# HYGROTHERMAL PERFORMANCE OF EXTERNAL WALL STRUCTURE ADJACENT TO BUILT-IN FURNITURE

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## ABSTRACT

Recently, condensation and mold problems in apartment buildings have been on the rise due to increased insulation and airtightness performance for energy savings. Occupants in residential buildings have suffered property damage due to condensation and mold problems on built-in furniture, especially in Korean apartment buildings. Generally, condensation and mold growth on built-in furniture were found during summer and winter on the back panels of the furniture and adjacent surfaces of the exterior walls. Therefore, the aim of this paper is to analyze the characteristics of thermal environment and condensation problems in the adjacent area around built-in furniture through hygrothermal analysis simulations. We compared the surface temperature and relative humidity in condensation vulnerable areas and evaluated the condensation risk under winter weather conditions in terms of the amount of clothes, the type of insulation material, and the installation of a vapor retarder.

## KEYWORDS

Hygrothermal Performance, External Wall Structure, Built-in Furniture, Condensation, Vapor Retarder

## 1. INTRODUCTION

For the purposes of saving energy, insulation and airtightness performance have been strengthened in Korean apartment buildings. Furthermore, due to the generation of interior vapors as well as the inflow of humid air from exterior environment, possibilities for condensation and mold growth in the building's interior have been on the rise (Hwang et al. 2015). In recent years, the damages caused by condensation account for approximately 16% of all disputes in Korean apartment buildings. In analyzing these disputes concerning condensation, various reasons, such as an absence of insulation or thermal bridges, were identified as leading causes. After moving in, residents found that living conditions led to condensation on the surface of finishing material or on floor, ceiling, and walls adjacent to the built-in furniture's back panels. It causes molds to grow inside the furniture, as seen in Figure 1. Such condensation and mold in the furniture can occur not only damages of furniture and finish materials but also damages of other materials such as bedding and clothes.

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***Figure 1**. Condensation and mold problems around the built-in furniture*

Recently, various studies to resolve condensation problems of built-in furniture or dressing rooms in apartment buildings have been conducted. Such studies include reports on the considerations of installation types and materials of built-in furniture (Lee 2008), and evaluations on the thermal environment inside the built-in furniture in new apartment buildings in winter (Lee et al. 2015). Aside from thermal environment evaluations, investigations into the airflow patterns in a microclimate by particle image velocimetry (PIV) (Mortensen et al. 2007), which analyzed an exterior-facing built-in furniture's airflow pattern, as well as an investigation of microclimate by CFD modelling of moisture interactions (Mortensen et al. 2007), which applied moisture modeling via computational fluid dynamics (CFD), were performed. In the status and cause of mold infestation in apartment houses based on a case study (Moon et al. 2008), the causes and occurrence trends of mold were analyzed. Furthermore, a research such as hygrothermal performance of exterior wall structures using a heat, air, and moisture model (Chang et al. 2015) has been conducted hygrothermal analysis on the external wall structure of the building by WUFI.

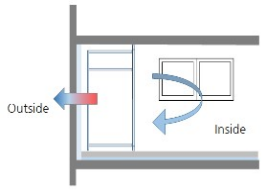
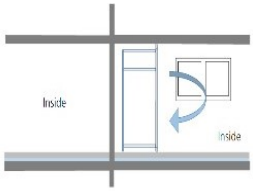
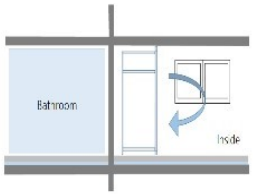
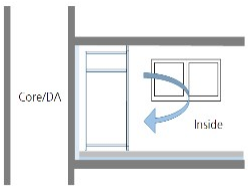
Studies on hygrothermal analysis are still required to understand and evaluate the causes of condensation in built-in furniture of apartment buildings. In this research, the wall configuration system of Korean apartments was studied and hygrothermal simulations for the purpose of one-dimensional heat and moisture transfer analysis were conducted to identify the condensation problem by comparing the surface temperature and relative humidity around the built-in furniture. Thus, the risk of condensation will be evaluated based on the amount of clothes in built-in furniture under living environment conditions, the type of insulation materials, and the installation of vapor retarders.

## 2. HYGROTHERMAL SIMULATION MODEL

### 2.1 Wall Structure

As shown in Table 1, built-in furniture installation spaces can be categorized into four different types according to their plan composition. Section A is a type of housing with built-in furniture installed adjacent to external wall and is considered to have the highest possibility of condensation problems due to the decrease of temperature around the back panel of the furniture. For the evaluation of hygrothermal performance of external wall structure adjacent to built-in furniture in this study, we made simulation models, in which a built-in furniture was installed to external wall structure directly faced to the exterior weather condition. The wall configuration of assessment in this study, which comply with the current Korean insulation standards for apartment, is as shown in Figure 2. In Korea, all construction companies apply an internal wall insulation system to apartments. Commonly used insulation materials are Expandable Polystyrene (EPS), Extruded Polystyrene (XPS), and Polyisocyanurate (PIR), with most opting to use EPS. According to Building Energy Savings Criteria for a newly-built apartment in Korea, the EPS thickness should be more than 155 mm for external walls of living rooms facing outdoor air in central regions of Korea.

***Table 1.*** *Section Types around Built-in Furniture*

| *Section A* | *Section B* | *Section C* | *Section D* |
|---|---|---|---|
|  |  |  |  |



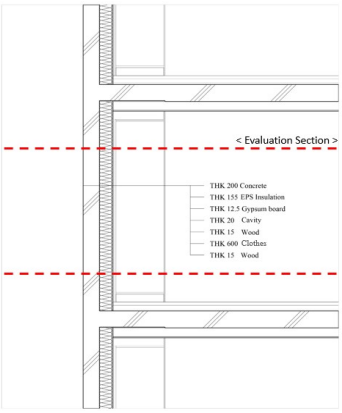




***Figure 2****. The Section of Wall Structure*

## 2.2 WUFI Simulation Model

For the purpose of this study, the moisture performance simulation model WUFI Pro 5.3, which is a Windows-based program for the hygrothermal analysis of building envelope constructions, was selected. The WUFI simulation model is a transient heat and mass transfer model, which can be used to assess the heat and moisture distributions for a wide range of building material classes and climatic conditions.

***Table 2.*** *Material Properties*

| *Material* | | *Thickness (mm)* | *Bulk Density ($kg/m^3$)* | *Porosity ($m^3/m^3$)* | *Specific Heat Capacity (J/kgK)* | *Thermal Conductivity (W/mK)* | *Vapor Diffusion Resistance Factor (-)* |
|---|---|---|---|---|---|---|---|
| Concrete | | 200 | 2300 | 0.18 | 850 | 1.60 | 180 |
| Insulation | EPS | 155 | 25 | 0.95 | 1500 | 0.034 | 50 |
| | XPS | | 40 | 0.95 | 1500 | 0.034 | 50 |
| | PIR | | 40 | 0.95 | 1500 | 0.034 | 100 |
| Gypsum Board | | 12.5 | 850 | 0.65 | 850 | 0.18 | 8.3 |
| Cavity | | 20 | 1.3 | 0.999 | 1000 | 0.13 | 0.56 |
| Furniture (Veneer Plywood BFU 100) | | 15 | 427 | 0.66 | 2500 | 0.16 | 188 |
| Clothes (Cellulose Fiber) | | 500 | 70 | 0.95 | 2500 | 0.04 | 1.5 |
| Air in Furniture | | 50 | 1.3 | 0.999 | 1000 | 0.28 | 0.32 |
| Furniture Door (Veneer Plywood BFU-BU) | | 15 | 708 | 0.53 | 2500 | 0.16 | 242 |
| Vapor Retarder | | 0.3 | 130 | 0.001 | 2300 | 2.3 | 30000 |
| Reflective Vapor Retarder | | | | | | | 2000000 |

Building Energy Savings Criteria, ASHRAE Handbook Fundamentals, and the WUFI Database were referenced for material properties of the wall and vapor retarders, which are shown in Table 2. In the case of using a reflective vapor retarder, radiation occurred in the air layer that was in contact with the reflective vapor retarder. Thus, for the air layer where the radiation occurs, thermal conductivity and vapor diffusion resistance (μ) concerning thickness were applied respectively. When the thickness of cavity was 20 mm, thermal conductivity was 0.05 W/mK, and the vapor diffusion resistance was 0.56. These values were from WUFI Pro 5.3 Manual.

Exterior and interior conditions were as shown in Table 3. Seoul's climate data was used for the exterior climate conditions, and orientation and inclination were set as North and 90 degrees, respectively. Considerations on rain and radiation were excluded. Sine graph was applied for interior climate conditions based on interior temperature and humidity data measured in apartments during summer and winter. The temperature mean value was set at 25 ℃, amplitude at ±4℃, and the relative humidity mean value at 70%, amplitude at 20%. Surface heat transfer coefficients were applied for the exterior at 23.26 W/m$^2$K and the interior at 9.09 W/m$^2$K according to Building Energy Savings Criteria. The calculation period was set during winter (between December 1 to February 28, for a total of 2,160 hours, and with an interval of 1 hour). Monitors were installed between concrete and insulation where is prone to interstitial condensation, and between gypsum board surface and furniture surface where are prone to surface condensation.

***Table 3.*** *Exterior and Interior Conditions*

| *Category* | *Input* | |
|---|---|---|
| Exterior | Location | Weather data for Seoul, Korea |
| | Orientation / Inclination | North / 90° |
| Interior | Temperature | 21-29 ℃ |
| | Relative Humidity | 50-90 % (high humidity) |

***Table 4.*** *Simulation Cases (O: installed, -: uninstalled)*

| *Case* | | *clothes* | *Installed Location of Vapor Retarder* | | | |
|---|---|---|---|---|---|---|
| | | | *P1* | *P2* | *P3* | *P4* |
| Case 1 | 1-1 | - | - | - | - | - |
| | 1-2 | O | - | - | - | - |
| Case 2 Insulation | 2-1 | O | - | - | - | - |
| | 2-2 | O | - | - | - | - |
| Case 3 Vapor Retarder | 3-1 | O | O | - | - | - |
| | 3-2 | O | - | O | - | - |
| | 3-3 | O | - | - | O | - |
| | 3-4 | O | - | - | - | O |
| Case 4 Reflective Vapor Retarder | 4-1 | O | O | - | - | - |
| | 4-2 | O | - | O | - | - |
| | 4-3 | O | - | - | O | - |
| | 4-4 | O | - | - | - | O |

## 2.3 Simulation Cases

As shown in Table 4, simulation cases were planned to evaluate condensation risks of built-in furniture according to the amount of clothes, the type of insulation, and the installation of vapor retarders. Case 1 involved the reference model. Case 1 was divided into two categories according to living conditions, of which one had no clothes and the other had clothes inside the furniture. Case 2 involved a variation in

the insulation material from Case 1-2, where clothes were inside the furniture. Case 2-1 used XPS and Case 2-2 used PIR. For the installation of vapor retarders, Case 3 indicates a model of a vapor retarder and Case 4 involved a reflective vapor retarder with emissivity as 0.05. Cases 3 and 4 were classified according to locations of vapor retarders installed. As shown in Figure 3, locations of vapor retarders were divided into four; between concrete and insulation (P1), between insulation and gypsum board (P2), between gypsum board and cavity (P3), and between cavity and furniture (P4).

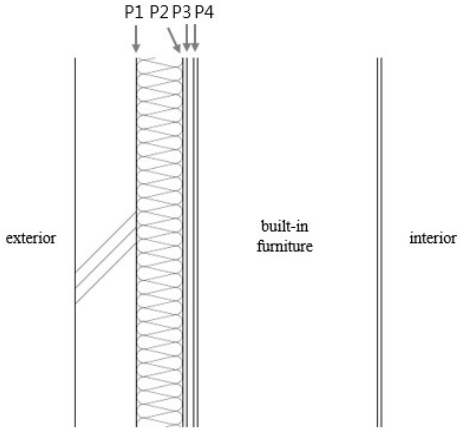



***Figure 3**. Installed Location of Vapor Retarder*

## 3. SIMULATION RESULTS

### 3.1 Surface Temperature and Relative Humidity

The temperature and relative humidity between concrete and insulation, the gypsum board surface, and the furniture surface for each case are shown in Table 5. All cases had approximately the same temperature range in between concrete and insulation, except for Case 1-1. The temperatures of the gypsum board surface and the furniture surface were distributed around a similar range except for Case 1-1. Relative humidity was distributed of high range in the order the furniture surface (74.6–98.7%), between concrete and insulation (81.3–96.8%), and the gypsum board surface (67.2–95.0%).

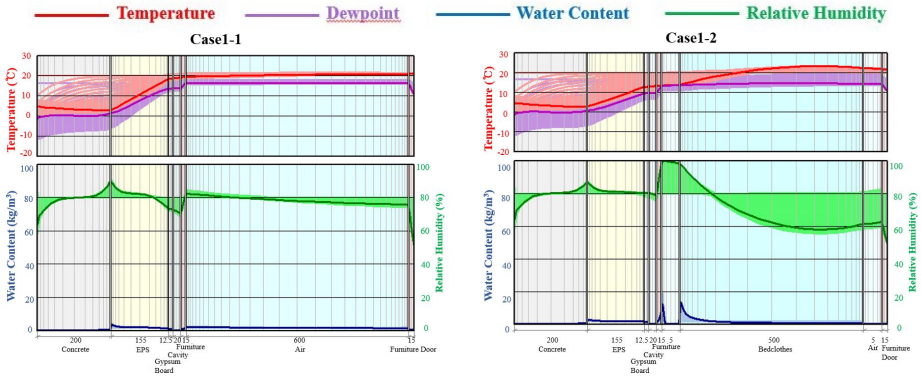
***Table 5.** Surface Temperature and Relative Humidity*

| *Case* | | *Temp. of P1 (℃)* | *RH of P1 (%)* | *Temp. of P3 (℃)* | *RH of P3 (%)* | *Temp. of P4 (℃)* | *RH of P4 (%)* |
|---|---|---|---|---|---|---|---|
| Case 1 | 1-1 | -14.5–6.8 | 81.9–96.8 | 15.9–21.1 | 67.2–78.7 | 17.5–21.9 | 74.6–82.4 |
| | 1-2 | -14.9–6.5 | 81.7–92.1 | 4.1–16.9 | 77.8–83.0 | 4.9–17.6 | 83.1–96.8 |
| Case 2 | 2-1 | -14.9–6.5 | 81.8–92.1 | 4.2–17.1 | 77.8–83.0 | 5.0–17.8 | 83.0–96.8 |
| | 2-2 | | 81.3–88.7 | 4.2–17.2 | 79.3–87.4 | 5.0–17.8 | 83.0–97.4 |
| Case 3 | 3-1 | -14.9–6.5 | 82.8–93.3 | 4.1–16.9 | 77.8–83.1 | 4.9–17.6 | 83.1–96.8 |
| | 3-2 | | 81.7–92.1 | 4.2–16.9 | 80.3–92.3 | 5.0–17.6 | 83.1–98.1 |
| | 3-3 | | 81.7–92.1 | 4.2–17.0 | 81.6–90.2 | 5.0–17.6 | 83.2–98.4 |
| | 3-4 | | 81.7–92.1 | 4.2–16.9 | 66.6–78.2 | 5.0–17.6 | 83.2–98.4 |
| Case 4 | 4-1 | -14.9~6.5 | 82.8~92.8 | 4.1~16.9 | 77.8~83.1 | 5.0~17.6 | 83.1~96.8 |
| | 4-2 | | 81.7~92.0 | 4.2~16.9 | 80.4~95.0 | 5.0~17.6 | 83.1~98.3 |
| | 4-3 | | 81.7~91.9 | 3.9~16.5 | 60.7~80.9 | 5.5~17.8 | 83.0~98.0 |
| | 4-4 | | 81.7~92.0 | 3.9~16.5 | 60.7~80.9 | 5.5~17.8 | 83.1~98.7 |

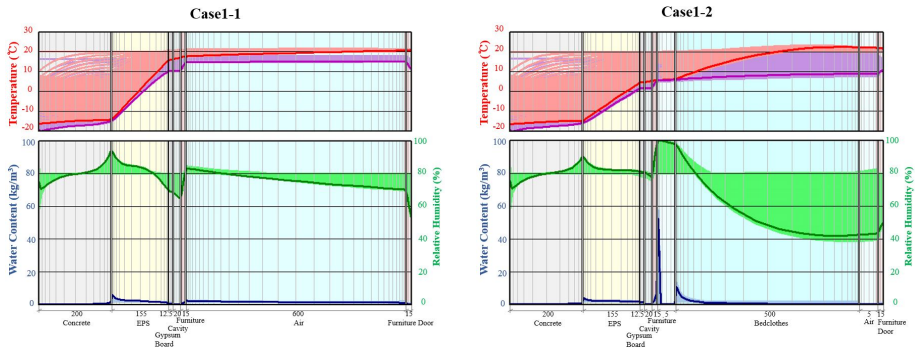
During the analysis period, we were able to identify the time when temperature was the lowest while relative humidity was the highest, or temperature was the highest while relative humidity was the lowest by analyzing each time's climate data.

As a result, the coldest/dampest time were recorded on January 13 at 08:00 (temperature -16.2 ℃, humidity 76.3%), whereas the hottest/driest time were witnessed on December 20 at 16:00 (temperature 4.6 ℃, humidity 63.7%). With these times as a target, the temperature and humidity of Cases 1-1 and 1-2 were evaluated to find out the effects of the amount of clothes inside a built-in furniture. The results of evaluation are shown in Figure 4.

In comparing Case 1-1 (no clothes inside the furniture) with Case 1-2 (clothes inside the furniture), temperature and dew point temperature became almost identical at between concrete and insulation in Case 1-1 and on the furniture surface in Case 1-2. Relative humidity was the highest at between concrete and insulation in Case 1-1 and on the furniture surface in Case 1-2. In addition, in Case 1-2, the temperature and relative humidity were widely distributed inside the built-in furniture. This indicates that the clothes inside the furniture may have exacerbated the thermo-humidity condition of furniture. Furthermore, whereas the lowest relative humidity was approximately 58% during the hottest/driest time, the relative humidity decreased to 42% during the coldest/dampest time




(a) Hottest/driest time (December 20 at 16:00)




(b) Coldest/dampest time (January 13 at 08:00)

***Figure 4**. Simulation Results for Case 1*

### 3.2 Condensation Risk

Locations between concrete and insulation or the furniture surface were considered as condensation vulnerable areas, so monitors were installed in these areas to evaluate the condensation risk of each case. Whereas gypsum board surface (P3) is known to attract condensation and mold in living conditions, simulation results showed that condensation did not occur. Table 6 shows that the percentage of condensation occurrence time (hours) during the simulation period (2,160 hours) for each case.

***Table 6.*** *Condensation Risk*

| *Case* | | *Concrete-Insulation (P1)* | *Furniture Surface (P4)* |
|---|---|---|---|
| Case1 | 1-1 | 65% (1394 hours) | - |
| | 1-2 | 3% (59 hours) | 91% (1,974 hours) |
| Case2 | 2-1 | 3% (64 hours) | 91% (1,973 hours) |
| | 2-2 | - | 92% (1,980 hours) |
| Case3 | 3-1 | 21% (454 hours) | 91% (1,974 hours) |
| | 3-2 | 3% (70 hours) | 92% (1,990 hours) |
| | 3-3 | 4% (84 hours) | 93% (2,000 hours |
| | 3-4 | 4% (84 hours) | 93% (2,000 hours) |
| Case4 | 4-1 | 17% (360 hours) | 91% (1,974 hours) |
| | 4-2 | 3% (59 hours) | 92% (1,991 hours) |
| | 4-3 | 2% (38 hours) | 92% (1,981 hours) |
| | 4-4 | 2% (39 hours) | 93% (2,000 hours) |

If the built-in furniture kept no clothes (Case 1-1), only interstitial condensation occurred during the simulation period. However, if clothes were kept inside the furniture (Case 1-2), which more closely resembles a practical living condition, the interstitial condensation risk was reduced but the condensation risk on the furniture surface was very high. Thus, a case which clothes are kept inside the furniture is more likely to cause condensation, and is expected to cause residents' inconvenience.

Case 2 are the results according to different insulation materials. During the simulation period, in using XPS (Case 2-1), interstitial condensation occurrence time increased by 6 hours whereas surface condensation occurrence time decreased by 1 hour compared to the use of EPS (Case 1-2). Because the thermal conductivity and the vapor diffusion resistance of XPS are similar to that of EPS, both are prone to a similar level of a condensation risk. On the other hand, the vapor diffusion resistance of PIR is two times higher than EPS. Therefore, PIR may be effective in preventing interstitial condensation. However, because condensation occurrence time on the furniture surface will be increased, PIR may be disadvantageous for the purpose of reducing a surface condensation risk.

In regard to the type of vapor retarders, the results indicated that a vapor retarder was not effective in preventing interstitial or surface condensation. Although a reflective vapor retarder was not effective in preventing condensation on the furniture surface, it reduced interstitial condensation occurrence time by up to 54.8% (46 hours) if installed on the gypsum board surface, in contrast to a vapor retarder.

The results according to locations of vapor retarders included the following. If installed at P1, the risk of interstitial condensation increased from 3% to 21% in case of a vapor retarder and 17% in case of a reflective vapor retarder. Therefore, it is suggested to avoid placing vapor retarders at P1. If installed at P2, risks were similar to that of the reference model (Case1-2). For the P3 and P4 locations, the results were differed according to the type of vapor retarders. Both interstitial and surface condensation occurrence time increased when a vapor retarder was used. On the other hand, a reflective vapor retarder decreased the interstitial condensation occurrence time by 21 hours compared to Case 1-2.

In order to reducing the interstitial condensation, a reflective vapor retarder placed at P3 or P4 was effective. In preventing condensation on a furniture surface, regardless of the location, a vapor retarder and a reflective vapor retarder were similar in their effectiveness compared to Case 1-2. Therefore, in evaluating both interstitial and surface condensation risks, Case 4-3 which interstitial condensation risk was reduced and surface condensation risk was similar to Case 1-2 is probably the most effective.

## 4. CONCLUSIONS

Condensation risks were derived from hygrothermal analysis of built-in furniture adjacent to external wall of a newly-built Korean apartment in terms of the amount of clothes, the type of insulation material and the installation of vapor retarders.

It was found that with no clothes only interstitial condensation occurs inside furniture, but with clothes kept inside, a surface condensation risk became very high.

XPS and EPS have similar level of condensation risks. However, PIR, with a higher vapor diffusion resistance, was effective in preventing interstitial condensation.

Neither a vapor retarder nor a reflective vapor retarder were effective in preventing surface condensation regardless of installation location. However, if a reflective vapor retarder was installed at locations such as P3 and P4, it was effective in reducing interstitial condensation risk. Considering both interstitial and surface condensation, Case 4-3 (installing a reflective vapor retarder at P3) was deemed to be the most effective to reduce condensation because interstitial condensation was reduced whereas surface condensation was similar to that of the reference model (Case 1-2).

Condensation was likely to occur on the furniture surface when clothes were kept inside built-in furniture similar to a practical living condition, causing residents' inconvenience. Thus, to reduce potential inconvenience and property damages, advanced research on preventing surface condensation is needed in the future.

## ACKNOWLEDGEMENTS

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