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E/V Shaft Cooling Method as a Stack Effect Countermeasure in Tall Buildings

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Abstract

The higher the building height and the larger the temperature difference between the outdoor and indoor space, the more remarkable is the draft driven by the stack effect in high-rise buildings. Moreover, the stack effect can bring about the deterioration of habitability and the degradation of the performance of the indoor control system in high-rise buildings. In this study, as a measure to attenuate the stack effect, the E/V shaft cooling method was proposed and its performance was compared with the conventional stack effect control method for strengthening the air-tightness of the building using a numerical simulation method. The total decreasing ratios on the stack effect in a building were compared, and the probabilities of the secondary problems were analyzed. The results show that the E/V shaft cooling is very effective to decrease the stack effect in a high-rise building in terms of the reduction performance and application. Moreover, this method does not cause secondary problems, such as stack pressure transition to other walls, unlike the conventional stack effect mitigation method.

Keywords: Tall building, Stack effect, E/V shaft cooling, Building air-tightness

1. Introduction

When the building height increases, the magnitude of the stack effect also increases. The stack effect could cause a number of problems including unpleasant noise and strong drafts through the doors, and malfunctioning of the elevators and doors in tall buildings. In addition, the airflow caused by the stack effect increases heating and cooling loads and lowers the performance of fire safety systems in buildings. Therefore, it is important to effectively control the stack effect for the enhancement of habitability and for energy savings in tall buildings. Controlling the stack effect means reducing the magnitude of the cause of the stack effect - that is, minimizing the temperature or pressure differences between the inside and outside air, air-tightened building envelope, and segmentation of elevator shafts and stairwells. The mitigation measures for the stack effect in tall buildings can be classified into two measures: active and passive mitigation measures. Active measures refer to actions taken in the mechanical system design specification to permit two strategies to mitigate the stack effect. Passive measures refer to the measures taken in the fundamental design and disposition of programmatic elements of the tower as well as specific measures for the architectural elements of the exterior wall, and the builder's work (Weismantle and Leung, 2007).

Many studies on how to mitigate the stack effect have involved passive measures. Tamura and Wilson suggested a method of strengthening building envelopes to reduce the influence of the stack effect. They suggested installing additional separations near doors that excessive pressure is acting on (Tamura and Wilson, 1967). In addition, Tamura confirmed that stack effect pressure is shared on every wall according to the relative air-tightness of the walls, and arranged it as a thermal draft coefficient (TDC) concept (Tamura, 1994). Hayakawa and Togari suggested that the excessive pressure on a wall can be divided by installing additional separations (Hayakawa and Togari, 1988). Jo analyzed the stack effect of high-rise residential buildings in Korea with field measurement and simulation and suggested that an additional door be installed at the airflow path between the residential main entrance and the elevator hall on the floors that have excessive pressure (Jo et al., 2007). Lee proposed the method of dividing excessive pressure by installing a revolving door on horizontal airflow paths in buildings (Lee et al., 2012). ASHRAE suggested that strengthening the air-tightness of the building envelope is the most important measure for mitigating the stack effect in tall buildings, and as the next best thing is strengthening the air-tightness of walls inside buildings (ASHRAE, 1993). CMHC determined that strengthening the air-tightness of walls inside buildings can improve stack effect problems (Jacques, 1996).

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Conversely, Lovatt et al. argued that strengthening the air-tightness of specific walls inside buildings without evenly strengthening the air-tightness of building envelopes can worsen stack effect problems (Lovatt and Wilson, 1994). When the air-tightness of specific walls inside buildings is strengthened, the pressure can be transferred to these strengthened walls because they share the pressure from other walls where the air-tightness is relatively low. Furthemore, installing additional separations and strengthening the air-tightness of the building envelope has limitations in terms of building design considerations, cost, and builder's quality. Though these measures are partly applied to the building, the effect would be small. Therefore, to minimize the stack effect, innovative measures that do not have the limitations of conventional measures are needed.

In this study, as an advanced measure, the E/V shaft cooling method is proposed to attenuate the draft in tall buildings. The concept of E/V shaft cooling is described, the performance is analyzed using network simulation, and the features of E/V shaft cooling are compared with the conventional attenuation method (i.e., strengthening the air-tightness of the building).

2. E/V Shaft Cooling Method (Lee and Song, 2010)

2.1. Principle of stack effect reduction

The draft rate cause by the stack effect can be described as follows:

$$Q = \alpha A \sqrt{\frac{2}{\rho}\Delta P} \tag{1}$$

where Q is the airflow rate (the draft rate) [m^3/s], α is the discharge coefficient [-], A is the representative air leakage area [m^2], and ΔP is the pressure difference between the building components.

The factor that triggers the stack effect and its magnitude (i.e., pressure gradient between the outdoor environment and indoor spaces) is determined by the height of the building and temperature differences between the outdoor environment and indoor spaces, as shown in Eq. (2).

$$\Delta P = g(h - h_{npl})\rho_o(T_i - T_o)/T_i \tag{2}$$

where ΔP is the pressure difference (gradient) between the outdoor environment and indoor spaces caused by stack action (Pa), g is the gravitational constant (m/s^2), h is the building height of interest (m), h_{npl} is the height of the neutral pressure level (m), ρ is the air density (kg/m^3), T_i is the indoor temperature (K), and T_o is the outdoor temperature (K).

As shown in Eq. (1), the draft is controlled by adjusting the αA and ΔP. The conventional method (strengthening the air-tightness of the building) is a measure to control the αA; whereas, the E/V shaft cooling method controls the $\sqrt{\Delta P}$. To minimize the stack effect by controlling the αA, the air-tightness of the interior and exterior walls in a building should be strengthened by the same ratio. If only the air-tightness of a specific wall is strengthened and the pressure distribution ratio among the walls is changed, the pressure will be transited to other walls. This phenomenon is common and is called a secondary problem.

As shown in Fig. 1, the E/V shaft natural cooling system reduces the stack effect by reducing the temperature difference between the outdoor environment and indoor spaces, which is one of the factors that determines the magnitude of the stack effect. That is, an E/V shaft and the outdoor air are connected through a duct to supply outdoor air into the shaft space. Apart from the stack

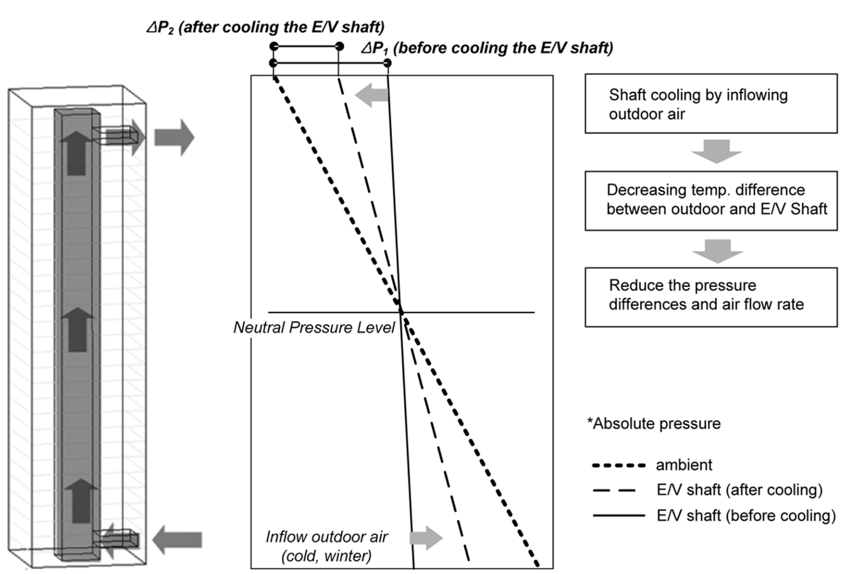

Figure 1. Principle of the stack effect reduction using the E/V shaft cooling system.

effect that occurs in the building, there is a stack effect that occurs in the duct for shaft cooling due to the density differences between the outdoor air and the air in the shaft, and this stack effect becomes the driving force causing the outdoor air to flow into the shaft. Using this stack effect, the cold outdoor air in winter naturally flows into the E/V shaft and is exhausted through the top of the shaft. Through this process, the temperature in the E/V shaft is decreased, and consequently, the temperature difference between the outdoor air and the air in the E/V shaft is reduced, thereby reducing the stack effect in the entire building. Here, the E/V shaft space is cooled because this space is the primary vertical air flow path in the building. Therefore, the E/V shaft cooling system suggested in this study can be considered a way to reduce the stack effect using the stack effect. Fig. 1 shows the principle of the stack effect reduction using the E/V shaft cooling system.

2.2. System configurations and control principles

The E/V shaft cooling system consists of duct systems and pan systems that are used to introduce the outdoor air or exhaust the air in the shaft; dampers used to adjust the amount of air flow; and temperature sensors and absolute pressure sensors, which are used to obtain data needed to control the system. A summary of the configuration of the E/V shaft cooling system is shown in Fig. 2.

If the temperature in the E/V shaft is cooled by the cold outdoor air and goes below the dew point of the E/V shaft space, condensation may occur at the E/V shaft interior wall, resulting in IAQ problems or mechanical problems. Therefore, the temperature in the E/V shaft is monitored by the temperature sensors installed at various parts

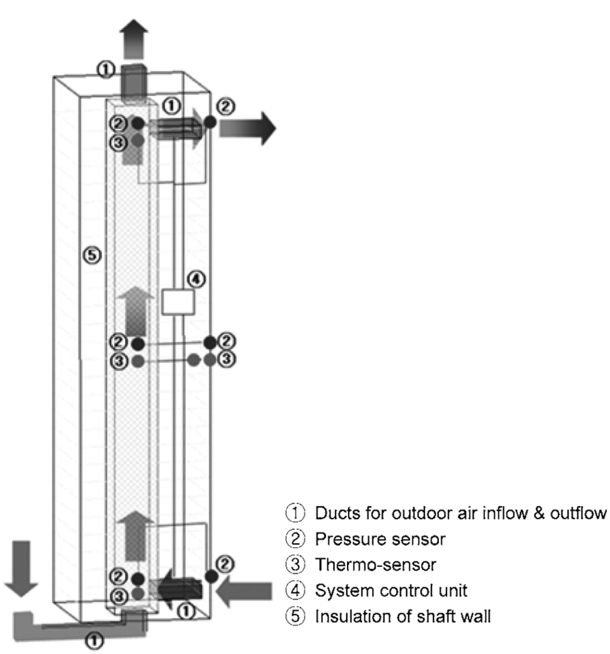

Figure 2. Configuration of the cooling system.

inside the shaft, and the amount of outdoor air introduced into the shaft is adjusted by the dampers and the on/off control of the cooling system, so that the temperature in the E/V shaft does not go below the dew point.

If the neutral pressure level of the shaft goes up or down due to the operation of the E/V shaft cooling system, the stack effect reduction efficiency may be decreased, and the pressure may be increased in the area on the opposite side of the direction of movement of the neutral pressure level, leading to secondary problems. Therefore, considering this property, it is important to adjust the amount of inflowing outdoor air into the E/V shaft and the air flow exhausted from the E/V shaft to be the same as when the E/V shaft cooling system is operated. Therefore, this system adjusts the amount of the outdoor air introduced into the E/V shaft and exhausted from the E/V shaft to be equal. Before adjusting the airflow rate in the shaft space, the pressure differences between the shaft and indoor spaces are measured by an absolute pressure gauge in the upper part and lower part of the building and compared to determine whether the neutral pressure level has moved. As mentioned above, the shaft cooling system cools the inside of the shaft based on the precondition that the neutral pressure level is fixed, and thus, it can reduce the pressure distribution and air flow in each part of the building to the same ratio. This is the main feature of the E/V shaft cooling system, but another representative feature is that the system can reduce the magnitude of the stack effect itself throughout the building. However, most existing measures mitigate the stack effect in relation to the local pressure distribution and cannot reduce the magnitude of the stack effect itself throughout the building.

To operate the E/V shaft cooling system effectively, the insulation performance of the E/V shaft sections should be enhanced because the cooling efficiency of the E/V shaft may be reduced or the room heating load of the building may be increased by thermal conduction when temperature gradients occur between the inside of the shaft and indoor spaces due to shaft cooling.

In addition, the amount of outdoor air to be introduced and the dimensions of the duct systems for E/V shaft cooling should be determined by considering the target amount of the reduction of stack effect-related problems, indoor air conditions, outdoor air conditions, the amount of indoor air flowing into the E/V shaft due to the stack effect, and the heat insulating performance of the E/V shaft walls. Additionally, the target cooling temperature should be determined considering outdoor air conditions; that is, the range of outdoor air conditions that would demand cooling operation should be set taking into consideration the characteristics of the subject building and local climate conditions. Another important condition for the implementation of the cooling system is that the vertical distribution of the cooling temperature for the E/V shaft should be made uniform because it is the most important factor for maximizing the performance of the cooling system to reduce the stack effect. For instance, if the temperature distribution in the shaft is not uniform, part of the shaft could reach the dew point temperature before the entire shaft reaches the target cooling temperature, making further cooling impossible.

3. Performance of E/V Shaft Cooling

3.1. Simulations

The stack effect reduction characteristics of E/V shaft cooling in high-rise buildings was analyzed using network simulation (CONTAMW). The physical characteristics of strengthening the building's air-tightness were analyzed and the results were compared with the results of the E/V shaft cooling system.

The target building was simply modeled to represent the features of ordinary office buildings. This building is composed of 30 floors above ground and 5 floors underground. The features of the building are shown in Table 1 and Fig. 3.

As shown in Table 2, the outdoor and indoor air temperature was set at −11.9ºC and 22ºC, respectively. The air leakage area of the exterior wall of the target building is 2 cm^2/m^2. The air leakage areas of the other parts were set up using the CONTAMW library data, ASHRAE data, and field-measured data in this study.

In this study, two kinds of countermeasures to reduce the stack effect in tall buildings were compared. One is strengthening the air-tightness of the building (Case 1 and 2) and the other is the E/V shaft cooling method (Case 3).

As shown in Table 3, four simulation cases were analyzed. In the base case, there were no measures for the stack effect. In Case 1, as an architectural method to attenuate the stack effect, the air-tightness of a specific wall was strengthened. In Case 2, all wall components were air-tightened. Finally, the E/V shaft was cooled in Case 3.

The reduction ratio of the air leakage area (αA) at each part of the building in Case 2 was set to be equal to the

Table 1. Building features

Items	Contents
Building type	Office
floors	30 floors above ground and 5 floors underground
Core plan	A center core on open plan
E/V plans	4 for passengers (1st~30th, 2 per shaft) 2 for shuttles (B5~1st) 1 for emergencies (B5~30th)
Staircase	Sharing halls with the emergency E/V Setting doors to the emergency E/V halls and doors to the staircase on all floors
Parking places	B5~B1 Connected 5 floors underground by ramps
1st floor's main entrance	A vestibule type with 2 double swing doors

Table 2. Basic input data for the simulations

Items	Contents
Temperatures	Outdoor: −11.9°C, Indoor: 22°C
Air leakage area of exterior wall	2 cm^2/m^2
Air leakage area of interior doors	E/V doors: 480 cm^2/item Doors emergency E/V halls: 16 cm^2/item Doors to the staircase: 16 cm^2/item 30th floor's E/V hall door : 32 cm^2/item
Air leakage area of 1st floor's main entrance	Double swing door : 32 cm^2/item

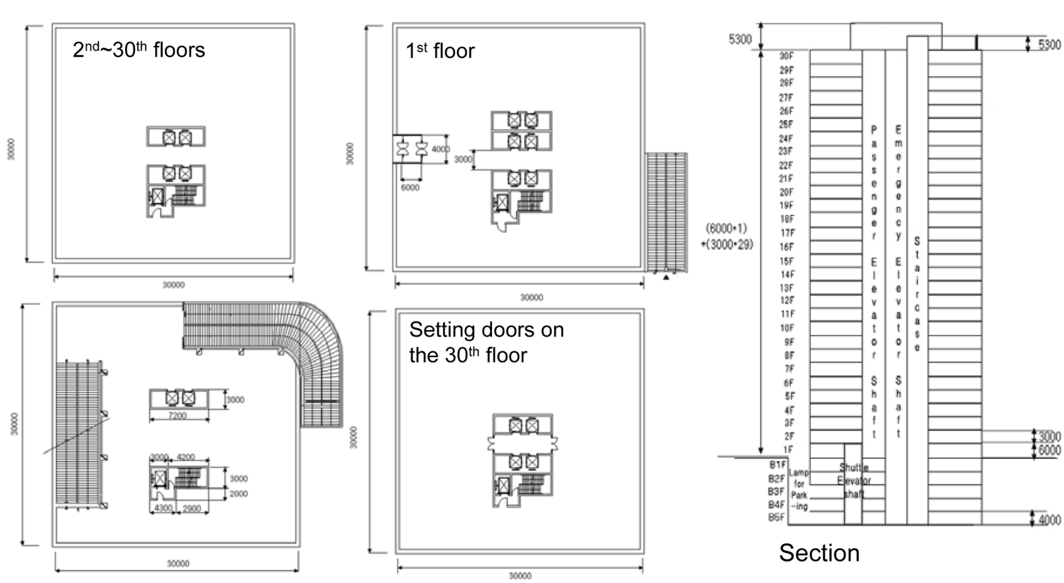

Figure 3. Plans and a section of the target building.

Table 3. Simulation cases

Cases	Conditions
Base case	See base case input data in Table 2
Case 1: strengthening the air-tightness of a specific wall	The air leakage areas of the 1st floor's E/V doors for passenger were decreased by 1/2 compared to the base case
Case 2: strengthening the air-tightness of all the walls	The air leakage areas of all the walls had a 13% reduction
Case 3: cooling the E/V shafts	All the E/V shafts had cooling to 13°C (above the dew point temperature); the staircase was not cooled.

average reduction ratio of the $\sqrt{\Delta P}$ in Case 3. The result of each case was compared with the base case.

3.2. Discussions

The draft rate on every interior and exterior wall of the building in each case is shown in Fig. 4, and the pressure difference is shown in Fig. 5. The whole draft rate of the building in each case and its reduction ratio compared to the base case are shown in Fig. 6.

3.2.1. Case 1: strengthening the air-tightness of a specific wall

As shown in Fig. 4(b), the draft rate through the 1st floor was decreased compared to the base case. Conversely, the pressure differences at the 1st floor components, such as the passenger and emergency E/V doors, were increased, as shown in Fig. 5(b). This result implies that strengthening the air-tightness of a specific wall causes the pressure to transition to the other walls. Furthermore, as shown in Fig. 4(b), the draft rates on the other floors are almost the same as in the base case. From this result, the effect of strengthening the air-tightness of a specific wall for decreasing the stack effect was small with regard to the whole building. Though the air leakage areas of the 1st floor passenger E/V doors were set at ½ (a reduction ratio of 50%) of the base case, the reduction ratio of the draft through the E/V door was decreased to 37.6%. This is because the total air leakage area on the air flow path is determined by several air leakage areas of the walls in the air-flow path, as shown in Eq. (3). This result implies that even if the air-tightness of a specific wall is strengthened, the draft reduction effect is not decreased with the same ratio.

$$\alpha A = \frac{1}{\sqrt{\left(\frac{1}{\alpha_1 A_1}\right)^2 + \left(\frac{1}{\alpha_2 A_2}\right)^2 + \cdots + \left(\frac{1}{\alpha_n A_n}\right)^2}} \quad (3)$$

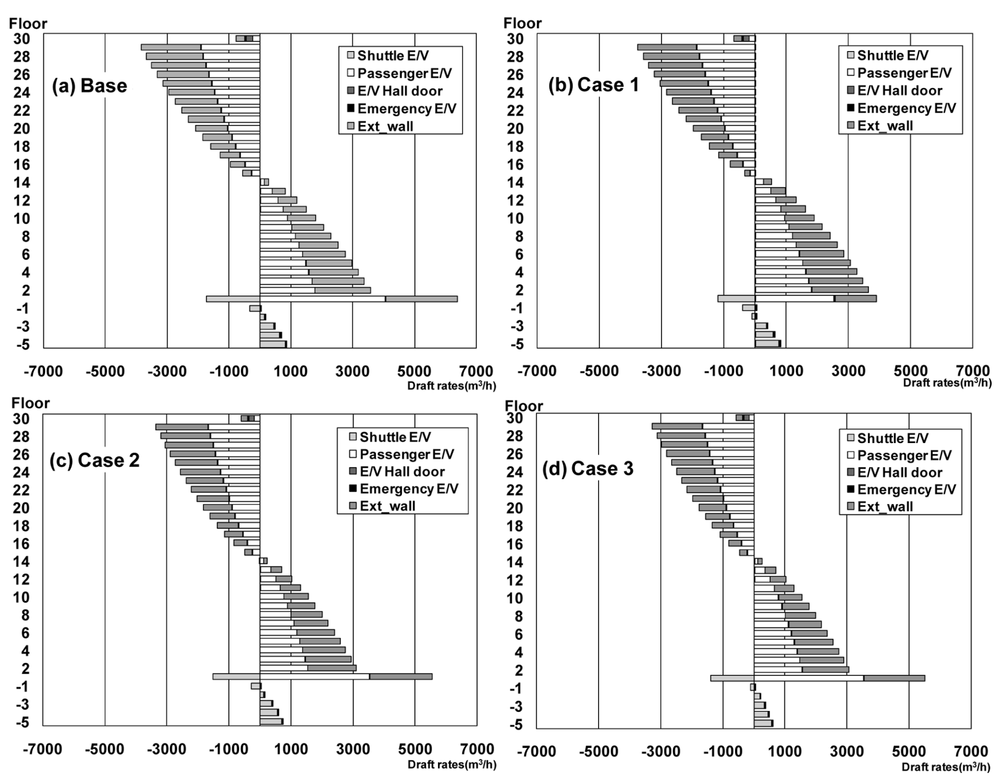

Figure 4. Draft through each wall of the building.

3.2.2. Case 2: strengthening the air-tightness of all the wall components

As shown in Fig. 4(c), the draft through each part of the building showed a decrease of 13% compared with the base case. This reduction rate is equivalent to those of air leakage area reduction, as shown in Table 3. However, the pressure distributions of the building components were not changed compared to the base case (see Figs. 5(a) and 5(c)) because the air-tightness of all wall components were strengthened with the same ratio, and as a result, the pressure distribution rate of the specific wall was not changed. In addition, the secondary problems caused by the pressure transition were not observed because the pressure distribution was not changed.

The draft reduction ratio (13%) of the whole building was equal to the reduction ratio of the air leakage area (αA) on each wall, as shown in Fig. 6.

3.2.3. Case 3: E/V shaft cooling

As shown in Figs. 4(d) and 5(d), the draft and pressure on each part of the building were decreased with almost the same ratios. A small difference from the base case was caused because the staircase of the building was not cooled.

Secondary problems were not discovered because the pressure distribution was essentially unchanged. However, the neutral pressure level at the E/V shafts was slightly changed because the staircase was not cooled. Moreover, the pressure distribution ratios among the walls on every floor were not changed. The draft reduction ratio (13.1%) of the whole building was similar to the average reduction ratio (13%) of the $\sqrt{\Delta P}$ on each part of the building due to cooling the shafts, as shown in Fig. 6.

From the above results and the fact that the reduction ratio of the αA in Case 2 was set to be equal to the average reduction ratio of the $\sqrt{\Delta P}$ in Case 3, it is determined that the E/V shaft cooling method has the same effect as strengthening the air-tightness of all the wall components.

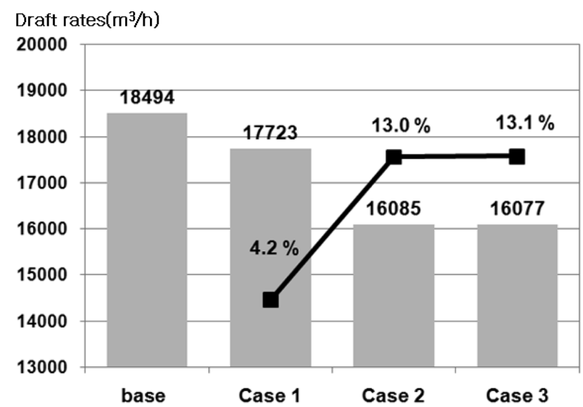

Figure 6. Whole draft rate of the building and its reduction ratio in relation to the base case.

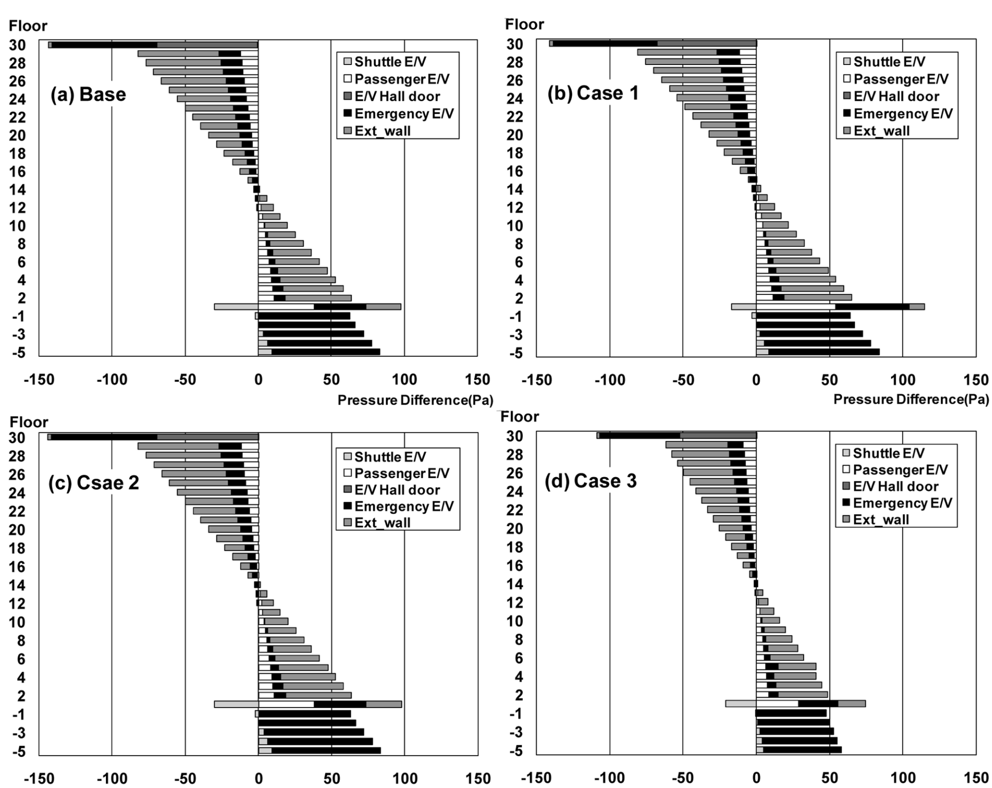

Figure 5. Pressure at each wall of the building.

4. Conclusions

In this study, as an innovative solution for mitigating the stack effect in high-rise buildings, the E/V shaft cooling method was proposed, and the performance was analyzed using a network simulation method. The results are as follows:

- As a stack effect reduction measure, strengthening the air-tightness of a specific wall was performed with the limit that the draft reduction effect was discovered at the specific wall, but the other parts were nearly changed. Moreover, secondary problems, such as the pressure transition, were detected.
- In the case where the air-tightness of the wall components of the whole building was increased, the draft reduction ratios were identical for the wall components in the whole building, and the reduction ratio was the same as the reduction ratio of the air leakage area on each wall. In addition, secondary problems were not discovered. However, strengthening the air-tightness of the wall components of the whole building requires special construction technologies and is a high cost solution.
- In the case of cooling the E/V shafts, a similar draft reduction effect to strengthening the air-tightness of the wall components of the whole building was achieved easily.
- As a stack effect reduction measure, the E/V shaft cooling method is more useful than strengthening the building air-tightness in terms of the construction, cost, and application.

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