Energy Efficiency Analysis of Internally and Externally Insulated Apartment Buildings

Seung-Yeong Song*, Myoung-Souk Yeo, Bo-Kyoung Koo and Soo-Jin Lee

1 Professor, Department of Architectural Engineering, Ewha Womans University, Korea
2 Professor, Department of Architecture, Seoul National University, Korea
3 Graduate Student, Department of Architectural Engineering, Graduate School, Ewha Womans University, Korea

Abstract

Apartment buildings are the most common type of residential buildings in Korea, where hot water heating pipes are installed in the floor structures. An internal insulation system (IIS) has been applied to the outside walls of most Korean apartment buildings, so there are many cases in which the layer of insulation is disconnected by structural components at the wall-slab joints. These joints become thermal bridges where heat transfer increases. An external insulation and finish system (EIFS) is a possible solution to this problem. In this study, the surface temperature distributions of actual apartment buildings with an IIS and an EIFS were investigated with an infrared thermal imaging camera. Annual heat losses and gains through the wall-slab joints with an IIS and an EIFS were calculated by three-dimensional transient heat transfer simulations in which hot water heating was excluded and included, respectively, in order to evaluate not only the heating and cooling loads, but also the heating efficiency when the building is actually heated. The results show that the amount of heat transfer through the wall-slab joints with an IIS is considerable, even though additional insulation is installed under the slab, and the EIFS significantly reduces the heating and cooling loads and improves the heating efficiency.

Keywords: thermal bridge; internal insulation; external insulation; floor hot water heating

1. Introduction

Due to greenhouse gas emissions and global warming problems, many countries have endeavored to construct more energy-efficient buildings. In Korea, the building sector accounts for over 24% of the total national energy consumption, and the energy consumption in apartment buildings, which are the most common type of residential buildings, is about 36% of the total energy consumption in the building sector. Compared to commercial buildings, apartment buildings are envelope-load-dominated buildings with low internal heat gains from occupants, lighting, and equipment. Therefore, the heating load is much larger than the cooling load in the Korean climate, and thermal insulation plays a key role in reducing energy consumption. In addition, the conductive heat transfer through the envelope should be reduced because the hot water pipes used for radiant heating are installed in the floor structures of Korean apartment buildings.

An internal insulation system (IIS) has been applied to the outside walls of most Korean apartment buildings since the first modern apartment building was built in the early 1960s. Consequently, there are many cases in which the layer of insulation is disconnected due to structural components at the wall-slab and wall-wall joints in the envelope. These joints become thermal bridges in which heat transfer increases. In particular, the amount of heat loss is large at the wall-slab joints adjacent to hot water heating pipes (Fig. 1. (a)). Conversely, an external insulation and finish system (EIFS) can eliminate the thermal bridge by continuing the layer of insulation at these joints (Fig. 1. (b)). Also, an EIFS can improve the heating efficiency because a thermal mass with high heat capacity, such as a concrete wall, is located on the warm side.

The aim of this study was to evaluate the feasibility of an EIFS in terms of energy conservation. The present state of EIFS in the market was surveyed. The surface temperature distributions of actual apartment buildings with an IIS and an EIFS were investigated with an infrared thermal imaging camera in the winter. The front, side, and rear wall-slab joints of a recently completed apartment building were selected as typical thermal bridges adjacent to hot water heating pipes. Annual heat losses and gains through these joints with an IIS and an EIFS were evaluated by three-
dimensional transient heat transfer simulations capable of reflecting the thermal bridging effect and the heat capacity difference according to the insulation location at the same time.

2. Present State of EIFS in the Market

An EIFS consists of the following: an insulation board, a base coat with reinforcing mesh, and a finish from inside to outside. The insulation board is either adhesively or mechanically fixed to the walls (Table 1). For a mechanically fixed system, tracks are inserted into the insulation board, which is fixed with tracks and a small amount of adhesive. A ventilated EIFS is also available, which eliminates moisture via an air cavity. In addition, there are integrated systems, which combine the insulation board with the finish material. In Korea, adhesively fixed systems are the most common, and expanded polystyrene is used as the insulation material (Table 2.).

3. Surface Temperature Distributions of Apartment Buildings with an IIS and an EIFS

Two apartment buildings (EIFSa and EIFSb) were found in which an EIFS was applied to the entire outside wall. They are located in Gimpo and Sungnam, respectively. For the IISs, the systems were the same as those in the EIFSs. Infrared thermal imaging cameras were used to measure the surface temperatures of the buildings. Table 3 summarizes the buildings investigated.

Table 2. EIFS in the Market

| Manufacturer | Insulation material | Fixing method | Fixing method | Ventilated system |
|--------------|---------------------|---------------|---------------|------------------|
| A (Korea)    | Expanded polystyrene | O             | X             | X                |
| B (Germany)  | Expanded polystyrene | O             | O             | X                |
|              | Mineral fiber       | O             | O             |                  |
|              | Foam                | O             | X             |                  |
| C (USA)      | Expanded polystyrene | O             | O             |                  |
| D (Japan)    | Expanded polystyrene | X             | O             |                  |
|              | Phenol foam         | O             | O             |                  |
|              | Mineral fiber       | X             | X             |                  |
|              | Glass fiber         | O             | X             |                  |

Table 3. Summary of the Apartment Buildings to Investigate Surface Temperature Distributions

| Item                  | Apartment building | Apartment building | Apartment building | Apartment building |
|-----------------------|--------------------|--------------------|--------------------|--------------------|
|                       | EIFSa              | IISa               | EIFSb              | IISb               |
| Insulation system     | (Expanded polystyrene insulation, adhesively fixed) | (Expanded polystyrene insulation, adhesively fixed) | (Expanded polystyrene insulation, mechanically fixed) | (Expanded polystyrene insulation, mechanically fixed) |
| Envelope              | Same               | Same               | Same               | Same               |
| U-value               | (This value is mandated by the building regulations.) | (This value is mandated by the building regulations.) | (This value is mandated by the building regulations.) | (This value is mandated by the building regulations.) |
| Location              | Gimpo, Gyeonggi-do, Korea | Gimpo, Gyeonggi-do, Korea | Sungnam, Gyeonggi-do, Korea | Sungnam, Gyeonggi-do, Korea |
| Building size         | 15 floors, 2 basement levels, 4 buildings, 220 units | 12–15 floors, 1 basement level, 6 buildings, 294 units | 25–38 floors, 3 basement levels, 4 buildings, 803 units | 21–27 floors, 3 basement levels, 3 buildings, 203 units |
| Date of completion    | 10.2006            | 11.2006            | 10.2006            | 10.2003            |

Table 4. Summary of the Infrared Thermal Imaging Data

| Item                  | Apartment buildings 07:26 a.m. 17.01.2008 | Apartment buildings 07:16 a.m. 16.01.2008 |
|-----------------------|--------------------------------------------|--------------------------------------------|
|                       | /outside air temperature                     | /emissivity                                 |
|                       | -10.5°C/0.9                                 | -9.0°C/0.9                                  |
| Infrared thermal imaging camera | NEC San-ei Instruments, Ltd. | TH9100Pro                                   |
| Model                 |                                            |                                            |
| Measuring range       | Range 1 40 to 120°C                         | Range 2 0 to 500°C                         |
| Resolution            | Range 1 0.08°C at 30°C, 0.03°C at 30°C, 60Hz | Range 2 0.08°C at 30°C, 0.03°C at 30°C, 60Hz |
| Accuracy              | ±2°C or ±2% of reading, whichever is greater |                                            |
| Spectral range        | 8 to 14 µm                                  |                                            |
| Thermal image pixels  | 320 x 240                                   |                                            |
Korea, respectively. To compare the heat losses of actual apartment buildings with an IIS and an EIFS, the surface temperature distributions of EIFSa, EIFSb, and other neighboring apartment buildings with an IIS (IISa and IISb) were investigated with an infrared thermal imaging camera at dawn in the winter, while heated. Summaries of the apartment buildings and the infrared thermal imaging data are shown in Table 3 and Table 4, respectively. The external appearances and infrared thermal images of the apartment buildings are shown in Fig.2 and Fig.3.

Comparing EIFSa and IISa, the mean surface temperatures of EIFSa are lower by 5.3°C and 7.6°C at the front and side walls, respectively, based on the surface temperatures of the points displayed in Fig.2 (b), even though U-value of each envelope is the same. For EIFSb and IISb, which have more floors than EIFSa and IISa, the mean surface temperatures of EIFSb are also lower by 5.2°C and 7.8°C at the front and side walls, respectively, based on the surface temperatures of the points displayed in Fig.3 (b). These results show that the amount of heat loss through the wall-slab joints is considerable in apartment buildings with an IIS.

4. Annual Heat Losses and Gains through the Wall-slab Joints with an IIS and an EIFS

4.1 Evaluation methods

The front, side, and rear wall-slab joints were selected on a typical floor with an expanded balcony in the apartment building E, which has an IIS and was recently completed in Seoul. Annual heat losses and gains through these joints with an IIS and an EIFS were calculated by three-dimensional transient heat transfer simulations in order to simultaneously reflect the thermal bridging effect, which has the nature of multi-dimensional heat flow, and the heat capacity difference according to the insulation location. The Physibel Voltra 6.0W program was used as a simulation tool. This program is a commercial code that analyzes three-dimensional transient heat transfer, based on the finite difference method.

4.1.1 Geometry modeling

The locations of the front, side, and rear wall-slab joints are shown in Fig.4. Vertical sections of the front wall-slab joints with an IIS and an EIFS are shown in Fig.5. A PVC-framed double window system was applied to this joint. For the IIS, 60 mm thick mineral fiber insulation was additionally installed under the slab to reduce the heat transfer through the thermal bridge. Fig.6 shows the simulation models built by extending the two-dimensional sections, as shown in Fig.5., by 1,000 mm along the z-axis. The guardrail, which is not expected to influence the heat transfer, was ignored, and the window frame was simplified to allow for a convenient calculation. Vertical sections of the side wall-slab joints with an IIS and an EIFS are shown in Fig.7. For the IIS, 15 mm thick expanded polystyrene
insulation was additionally installed under the slab to prevent condensation on the inside surface caused by the thermal bridge. Fig. 8 shows the simulation models. Vertical sections of the rear wall-slab joints with an IIS and an EIFS are shown in Fig. 9. For the IIS, 60 mm thick mineral fiber insulation was also installed under the slab to reduce the heat transfer through the thermal bridge. Fig. 10 shows the simulation models.

In each joint, the inside surface areas of the simulation models for an IIS and an EIFS were set to be the same. It was assumed that mineral fiber insulation was applied to the wall, considering that the requirements for fire resistance have been increasing. And it was assumed that the EIFS was fixed with adhesive.

4.1.2 Definitions of heat loss and gain, simulation cases, and hot water heating conditions

In this study, the heat loss is defined as the amount of heat that is transferred from the inside air to the structure through the inside surface (Q1 in Fig. 11). The heat gain is defined as the amount of heat that is transferred from the structure to the inside air through the same surface (Q2 and Q3 in Fig. 11). In other words, the heat loss is the sum of the transferred heat when the inside air temperature is higher than the inside surface temperature, and the heat gain is the sum of the transferred heat when the inside air temperature is lower than the inside surface temperature.

Hot water heating pipes are placed in all of the simulation models. If the hot water heating is not modeled in the simulation (namely, Q3 = 0 in Fig. 11), the heat loss and gain indicate the heating and cooling loads, respectively. If the hot water heating is modeled in the simulation, the heat loss and gain indicate the heating efficiency when the building is actually heated. Table 5 shows the meanings of heat loss and gain according to the hot water heating modeling. In this study, two cases were simulated: the hot water heating was excluded and included, respectively, in order to evaluate not only the heating and cooling loads, but also the heating efficiency.

The hot water heating conditions for the simulation including hot water heating are shown in Table 6. Heating schedule in Table 6 was based on a previous study (Song, 1998) that reports the hot water supply pattern in accordance with the lowest daily outside air temperature in Korean apartment buildings. Table 7 shows the monthly outside air temperature conditions of Seoul and the number of hours requiring heating, based on the hourly standard weather data of Seoul (MOCIE, 1996). In July and August, hot water heating is not required because the lowest daily outside air temperature exceeds 15°C at all times. In June and September, the numbers of hours requiring heating are no more than 8 hours and 16 hours out of 720 possible hours, respectively. Thus, in this study, the period from June to September was excluded for the simulation including hot water heating.

Annual three-dimensional transient heat transfer
Fig. 9. Vertical Section of the Rear Wall-Slab Joint

(a) IIS
(b) EIFS

Fig. 10. Simulation Model of the Rear Wall-Slab Joint
(x: 2,125.8 mm, y: 2,690.0 mm, z: 1,000.0 mm)

(a) IIS
(b) EIFS

Fig. 11. Definitions of Heat Loss and Gain
(Q1: heat loss, Q2 and Q3: heat gain)

Table 5. Meanings of Heat Loss and Gain According to the Hot Water Heating Modeling

| Hot water heating modeling | Type | Meanings                      | Remarks                |
|----------------------------|------|-------------------------------|------------------------|
| X                          | Heat loss | Heating load                  | The lower, the better. |
| O                          | Heat gain | Cooling load                  | The lower, the better. |
|                            | Heat loss | Heating efficiency            | The lower, the better. |
|                            | Heat gain | Heating efficiency            | The higher, the better. |

Table 6. Hot Water Heating Conditions for the Simulation Including Hot Water Heating

| The lowest daily outside air temperature (°C) | Heating frequency (Times/Day) | Heating time | Number of hours requiring heating (Hours/Day) | Hot water temperature (°C) |
|-----------------------------------------------|------------------------------|--------------|-----------------------------------------------|---------------------------|
| Below -10                                     | 3                            | 4–7, 11–13, 17–20 | 8                                             | 65                        |
| -10–5                                        | 3                            | 4–6, 11–13, 17–20 | 7                                             |                           |
| -5–15                                        | 2                            | 4–6, 17–19    | 4                                             |                           |

Table 7. Monthly Outside Air Temperature Conditions of Seoul and the Number of Hours Requiring Heating

| Month | Average daily temperature (°C) | Distribution of the lowest daily outside air temperature (Days) | Number of hours requiring heating |
|-------|--------------------------------|---------------------------------------------------------------|----------------------------------|
|       | Below -10                      | -10–5                                                        | 15                               |
| Dec.  | 20.0                           | 5.8                                                          | 34.0                             |
| Feb.  | 23.0                           | 5.8                                                          | 28.4                             |
| May   | 23.0                           | 5.8                                                          | Using standard weather data of Seoul |
| Jun.  | 26.0                           | 5.8                                                          | 22.7                             |

Table 8. Calculation Parameters

| Calculation parameter                  | Assigned value |
|----------------------------------------|----------------|
| Time step interval                     | 30 minutes     |
| Start-up calculation duration          | 6 days         |
| Maximum number of iterations          | 10,000         |
| Maximum temperature difference        | 0.0001°C       |
| Heat flow divergence for total object | 0.001%         |
| Heat flow divergence for worst node   | 1%             |

Table 9. Boundary Conditions

| Month | Inside Air temperature (°C) | Surface heat transfer coefficient (W/m²°C) | Outside Air temperature (°C) | Surface heat transfer coefficient (W/m²°C) |
|-------|-----------------------------|-------------------------------------------|-----------------------------|-------------------------------------------|
| Dec.  | 20.0                        | 5.8                                       | Sol-air temperature         | 34.0                                      |
| Feb.  | 23.0                        | 5.8                                       | Using standard weather data of Seoul |
| May   | 23.0                        | 5.8                                       |                             |                                           |
| Jun.  | 26.0                        | 5.8                                       |                             |                                           |
| Aug.  |                             |                                            |                              |                                           |

Table 10. Material Properties

| Material | Thermal conductivity (W/m°C) | Density (kg/m³) | Specific heat (J/kg°C) |
|----------|-----------------------------|-----------------|------------------------|
| Concrete | 1.720                       | 2,240           | 879                    |
| Light concrete | 0.114                      | 650             | 1,173                  |
| Cement mortar | 0.930                     | 1,950           | 921                    |
| Gypsum board | 0.326                     | 940             | 1,130                  |
| Mineral fiber insulation | 0.035                 | 50              | 838                    |
| Expanded polystyrene extruded insulation | 0.029             | 43              | 1,220                  |
| Expanded polystyrene extruded insulation | 0.170               | 1,390           | 900                    |
| Glass     | 1.000                       | 2,470           | 750                    |
| X-L pipe  | 0.324                       | 930             | 1,600                  |
| Water     | 0.660                       | 979             | 4,188                  |
| Adhesive EIFS only | 0.353                 | 1,493           | 717                    |
| Base coating | 0.181                    | 1,761           | 914                    |
| Finish    | 0.196                       | 1,521           | 965                    |

Table 11. Material Properties
simulations were performed with a time step interval of 30 minutes. The calculation parameters are shown in Table 8., and the boundary conditions are shown in Table 9. (Silvers, 1985, ASHRAE, 2001). The material properties are shown in Table 10. (Song, 1998, ASHRAE, 2001, Lee, 1992, CWCT, 2001, Song, 2008). To increase the accuracy of the calculation, the thermal conductivity, density, and specific heat of the materials in the EIFS were measured at the Korea Testing and Research Institute for Chemical Industry.

4.2 Evaluation results

4.2.1 Front wall-slab joint

The volumes of insulation used for the simulation models are 0.159 m$^3$ for the IIS and 0.084 m$^3$ for the EIFS, as shown in Table 11., which indicates that the EIFS has 47.4% less insulation than the IIS. This difference occurs because there is no additional mineral fiber insulation under the slab in the EIFS, as shown in Fig.5. For the case excluding hot water heating, the annual heat losses for the IIS and EIFS are 1,800.6 GJ and 1,679.3 GJ, respectively, which indicates that the EIFS has 6.7% less heating load than the IIS (Table 11.). The annual heat gains of the IIS and EIFS are 30.1 GJ and 28.7 GJ, respectively, which indicates that the EIFS has 4.6% less cooling load than the IIS (Table 11.). For the case including hot water heating, the annual heat losses for the IIS and EIFS are 1,459.8 GJ and 1,398.7 GJ, respectively, which indicates that the EIFS has 4.2% less heat loss than the IIS when the building is heated (Table 11.). The annual heat gains of the IIS and EIFS are 868.5 GJ and 912.6 GJ, respectively, which indicates that the EIFS has 5.1% more heat gain than the IIS when the building is heated (Table 11.). These results show that the amount of heat transfer through the wall-slab joints with an IIS is considerable, as shown in the infrared thermal images in Fig.2. and Fig.3. Also, these results indicate that the EIFS for the front wall-slab joint reduces the heating and cooling loads, as well as the amount of insulation, and improves the heating efficiency. Fig.12. shows the temperature distributions of the front wall-slab joints with an IIS and an EIFS for the lowest annual outside air temperature for the case including hot water heating.
4.2.2 Side wall-slab joint

The volumes of insulation used for the simulation models are 0.286 m³ for the IIS and 0.300 m³ for the EIFS, which indicates that the EIFS has 4.9% more insulation (Table 11.). For the case excluding hot water heating, the annual heat losses for the IIS and EIFS are 659.3 GJ and 415.1 GJ, respectively, which indicates that the EIFS has 37.0% less heating load (Table 11.). The annual heat gains of the IIS and EIFS are 5.7 GJ and 3.1 GJ, respectively, which indicates that the EIFS has 45.9% less cooling load (Table 11.). For the case including hot water heating, the annual heat losses for the IIS and EIFS are 423.5 GJ and 299.3 GJ, respectively, which indicates that the EIFS has 29.3% less heat loss when the building is heated (Table 11.). The annual heat gains of the IIS and EIFS are 768.9 GJ and 855.8 GJ, respectively, which indicates that the EIFS has 11.3% more heat gain when the building is heated (Table 11.). These results indicate that the EIFS for the side wall-slab joint reduces the heating and cooling loads and improves the heating efficiency largely with a small increase in the volume of insulation. Fig.13. shows the temperature distributions of the side wall-slab joints with an IIS and an EIFS for the lowest annual outside air temperature for the case including hot water heating.

4.2.3 Rear wall-slab joint

The volumes of insulation used for the simulation models are 0.255 m³ for the IIS and 0.164 m³ for the EIFS, which indicates that the EIFS has 35.6% less insulation (Table 11.). For the case excluding hot water heating, the annual heat losses for the IIS and EIFS are 1,304.7 GJ and 1,145.9 GJ, respectively, which indicates that the EIFS has 12.2% less heating load (Table 11.). The annual heat gains of the IIS and EIFS are 19.6 GJ and 17.4 GJ, respectively, which indicates that the EIFS has 11.3% less cooling load (Table 11.). For the case including hot water heating, the annual heat losses of the IIS and EIFS are 994.4 GJ and 924.2 GJ, respectively, which indicates that the EIFS has 7.1% less heat loss when the building is heated (Table 11.). The annual heat gains for the IIS and EIFS are 1,006.1 GJ and 1,079.8 GJ, respectively, which indicates that the EIFS has 7.3% more heat gain when the building is heated (Table 11.). These results indicate that the EIFS for the rear wall-slab joint reduces the heating and cooling loads, as well as the amount of insulation, and improves the heating efficiency. Fig.14. shows the temperature distributions of the rear wall-slab joints with an IIS and an EIFS for the lowest annual outside air temperature for the case including hot water heating.

5. Summary and Conclusions

Apartment buildings are the most common type of residential buildings in Korea, where hot water heating pipes are installed in the floor structures. An internal insulation system (IIS) is applied to the outside walls of most Korean apartment buildings, so there are many cases in which the layer of insulation is disconnected by structural components at the wall-slab and wall-wall joints in the envelope. These joints act as thermal bridges where heat transfer increases. In particular, the amount of heat loss is large at the joints adjacent to hot water heating pipes. An external insulation and finish system (EIFS) is one possible solution to this problem. The present state of EIFS in the market was surveyed. The surface temperature distributions of actual apartment buildings with an IIS and an EIFS were investigated with an infrared thermal imaging camera at dawn in the winter. The front, side, and rear wall-slab joints of a recently completed apartment building were selected as typical thermal bridges adjacent to hot water heating pipes. Annual heat losses and gains through these joints with an IIS and an EIFS were calculated by three- dimensional transient heat transfer simulations in which hot water heating was excluded and included, respectively, in order to evaluate not only the heating and cooling loads, but also the heating efficiency when the building is actually heated. The results show that the amount of heat transfer through the wall-slab joints with an IIS is considerable, even though additional insulation is installed under the slab to reduce the heat transfer. For the front and rear wall-slab joints, the EIFS reduces the heating and cooling loads, as well as the amount of insulation, and improves the heating efficiency. For the side wall-slab joint, the EIFS reduces the heating and cooling loads and improves the heating efficiency largely with a small increase in the volume of insulation.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 20090084666). The work was supported by the Ewha Global Top 5 Grant 2011 of Ewha Womans University.

References

1) Song, S. (1998) A study on the method for determining the optimal insulation details of thermal bridge at the joints of apartment building envelope. Ph.D Thesis. Seoul: Seoul National University.
2) MOCT. (1996) Reports on the development of standard computer software and weather data for cooling and heating load calculation. Seoul: Korean Ministry of Commerce, Industry and Energy.
3) Silvers, J.P. and Tye, R.P. (1985) A survey of building envelope thermal anomalies and assessment of thermal break materials for anomaly correction, in: Proceedings of the Department of Energy Workshop on Building Envelope Thermal Anomalies. Oak Ridge: Oak Ridge National Laboratory.
4) ASHRAE. (2001) ASHRAE handbook 2001 fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers.
5) Lee, T. and Lee, J. (1992) Introduction to heat transfer. Seoul: Heejungdang.
6) CWCT. (2001) PACETS version 1 disk number 090. Bath: Center for Window and Cladding Technology.
7) Song, S., Yi, J. and Koo, B. (2008) Insulation plan of aluminum curtain wall-fastening unit for high-rise residential complex. Building and Environment, 43 (7), pp.1310-1317.
8) Physibel. (2002) RADCON Manual. Belgium: Physibel.