Article

Improvement of the Korean Design Criteria on Wall-To-Wall Junctions to Prevent Condensation in Apartment Houses

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Abstract: Maintaining a proper temperature and humidity in a living space is very important for the health and comfort of apartment residents. Poor residential thermal conditions are recognized as a potential risk to the overall physical health. Thus, building development criteria that maintain an indoor environment separate from the outside environment have been continuously strengthened. However, this has not been the case in Korea, with regards to design criteria for the prevention of indoor condensation. In Korea, condensation occurs indoors frequently, during the winter season. When the outside temperature is low during the winter, a high indoor temperature and humidity would affect the indoor building materials and cause condensation. This study investigated and analyzed the indoor temperature and humidity during winter—when there is a significant difference in the outdoor and indoor temperatures—and conducted a survey on the residents’ lifestyles. Construction design criteria were found to be different from those of the past, and possible causes of changes in temperature and humidity were examined. We intended to establish enhanced design criteria that would prevent indoor condensation, by comparing our results to that of a study conducted in 2003.

Keywords: South Korea; indoor temperature; indoor humidity; condensation; design criteria

1. Introduction

Maintaining optimal residential thermal conditions is critical for the physical comfort of a resident in their choice of dwelling [1,2]. Poor residential thermal conditions are recognized as a potential health risk [3–8]. Therefore, in order to achieve pleasant thermal conditions, protect human health, and improve the quality of life, it is necessary to maintain adequate indoor temperatures and humidity levels in houses [1,9]. In Korea, design criteria have been established for the envelopes of residential buildings, which can maintain its indoor spaces separate from the cold outdoor environment, in winter [10].

In Korea, design criteria have been developed to prevent winter condensation because indoor condensation frequently occurs in winter. The overall rates of flaws in Korea are 72% for construction, 16% for machinery, 6% for electricity, and 6% for civil engineering. The construction sector accounted for 72% of all flaws—the highest percentage. The types of flaws in the construction sector are mainly indoor furniture, indoor condensation, tile, and window frame types. Flaws related to condensation account for a large portion of the flaw rate [11]. Among the many causes of frequent condensation are activities by the residents, who produce a considerable amount of humidity in indoor spaces. According to previous studies, the ‘ondol’ radiant floor heating system is used to maintain a high
indoor temperature in most apartments, and a significant amount of moisture is generated by water boiled while cooking, through the use of humidifiers, or when drying clothes indoors [12,13]. Excessive indoor moisture can cause a drastic increase in dust and mold growth, while encouraging microbes to diffuse into the human body, resulting in health problems such as asthma [3–6,13–17]. Indoor humidity is also a global issue, owing to its negative effects on building materials [18]. In addition, indoor humidity can cause condensation when the outdoor temperature is low enough to cause the development of a thermal bridge [19].

Windows, doors, and walls that are in direct contact with outdoor air are the main areas where condensation occurs, and efforts have been made in Korea, to establish design criteria that would reduce condensation in these areas [10]. Therefore, in this study, we have presented winter temperature measurements collected within actual residential living conditions and compared our results to those of a 2003 study [20]. We also undertook basic research to establish accurate design criteria by confirming building envelope design standards. In contrast to those in 2003, the design criteria for building envelopes have changed. Therefore, the design standards for preventing condensation also needs to be changed. Currently, Korea’s condensation prevention design standards do not reflect changes in the design criteria of buildings or lifestyle changes. Therefore, we intended to use data from this study for establishing suitable design criteria for preventing winter condensation, which ideally would reflect both the exterior envelope of the building and the living conditions of its residents.

2. Research Background

2.1. Korean Apartment

The floor plan of a general apartment in Korea is shown in Figure 1. The key areas susceptible to condensation are marked as (a), (b), and (c) (Figure 2), and the respective photos are presented in Figure 3.

Wall-to-wall joints, a focus of this study, are susceptible to condensation. The corners in contact with outer walls are where thermal bridges occur due to the connection with the upper or lower slabs.
2.2. Design Criteria for Preventing Condensation in Korea

In Korea, the design criteria for condensation prevention were enacted by a 2014 law, which stipulate an ideal indoor temperature of 25 °C and a relative humidity of 50%. These criteria were calculated using the temperature difference ratio (TDR) between the external temperature and the indoor temperature, and a value was established for each building element (Table 1). The TDR is a relative ratio that expresses the difference between indoor and outdoor temperatures. This criterion is used to evaluate condensation according to outdoor temperature changes—assuming an indoor temperature of 25 °C and a relative humidity of 50%—and it ranges from zero to one depending on the formula used.

$$TDR = \frac{T_i - Tm}{T_i - (TO)} \quad (1)$$

$T_i$: Indoor temperature (°C)
$TO$: Outdoor temperature (°C)
$Tm$: Minimum indoor surface temperature at the measurement point.
TDR: Temperature difference ratio.

Not all countries use the TDR to calculate criteria for preventing condensation, and the criteria vary from one country to another. Table 1 lists Korea’s design criteria for condensation prevention, which are subdivided, compared to the criteria of other countries.
Table 1. Design criteria for preventing condensation in Korea.

| Door     | Front door | Fire door | Door point | Frame point | Wall junction point |
|----------|------------|-----------|------------|-------------|---------------------|
|          |            |           | I [-20°C]  | II [-15°C]  | III [-10°C]         |
|          |            |           | 0.30       | 0.33        | 0.38                |
|          |            |           | 0.22       | 0.24        | 0.27                |
| Window   | Glass center point | 0.16 (0.16) | 0.18 (0.18) | 0.20 (0.24) |
|          | Glass edge point  | 0.22 (0.26) | 0.24 (0.29) | 0.27 (0.32) |
|          | Frame point   | 0.25 (0.30) | 0.28 (0.33) | 0.32 (0.38) |

* Lowest temperature region. ( ) represents an aluminum window.

2.3. Design Criteria for Preventing Condensation in the EU

In the UK, the humidity criterion is established according to the indoor environment in the “BS 5250:2011 code of practice for the control of condensation in buildings” [21], and the temperature factor for each application is presented. Additionally, the publication entitled “Building Regulations 2010 ‘Site preparation and resistance to contaminants and moisture: Approved document C 1,2’” [22] provides U-values or guidelines on the causes and solutions for condensation problems caused by soil and the surrounding environment (C2: interstitial and surface condensation/BRE IP17/01: Assessing the effects of thermal bridging at junctions and around openings, 2011) [23]. New residential buildings are required to comply with the requirement of a BRE IP 1/06 temperature coefficient of 0.75, for building use, according to the BR 497 temperature coefficient calculation method. For larger temperature coefficient values, higher heat insulation performance is required. In the UK, the requirement for dew condensation prevention performance is converted into the TDR, resulting in the TDR for the wall portions being defined as 0.25 for residential buildings and 0.5 for commercial buildings (Figure 4).

The Netherlands states that the criteria for new buildings found in the “Regeling Bouwbesluit: 2012” [24] are based on “Factor van de temperatuur” (temperature factor) and that the temperature coefficient should be 0.5 or more in accordance with NEN 2778 [25]. The value for insulation performance is also established as 0.042 W/m·K. Energy efficiency and thermal conductivity have been proposed,
depending on the site for new buildings and buildings according to NEN 1068/NEN-EN 12667 [26,27]. The Dutch condensation design criteria use the TDR, which is 0.35 for residential buildings at a temperature of 18 °C and 67% humidity and 0.5 for commercial buildings at a temperature of 18 °C and 56% relative humidity (Figure 4).

In Germany, “EnEV 2014: die neu Energieeinsparverordnung” (the new Energy Saving Ordinance) [28], a building energy conservation ordinance, presents the required insulation performance of a building. For example, the insulation performance of the outside wall should be designed to have a heat transfer coefficient (U) of 0.28 W/m²·K or less, and this value should be 0.20 W/m²·K or less for the roof or the upper wall. In addition, the heat loss values for each part are presented in detail in the Appendix DIN 4108 Beiblatt 2: 2019-06 [29], Wärmeschutz und Energie-Einsparung in Gebäuden (thermal insulation and energy savings in buildings), which is a German standard and not a law, but it provides a certain level of protection against condensation. With regard to the performance criteria for the outside walls, the heat resistance coefficient (R) should be 1.20 m²·K/W or more. The thermal resistance factor for each bulk density and thickness value are presented in the design, for reference. The calculation of R assumes an indoor temperature of 20 °C, 50% relative humidity, and an ambient air temperature of −5 °C. For reference, the wall regulations are given in ISO 10211, and the window regulations are given in ISO 13788.

France uses a TDR of 0.48 at an indoor temperature of 18 °C and a relative humidity of 55%. Belgium uses a TDR value of 0.30 only for residential buildings, while Finland uses 0.39 for an indoor temperature of 21 °C and a relative humidity of 52%. Austria’s TDR is 0.30 when the room temperature is 20 °C and the relative humidity is 65% (Figure 4).

2.4. Design Criteria for Preventing Condensation in the US

The United States refers to the provision and control of indoor conditions, thermal bridges, and internal/external condensation conditions, using the 2013 ASHRAE Handbook—Fundamentals [30]. However, as this document does not provide specific values, criteria from other associations and organizations should also be considered. It is provided in the form of specifications utilizing the Condensation Resistance Factor (CRF), recently proposed by the American Architectural Manufacturers Association (AAMA). This condensation prevention criterion is applied by considering the indoor and outdoor temperature, humidity, and other factors, for each part. This dew condensation resistance coefficient is calculated using the AAMA standard entitled 1503-09: Voluntary test method for thermal transmittance and condensation resistance of windows, doors, and glazed wall sections [31]. These other standards provide a non-condensation evaluation method using the dew condensation resistance factor in specifications, such as NFRC 500-2010/500UG-2002.

2.5. Design Criteria for Preventing Condensation in Japan

Condensation prevention criteria in Japan must show that condensation does not occur, through tests conducted at the specification standard of the Housing Performance Evaluation Labeling Association and certain internal conditions (outside temperature of −4.7 °C, room temperature of 15 °C, relative humidity of 50%) [32]. The criteria for clients on the rationalization of energy use for houses (CCREUH) provides for the regulation of condensation, in Japan. This regulation provides a method for the prevention of surface condensation by stipulating the installation location and construction method of insulation materials in the building thermal environment performance section [33].

2.6. Design Criteria for Preventing Condensation in Australia

Australia uses minimal design requirements for condensation, as documented in the Condensation in Buildings Handbook and in the National Competition Council (CCC) Code of the Australian Building Codes Board (ABCB) [34]. The regulations cover three areas—surface, water vapor entering from the outside air, as well as treatment methods and design criteria for indoor vapor circulation. In the ABCB
handbook, a criterion calculation method has been proposed, which uses the factor of temperature to prevent the internal and external surface condensation of ISO 13788:2012.

2.7. Design Criteria for Preventing Condensation in China

In the “Thermal Design Code for Civil Buildings” (GB 50176-93), China was divided into five building thermal design partitions—severe cold, cold, hot summer and winter, warm and hot summer, and warm winter region. For example, there are two indicators for the severe cold region—the main indicators (the average temperature of the coldest month is less than −10 °C) and the auxiliary indicators (the number of days with an average daily temperature less than 5 degrees is more than 145). Additionally, the U-value of the external wall of the residential building is 1.0 or less, and the roof is specified as 0.8 or less.

The design criteria for condensation are the result of recalculating and summarizing the TDRs (Figure 4). The Korean design criteria are overall lower than those of other countries.

3. Methods

3.1. Experimental Outline

Data collection in this study was conducted during January–February, 2015. Management offices for apartment complexes allowed us to explain to the residents the motives and purpose of the measurements. After permission was obtained, visitation schedules were established for each household to install monitoring equipment in the living room. The temperature and humidity were recorded every ten minutes. To investigate temperature and humidity in each home, a simple questionnaire was also used to obtain specific information regarding the number of family members, laundry dryers, dehumidifiers, humidifiers, ventilation times, and the auxiliary heating devices in use. This study conducted a survey on indoor temperature and relative humidity, following the methods employed in past research. In the past study, a simple survey on indoor temperature during winter, relative humidity, and lifestyles was conducted from January to March, 2003 (Table 2).

| Number of Apartments | Study Period                  |
|----------------------|-------------------------------|
| 2003                 | 189                           | 27 January–5 March 2003     |
| 2015                 | 120                           | 15 January–26 February 2015 |

3.2. Instrumentation

An MSR 145 logger (MSR, Switzerland) was used to measure and record the indoor temperature and humidity. The logger automatically measured and stored the temperature and relative humidity data between −20 and −65 °C and in the range of 0–100%, respectively, with accuracy levels of ±0.5 °C and ±2%, respectively. The logger was installed in the living room of each apartment (Figure 5). To prevent the influence of radiant heat from heaters or direct sunlight through windows, the device was attached to a wall or to furniture at a height of 1.5 m. After one week, the logger was retrieved from the household. Outdoor temperature and humidity data were obtained from the nearest Korea Meteorological Administration weather station.
3.3. A Summary of the Precedent Study

In a study conducted in January of 2003, the temperature and humidity of indoor areas of 189 apartment units in Korea were surveyed. Additionally, this study also helped to establish the design criteria for prevention of condensation (Table 2).

4. Results

4.1. Outdoor Conditions

The cumulative average temperature for winter (December to February) in Korea is 10.6 °C, and the relative humidity ranges from 49.1% to 72.3% [35]. The average outdoor temperature during the period from January 15 to February 10, 2015, was 13.66 °C, with a low temperature of −13.46 °C. The relative humidity ranged from 21.4% to 100%, at the most (Figure 6).

4.2. Distributions of the Indoor Temperature, Relative Humidity, and Absolute Humidity

The results of an analysis of 120 apartment units (Figure 7) found that approximately 83% of indoor temperatures were between 20 and 23 °C, over 80% of the relative humidity measurements were between 40 and 60%, and over 86% of the absolute humidity measurements were between 0.006 and 0.011 kg/kg’. The data showed that South Korean residents were more likely to keep their indoor temperatures around 20 °C–23 °C and their relative humidity was in the range of 40–60%, during...
winter. These data confirmed that Korean residents try to keep their indoor environment warmer during winter, compared to people in other countries [36,37].

The cumulative frequency was analyzed using the measured temperature and humidity results. These results are shown in Table 3. The cumulative frequencies and temperatures of 120 apartments were analyzed. The 85% cumulative frequency of the surveyed households was 23.66 °C, the relative humidity was 57.6%, and the absolute humidity was 0.01050 kg/kg'. The 90% cumulative frequency of the surveyed households was 24.10 °C, the relative humidity was 58.8%, and the absolute humidity was 0.01096 kg/kg'. The 95% cumulative frequency of the surveyed households is 24.78 °C, the relative humidity was 59%, and the absolute humidity was 0.01154 kg/kg'.

### Table 3. Cumulative levels of temperature and humidity for all apartments.

| Cumulative Level (%) | Temperature (°C) | Relative Humidity (%) | Absolute Humidity (kg/kg') |
|----------------------|------------------|-----------------------|---------------------------|
| 85                   | 23.66            | 57.6                  | 0.01050                   |
| 90                   | 24.10            | 58.8                  | 0.01096                   |
| 95                   | 24.78            | 59                    | 0.01154                   |

### 4.3. Comparison with Earlier Work

#### 4.3.1. Temperature

As a result of the 2003 survey, the values ranging from 21 °C to 25 °C accounted for 83% of all temperature values, and 23 °C was the highest value. However, the results of the 2015 survey showed that temperatures between 20 °C and 22 °C accounted for 83% of all temperature values, with 21 °C being the highest rate. The 2003 findings were evenly distributed, at 23 °C. However, the results of the 2015 survey showed that the temperatures of 20 °C to 22 °C were high and were not evenly
distributed. The average values were 22.9 °C in 2003 and 22.2 °C in 2015. There was no difference between the temperatures (Figure 8). Occupants of all households studied were exposed to higher indoor temperature levels than those recommended by the government.

![Figure 8. Comparison between earlier results and the current results for the (a) temperature and (b) relative humidity distributions.](image)

The apartment envelope design standards of 2015 for the outer wall alone were significantly different compared to those of 2003. The thermal transmittance value (U-value) of the outer walls in Korea was 0.47 in 2001, and dropped to 0.21 in 2016 (Table 4). Despite the enforced criteria (Table 5), the temperature distribution varied greatly, while average indoor temperature remained more or less the same. These results indicated that Korean households tended to keep their apartments warm.

| Table 4. Design standards for apartment. |
|-----------------------------------------|
|                                         |
| **2001** | **2016** |
| --- | --- | --- | --- |
| Roof U-value [w/m² k] | 0.29 | 0.15 |
| External wall U-value [w/m² k] | 0.47 | 0.21 |
| Floor U-value [w/m² k] | 0.35 | 0.18 |

| Table 5. Indoor temperature and humidity design criteria. |
|----------------------------------------------------------|
|                                                          |
| **2003** | **2015** |
| --- | --- | --- | --- |
| Average Temperature | 22.9 | 22.2 |
| Average Humidity | 41.9 | 50 |
| Criteria | 25 | 25 |

4.3.2. Humidity and Temperature

In the results of the 2003 survey, values ranging from 30% to 50% accounted for 75% of all relative humidity values, with 40% being the highest value. However, the results of the 2015 survey showed that relative humidity values between 40% and 60%, accounted for 77% of all relative humidity results. Additionally, 50% was the highest rate. The average values were 41.9% in 2003 and 50% in 2015. As mentioned earlier, Korean residents maintain a warm environment by adjusting the indoor temperature. However, relative humidity might vary by indoor lifestyle and there is a possibility of an increase in relative humidity with the enforced envelope design criteria for windows and doors, based on the guidelines on the use of high-performance materials in construction, since 2000.

Comparing the temperature and humidity results from 2003 and 2015, the mean temperature values were not found to have differed greatly. However, the average relative humidity was 8.1% higher in 2015 than in 2003 (Table 5).
4.3.3. Response

The average number of family members in the households investigated in this study was 2.85, as compared to 5.1 occupants in the 2003 study [20]. This was likely due to a change in lifestyle. In the 2000s, the distribution of family members was as follows—8.4% (five or six people), 48.2% (three or four people), 12.3% (two people), and 15.5% (one person) for four families. However, by 2020, the estimated ratio of family members was expected to be 4.7% (five or six people), 41.5% (three or four people), 18.9% (two people), and 21.5% (one person) [38]. The survey results also showed that the methods used to dry clothes indoors have changed; while the rates of drying clothes in the living room are still similar, laundry and balcony drying methods have increased (Table 6). The living room was the main indoor drying location, followed by balconies and bedrooms. Only 10% of households used an electric dryer. Countries in the North America and Europe commonly use clothes dryers, and research has assessed their energy usage [39]. Indoor drying of laundry is a characteristic of Korean households which can increase the relative humidity of indoor rooms, and research has been conducted on the use of ventilation fans to reduce the amount of water vapor generated by this practice [40]. The use of humidifiers has generally doubled, as compared to that in the 2003 study. Most households circulated fresh air by opening windows; indoor air was circulated once a day in 70% of households, with each ventilation period not exceeding ten minutes.

| Characteristics of apartment residents. | 2003 | 2015 |
|----------------------------------------|------|------|
| **Total Household Members**            | 5.1  | 2.85 |
| Clothes-drying locations               |      |      |
| Balcony (%)                            | 1    | 26   |
| Living room (%)                        | 54   | 58   |
| Bedroom (%)                            | 45   | 18   |
| Electric dryer                         |      |      |
| Yes (%)                                | -    | 10   |
| No (%)                                 | -    | 90   |
| Humidifier                             |      |      |
| Yes (%)                                | 25   | 48   |
| No (%)                                 | 56   | 18   |
| NA (%)                                 | 19   | 35   |
| Ventilations per day                   |      |      |
| Once (%)                               | 34   | 70   |
| Twice or more (%)                      | 66   | 30   |
| Ventilation duration                   |      |      |
| <10 min (%)                            | 43   | 53   |
| 10–30 min (%)                          | 44   | 40   |
| >30 min (%)                            | 13   | 7    |

4.3.4. Changes in Design Standards for Windows and Doors

Design criteria for the walls and windows that comprise the building envelope, have been strengthened [41]. Standards for the mandatory use of high-performance materials have been established since 2000. From 2000 to 2012, the U-value for windows was 2.632 W/m² K and the air permeability was grade 2 (2 m³/h m²). In 2012, high airtight insulation doors emerged, with a U-value of 1.8 W/m² K and air-permeability of grade 2 (2 m³/h m²). This standard changed to a U-value of 1.2 W/m² K in 2015, and air permeability changed to grade 1 [42]. In other words, the standards of windows and doors, which are part of the building envelope, have been strengthened in terms of both the U-value and air permeability (Table 7).
Table 7. Design standards for high-efficiency energy equipment and appliances.

|                | 2000      | 2012      | 2015      |
|----------------|-----------|-----------|-----------|
|                | U-Value W/(m²·K) | Air-Permeability (m³/h m²) | U-Value W/(m²·K) | Air-Permeability (m³/h m²) | U-Value W/(m²·K) | Air-Permeability (m³/h m²) |
| Window         | 2.632     | 2         | 2.632     | 2 m³/h m²              | -          | -                       |
| Door           | -         | -         | 1.8       | 2 m³/h m²              | 1.2        | 1                       |

4.4. Temperature Difference Ratio

Wall-to-wall joints, one of the areas susceptible to condensation, usually experience condensation at the corners or the points meeting the upper/lower slab (Figure 2). The minimum temperature in some regions of Korea during winter can be as low as −20 °C. At an outside temperature of −20 °C (based on a room temperature of 25 °C and a relative humidity of 50%), the Korean design criteria for preventing coagulation is 0.25. The temperature at which condensation starts to occur is 13.75 °C. In other words, condensation begins when the surface temperature of a wall drops below 13.75 °C. If the exterior temperature is −20 °C, the interior wall surface must be designed to maintain a temperature above 13.75 °C.

\[ TDR = 0.25 = \frac{25 - x}{25 - (-20)}, X = 13.75 \text{ (°C)} \]  \hspace{1cm} (2)

The design criteria for preventing condensation (based on a room temperature of 25 °C and a relative humidity of 50%) were derived from the temperature and humidity results of 189 apartment units, in 2003 (Table 8), but they did not meet the current design criteria.

Table 8. Improvement of the Korean design criteria for prevention of condensation.

| TDR          | I (−20°C) * | II (−15°C) * | III (−10°C) * |
|--------------|-------------|--------------|---------------|
| Criteria of Wall Corners (2003) | 0.25 | 0.26 | 0.28 |
| Criteria of Wall Corners (2015)   | 0.20 | 0.23 | 0.26 |

* Lowest temperature region.

As the living environment have changed and the design criteria pertaining to building envelopes have also been strengthened, condensation prevention should also reference the present conditions. The temperature and humidity for preventing condensation in 90% of all apartments in Korea are 24 °C and 58%, respectively, and the dew point temperature at which condensation starts to occur is 15.2 °C. The criteria should, thus, be designed to be higher than the current values by more than 1.45 °C, based on the dew point temperature.

\[ TDR = 0.20 = \frac{25 - x}{25 - (-20)}, X = 16 \text{ (°C)} \]  \hspace{1cm} (3)

In conclusion, if the exterior temperature is −20 °C, the interior wall surface must be designed to hold the temperature above 15.2 °C. This results in a TDR of 0.20. (Table 8).

5. Discussion

This study focused on establishing a design basis to prevent condensation by examining the indoor temperature and humidity range of Korean apartments, during winter. Occupants of all households studied were exposed to higher indoor temperature levels than those recommended by the government. Only 22% of the households maintained an appropriate temperature range of 18–20 °C. In a study similar to this one, a one-year study of rental housing in Seoul found that the indoor temperature maintained in rental housing was on average temperature 22.7 ± 0.6 °C during January [1]. These
results indicated that Korean households tended to keep their apartments warm. The relative humidity was generally maintained between 40% and 60%. Moisture can damage the building structure and the finishing and furnishing materials, and it is a direct cause of human discomfort. Moreover, high indoor humidity promotes the growth of mold, which can have adverse health impacts on the occupants [43]. As compared to previous studies, the relative humidity tended to vary more than the temperature. There are two important aspects with respect to changes in temperature and humidity. First, with regard to lifestyle changes over time, the average number of occupants per household had declined from 5.1 to 2.89, as a result of changes in the composition of Korean families. Despite this decrease in the number of persons occupying households, relative humidity levels have increased markedly. This could be attributed to the reduced ventilation level and increased humidifier usage, as shown in Table 6. The results in Table 6 showed that ventilation was insufficient in this study, compared to the 2003 data. Indeed, only 47% of households are ventilated for more than ten minutes per day, as shown in Table 6.

In addition to lifestyle changes, design criteria pertaining to the building envelope, i.e., walls, windows, doors, have also changed. Compared to the 2000 design criteria, the 2015 design basis has been further strengthened [41] (Table 4). Accurate design criteria for preventing coagulation are required according to these enhanced design criteria. The results of our survey showed that there were changes in the building envelope and changes in the living conditions of residents. In addition, the results of calculating the TDR showed that the internal surface temperature must be at least 1.4 °C higher than the current design criteria, to prevent condensation.

Although no air-tightness estimations were made during this study, an assessment of 487 apartments that have been monitored and that are similar to those in this study have demonstrated that the windows and doors were directly related to air-tightness estimations [44]. Consequently, as the design criteria for windows and doors had changed, the indoor relative humidity might possibly increase with the better air-tightness of the apartment buildings.

The amendment of design standards to reduce condensation is a national effort to reduce the occurrence of dew condensation in interior areas, as well as to change the old laws and to create a healthy and pleasant environment for residents. Therefore, it is very important to determine the TDR value considering “actual living conditions” (Table 8). Compared with other countries, wall design standards have been strengthened, but the design criteria must be strengthened, as these values pertain to an area where considerable winter condensation occurs. Moreover, the consideration of only the wall TDR is a limitation of this study. Therefore, revisions to the TDR values such as those pertaining to windows and doors, and considering cumulative frequencies can be the focus of future research.

6. Conclusions

Maintaining adequate indoor temperatures and humidity levels in homes is necessary to achieve comfortable thermal conditions. The results of this study indicated that Korean households tended to keep their apartments warm and at a mild relative humidity level. Compared to a 2003 study, 2015 results showed significant changes in temperature and humidity due to changes in the living environments of residents and changes in the outer envelope of apartment buildings. Analysis showed that the relative humidity in 2015 was higher than that in 2003, and the enforced envelope design criteria were likely to contribute to a more air-tight indoor environment and a higher relative humidity. Design criteria to prevent condensation should, therefore, be strengthened to reflect these changes and should focus on minimizing winter condensation, taking into consideration residents’ current living environments.

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Data Availability: The datasets used and analyzed in the current study are available from the corresponding author upon a reasonable request.

References

1. Lee, D.; Lee, K.; Bae, H. Characterization of indoor temperature and humidity in low-income residences over a year in Seoul, Korea. *Asian J. Atmos. Environ.* 2017, 11, 184–193. [CrossRef]

2. Hong, S.H.; Lee, J.M.; Moon, J.W.; Lee, K.H. Thermal comfort, energy and cost impacts of PMV control considering individual metabolic rate variations in residential building. *Energies* 2018, 11, 1767. [CrossRef]

3. Hyndman, S.J.; Vickers, L.M.; Htut, T.; Maudner, J.W.; Peock, A.; Higenbottam, T.W. A randomized trial of dehumidification in the control of house dust mites. *Clin. Exp. Allergy J. Br. Soc. Allergy Clin. Immunol.* 2000, 30, 1172–1180. [CrossRef]

4. Singh, J. Occupational exposure to mould in buildings. *Indoor Built. Environ.* 2001, 10, 172–178. [CrossRef]

5. Koskinen, O.M.; Husman, T.M.; Meklin, T.M.; Nevalainen, A.L. The relationship between moisture or mould observations in houses and the state of health of their occupants. *Eur. Respir. J.* 1999, 14, 1363–1367. [CrossRef] [PubMed]

6. Engman, L.H.; Bornehag, C.-G.; Sundell, J. ‘How valid are parents’ questionnaire responses regarding building characteristics, mouldy odour, and signs of moisture problems in Swedish homes? *Scand. J. Public Health* 2007, 35, 125–132. [CrossRef] [PubMed]

7. Howden-Chapman, P.; Saville-Smith, K.; Crane, J.; Wilson, N. Risk factors for mold in housing: A national survey. *Indoor Air.* 2005, 15, 469–476. [CrossRef]

8. Lloyd, C.R.; Callau, M.F.; Bishop, T.; Smith, I.J. The efficacy of an energy efficient upgrade programme in New Zealand. *Energy Build.* 2008, 40, 1228–1239. [CrossRef]

9. Mercer, J.B. Cold—an underrated risk factor for health. *Environ. Res.* 2003, 92, 8–13. [CrossRef]

10. Ministry of Land, Infrastructure and Transport (MOLIT). Criteria for the Prevent Condensation. Available online: https://bit.ly/2GpdzV1 (accessed on 4 June 2019).

11. Park, S.H. A Study on Condensation Resistance Assessment and the Derivation of Economical Window Designs Considering TDR and U-Factor for Apartment Buildings. Ph.D. Thesis, Ewha Univerisity, Seoul, Korea, 2019.

12. Kim, J.; Kim, T.; Leigh, S. Double window system with ventilation slits to prevent window surface condensation in residential buildings. *Energy Build.* 2011, 43, 3120–3130. [CrossRef]

13. Galvin, R. Solving mold and condensation problems: A dehumidifier trial in a suburban house in Britain. *Energy Build.* 2010, 42, 2118–2123. [CrossRef]

14. Mäkinen, T.M.; Juvonen, R.; Jokelainen, J.; Harju, T.H.; Peitso, A.; Bloigu, A.; Silvennoinen-Kassinen, S.; Leinonen, M.; Hassi, J. Cold temperature and low humidity are associated with increased occurrence of respiratory tract infections. *Respir. Med.* 2009, 103, 456–462. [CrossRef]

15. Mouritzoukou, E.G.; Falagas, M.E. Exposure to cold and respiratory tract infections. *Int. J. Tuberc. Lung Dis.* 2007, 11, 938–943. [PubMed]

16. Smith, K.M.; Svendsen, S. The effect of a rotary heat exchanger in room-based ventilation on indoor humidity in existing apartments in temperate buildings. *Energy Build.* 2016, 116, 349–361. [CrossRef]

17. Bornehag, C.G.; Sundell, J.; Bonini, S.; Custovic, A.; Malmberg, P.; Skerfving, S.; Sigsgaard, T.; Verhoeff, A. Dampness in buildings as a risk factor for health effects, EUROEXPO: A multidisciplinary review of the literature (1998–2000) on dampness and mite exposure in buildings and health effects. *Indoor Air.* 2004, 14, 243–257. [CrossRef] [PubMed]

18. Lucas, F.; Adelard, L.; Garde, F.; Boyer, H. Study of moisture in buildings for hot humid climates. *Energy Build.* 2002, 34, 345–355. [CrossRef]

19. Wang, F.; Yoshida, H.; Kitagawa, H.; Matsumoto, K.; Goto, K. Model-based commissioning for filters in room air-conditioners. *Energy Build.* 2005, 37, 1225–1233. [CrossRef]

20. Kim, J.Y.; Hwang, H.J.; Kim, L.H. A Study on the Prevention of Condensation in Household of Apartment Buildings; Housing and Urban Research Institute: Daejeon, Korea, 2003.

21. Standard Policy and Strategy Committee. BS 5250; 2011 Code of Practice for Control of Condensation in Buildings, BSI. December 2011; SPSC: London, UK, 2011; ISBN 978-0-580-93804-7.
22. The Building Regulations. Site Preparation and Resistance to Contaminants and Moisture: Approved Document C 1,2.; The Building Regulations: UK, 2010; pp. 12–38, ISBN 978-1-85946-509-7.

23. BRE IP17/01; Assessing the Effects of Thermal Bridging at Junctions and Around Openings. 2011. Available online: https://www.brebookshop.com/details.jsp?id=190683 (accessed on 7 March 2006).

24. Regeling Bouwbesluit: 2012 Are Based on “Factor van de Temperatuur”. Available online: https://bit.ly/2Pgg8pG (accessed on 4 June 2019).

25. International Organization for Standardization. NEN 2778; ICS Code 91.120.30; Moisture Control in Buildings; ISO: NEN, The Netherlands, 2015; pp. 10–72.

26. International Organization for Standardization. NEN 1068; ICS Code 91.120.10; Thermal Insulation of Buildings—Calculation Methods; ISO: NEN, The Netherlands, 2012.

27. International Organization for Standardization. NEN-EN 12667; ICS Code 91.100.01, 91.120.10. Thermal Performance of Building MATERIALS and Products, Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods, Products of High and Medium Thermal Resistance; ISO: NEN, The Netherlands, 2001.

28. Melita, T. Energy Savings Ordinance (EnEV) and Renewable Energies Heat Act (EEWärmeG) apply in parallel. Books on Demand 2016, 1, 1–249.

29. DIN 4108 Beiblatt 2: 2019-06, Thermal Insulation and Energy Economy in Buildings; Supplement 2: Thermal Bridges. 2019. Available online: https://dx.doi.org/10.31030/3054799 (accessed on 13 June 2019).

30. ASHRAE. Archives of the American Society of Heating, Refrigerating and Air-Conditioning Engineers; ASHRAE Handbook 2013 Fundamental; ASHRAE: New York, NY, USA, 2013; pp. 257–881, ISBN1 9781628705355; ISBN2 1628705353.

31. American Architectural Manufacturers Association. AAMA Standard 1503-09: Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections. Schaumburg, U.S. Available online: https://aamanet.org/pages/crf-tool (accessed on 4 June 2019).

32. Jeoung, C.W.; Kim, H.S.; Jeoung, S.H.; Kim, Y.T.; Song, D.S. Comparison and analysis of domestic and foreign standards for preventing the condensation in multi-residential house. Proc. SAREK Conf. 2013, 6, 514–518.

33. Evans, M.; Shui, B.; Takaqi, T. Country Report on Building Energy Codes in Japan; Pacific Northwest National Laboratory: Richland, WA, USA, 2009; pp. 5–18.

34. Australian Building Code Board. Available online: https://www.abcb.gov.au/ (accessed on 4 June 2019).

35. The Korea Meteorological Administration. Available online: https://bit.ly/2Gu874t (accessed on 4 June 2019).

36. Quinn, A.; Shaman, J. Indoor temperature and humidity in New York City apartments during winter. Sci. Total Environ. 2017, 583, 29–35. [CrossRef]

37. Zang, H.; Yoshino, H. Analysis of indoor humidity environment in Chinese residential buildings. Build. Environ. 2010, 45, 2132–2140. [CrossRef]

38. Lee, N.S.; Sub, K.S. Change of lifestyle by changing member of family. Korean Inst. Inter. Des. 2007, 9, 54–58.

39. Cetina, K.S.; Tabares-Velasco, P.C.; Novoselac, A. Appliance daily energy use in new residential buildings: Use profiles and variation in time-of-use. Energy Build. 2014, 84, 716–726. [CrossRef]

40. Lim, Y.H. Development of the Water Vapor Control Algorithm for Preventing Condensation Considering the Water Vapor Generation and Diffusion in Multi-Residential House. Master’s Thesis, Sungkyunkwan University, Seoul, Korea, 2016.

41. Ministry of Land, Infrastructure and Transport (MOLIT). Energy-Saving Design Criteria of Building. Available online: https://bit.ly/2UpcpOd (accessed on 4 June 2019).

42. Ministry of Trade, Industry and Energy (MOTIE). Design Standards for High Efficiency Energy Equipment and Appliances. Available online: https://bit.ly/2IMqCmn (accessed on 4 June 2019).

43. Lourenço, P.B.; Luso, E.; Almeida, M.G. Defects and moisture problems in buildings from historical city centres: A case study in Portugal. Build. Environ. 2006, 41, 223–234. [CrossRef]

44. Ji, K.H.; Shin, H.K.; Han, S.W.; Cho, H.; Jo, J.H. Airtightness estimation of apartment units using a multiple regression analysis. J. KIAEBS 2017, 11, 465–475.