park presented a method to attenuate the problems through the cooling of elevator shafts, which are major paths of air flow, in addition to an existing stack effect attenuation countermeasure that adds partitions to interrupt air flow paths\(^1\). In addition, Tamblyn examined a way to use a mechanical ventilating system to adjust the distribution of pressure by the stack effect\(^1\).  

However, though many researches have been carried out to-date, stack effect problems continue to be reported. In addition, quantitative definitions for currently applied countermeasures have not been thoroughly examined. Therefore, this study aimed to quantitatively examine the stack effect attenuation characteristics of revolving doors that are generally applied as a countermeasure for the stack effect. Revolving doors, ordinarily installed at the entrance to the lobby to efficiently control air-conditioning in the lobby space by minimizing the infiltration of outdoor air at the entrance, have become a common countermeasure to attenuate the stack effect.  

This study used simulation analysis to quantitatively examine the stack effect attenuation characteristics of revolving doors at the whole building level and at a partial building level. In addition, the characteristics of building height and the airtightness of the building envelope were investigated.

2. Methodology

2.1 Research Target Building

In order to examine the stack effect attenuation characteristics, CONTAMW, a network simulation tool that can investigate changes in the air flow and pressure between spaces in a building, was used. CONTAMW is a general purpose, multi-zone (nodal) airflow and contaminant transport analysis tool that can be used to determine inter-zone pressure differences, airflow rates and contaminant transport in complex building structures. This tool was developed by the Building and Fire Research Laboratory of NIST for the analysis of building ventilation systems and has evolved and adapted to accommodate a wide range of building engineering disciplines from indoor air quality analysis to smoke management system design\(^1\).  

CONTAM has been extensively validated and provides an intuitive user interface that can be used to build an airflow network\(^1\).  

CONTAMW performs airflow calculations using the mass flow powerlaw formula for the following types of airflow elements,

\[ F = C(\Delta P)^n \]

where \( F \) is the mass flow rate, \( \Delta P \) is the pressure difference across a flow path, \( C \) is the flow coefficient and \( n \) is the flow exponent.

A target building for simulations was an ordinary office building having 30 floors aboveground and 5 floors underground. Table 1. outlines the target building and Fig.1. illustrates its plane and elevation. The target building had an open plan with a center core on each floor, and the center core consisted of an emergency staircase, four passenger elevators, two shuttle elevators, and an emergency elevator. The passenger elevators, divided by two shafts for every two elevators, were operated between the 1st floor and the 30th floor aboveground. The shuttle elevators were operated between the 5th floor underground and the 1st floor aboveground, and the emergency elevator was operated on each floor. The vestibule space that runs through the emergency staircase was used as an elevator hall for emergencies. The entrance of the ground floor (1F) had a vestibule-type structure that uses two double swing doors. The underground parking lots and all the underground floors were connected outdoors by ramps.

Table 2. shows simulation conditions, which were for wintertime when the stack effect is significant. The outdoor temperature was set at -11.9°C, the lowest temperature expected in Seoul, Korea. The indoor temperature was set at 22°C, a standard heat setting for office buildings. The airtightness performance
of the building envelope was set to 2 \([\text{cm}^2/\text{m}^2]\) as an actual measured value. The airtightness performance of the 1F entrance and internal partition doors were established on the basis of the CONTAMW library, actual measured data, ASHRAE data, and so on.

The vestibule door of the emergency E/L hall was very tightly constructed in order to minimize the influence of the emergency core portion and to emphasize the characteristics of the applied revolving doors. Tables 3. describe the simulation cases. Case 1 examined the effect that types and open/close states of the 1F entrance had on the stack effect. Case 2 examined the effect that a change in building height or number of floors had on the stack effect. Case 3 examined the influence of a change in the airtightness of the building envelope.

### 3. Result

#### 3.1 Effects of Type and Open/Close States of the 1F Entrance (Case 1)

Fig.2. shows the distribution of pressure that means the differences of air pressure of drafts on each floor.

In Case 1, the type of entrance to the ground floor (1F) was set as a vestibule with two double swing doors and a vestibule with a revolving door and a double swing door. In applying the revolving door, only the outside door of the vestibule was set as the revolving door (Case 1-3). The condition of a vestibule with two double swing doors was divided into two scenarios: all of the swing doors were open (Case 1-2) and all of the swing doors were closed (Case 1-1). The scenario in which the swing doors were open was applied on the assumption that people were passing through the doors (Case 1-2). The quantity of drafts for each case was compared based on the case of applying the revolving door.

When the swing doors were closed (Case 1-1) and the revolving door was installed (Case 1-3), the drafts of the ground floor (1F) had similar values. However, when the swing doors were open (Case 1-2), an approximately 28% increase resulted in the amount of drafts in the ground floor (1F) as compared with Case 1-1 and Case 1-3. This result suggests that doors with varied open areas, like swing doors when people pass

| Contents                  | Case No. | Condition       | 1F entrance       |
|---------------------------|----------|-----------------|-------------------|
| Type of 1F entrance       | 1-1      | -               | Swing door (close) |
|                           | 1-2      | -               | Swing door (open)  |
|                           | 1-3      | -               | Revolving door     |
| Building height (No. of floor) | 2-1      | 30              | Swing door (open)  |
|                           | 2-2      | 30              | Revolving door     |
|                           | 2-3      | 45              | Swing door (open)  |
|                           | 2-4      | 45              | Revolving door     |
|                           | 2-5      | 60              | Swing door (open)  |
|                           | 2-6      | 60              | Revolving door     |
| Air leakage areas of exterior wall (cm²/m²) | 3-1      | 0.5             | Swing door (open)  |
|                           | 3-2      | 0.5             | Revolving door     |
|                           | 3-3      | 1               | Swing door (open)  |
|                           | 3-4      | 1               | Revolving door     |
|                           | 3-5      | 2               | Swing door (open)  |
|                           | 3-6      | 2               | Revolving door     |
|                           | 3-7      | 5               | Swing door (open)  |
|                           | 3-8      | 5               | Revolving door     |
|                           | 3-9      | 10              | Swing door (open)  |
|                           | 3-10     | 10              | Revolving door     |

![Fig.2. Pressure Difference (ΔP) at Every Wall of the Building](image)
through, offer a disadvantage in dealing with drafts from the stack effect. Therefore, the revolving door was confirmed as an effective means to minimize the change in size of an open area during the passage of people through a space.

When the swing doors were open (Case 1-2), drafts increased about 6% as compared to when the swing doors were closed and the revolving door was applied (Cases 1-1, 1-3). This increment of draft value in the ground floor (1F) differed greatly from the 28% increase experienced in Case 1-2 with open swing doors. The phenomenon is understood to be generated because the 1F entrance was just one of many air flow paths of the whole building although it was a major air flow path in the building. In other words, at the whole building level, it means that the revolving door as a partial countermeasure on the stack effect was not very effective.

This result is confirmed by the distribution of the pressure on every wall of the building when the swing doors were open (Case 1-2) and when the revolving door was applied (Case 1-3). In Case 1-3, there was a significant change in the distribution of pressure among the walls of the ground floor (1F). Yet the change in pressure distribution on other floors was low because the movement of the neutral pressure level by applying the revolving door was slight.

3.2 Change in the Building Height (Case 2)

Fig. 3 shows the draft reduction ratios in the ground floor (1F) and in the whole building when applying the revolving door as the 1F entrance.

As shown in Fig. 3, when the revolving door was applied at the 1F entrance, the draft reduction ratios in the ground floor (1F) at each building height ranged from 27.9% to 28.5%. In addition, in the entire building, the draft reduction ratios ranged from 3.2% to 6.1%. Similar to the results of Case 1, when the revolving door was applied partially to the ground floor (1F), the draft reduction ratios in the ground floor (1F) were large, but were significantly small when viewed at a whole building level. As building height increased, the draft reduction ratios in the ground floor (1F) increased by inches. However, there was a contrary result within the whole building. The draft reduction ratios in the entire building decreased as building height increased because air flow paths of the building increased in number as building height increased and, accordingly, the influence as a major air flow path of the 1F entrance was reduced at the whole building level. Meanwhile, the draft reduction ratios in the ground floor (1F) increased slightly as building height increased due to the decrease in the upward movement of the neutral pressure level of the building as the building height increased by applying the revolving door. The pressure level on the ground floor (1F) became high due to the upward movement of the neutral pressure level, and it therefore became a factor in increasing drafts. A change in the air leakage area of the exterior wall in the ground floor (1F) by applying the revolving door was identical in each condition. The air leakage area is another factor to determine the quantity of drafts, which shows the distribution of the pressure on every wall in the 30-story building and 60-story building. The upward movement of the neutral pressure level in the 30-story building was larger than the 60-story building when the revolving door was applied. Considering that the change of the neutral pressure level was proportional to a change in the pressure acted on each floor under the condition of identical indoor and outdoor temperatures, the pressure acted on a reference floor in the 60-story building was changed by about 1.7 Pa as the revolving door was applied. On the other hand, there was a change of about 1.9 Pa in the 30-story building. As a result, when the revolving door was applied partially as a stack effect countermeasure, the effectiveness at the whole building level decreased as building height increased.

3.3 Change in the Airtightness Performance of the Building Envelope (Case 3)

The air leakage areas of the envelopes of the target buildings were 0.5, 1, 2, 5, and 10 cm²/m². To calculate the draft reduction ratios by applying the revolving door, a vestibule with two open double swing doors and a vestibule with a revolving door and a double swing door were applied, respectively, as the 1F entrance for each scenario.

As shown in Figs. 4 and 5, when the revolving door was applied, the draft reduction ratios of the ground floor (1F) in each condition ranged from about 8.5% to 41.4%. In addition, in the whole building, the draft reduction ratios ranged from about 1.0% to 20.4%. The draft reduction ratios in the whole building were lower than the draft reduction ratios in the ground floor (1F), as explained in the results examined in each zone. At the same time, the draft reduction ratios both in the ground floor (1F) and in the whole building decreased as the envelope airtightness performance decreased. This decrease was due to the influence of the 1F entrance as a major air flow path in the building being reduced as the envelope airtightness performance decreased.
This result is confirmed in Fig.6., which shows the distribution of the pressure on every wall of the building in scenarios in which air leakage areas were 0.5 \( \text{cm}^2/\text{m}^2 \) and 10 \( \text{cm}^2/\text{m}^2 \), and a change in the pressure distribution at each wall of the ground floor (1F) by applying the revolving door was larger when the air leakage area was 0.5 \( \text{cm}^2/\text{m}^2 \) than 10 \( \text{cm}^2/\text{m}^2 \). The movement of the neutral pressure level of the building by applying the revolving door was also larger when the air leakage area was 0.5 \( \text{cm}^2/\text{m}^2 \) than when it was 10 \( \text{cm}^2/\text{m}^2 \).

Therefore, the influence of the 1F entrance as a major air flow path was larger when the air leakage area was 0.5 \( \text{cm}^2/\text{m}^2 \) than when it was 10 \( \text{cm}^2/\text{m}^2 \) because the higher the airtightness performance of the building envelope, the larger the relative air leakage area of the 1F entrance compared to the air leakage area of the envelope. As a result, in the case where the revolving door was applied partially as a stack effect countermeasure, the effectiveness increased as the airtightness performance of the building envelope increased.
3.4 Effect of the Installation Locations and Number of Revolving Doors (Case 4)

Case 4 examined the stack effect characteristics dependent on the installation locations and number of revolving doors. Experiment conditions for Case 4 are shown in Table 4. In Case 4, the building was largely divided into three parts: a ground floor (1F), reference floors (2F-30F), and underground floors (B5-B1). The installation locations and number of revolving doors were determined in consideration of major air flow paths of each of the three parts of the building. The entrance to the ground floor (1F), the approach of the passenger elevator hall of the ground floor (1F), the approach of the shuttle elevator hall of the ground floor (1F), the approach of the passenger elevator hall of every reference floor, and the approach of the shuttle elevator hall of every underground floor were set as locations to apply revolving doors. Mixtures of revolving door installation locations were also included as conditions to examine the draft reduction characteristics.

Table 4. Simulation Cases (for Case 4)

| Cases | a | b | c | d | e |
|---|---|---|---|---|---|
| 1-2 | × | × | × | × | × |
| 4-1 | ○ | × | × | × | × |
| 4-2 | × | ○ | × | × | × |
| 4-3 | × | × | ○ | × | × |
| 4-4 | × | × | × | ○ | × |
| 4-4 | × | × | × | ○ | × |
| 4-6 | ○ | × | × | × | ○ |
| 4-7 | × | ○ | ○ | × | × |
| 4-8 | ○ | ○ | ○ | × | × |
| 4-9 | × | ○ | × | × | × |
| 4-10 | ○ | ○ | ○ | ○ | ○ |

Table 4. Conditions of Revolving Doors (Installed: ○, not installed: ×)

a: 1F entrance
b: Both sides of approach to E/L hall for passenger in 1F
c: Approach to E/L hall for shuttle in 1F
d: Both sides at approach to E/L hall for passenger in 2F - 30F
e: Approach to E/L hall for shuttle in B2 - B5

Fig. 7 shows the study results, including the amount of drafts in the whole building of each scenario and the relative ratio of each scenario based on the amount of drafts in the entire building when the entrance of the ground floor (1F) was open. All applied revolving doors were assumed to have an identical airtightness performance. The main results were as follows:

1) In the cases (Cases 4-1, 4-2, 4-3) in which revolving doors were installed at one of the major air flow paths in the ground floor (1F), Case 4-2 in which the revolving doors were installed at the approach of the passenger elevator hall showed the highest draft reduction ratio. Case 4-1 in which the revolving door was installed at the entrance showed the second highest draft reduction ratio, and Case 4-3 in which the revolving door was installed at the approach of the shuttle elevator hall showed the lowest draft reduction ratio. In other words, even though revolving doors having identical airtightness performance were used, differences in the draft reduction effects were generated by the relative influences among the air flow paths. In the cases (Cases 4-4, 4-5) in which revolving doors were installed at the air flow paths of multiple floors such as all reference floors or all underground floors, the draft reduction ratios were generally higher than the cases (Cases 4-1, 4-2, 4-3) in which revolving doors were installed at a single floor. However, it was shown that even though revolving doors were installed at the air flow paths of multiple floors, according to the relative influences among the air flow paths, it was less effective than when revolving doors were installed at a single floor. For example, Case 4-5 in which revolving doors were installed at all underground floors showed a lower draft reduction ratio than Case 4-2, in which revolving doors were installed at the approach of the passenger elevator hall of the ground floor (1F).

2) As shown in Cases 4-4, 4-6, 4-9, and 4-10, when air flow paths to the passenger elevator halls of all the reference floors were intercepted, considering that most air flow in a building is generally through the passenger elevator shafts, a very high draft reduction effect was detected. Meanwhile, even in this condition, the phenomenon by relative influences among air flow paths as mentioned above was generated. For example, Case 4-9 in which revolving doors were additionally installed at the approach of the passenger elevator hall of the ground floor (1F) compared to Case 4-4 showed a higher draft reduction ratio than Case 4-6 in which revolving doors were additionally applied at the entrance of the ground floor (1F) and at the approaches of shuttle elevator halls of all underground floors.

Moreover, it was shown that the relative influences of other air flow paths increase when the air flow path having the greatest influence is intercepted, as, for example, the draft reduction ratio between Case 4-4 and Case 4-9 (52.9%). In Case 4-9, revolving doors were additionally installed at the approach of the passenger elevator hall of the ground floor (1F) as compared to Case 4-4, and the draft reduction ratio was larger than between Case 1-2 and Case 4-2 (10.4%); in Case 4-2, revolving doors were installed at the approach of the passenger elevator hall of the ground floor (1F) under the condition that air flow paths to the passenger elevator halls of all the reference floors were not intercepted.

3) When air flow paths having a mid-level influence were intercepted, the relative influences of the air flow paths having a higher level influence than the mid-level influence became larger, but the relative influences of the air flow paths having the lower level influence became smaller. For example, when the approach of the passenger elevator hall of the
ground floor (1F) was the intercepted air flow path having a mid-level influence, the draft reduction ratio between Case 4-2 and Case 4-9 was 94.5%; in Case 4-9, revolving doors were additionally installed at the approaches of the passenger elevator halls of all the reference floors as compared to Case 4-2, and the draft reduction ratio was larger than between Case 1-2 and Case 4-4 (89.5%); in Case 4-4, revolving doors were installed at the approaches of the passenger elevator halls of all reference floors under the condition that revolving doors were not installed at the approach of the passenger elevator hall of the ground floor (1F). The draft reduction ratio between Case 4-2 and Case 4-7 was 2.5%; in Case 4-7, a revolving door was additionally installed at the approach of the shuttle elevator hall of the ground floor (1F) as compared to Case 4-2, and the draft reduction ratio was smaller than between Case 1-2 and Case 4-3 (5.5%); in Case 4-3, a revolving door was installed at the approach of the shuttle elevator hall of the ground floor (1F) under the condition that revolving doors were not installed at the approach of the passenger elevator hall of the ground floor (1F).

2) The draft reduction effect by applying revolving doors to a building as a partial countermeasure to the stack effect was affected by the height of the building and the airtightness performance of the building envelope. At the whole building level, especially, the greater the number of floors, the lower the airtightness performance of the building envelope, the lower the draft reduction effect. In other words, the greater the number of major air flow paths in the building, the smaller the relative air leakage area of the partially applied revolving doors as compared with the air leakage area of other air flow paths, and the lower the draft reduction effect.

3) The draft reduction effect depends on the application method of revolving doors such as the installation point and the installation number because the influences of the major air flow paths in a building differ from one another. Accordingly, in order to effectively reduce drafts in buildings, the relative influences among the major air flow paths should be considered at a whole building level.

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Fig.7. Drafts in the Whole Building and Draft Reduction Ratios

4. Conclusions

In this study, the characteristics of revolving doors as a countermeasure to the stack effect in high-rise buildings were quantitatively examined through numerical simulations, and the results are as follows:

1) When a revolving door was applied at the entrance of the ground floor (1F), drafts were somewhat reduced in the ground floor (1F) as compared to the absence of a revolving door. However, at the whole building level, the draft reduction effect was negligible.
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