A Study on Cooling Energy Savings Potential in High-Rise Residential Complex Using Cross Ventilated Double Skin Facade

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Abstract

The housing market in Korea is changing rapidly. As multi-functional high-rise residential complexes become popular, occupants need more comfortable indoor environment as well as more usable spaces than ever before. These trends force to increase the energy usage for environmental controls, especially for cooling. Thus, this study aims at reducing the cooling energy requirements of high-rise residential complex by maximizing the possibilities of natural ventilation strategies through cross ventilated Double Skin Façade. Based on ESP-r simulations, it was confirmed that the Double Skin Façade could reduce up to 30~40% of cooling energy compared to the conventional façade designs.

Keywords: double skin façade; high-rise residential complex; energy savings; cooling energy

1. Introduction

1.1 Background and Objectives

Public awareness on environmental issues such as global warming and ozone depletion has been increased substantially over the last few years and the implications for building energy conservation are widely appreciated. Recently multidisciplinary efforts to tackle these global dangers by reducing building energy usage are being actively carried out.

In contrast to these global environmental concerns, residential building constructions are being dictated by the need for maximizing land efficiency, utilizing more interior spaces and better comfort. At the same time, these needs cause various global environmental problems. If we closely look into these matters from the point of view of energy consumption, high-rise buildings have difficulties in applying natural ventilation because of strong wind pressure at building façade with increased height. This necessitates applying mechanical ventilation system in high-rise buildings. Since they have to rely on fully mechanical ventilation system for their ventilation needs, the cooling energy usage increases dramatically. The existing balcony designs are extended to an interior space, which has the effect of destroying the buffer zone that connects the interior space to the outdoor environment. The absence of space such balcony causes heating and cooling energy consumption to sharply increase. This not only affects the global environment, but also exasperates the financial burden being borne by the occupants who are already suffering from the increased electricity costs for the air-conditioning.

Accordingly, this paper deals with environmental problems caused from the absence of buffer zones in high-rise residential complexes, especially concentrating on the solution of reducing cooling energy consumption by utilizing natural ventilation through double skin façade. This concept is the main focus of this study, and the potential cooling energy efficiency improvements with cross ventilated double skin façade were analyzed by using computer simulation.

1.2 Methods and Process

This study focused mainly on how building envelope is designed, especially cross ventilated double skin façade, could create energy efficiency in high-rise residential complex’s balcony area. First, to inquire into the possibility of natural ventilation in a high-rise residential complex, its loads were calculated, and the loads were evaluated by changing the building’s skin. Next, an established building envelope design and another design using double skin were compared and analyzed with respect to their energy consumption. ESP-r was used as a simulation tool for this purpose.

The building selected as a case study was located in M district of municipal S. That building is a south-facing 204.96m² apartment with a living room. Also, to handle typical problems caused by high-rise building, apartment unit placed at 81m (27th floor), was chosen as shown in Fig 1.
To calculate the wind speed at great heights, the following formula (1), the power law wind profile is used.

\[
U_l = \frac{K}{10} \times Z_l^{1.4} \\
U_l: \text{wind speed}[\text{m/s}] \text{ at altitude } Z_l \\
Z_l: \text{altitude}[\text{m}] \\
U_{10}: \text{wind speed}[\text{m/s}] \text{ at altitude of 10m} \\
K, a: \text{constants, set values to 0.21, 0.33, assumed that building is situated within a city.}
\]

2. Investigations

2.1 Building load-simulation

The load composition of block A where case building is located is shown in Fig 2.

It demonstrates that loads due to heat gain/heat loss through building envelope took largest portion. Accordingly, in order to improve the energy efficiency of building, a highly energy-efficient skin design needs to be implemented.

2.2 Natural ventilation calculation method

To calculate the building’s natural ventilation, ESP-r program uses calculation formula considering wind pressure, buoyancy and stack effect. The method used for calculating wind pressure is as follows.

\[
P_i = \frac{1}{2} \rho U_{rd}^2 \\
P_i: \text{total pressure at boundary condition node} \\
C_{p,i,d}: \text{wind pressure figures at node position (i) following wind direction (d)} \\
U_{rd}: \text{wind speed-height(r), direction (d)} \\
\rho_o: \text{outside air density}
\]

Buoyancy calculations use Bernoulli’s formula to get static one-dimensional interpretation and it is as follows.

\[
\Delta P_i = \left( P_{1} + \rho V_{1} \right) - \left( P_{2} + \rho V_{2} \right) + \rho g (Z_i - Z_r) (p_d) \\
\Delta P_i: \text{Total pressure difference} \\
P_{1}, P_{2}: \text{static pressure being used, existing static pressure} \\
V_{1}, V_{2}: \text{inflowing or existing air current speed (m/s)} \\
g: \text{gravity acceleration (9.81 m/s}^2) \\
Z_i, Z_r: \text{height (m)} \\
\rho: \text{density of air current (kg/m}^3) \text{ passing through a node}
\]

Stack effect calculations use the method of showing the average air current density. The calculations are as follows.

\[
P_i = \frac{1}{2} \rho U_{rd}^2 - \rho g h_i \\
P_i: \text{total pressure at boundary condition node} \\
P_i: \text{total pressure at boundary condition node} \\
C_{p,i,d}: \text{wind pressure figures at node position (i) following wind direction (d)} \\
U_{rd}: \text{wind speed-height(r), direction (d)} \\
h_i: \text{height at node j} \\
\rho_o: \text{outside air density}
\]

2.3 Concept of Double Skin Façade

The function of building envelope can be categorized by indoor environmental controls, structural, aesthetic and maintenance requirements. In terms of heating, building envelope acts as a filter to the outdoor environment and keeps the indoor environment from losing heat. To maximize the performance of building envelope, double skin façade was developed. The double façade typically consists of two separate glass skins with an air space between. Shading and light directing devices may be situated between the two skins, and ventilation air circulates in this space. The outer façade should protect the interior from wind, rain and noise, allowing the inner windows to be opened to provide natural ventilation. To correspond with changing outdoor environment dynamically, double skin uses two layers of skin to more efficiently absorb and dampen the effects of outside conditions. Types of double skin include hall type, box type and stack type among others.

One of the hall type examples is the Devis-Gebäude in Berlin(Fig 3). The hall type double skin actively introduces natural ventilation, with its outer façade being glass blinds which are power-operated, and there are additional blinds to cut off direct sunlight. In winter, the glass blinds are closed to minimize heat loss and in summer, they are opened as much as possible to minimize the heat accumulation on the façade.
An example of box type double skin is shown in the SUVA building in Basel (Fig 4). If the occupants want natural ventilation, they can open the windows to inflow fresh air directly. In winter, the heated air in the cavity can flow into the rooms and reduce heating energy requirement.

This study proposes a box type double skin system that makes use of buoyancy of the building’s cavity creating cross ventilation. When cooling load is generated, it is expected that heat will accumulate in the cavity and cause the air temperature of the cavity to become higher than temperature outside, resulting in a stack effect. When the cavity temperature is higher than outside temperature, grills are opened to let in a minimum of outside air current needed for ventilation to flow in directly inside, as shown in area ① of Fig 6.

The openings at the bottom and top of the cavity can also be opened for maximum ventilation. When heating load is generated, it is expected that the air temperature inside the cavity will again be higher than the temperature outside, and the cavity can be used to provide a minimum amount of ventilation needed by inducing air at the opposite side. When heating or cooling loads are not being generated, the windows can be opened to directly draw outside air, allowing minimum and maximum ventilation rate.

To shade sunlight, blinds have been installed within the cavity, and when the interior temperature rises above 20°C, they are set to close. The double skin facade construction and principles of their seasonal operation are shown in Fig 6 and the control algorithm is shown in Fig 5.
3. ESP-r Simulation
3.1 Alternative building envelopes

In order to compare the cooling energy performance of double skin system, three skin designs were selected and compared.

- **Case 1**: Windows were not installed at the outer skin as an open balcony. This type of skin was popularly implemented in Korea’s early public housing in general. In case 2, windows were installed at the outer skin as an enclosed balcony, and this type of skin is still generally used. In case 3, the balcony area was utilized as interior space into an extended balcony. This is actually being planned for the sample building. As look closely at the thermal environment for these three skin designs, the results are summarized in table 1, and Fig 7.

![Double-Skin Façade](image)

![Alternative Cases](image)

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### Table 1. Distinguishing features of each skin design

| Case  | Characteristics                  | Shading overhang | Thermal environment                                                                 | Ventilation               | Windows                          |
|-------|---------------------------------|------------------|-------------------------------------------------------------------------------------|---------------------------|----------------------------------|
| Case 1| Open balcony                    | Yes              | - Summer season solar protection by overhang.                                        | -transition: natural     | Double glazing at inner skin     |
|       |                                 |                  | - Increase in heat gain/heat loss due to absence of buffer zone between outside and inside. | ventilation              |                                  |
| Case 2| Enclosed balcony                | Yes              | - Summer season solar protection by overhang.                                        | -transition: natural     | Single and double glazing at outer and inner skin |
|       |                                 |                  | - Heating load in winter season diminished due to a buffer zone between outside and inside. | ventilation              |                                  |
| Case 3| Extended balcony into interior space | No             | - Increase in heat gain/heat loss due to absence of buffer zone between outside and inside. | Min. ventilation annually (Mechanical ventilation) | Double glazing (fixed windows) |
| Case 4| Double skin                     | Yes              | - Summer season solar protection by overhang.                                        | -transition: natural ventilation | Single and double glazing at outer and inner skin |
3.2 Input data
The building construction would be the same for each skin. The input data for each skin are shown in Table 2. For case 2, the balcony width was 1.5m, and for case 4, the cavity layer width was 0.5m. Blinds were applied only for case 3 and case 4.

Table 2: Construction Details

| Item       | Exterior Wall | Interior Wall | Roof |
|------------|---------------|---------------|------|
| Section    |               |               |      |
| U-factor   | 0.52W/m²°C    | 4.545W/m²°C   | 0.46W/m²°C |

| Item       | Interior Floor | Ground Floor | Window |
|------------|----------------|--------------|--------|
| Section    |                |              |        |
| U-factor   | 0.46 W/m²°C    | 1.22 W/m²°C  | 1.22 W/m²°C |

3.3 Energy performance analysis for each skin
Each skin’s energy performance for a peak cooling load on August 22nd is compared and shown in Fig 11. On August 22nd, the solar radiation showed normal intensity and outside average temperature was over 26°C, thus demonstrated a typical summer weather. The energy required for cooling was highest for case 3, then cases 2, 1 and 4 respectively.

The main reason for each skin’s cooling load differences is due to the differences in solar gain and ventilation rate. First, looking at the differences in solar heat gain, case 3 showed the highest due to the lack of shading devices, as shown in Fig 8 and then cases 1, 2 and 4 followed respectively. The difference between cases 2 and 3 is mainly due to the fact that in case 2, there was a structure on the outer surface of the balcony that acted as an overhang. In case 4, the cavity width was smaller than the width of case 1 and 2 and thus its capacity to function as a buffer zone diminished accordingly, but the blinds inside the double skin protected the sunlight, cutting off solar gain.

When the ventilation rate of each skin is compared, case 1 shows the largest ventilation rate, as shown in Fig 9, and the rest are ranked cases 4, 2 and 3. This is because the case 1 had an open balcony and there was relatively little resistance to ventilation. With cases 2 and 4, when the outside wind speed was zero, case 4’s cavity still had buoyancy effect, which in turn caused case 4 to have relatively more ventilation rate than case 2. When the cooling energy of cases 1 and 2 are compared, case 1 had more solar gain, but case 2 had less ventilation rate. The case 1 showed lower cooling energy level, this means more heat could be removed through ventilation than solar heat gain.

Dynamic temperature variations in the cavity, balcony and outside on the day of August 22nd are shown in Fig 10.

When outside temperature reached to its highest, the cavity temperature rose 2.5°C above the outside temperature, whereas the balcony temperature did not. Also, when outside temperature was over 26°C, the average temperature for cavity was 28.8°C, that of balcony was 27.8°C, and outside was 27.9°C, meaning there were no significant temperature differences. In addition, it appears that the reasons for the temperature difference between cavity and balcony were: ① different dimensions of their openings that causes different ventilation rate at 4.2 ACH and 9.6 ACH, ② different width that causes different convection heat transfer.
Fig. 11. Energy performance analysis (August 22)
Looking at the possibilities of natural ventilation for case 4, during the July - September period, natural ventilation was put into effect when the outside temperature was below 26°C. The average ventilation rate was 6.7 ACH ranged from minimum of 0.7 ACH to maximum of 24.5 ACH. When wind speed was zero, cavity’s buoyancy still produced the minimum level of ventilation required. Accordingly, it is concluded that natural ventilation was being provided within the minimum and maximum range of ventilation required for sufficient comfort.

3.4 Analysis of Energy consumption and cost for each skin

When the cooling energy for each skin is converted to 204.96 m² of conditioned space, the results are shown in Fig 12. Indoor setpoint temperature was set to 26°C for each case, and it was assumed that the cooling system started when the temperature rise over 26°C. Fig 12 shows the energy consumption of each skin design. With cases 3 and 4, the difference of 5,399.4kWh in cooling energy consumption has been observed.

4. Conclusion

Having compared the cross ventilated double skin façade design proposed by this study, case 4, to the other skin designs, it was shown that case 4 had the lowest cooling energy consumption level, followed by the open balcony, case 1, and an enclosed balcony, case 2, then the extended balcony, case 3. When compared the cross ventilated double skin system of case 4 to the extended balcony of case 3, which is being scheduled for the sample building, the annual savings in terms of cooling energy was 5,399.4 kWh. In case of natural ventilation, the average ventilation rate was 6.7 ACH, minimum rate of 0.7 ACH and maximum rate of 24.5 ACH, which means even when wind speed was at zero or very fast, the ventilation rate stayed within the minimum and maximum rate required for comfort. What was thought to be a weakness of the double skin façade, the temperature increase in the cavity during the summer season, turned out to be an average increase of about 1.1°C when compared with the outside temperature, not such a significant difference. In addition, in terms of interior space usage, the double skin façade takes only 7 m² of floor area. Considering the cases 1 and 2, the loss of their interior space was 42 m² for the balcony.

Thus, the cross ventilated double skin façade could be a solution for the contemporary high-rise buildings allowing natural ventilation with minimal space loss.

Future study should be a comparative analysis of not only cooling energy performance but also heating energy performance as well, thus making a comprehensive evaluation on annual energy performance, and more studies on double skin designs that integrate natural ventilation schemes with more energy efficient building service systems such as radiant cooling.

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