International Journal of Engineering & Technology, 8 (1.4) (2019) 13-26

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

An Analysis of the Moisture Content of Internal Insulation Structures According to the Installation of Vapor Retarder Based on Meteorological Data by Region: Focused on South Korea

Hyang-In Jang[1], Kyung-Soo Kim[2], Soung-Wook Hong[3], Chang-Ho Choi[4]*

[1]Institute of Green Building and New Technology, Mirae Environment Plan Architects, Seoul, Korea
[2]Institute of Green Building and New Technology, Mirae Environment Plan Architects, Seoul, Korea
[3]Institute of Green Building and New Technology, Mirae Environment Plan Architects, Seoul, Korea
[4]Department of Architectural Engineering, Kwangwoon University, Seoul, Korea
**Corresponding author E-mail: choi1967@kw.ac.kr*

Abstract

In South Korea, concealed condensation evaluations are carried out based on the ‘condensation prevention design standards for apartment housing,’ which only consider evaluations of the surface condensation of a structure (temperature). In addition, the evaluations consider only the monthly average outdoor temperature upon classifying outdoor conditions into three regions, which will not yield accurate results in terms of an assessment of condensation. Furthermore, cases of condensation and reverse condensation occur frequently due to a lack of regulations concerning the installation of vapor retarding layers within internal insulation structures where multiple occurrences of condensation may develop. To analyze levels of condensation according to the meteorological conditions of each region regarding internal insulation walls according to the presence or absence of vapor retarding layers, this study collected meteorological data from 20 different regions in South Korea, and undertook evaluations using simulations. The conclusions of this research are as follows. 1) The results of extracting meteorological data factors to undertake evaluations of concealed condensation indicated that temperature, relative humidity, total solar radiation, diffuse sky radiation, wind speed, wind direction, and precipitation have relevance. 2) The results of concealed condensation simulation evaluations using the meteorological data of 20 regions of South Korea presented differences according to the meteorological characteristics of each region, with concealed condensation found to have a more sensitive effect on a structure in regions closer to the coast. 3) For internal insulation structures installed with vapor retarding layers, the incidence of concealed condensation was high in coastal regions; in the case of internal insulation structures that were not installed with vapor retarding layers, the incidence of concealed condensation was low in Southern regions where high temperatures were present. 4) The results of a comparative analysis indicated that across all regions, the incidence of concealed condensation was lowest in internal insulation structures installed with vapor retarding layers.

Keywords: *Condensation, Outdoor meteorological data, ISO 13788, EN 15026, Moisture content.*

1. Introduction

1.1. Background and purpose of the study

The moisture transmission performance of a structure, in terms of ISO 13788 (Monthly Method) proposed by the International Organization for Standardization (ISO), is determined by the amount of evaporation in comparison to the accumulated amount of condensation per year according to the Glaser method for the temperature and humidity of the structure, and the monthly average data (temperature, humidity) of each region is applied as the outdoor boundary conditions[1]. In addition, EN 15026 (Dynamic Method) defined in Germany is calculated by the change of enthalpy through heat and material equilibrium, the amount of liquid transferred by the capillary phenomenon, and the amount of water vapor transferred by water vapor pressure, and the concealed condensation of the structure is evaluated by considering the climate data (temperature, humidity, wind speed, wind volume, moisture, shortwave absorption, and precipitation) that affects the moisture movement[2]. While both standards determine the outdoor conditions based on average data by region, the ‘condensation prevention design standards for apartment houses,’ as evaluated in South Korea, are only classified into 3 geographical regions and divided into -20℃, -15℃, and –10℃ based on monthly average daily lowest open air temperature[3]. It is thus impossible to accurately determine condensation, because various meteorological factors and areas of the outdoor weather data are not classified and evaluated. Condensation has gradually increased as the air-tightness performance of buildings has improved, but the condensation evaluation method has not been revised. In addition, the evaluation of condensation exclusively through dew point temperatures is not considered to be a systematic evaluation method compared to condensation evaluation methods found overseas.

Concealed condensation occurs across multiple locations in buildings composed of internal insulation structures where it is impossible to continually apply insulation materials. Internal insulation structures are installed with insulation materials in the interior of the structure. This causes interior surface temperatures to drop lower than the dew point temperature, entailing a high possibility of condensation. In particular, due to the low moisture resistance of the structure (concrete), liquid transfers occur through pores due to the capillary phenomenon. Should the evaporation of vapors be delayed or become impossible, the chances of condensation formation upon accumulation within the structure increase. Means of preventing this include the installation of a vapor retarding layer on the indoor surface. Despite this being effective in reducing the formation of condensation during the winter season, the chances of reverse condensation are greatly increased during the summer season due to the retardation of evaporation [4].
In light of this, to propose a means of improving evaluations of concealed condensation in South Korea this study collected meteorological data from 20 different regions in the country and analyzed the extent to which the above phenomenon occurred. Thereafter, based on the meteorological data of each region and for the purpose of extracting moisture content according to the installation or non-installation of vapor retarding layers within an internal insulation structure, this study had the goal of undertaking simulated evaluations through an analysis model. In light of this, the ultimate goal of this study was to establish basic research data that may be applied to advance the evaluations of concealed condensations in South Korea.

1.2. Procedure and method of the study

This study examined the outdoor meteorological data factors and selected 20 regions of South Korea to collect meteorological data. Afterwards, based on WUFI, which is a simulation program capable of analyzing heat and moisture in abnormal conditions, a comparative analysis was performed on the concealed condensation incidence rate of interior insulation structures with a high incidence of concealed condensation. The procedure of this study is as shown in Fig. 1.
First, the concealed condensation occurrence mechanism according to meteorological factors was examined in order to evaluate the concealed condensation moisture content based on the regional meteorological data of this study. Second, outdoor meteorological data factors were derived by observing the concealed condensation occurrence mechanism, and hourly meteorological data of 20 regions. Data was also collected through the Meteonorm program which considers the regional characteristics of South Korea, based on longitude, latitude and altitude. Third, upon selecting internal insulation structures according to the existence of vapor retarding layers, further analysis was undertaken based on the collected meteorological data using an abnormal condition analysis simulation tool known as WUFI. Fourth, the results of concealed condensation moisture content of the structure according to the changes of weather data of each region were compared and analyzed.

Introduction

Study

- The Mechanism of Concealed Condensation Occurrences
- The Mechanisms of Condensation Occurrences According to the Existence/Non-existence of Vapor Retarding Layers within the Insulation Structure
- Implications of Concealed Condensation Considering Regional Characteristics

Collecting regional meteorological data

- The Mechanism of Concealed Condensation Occurences
- Deduction of Outdoor Meteorological Data Factors
- Results of Collecting and Analyzing Meteorological Data by Region

Method

- Selection of Lightweight Structural Modules for Performance Evaluations
- Overview of the Transient Analysis Tool WUFI

Performance evaluation

- Analysis Results of Concealed Condensation Moisture Content of Structures According to the Installation of Vapor Retarding Layers by Region

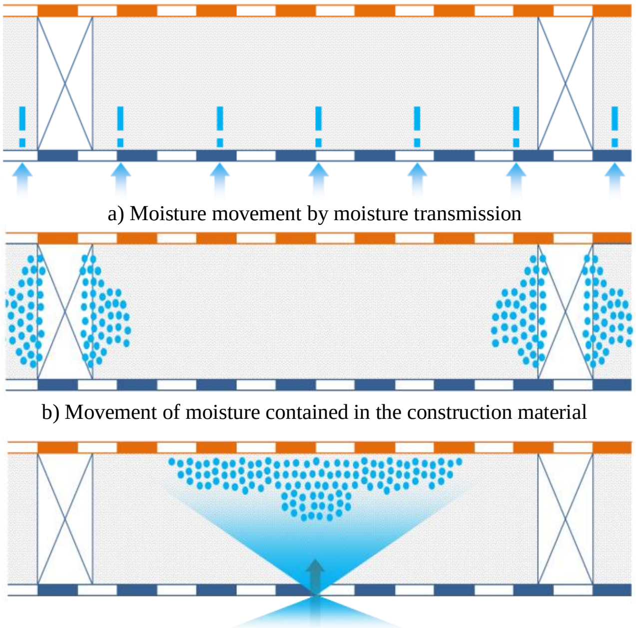
Conclusion

Fig. 1: Study procedure

2. Mechanism of the Occurrence of Concealed Condensation & Review of Past Studies

2.1. Concealed condensation occurrence mechanism

The phenomenon of concealed condensation in a building structure is caused by moisture transfer by water vapor diffusion, moisture storage of the structure, and liquid transfer by capillary phenomenon, and the details of the classification items are as follows.
Moisture transfer in a building structure consists of the transfer of water vapor and liquid. The movement of water vapor, as shown in Fig. 2, is classified into moisture movement in the structure through moisture transmission, movement of moisture contained in the construction material, and direct movement of moisture particles through convection. According to a study by Fraunhofer IBP in Germany, moisture movement through convection is reported to be approximately 1,600 times greater than that of general diffusion.



a) Moisture movement by moisture transmission

b) Movement of moisture contained in the construction material

c) Moisture movement by convection

Fig. 2: Moisture movement in a masonry structure

The storage of moisture contained in the structure is related to the bulk density [kg/m^3] and the porosity [m^3/m^3] performance. There are many pores on the surface of a structure, and water molecules are adsorbed in the inner pore surface and stored in the structure. The higher the relative humidity in the pores, the thicker the adsorbed water molecules become, and when the relative humidity in the pores decreases, the water molecules evaporate from the water molecule layer, resulting in heat absorption. As shown in Fig. 3, the water vapor movement (moisture transmission) in the pores of the structure occurs from the inside where the water vapor pressure is high compared to the outside, where the water vapor pressure is low. Afterwards, when the relative humidity of the pore is increased, a small condensate occurs on the surface of the pore and moves indoors in a small liquid state where the humidity is relatively low. The movement of water molecules on the surface of these pores is called Surface Diffusion. When the relative humidity in the pore reaches a critical point (usually 80% or more), a phenomenon of liquid movement due to capillary tension occurs inside the room[5].

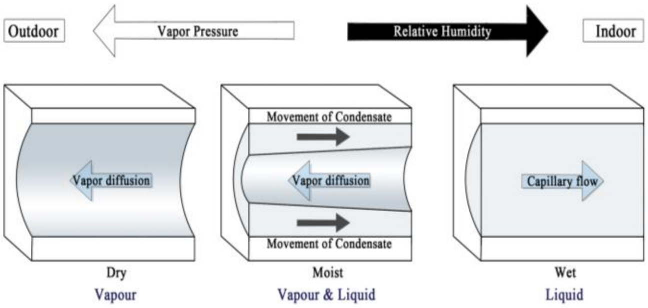
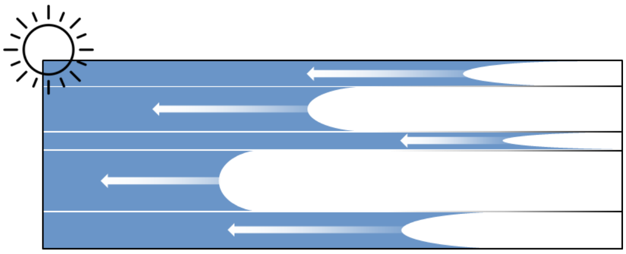
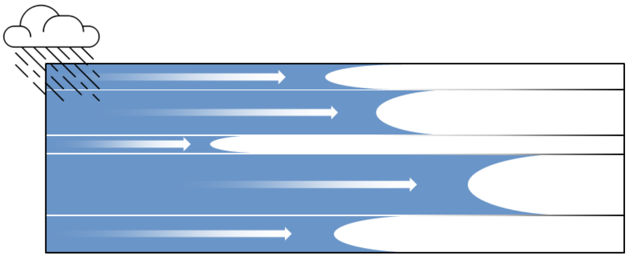


Fig. 3: Concealed condensation mechanism of structure according to the relative humidity of pores

The capillary phenomenon is caused by the cohesive force of water molecules and the difference in adhesive force between the contact surface and water molecules, as shown in Fig. 4. The mechanism of the capillary phenomenon can be explained as follows. In terms of outdoor rainwater, when the size of the pore is small, the area of the pore section is small so that the pressure inside the pore is larger than that of the capillary force to be absorbed. Therefore, the degree of water penetration is small and as the pore grows in size, this phenomenon intensifies. When the water is distributed and discharged from the material, the smaller the pore size, the larger the capillary force inside the pore, and therefore the speed of water distributed and discharged becomes stronger. Correspondingly, the larger the pore size, the smaller the capillary force[6].



a) Degree of absorption into the material



b) Degree of distribution and discharge speed in the material

Fig. 4: Capillary phenomenon by pore size

2.2. Mechanisms of the Occurrence of Condensation According to the Presence/Absence of Vapor Retarding Layers within the Insulation Structure

The mechanism by which moisture penetrates internal insulation during the winter season as shown in Fig. 5 is associated with an increase in the incidence of condensation as the interior surface temperature (t_{si}) becomes lower than the dew point temperature (t_{dp}) due to the insulation material installed in the interior area. In particular, in terms of the temperature at the interior boundary of the structure, given that the installation of insulation materials within the interior of the structure causes a rapid rise of temperature at the insulation material, the temperature at the boundary between the concrete and insulation material (t_1) becomes lower than the dew point temperature (t_a), resulting in a high rate of occurrence of condensation ($t_1<t_a$). In the event that indoor heating is suspended during the winter season, due to the absence of a means of storing heat within the internal insulation, the temperature of the surface of the walls can easily become lower compared to the external insulation, and as a result, the residual vapor in the structure rapidly freezes. In light of this, to reduce the incidence of condensation at the internal insulation, a vapor retarding layer must be installed across the entirety of the interior, or sufficient amounts of ventilation are needed to prevent the transfer of moisture due to differences in temperature. This however, carries the high possibility of reverse condensation during the summer season due to the inhibition of water vapor evaporations caused by the vapor retarding layer installed in the interior area.

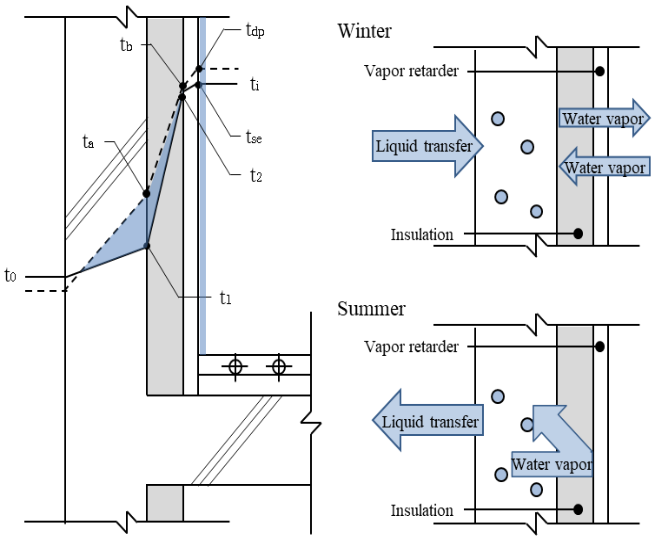


Fig. 5: Capillary phenomenon by pore size

2.3. Implications of Concealed Condensation Considering Regional Characteristics

As shown in Table 1, Oh SE Min et al. established that condensation is a defect that occurs during the construction phase, while Jeong Chan Woul et al. established condensation occurred according to insulation performance. Although You Shijun et al established the existence of differences in the rate of condensation occurrences according to climate characteristics, the study did not consider the rate of condensation occurrences based on whether a vapor retarding layer was applied to the walls of the structure. Although Klich Raaholdt Rein Kristian et al. established the effectiveness of installing vapor retarding insular materials for the prevention of condensation, the study did not consider climate characteristics. In light of this, past studies on condensation mostly involved research into the standards and methods of condensation prevention design according to the purpose of a building. Thus far, there has been a lack of studies on moisture content according to the existence of vapor retarding layers while considering regional characteristics. This results in difficulties when it comes to accurately predicting the volumes of concealed condensation due to a lack of consideration of regional characteristics, necessitating a further analysis based on regional characteristics that is carried out in this study. The lack of past studies regarding condensation and reverse condensation according to the installation/non-installation of vapor retarding layers, which becomes a problem for internal insulation, is particularly noted. Considering this, this study proposed a direction to improve the method of evaluating concealed condensation in South Korea and comparatively analyzed moisture content according to whether a vapor retarding layer was installed in the internal insulation structure through simulated evaluations.

Table 1: Preliminary studies of concealed condensation

Title	Local characteristics	Vapor retarder
A Study on the Effect of Material Properties Related to Liquid Transport on the Maximum Cumulative Condensation (2017) [7]	×	×
Comparison of Total Moisture Content by Internal Condensation Evaluation Method (2017) [8]	×	×
Study on the Improvement Plans of Condensation Defect Examples in Apartment Building (2017) [9]	×	×
Comparison and Analysis of Domestic and Foreign Standards for Preventing the Condensation in Multi-residential House (2013) [10]	×	×
A study on the Foundation of the Standard of Temperature and Humidity for Preventing Condensation in Apartment Housings (2011) [11]	×	×
Forecast on Internal Condensation at Balcony Ceiling of Super-high Apartment Building Faced with Open Air (2003) [12]	×	×
Establishment of Design Standards for Preventing Condensation in the Underground Space (2002) [13]	×	×
Improvement of wall condensation modeling with suction wall functions for containment application (2016) [14]	×	×
Simulation of condensation and liquid break-up on a micro-object with upper and lower movable walls using Lattice Boltzmann Method (2018) [15]	×	×
An algorithm to predict the transient moisture distribution for wall condensation under a steady flow field (2013) [16]	×	×
Study on moisture condensation on the interior surface of buildings in high humidity climate (2017) [17]	○	×
New National Museum in Oslo. Analysis of risk for condensation and possible mold growth in internal climatic sectioning walls and floors (2017) [18]	○	×

3. Collecting regional meteorological data by region for concealed condensation evaluation

3.1. Consideration of outdoor meteorological data factors affecting concealed condensation

In terms of outdoor conditions to evaluate concealed condensation, the conditions of the region where the structure is located should be utilized, and appropriate factors and risk factors must be reflected. In particular, annual data by the hour are required because the rate of change and the direction of humidity transfer is important. Meteorological data extraction should include critical conditions, and the average value of data for more than 10 years should be used to secure reliability. The climate data factors required to evaluate concealed condensation are dry-bulb temperature [℃], relative humidity [%], total solar radiation [W/m^2], diffuse sky radiation [W/m^2], wind speed [m/s], wind direction, and precipitation [mm]. The details of the analysis are as follows.

3.1.1. Dry-bulb temperature [℃]

The dry-bulb temperature is the temperature corresponding to the present temperature, which only considers the sensible heat of the atmosphere. As the temperature corresponding to the boundary condition when analyzing the concealed condensation of the structure, it is the factor (driving force) that generates thermal energy transfer between both fluids (indoor and outdoor) through a solid structure.

3.1.2. Relative humidity [%]

Relative humidity is the ratio of the saturated water vapor pressure to the water vapor pressure of the humid air under specific conditions, and represents the degree of humidification of the air. In other words, relative humidity is expressed as the ratio of the saturated water vapor pressure at the corresponding temperature to the saturated water vapor pressure at the dew point of a given humid air. Therefore, the relative humidity can be obtained by measuring the dew point because the actual amount of water vapor in a given air volume is equivalent to the saturated water vapor amount at the dew point. On sunny days, as shown in Fig. 6, the temperature and humidity are inversely related to each other, and when the volume of water vapor is constant, results in an increase in saturated water vapor as the temperature increases. In addition, since the volume of water vapor in the air does not change, it shows a constant state even at the dew point. On rainy days, the relative humidity is 100% because the temperature is almost the same as the dew point, and the dew point is high because of the increase of water vapor in the air[19].

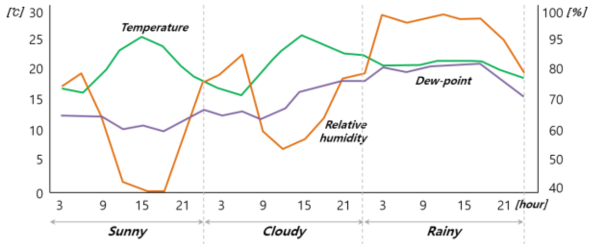


Fig. 6: Changes in temperature, humidity, and dew point according to weather conditions

The transfer of heat and mass energy due to temperature and relative humidity as presented in a psychometric chart were as shown in Fig. 7. The balance of energy in humid air is achieved through the transfer of heat and mass, and the driving force of the heat transfer is temperature difference. Once the air of State 1) meets with State 2) as shown in Fig. 7, heat and mass transfers occur in the direction of State 2). In the case in which the air of State 2) meets with State 3), the high temperature of State 3) results in a transfer of heat through the air to State 2), which is in a lower temperature state. In contrast, the mass transfer occurs in the opposite direction from State 2) to State 3) due to the relatively higher humidity of State 2). Such transfer of mass in the structure is presented as vapor diffusion.

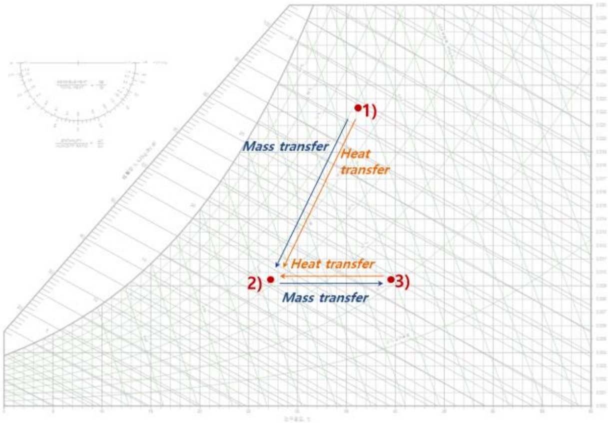


Fig. 7: Transfer of Heat and Mass along the Psychometric Chart

3.1.3. Total solar radiation [W/m^2]

Heat transfer is caused by the conduction at the surface of a structure, convection by air flow, and radiation heat exchange, and solar radiation in particular shows daily variation. Since solar radiation occurs in the shortwave radiation region, solar radiation can be expressed by shortwave radiation. Total solar radiation is the sum of direct solar radiation and diffuse sky radiation, which is scattered by the atmosphere. Generally, the heat transfer coefficient of a structure includes elements representing longwave radiation exchange with the surrounding surface, whereas solar radiation is calculated separately because it affects the surface temperature. In terms of the mechanism that affects the structure, the solar radiation on the outer wall is absorbed as heat, and some of this heat is accumulated in the structure and transferred to the room by unsteady static heat conduction. Fig. 8 shows the energy distribution according to the solar radiation energy spectrum, and the solar radiation energy is 120W/m^2 in the ultraviolet region, 630W/m^2 in the visible region and 600W/m^2 in the near infrared region, and the average value across the spectrum is 1,353W/m^2.

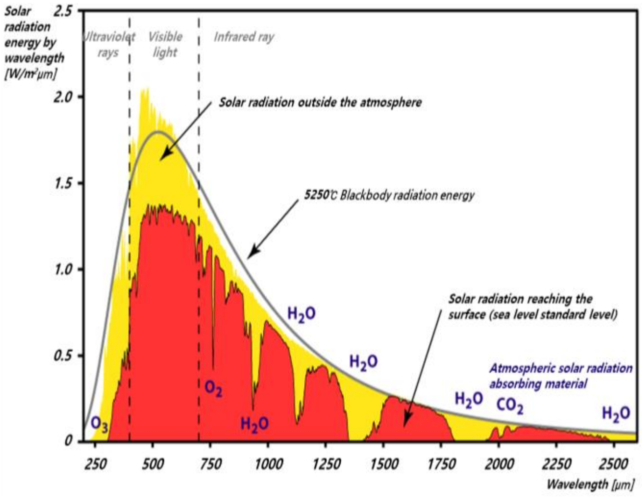


Fig. 8: Energy distribution according to solar radiation energy spectrum

3.1.4. Diffuse sky radiation [W/m^2]

Solar radiation is scattered in various directions by particles in the atmosphere while reaching the surface, and the amount of radiation emitted by scattering downward toward the surface is called diffuse sky radiation. Sky radiation is difficult to predict because it comes from all over the sky, and there is a significant difference depending on the amount of moisture or dust in the atmosphere on a particular day. The diffuse sky solar radiation increases as the solar altitude becomes higher and as the turbidity of the atmosphere increases. Radiation heat energy reaches the windows in the north, awnings, and other shaded areas of the building without direct sunlight by sky radiation.

3.1.5. Wind speed [m/s], wind direction, precipitation [mm]

The wind and precipitation data required to evaluate the performance of concealed condensation is necessary to calculate the precipitation to the envelope of the structure. While most of the precipitation on the envelope is not observed, it can be calculated using the wind and precipitation data as shown in Fig. 9. Precipitation R is represented as a vector having a certain angle due to the effects of wind, and Precipitation R_n, which is measured as the meteorological data, represents the volume of precipitation that falls perpendicular to the ground. R_D is the degree of precipitation reaching the envelope, and this value is obtained by multiplying the measured precipitation R_N by the wind speed V_{wind} and the characteristic coefficient R_2 of the experimental value. R_2 is derived from the ratio measured by the vertical precipitation and the wind speed, and the unit is [s/m].

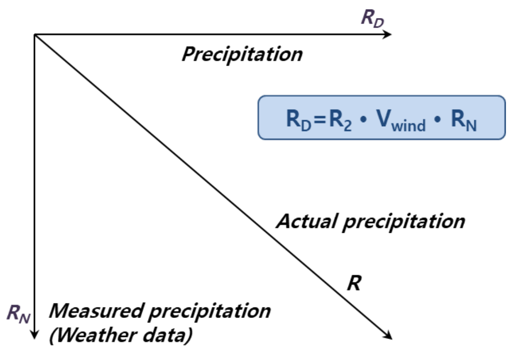


Fig. 9: Calculation of precipitation reaching the envelope

3.2. Outdoor meteorological data collection method

The outdoor conditions used to evaluate concealed condensation must be based on key conditions associated with the location of the structural subject to be evaluated. This relates to a format of meteorological data for the evaluation of building energy performance in which the average conditions are reflected in a Test Reference Year format. To undertake evaluations of the concealed condensation, the appropriate variables and risk rates must be reflected. Due to the importance of the direction and rate of change of the transfer of humidity, data reflected in yearly and hourly units is required. To evaluate the behavior of moisture in a structure, the averages of data collected over 10 years or more, data related to the vulnerable conditions (critical conditions) that result in the occurrence of condensation, and data including hourly precipitation, wind speed, and wind direction must be used.

Therefore, Meteonorm, a dedicated program for obtaining meteorological data, was used to collect outdoor meteorological data to evaluate concealed condensation. Meteonorm is capable of extracting climate data according to the latitude, longitude, and altitude of the location. The result values of the climate data include diffuse radiation, air temperature, dew point temperature, horizontal radiation, direct normal radiation, wind speed, and precipitation. In this study, the radiation value data of a 20-year period (1991-2010) and the temperature value data of a 10-year period (2000-2009) were analyzed. However, the margin of error of Meteonorm was presented as being 7% for radiation, 1.2 ℃ for temperature, and 2~3 % (rmse) for radiant heat; in the case of hourly output, there is a tendency for the total radiation of a sloped surface to be overestimated. As shown in Fig. 10, the regional data of South Korea was based on the selection of key cities where by the regional classifications included coastal regions, mountain regions, plain regions, northern, central, and southern regions, and data collected from the following 20 regions: Cheongju, Seoul, Incheon, Cheonan, Boryeong, Daejeon, Imsil, Gwangju, Mokpo, Wonju, Sokcho, Gangneung, Taebaek, Mungyeong, Uiseong, Geochang, Ulsan, Busan, Yeosu and Jeju.

Fig. 10: 20 meteorological data collection regions

3.3. Results and analysis of collected outdoor meteorological data

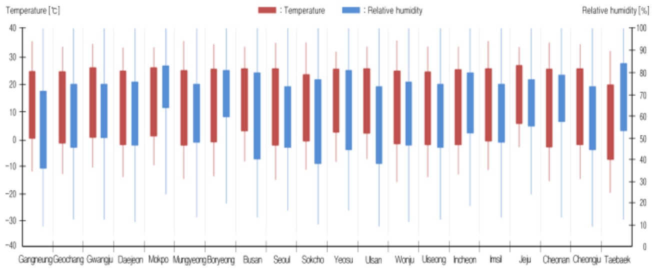
In this study, outdoor meteorological data of 20 regions of South Korea were collected based on Meteonorm in order to evaluate the total moisture content of concealed condensation according to regional meteorological data, as shown in Fig. 11, and based on the contents in the previous section, data were extracted for the following factors that affect the concealed condensation evaluation: temperature [℃], relative humidity [%], total solar radiation [W/m^2], diffuse sky radiation [W/m^2], wind speed [m/s], wind direction [-], and precipitation [mm]. The analysis results are as follows.

In terms of temperature, South Korea's geographic characteristics involve a higher elevation in the east and lower elevation in the west due to Mount Taebaek, resulting in an east-high-west-low topography. Therefore, as Mount Taebaek blocks the cold northwest seasonal wind and the temperature of the East Sea is higher than that of the Yellow Sea, within the same latitude, the inland region is colder than the coastal region in the winter, and the east coast region is warmer than the west coast region. For this reason, during the winter, the condensation and freezing phenomena of water vapor in structures will occur more rapidly in the inland areas. Thus, the effect on concealed condensation is more sensitive.

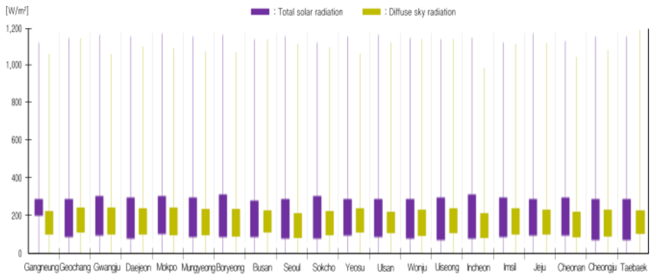
In terms of humidity, the relative humidity is higher in the coastal regions and lower in the inland regions. The amplitude of change shows a minimum of 3.3 in the inland regions and a maximum of 4.2 in the coastal regions. Therefore, due to the high relative humidity in the coastal regions, it is analyzed that the effect on the condensation of structures is more sensitive than that in the inland regions.

Although there was no significant difference in the total solar radiation and diffuse sky radiation of the 20 regions in South Korea, the total solar radiation and diffuse sky radiation tend to be lower in regions with high altitude.

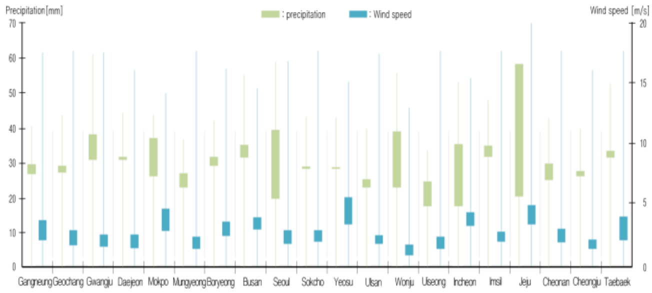
The precipitation is high due to the southeast and southwest seasonal winds from the Pacific coast and typhoons and heavy rains in the summer and autumn caused by the influence of the topography, but the precipitation is low in the winter because of the dry and cold northwest seasonal wind. In addition, due to the hot and dry northeast wind in the summer, there is more precipitation in the west compared to the east. In terms of wind speed, the seasonal winds are strong in the coastal and mountain regions, and for coastal and mountain regions in the west, the precipitation on the walls of the structures increases, which is considered to have a significant effect on the moisture content of the structures.



a) Meteorological data of 20 regions: Temperature and relative humidity



b) Meteorological data of 20 regions: Total solar radiation and diffuse sky radiation



c) Meteorological data of 20 regions: Precipitation and wind speed

Fig. 11: Meteorological data results of 20 regions in South Korea

4. Concealed condensation analysis based on regional meterological data

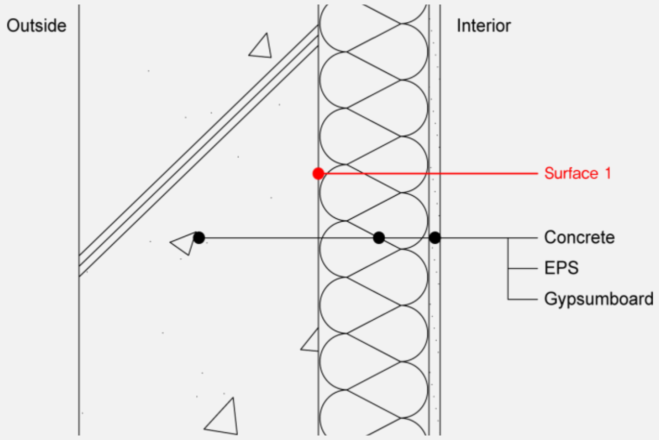
4.1. Concealed condensation evaluation model based on regional meterological data

As shown in Table 2, the model and environment settings for analysis were set up as a structure of interior insulation with a high incidence of concealed condensation after referencing previous studies [7, 8]. The structure is composed of 200mm-thick concrete with a water-cement ratio of 0.5, insulation material EPS panel of a thickness of 110mm with a thermal conductivity of 0.04 W/mK and a specific gravity of 15 kg/m3, and 9.5mm-thick gypsum board. The direction of the structure was configured as the northeast direction of Seoul, which is least affected by direct sunlight, and the performance was evaluated with the data of 20 regions collected by Meteonorm. The indoor conditions were configured based on the WTA Guideline, and the indoor temperature and humidity were estimated by calculation through a curve graph estimating the average temperature, amplitude, and the date of maximum indoor temperature and humidity based on the volume [kg, g] of water vapor in the room air. The room temperature and humidity were set to 25.5 ℃ and 57.5%, respectively, considering the standards presented in prior studies, and the temperature and humidity of the amplitude were set to 3.5 ℃ and

12.5%, respectively. In addition, in this study, the results according to the presence/absence of vapor retarding layers within the internal insulation structure were comparatively analyzed and the vapor retarding layers were installed in the interior of the structure. Considering past research findings that showed humidity cannot pass through if the vapor diffusion resistance coefficient of the vapor retarding layer of the internal insulation structure is high, the Sd-Value was set to 100/m [20].

Table 2: Font Specifications for A4 Papers

Property overview by material			
Factor	Concrete	Insulation material	Gypsum board
Thickness [mm]	200	110	9.5
Bulk density [kg/m^3]	2300	15	850
Porosity [m^3/m^3]	0.18	0.95	0.65
Thermal conductivity [W/mK]	1.6	0.032	0.18
Specific heat capacity [J/kgK]	850	1500	850
Water vapor diffusion resistance coefficient [-]	180	30	8.3
Moisture content RH:0.8 [kg/m^3]	85	0	6.3
Tmp-dep [W/Mk^2]	0.0002	0.0002	0.0002
Model section			



4.2. Concealed condensation evaluation method based on regional meteorological data

For the purpose of comparatively analyzing moisture content according to whether a vapor retarding layer is installed in the internal insulation structure based on regional meteorological data, a simulated evaluation was undertaken to compare total moisture content using the meteorological data collected from 20 regions in South Korea. The 20 regions of South Korea were classified into coastal regions, mountain regions, plain regions, northern, central, and southern regions. WUFI was used as the concealed condensation evaluation method tool, and a 5-year analysis was conducted. However, when evaluating the moisture content for the concealed condensation incidence, 4 years when moisture content did not converge were excluded and the performance comparison was performed for only a one-year period (8760h). The moisture content evaluation interface in the structure was simulated on the boundary surface (Surface 1) of the concrete and the EPS panel where the risk of concealed condensation was high, and when the moisture content exceeded 80% at the inner interface of the structure, the condensation threshold conditions were set by referring to the standards of prior studies on the risk of condensation. The reason why the rate of concealed condensation rises when relative humidity is greater than 80% is due to a rise in the chances of condensation formations due to the liquification of humidity trapped within a structure. As indicated in Table 3, the cases for the performance evaluation included Case 1 (Vapor retarder: yes), Case 2 (Vapor retarder, no). The two cases were then further classified according to region to include Gangneung(Case 1-1, Case 2-1), Busan(Case 1-2, Case 2-2), Incheon(Case 1-3, Case 2-3), Geochang(Case 1-4, Case 2-4), Seoul(Case 1-5, Case 2-5), Imsil(Case 1-6, Case 2-6), Gwangju(Case 1-7, Case 2-7), Sokcho(Case 1-8, Case 2-8), Jeju(Case 1-9, Case 2-9), Daejeon(Case 1-10, Case 2-10), Yeosu(Case 1-11, Case 2-11), Cheonan(Case 1-12, Case 2-12), Mokpo(Case 1-13, Case 2-13), Ulsan(Case 1-14, Case 2-14), Cheongju(Case 1-15, Case 2-15), Mungyeong(Case 1-16, Case 2-16), Wonju(Case 1-17, Case 2-17), Taebaek(Case 1-18, Case 2-18), Boryeong(Case 1-19, Case 2-19), and Uiseong(Case 1-20, Case 2-20). The performance evaluation in this study was undertaken using the following method.

First, based on the Case settings, the range and average of relative humidity across the outer boundary of the insulation material (Surface 1) was calculated according to the presence or absence of a vapor retarding layer in the internal insulation structure and according to each region.

Second, differences in relative humidity over the course of a year (8760h) were comparatively analyzed across the outer boundary of the insulation material (Surface 1) according to the presence or absence of a vapor retarding layer in the internal insulation structure.

Table 3: Case settings for performance evaluation

No.	Country	No.	Country	No.	Country
Case 1	Vapor retarder (yes)				
Case1-1	Gangneung	Case1-2	Busan	Case1-3	Incheon
Case1-4	Geochang	Case1-5	Seoul	Case1-6	Imsil
Case1-7	Gwangju	Case1-8	Sokcho	Case1-9	Jeju
Case1-10	Daejeon	Case1-11	Yeosu	Case1-12	Cheonan
Case1-13	Mokpo	Case1-14	Ulsan	Case1-15	Cheongju
Case1-16	Mungyeong	Case1-17	Wonju	Case1-18	Taebaek
Case1-19	Boryeong	Case1-20	Uiseong		
Case 2	Vapor retarder (no)				
Case2-1	Gangneung	Case2-2	Busan	Case2-3	Incheon
Case2-4	Geochang	Case2-5	Seoul	Case2-6	Imsil
Case2-7	Gwangju	Case2-8	Sokcho	Case2-9	Jeju
Case2-10	Daejeon	Case2-11	Yeosu	Case2-12	Cheonan
Case2-13	Mokpo	Case2-14	Ulsan	Case2-15	Cheongju
Case2-16	Mungyeong	Case2-17	Wonju	Case2-18	Taebaek
Case2-19	Boryeong	Case2-20	Uiseong		

4.3. Concealed condensation evaluation results and analysis based on regional meteorological data

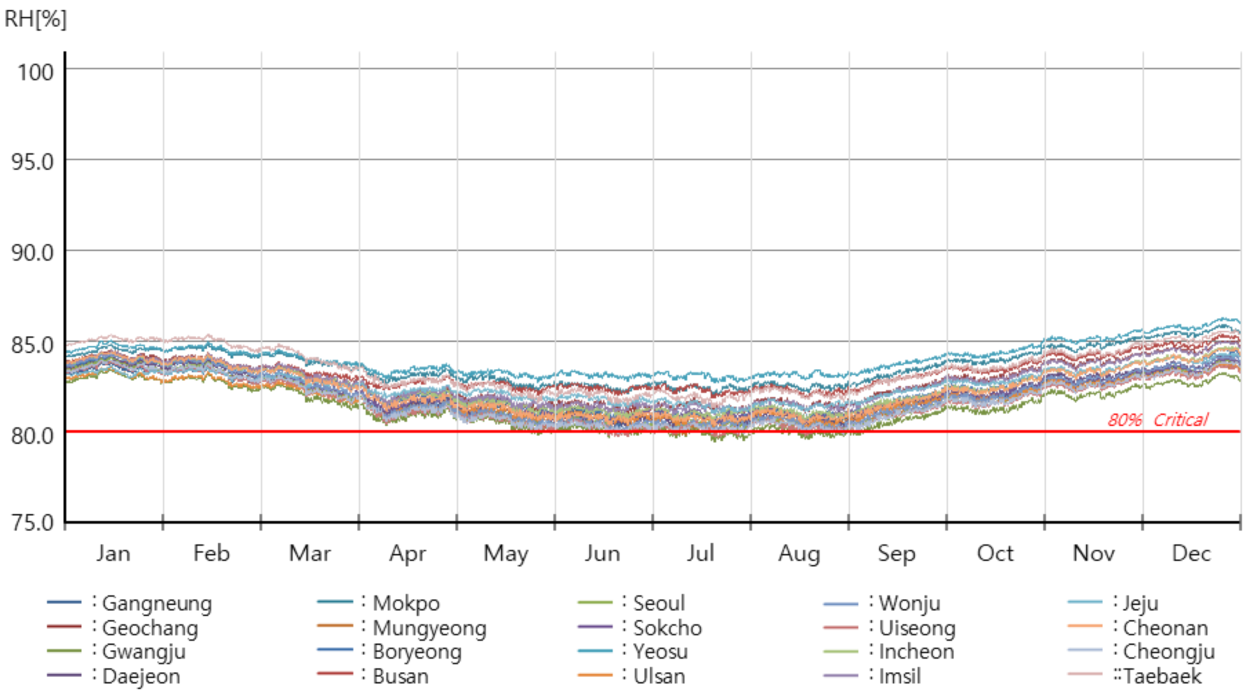


Fig. 12: Surface 1 relative humidity results by region: Case 1

In this study, as shown in Fig. 12, Fig. 13, Fig. 14, Table 4 and Table 5, the climate data of 20 regions in South Korea were applied to the interior insulation structure of an apartment housing complex with a high incidence of concealed condensation by means of a simulation evaluation. The results of analyzing the relative humidity outside the insulation are as follows.

First, the range of the moisture content (average) in each region for Case 1(Vapor retarder: yes) was as follows: Gangneung 80.2~84.0% (82.0%), Geochang 81.0~85.1% (82.8%), Gwangju 79.5~83.4% (81.4%), Daejeon 80.3~84.3% (82.1%), Mokpo 82.0~85.9% (83.7%), Mungyeong 79.8~84.0% (81.8%), Boryeong 80.6~84.6% (82.4%), Busan 81.9~85.4% (83.3%), Seoul 80.0~84.1% (81.8%), Sokcho 80.4~84.1% (82.2%), Yeosu 82.8~86.3% (84.1%), Ulsan 80.2~83.8% (81.9%), Wonju 80.0~84.3% (82.0%), Uiseong 79.7~83.9% (81.7%), Incheon 80.6~84.7% (82.5%), Imsil 81.0~85.0% (82.8%), Jeju 81.1~84.3% (82.6%), Cheonan 80.4~84.6% (82.4%), Cheongju 79.9~84.0% (81.8%), and Taebaek 81.4~85.6% (83.5%). The relative humidity of the corresponding location of each region is higher in the coastal regions, and the amplitude of change shows a minimum of 3.2 (coastal regions) and a maximum of 4.3 (inland regions); thus, structures in the coastal regions are considered to be more sensitive to the effect of condensation.

Second, the range of the moisture content (average) in each region for Case 2 (Vapor retarder: no) was as follows: Gangneung 90.2~92.7% (91.6%), Geochang 90.4~93.9% (92.4%), Gwangju 86.9~91.5% (89.8%), Daejeon 90.1~93.8% (92.3%), Mokpo

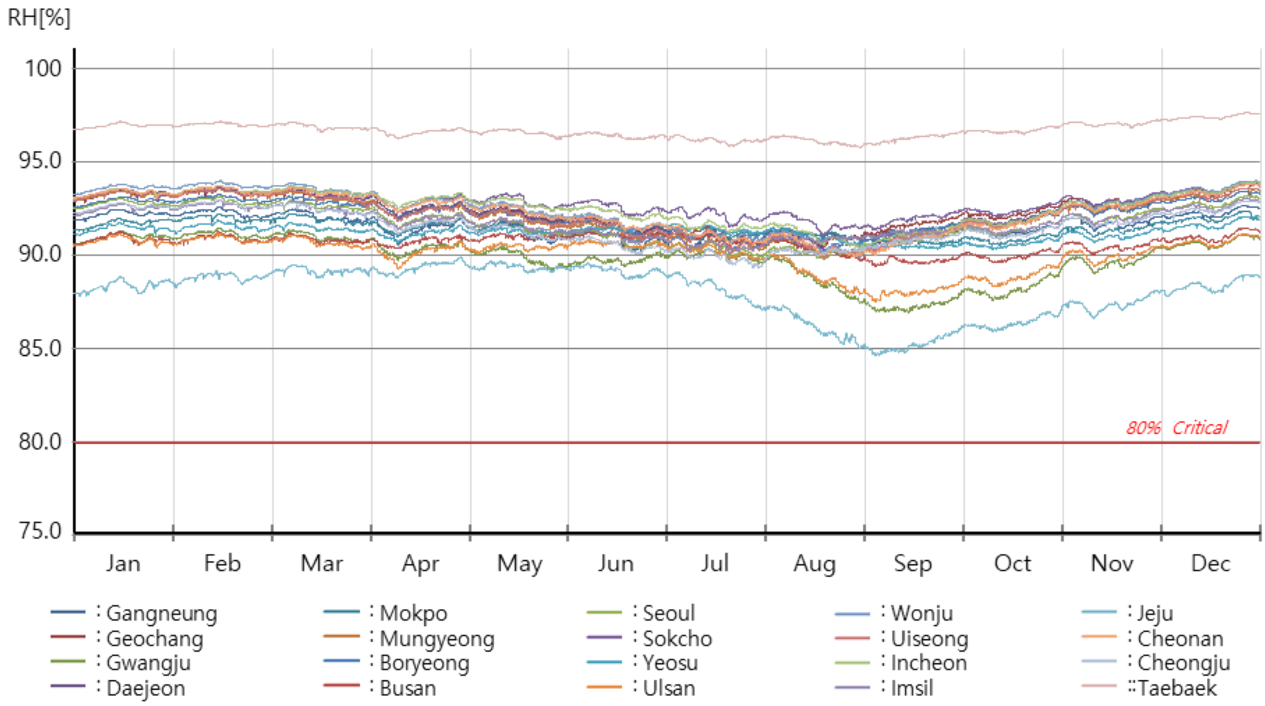


Fig. 13: Surface 1 relative humidity results by region: Case 2

90.6~92.4% (91.4%), Mungyeong 89.9~93.6% (92.1%), Boryeong 90.1~93.5% (92.1%), Busan 89.4~91.5% (90.7%), Seoul 89.8~93.2% (91.7%), Sokcho 91.1~93.9% (92.8%), Yeosu 90.3~92.1% (91.2%), Ulsan 87.5~91.2% (90.0%), Wonju 89.4~94.0% (92.4%), Uiseong 89.9~93.6% (92.2%), Incheon 90.3~93.9% (92.6%), Imsil 90.1~93.1% (91.8%), Jeju 884.6~89.9% (88.0%), Cheonan 89.9~93.8% (92.3%), Cheongju 89.3~93.0% (91.5%), and Taebaek 95.8~97.7% (96.7%). In Case 2, moisture content was low in the Southern regions where temperatures rise during the summer, while moisture content was relatively high in the Northern regions. In cases where vapor retarding layers were not installed, the non-inhibition of vapor evaporation within the structure resulted in an accelerated evaporation of vapor in regions presenting high temperatures during the summer seasons.

Third, moisture content within a structure was found to increase for all cases of Case 2-1~Case 2-20 (Vapor retarder: no) compared to Case 1-1~Case 1-20(Vapor retarder: yes). This indicated that internal insulation structures with vapor retarding layers had a lower risk of occurrence of concealed condensation across all 20 regions.

Fourth, in the case of Case 1, the condensation incidence (time) per hour is 87.9% (7704/8760h) in Gwangju, 99% (8676/8760h) in Mungyeong, 96.4% (8449/8760h) in Uiseong, and 99.2% (8692/8760h) in Cheongju, and 100% (8760/8760h) in all of the other regions. The analysis results show that the concealed condensation incidence is high due to the interior insulation structure. The incidence of concealed condensation in inland plain regions such as Gwangju, Mungyeong, Uiseong, and Cheongju is low, so it is analyzed that the concealed condensation incidence is low in regions where temperature, humidity, and precipitation are relatively unchanged.

Fifth, the hourly condensation incidence of Case 2 was presented as 100% across all regions. This was analyzed as being due to the absence of vapor retarding layers causing greater vulnerabilities to concealed condensation, and an increase in the incidence of concealed condensation due to the internal insulation structure.

Table 4: Surface 1 simulation evaluation results by region: Case 1

Region	Relative humidity distribution [%]	Average relative humidity [%]	Moisture content inside structure [%]	Time of moisture content ≥ 80% / Total time
Gangneung	80.2~84.0	82.0	100.0	8760 / 8760h
Geochang	81.0~85.1	82.8	100.0	8760 / 8760h
Gwangju	79.5~83.4	81.4	87.9	7704 / 8760h
Daejeon	80.3~84.3	82.1	100.0	8760 / 8760h
Mokpo	82.0~85.9	83.7	100.0	8760 / 8760h
Mungyeong	79.8~84.0	81.8	99.0	8676 / 8760h
Boryeong	80.6~84.6	82.4	100.0	8760 / 8760h
Busan	81.9~85.4	83.3	100.0	8760 / 8760h
Seoul	80.0~84.1	81.8	100.0	8760 / 8760h
Sokcho	80.4~84.1	82.2	100.0	8760 / 8760h
Yeosu	82.8~86.3	84.4	100.0	8760 / 8760h
Ulsan	80.2~83.8	81.9	100.0	8760 / 8760h
Wonju	80.0~84.3	82.0	100.0	8760 / 8760h
Uiseong	79.7~83.9	81.7	96.4	8449 / 8760h
Incheon	80.6~84.7	82.5	100.0	8760 / 8760h
Imsil	81.0~85.0	82.8	100.0	8760 / 8760h
Jeju	81.1~84.3	82.6	100.0	8760 / 8760h
Cheonan	80.4~84.6	82.4	100.0	8760 / 8760h
Cheongju	79.9~84.0	81.8	99.2	8692 / 8760h
Taebaek	81.4~85.6	83.5	100.0	8760 / 8760h

Table 5: Surface 1 simulation evaluation results by region: Case 2

Region	Relative humidity distribution [%]	Average relative humidity [%]	Moisture content inside structure [%]	Time of moisture content ≥ 80% / Total time
Gangneung	90.2~92.7	91.6	100.0	8760 / 8760h
Geochang	90.4~93.9	92.4	100.0	8760 / 8760h
Gwangju	86.9~91.5	89.8	100.0	8760 / 8760h
Daejeon	90.1~93.8	92.3	100.0	8760 / 8760h
Mokpo	90.6~92.4	91.4	100.0	8760 / 8760h
Mungyeong	89.9~93.6	92.1	100.0	8760 / 8760h
Boryeong	90.1~93.5	92.1	100.0	8760 / 8760h
Busan	89.4~91.5	90.7	100.0	8760 / 8760h
Seoul	89.8~93.2	91.7	100.0	8760 / 8760h
Sokcho	91.1~93.9	92.8	100.0	8760 / 8760h
Yeosu	90.3~92.1	91.2	100.0	8760 / 8760h
Ulsan	87.5~91.2	90.0	100.0	8760 / 8760h

Wonju	89.8~94.0	92.4	100.0	8760 / 8760h
Uiseong	89.9~93.6	92.2	100.0	8760 / 8760h
Incheon	90.3~93.9	92.6	100.0	8760 / 8760h
Imsil	90.1~93.1	91.8	100.0	8760 / 8760h
Jeju	84.6~89.9	88.0	100.0	8760 / 8760h
Cheonan	89.9~93.8	92.3	100.0	8760 / 8760h
Cheongju	89.3~93.0	91.5	100.0	8760 / 8760h
Taebaek	95.8~97.7	96.7	100.0	8760 / 8760h

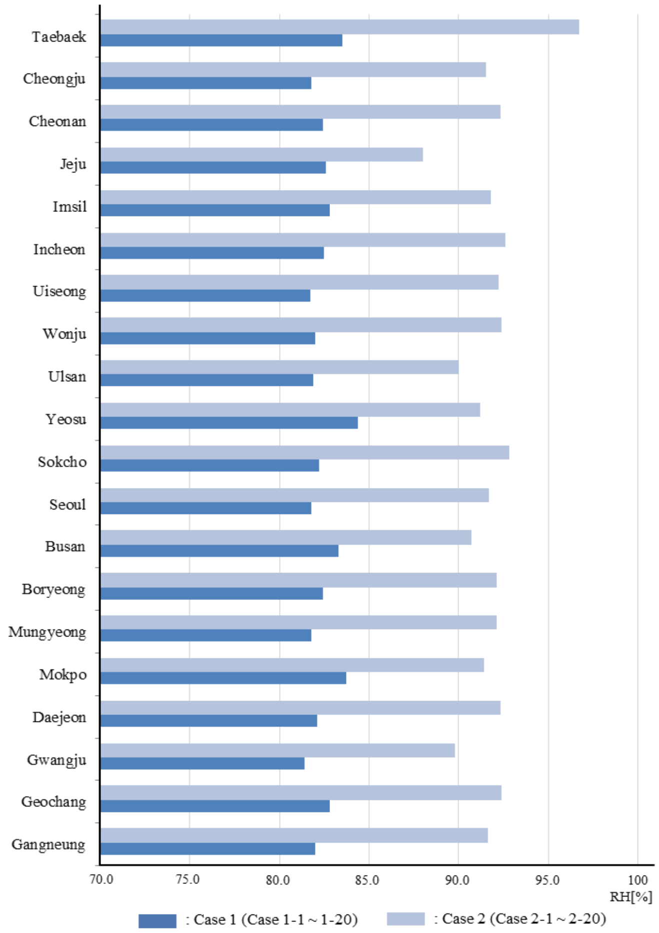


Fig. 14: Comparison of Performance Evaluation Results

5. Conclusion

To improve the concealed condensation evaluation method used in the ‘condensation prevention design standards for apartment houses’ which is the condensation evaluation standard in South Korea, this study collected meteorological data from 20 regions in South Korea and performed a simulation evaluation through an analysis model. The conclusions are as follows.

First, the regional meteorological data of South Korea collected in this study were classified into 20 regions considering the characteristics of coastal regions, mountain regions, plain regions, northern, central, and southern regions, and the outdoor meteorological data factors (temperature, relative humidity, total solar radiation, diffuse sky radiation, wind speed, wind direction, precipitation) were extracted for the concealed condensation evaluation.

Second, the simulated evaluation of the internal insulation structures installed with vapor retarding layers found changes in areas closer to coastal areas having higher relative humidity. This was analyzed as indicating greater sensitivities to the incidence of condensation in areas closer to the coast. The minimum amplitude of change was 3.2 (coastal region) while the maximum was 4.3 (inland region).

Third, the simulated evaluation of the internal insulation structure not installed with a vapor retarding layer indicated that in regions with higher temperatures, changes were present in areas presenting relatively lower relative humidity.

Fourth, the analysis of differences in moisture content according to the presence or absence of a vapor retarding layer indicated that the installation of a vapor retarding layer at the internal insulation structure is a method of reducing the incidence of condensation.

Fifth, as a result of comparing the incidence of condensation per hour, inland plain regions such as Gwangju, Mungyeong, Uiseong, and Cheongju showed a low incidence, so it is analyzed that the concealed condensation incidence is low in regions where temperature, humidity, and precipitation are relatively unchanged.

The meteorological data factors (temperature, relative humidity, total solar radiation, diffuse sky radiation, precipitation reaching the envelope) that affect the incidence of concealed condensation were extracted in this study, and the problems of the condensation evaluation standard in South Korea were verified through a simulation evaluation of an interior insulation structure by collecting the regional meteorological data of South Korea. In conclusion, it is deemed appropriate that the condensation evaluation standard of South Korea is

improved through the application of meteorological data factors, and it is recommended that vapor retarding layers be installed to lower the rate of condensation occurrences in internal insulation structures.
A limitation of this study that should be noted is that the subject of analysis was limited to an interior insulation structure with a high incidence of concealed condensation. In the future, it will be necessary to conduct follow-up research that applies more diverse circumstances and materials.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2017R1C1B2008728).

References

[1] IOS 13788, Hygrothermal Performance of Building Components and Building Elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation, (2012).
[2] BS EN 15026, Hygrothermal Performance of Building Components and Building Elements. Assessment of moisture transfer by numerical simulation, (2007).
[3] Ministry of Land, Infrastructure and Transport, Design Criteria for Condensation Control in Apartments, (2013).
[4] Manzan M, Zandegiacomo De Zorzi, E & Lorenzi W (2015), Experimental and numerical comparison of internal insulation systems for building refurbishment. *Energy Procedia* 82, 493-498.
[5] Guimarães AS, Delgado JMPQ, Azevedo AC & de Freitas VP (2018), Interface influence on moisture transport in buildings. *Construction and Building Materials* 162, 480-488.
[6] Hong SW, Kim KS, Park CY & Jang HI (2018), Comparison Analysis of Interstitial Condensation Occurrence Rate by Regional Weather conditions - Focused on 9 Regions in Korea. *International Journal of Engineering & Technology for Automobile Security* 2(1), 1-6
[7] Hong SW, Kang HS, Park CY & Jang HI (2017), A Study on the Effect of Material Properties Related to Liquid Transport on the Maximum Cumulative Condensation. *Jornal of KIAEBS* 11(6), 572-585
[8] Kim KS, Jang HY, Park CY, Yoo DC & Choi CH (2017), Comparison of Total Moisture Content by Internal Condensation Evaluation Method. *Jornal of KIAEBS* 11(6), 558-571
[9] Oh SM, Park SH & Joung KS (2017), Study on the Improvement Plans of Condensation Defect Examples in Apartment Building. *Korea Journal of Air-Conditioning and Refrigeration Engineering* 29(2), 82-88
[10] Jeong CW, Kim HS, Jeong SH, Kim YT, Song DS, Comparison and Analysis of Domestic and Foreign Standards for Preventing the Condensation in Multi-residential House, *2013 Summer Annual Conference Journal of Air-Conditioning and Refrigeration Engineering*, pp:514-519, http://www.sarek.or.kr/html/sub06_02b.jsp?yearmonth=2013&quarter=s
[11] Hwang HJ, Kim JY, Lee JS (2011), A Study on the Foundation of the Standard of Temperature and Humidity for Preventing Condensation in Apartment Housings, *Journal of LHI* 2(3), 269-276
[12] Choi YK & Ahn JB (2003), Forecast on internal condensation at balcony ceiling of super-high apartment building faced with open air. *Korean Journal of Construction Engineering and Management* 4(4), 155-163.
[13] Jung HS, Kang MW, An SJ & Leigh SB (2002), Establishment of Design Standards for Preventing Condensation in the Underground Space, *Journal of the Architectural Institute of Korea Planning & Design* 18(1), 249-259
[14] Lehmkuhl J, Kelm S, Bucci M & Allelein HJ (2016), Improvement of wall condensation modeling with suction wall functions for containment application. *Nuclear engineering and design* 299, 105-111.
[15] Asadollahi A & Esmaeeli A (2018), Simulation of condensation and liquid break-up on a micro-object with upper and lower movable walls using Lattice Boltzmann Method. *Physica A: Statistical Mechanics and its Applications* 498, 33-49.
[16] Ma X, Li X, Shao X & Jiang X (2013), An algorithm to predict the transient moisture distribution for wall condensation under a steady flow field. *Building and Environment* 67, 56-68.
[17] You S, Li W, Ye T, Hu F & Zheng W (2017), Study on moisture condensation on the interior surface of buildings in high humidity climate. *Building and Environment* 125, 39-48.
[18] Raaholdt RKK & Algaard E (2017), New National Museum in Oslo. Analysis of risk for condensation and possible mold growth in internal climatic sectioning walls and floors. *Energy Procedia* 132, 807-812.
[19] Huang P, Chew Y, Chang WS, Ansell M, Lawrence M, Latif E & Du H (2018), Heat and moisture transfer behaviour in Phyllostachys edulis (Moso bamboo) based panels. *Construction and Building Materials* 166, 35-49
[20] Annila PJ, Hellemaa M, Pakkala TA, Lahdensivu J, Suonketo J & Pentti M (2017), Extent of moisture and mould damage in structures of public buildings. *Case studies in construction materials* 6, 103-108.