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IoT strategy to solve condensation problem in residential building

사물 인터넷을 활용한 주거용 건물에서의 결로 해결 방안

2020 년 8 월

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Abstract

The building technology have been developed in a way to minimize damage from inadvertent moisture penetration and generation in the living space. Researches and building technologies related with the condensation in building is actively reviewed with applying appropriate combinations of insulation and ventilation. However, condensation still ranks high on the list of defect dispute issues for newly built apartment buildings in Korea. The building industry is trying to solve the issue by increasing the design criteria for condensation prevention. However, this may cause other unintended effects which this study was designed to address: The aim was to provide an Internet of Things (IOT) concept approach solution for preventing condensation in the balconies of Korean apartments, which is reported to be the most problematic space in a residential unit.

The research proceeded as follows to solve the condensation in the balcony space. Long-term monitoring was conducted to identifying the cause of condensation to derive a strategy to prevent condensation. The monitoring result revealed not only the construction factors of the balcony but also occupancy activity influences condensation. Condensation prevention effect through control of these factors were reviewed by EnergyPlus simulation (Insulation thickness and ventilation rate) and the control of occupancy activities were reviewed with the use of a field experiment. However, the uncertainty related to

the moisture generation rate by the occupants made it difficult to ascertain the building's physical parameter values. Although restricting the occupancy activity effectively lowered the moisture generation to prevention condensation occurrence.

Although a method to control the behavior of occupancy dose not ensure the effectiveness from the engineering point of view, it was confirmed that it is feasible by combining technology with the concept of IoT. Author installed IoT experiment onsite accessed by internet WiFi. Real-time data value collection and analysis algorithms are processed through micro-processor (Raspberry Pi) to operate the balcony door actuator and ventilation fan installed inside the balcony. As a result of the experiment it was confirmed that the condensation prevention control combined with the Internet of Things shorten the condensation occurrence time.

In this study, as a method for solving condensation in buildings categorized into fixed parameter and occupancy parameter. Fixed parameters are considered during design phase while occupancy parameters are applicable during use stage. Occupancy parameters are actively respond to changes in the indoor environment by using IoT technology to block the moisture transfer and remove generated moisture while fixed parameters are a way to reflect the possibility of condensation to derive insulation thickness and ventilation rate. Previously, the indoor condition of building was left to the autonomy of the occupants

after building have been constructed. Through this study provides a vision of designing to control the architectural feature in use stage of building is possible.

Keyword : Condensation, Korean apartment building, balcony space, Internet of Things (IoT), micro-processor (Raspberry Pi)
Student Number : 2013-30934

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Symbols

SYMBOL	MEANING	UNIT
A_j	Area of the jth adjacent surface	m^2
C_d	Discharge Coefficient	-
C_p	Specific heat capacity of air	J/kg K
C_T	Sensible heat capacity multiplier	-
$C_{z,i}$	Volumetric heat capacity for the ith node (V$C_p C_T$)	
$F_{gain,j}$	Fraction of internal gain from jth internal gain object defined in the RoomAir	-
$F_{HVAC,j}$	Fraction of output or supply air to the ith node from jth HVAC equipment	-
F_i	Fraction of zone air volume for ith node	-
$h_{i,j}$	heat transfer coefficient between the jth adjacent surface and ith node	W/m^2K
$h_{M,j}$	Moisture transfer coefficient between the jth adjacent surface	kg/m^2s
$\dot{m}$	Air mass flowrate	Kg/s
$\dot{m}_{AFNi,j}$	Mass flow rate from the jth node to the ith node	Kg/s
$\dot{m}_{sup,i,j}$	supply mass flow rate from the jth HVAC equipment	Kg/s
$N_{i,AFN}$	AFN objects connected to the ith node	-
$N_{i,HVAC}$	HVAC Equipment objects which provide supply air to the ith node	-
$N_{i,sur}$	number of adjacent surface with convective heat transfer for the ith node defined in the Room Air	-
$N_{i,g}$	number of internal gains for the ith node	-
$\dot{Q}_{i,j}$	Amount of internal sensible gain at the jth internal gain	W

SYMBOL	MEANING	UNIT
	object and ith node	
t	Temperature	°C
t_d	Dew-point Temperature	°C
T	Temperature	K
$T_{sup\,j}$	Supply Air temperature at the j^{th} HVAC equipment	°C
$T_{z,i}$	Air temperature at the i^{th} zone	°C
p_w	Water vapor partial pressure	kPa
p_{ws}	Water vapor saturation pressure	Pa
W	Opening Width	m
$W_{z,i}$	Air humidity ratio at the i^{th} zone	Kg/kg
v	Air flow velocity	m/s
V	Zone air Volume	m^3
ρ	Density	kg/m^3

Chapter 1. Introduction

1.1 Background and Purpose
1.2 Scope and Method

1.1. Background and Purpose

Built environments have been developed to reduce the factors affected by water content, with the aim of improving the comfortability of indoor conditions. However, one of the factors, which occurs due to the dynamics of indoor and outdoor conditions of temperature and humidity changes, creates the condensation. This surface moisture accumulation causes biological activities which deteriorate the performance of building materials.[1,2] This increases the maintenance costs during the use of the building. In addition to that, the dampness of building materials and the biological reactions contribute to the growth of molds which creates inadequate indoor air quality. This phenomenon may threaten occupants' health. When people are exposed to molds, it may cause severe health conditions such as respiratory illness,

[1] Hannu Viitanen et al., "Moisture and Bio-Deterioration Risk of Building Materials and Structures," *Journal of Building Physics* 33, no. 3 (2010).
[2] HLSC Hens, "Fungal Defacement in Buildings: A Performance Related Approach," *HVAC&R Research* 5, no. 3 (1999).

asthma, and allergies.[3,4,5] According to the World Health Organization, childhood asthma cases are related to condensation within the home.[6] Therefore, achieving condensation-free housing is an important aspect of the economic and environmental impacts on occupants' health.

For several decades, many researchers have accomplished condensation prevention through the use of carefully chosen building components. Building envelopes with adequate insulation strategies have been suggested to increase thermal resistance for the prevention of moisture on wall surfaces and layers.[7,8] Proper insulation spacers for double-glazed windows have been validated.[9] The mechanical ventilation strategies to compensate for thermal resistance have been suggested and developed.[10] The results of these studies have provided guidelines for condensation-free building designs for updating old buildings that need renovation.

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[3] Maria H Garrett et al., "Indoor Airborne Fungal Spores, House Dampness and Associations with Environmental Factors and Respiratory Health in Children," *Clinical and Experimental Allergy* 28, no. 4 (1998).

[4] Robert K Bush et al., "The Medical Effects of Mold Exposure," *Journal of Allergy and Clinical Immunology* 117, no. 2 (2006).

[5] William J Fisk, Quanhong Lei-Gomez, and Mark J Mendell, "Meta-Analyses of the Associations of Respiratory Health Effects with Dampness and Mold in Homes," *Indoor air* 17, no. 4 (2007).

[6] MS Jaakkola et al., "Indoor Dampness and Mold Problems in Homes and Asthma Onset in Children," *Environmental burden of disease associated with inadequate housing-A method guide to the quantification of health effects of selected housing risks in the WHO European Region. Geneva: World Health Organization* (2011).

[7] Rachel Becker, "Effects of Heating Patterns on Internal Surface Temperatures and Risk of Condensation," *Building and Environment* 28, no. 3 (1993).

[8] Mohammed A Hamdan, "Layered Wall Design to Prevent Moisture Condensation on Its inside Surface," *Energy conversion and management* 43, no. 14 (2002).

[9] Seung-Yeong Song et al., "Evaluation of inside Surface Condensation in Double Glazing Window System with Insulation Spacer: A Case Study of Residential Complex," *Building and environment* 42, no. 2 (2007).

[10] Jing Liu, Hiroyoshi Aizawa, and Hiroshi Yoshino, "Cfd Prediction of Surface Condensation on Walls and Its Experimental Validation," ibid.39, no. 8 (2004).

Although a strong foundation of condensation strategies exists in the field of building engineering, the condensation problem still exists – even in newly built residential environments. In Korea, as shown in Figure 1.1, there is a dispute between consumers and constructors related to condensation defects on newly constructed residential buildings. These types of problems ranked third-highest based on data collected from 2010 to 2015.[11] This is the highest ranked after the defect categories of fault sound absorption and malfunction defects, according to data obtained from "Defect Review Dispute Resolution Committee" under the Ministry of Land, Infrastructure and Transport in Korea.

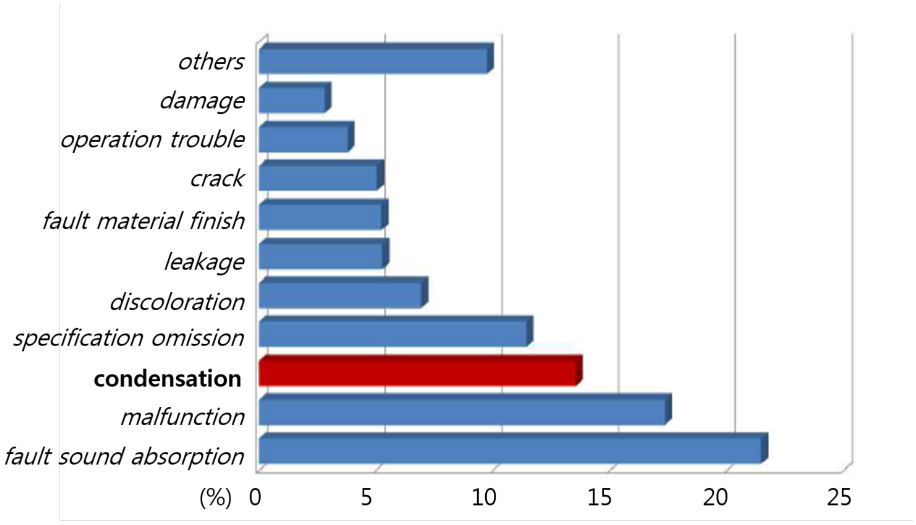

Figure 1. 1. Defect ratio by type of dispute resolution by dispute resolution committee of Ministry of Land, Infrastructure and Transport in Korea [12]

[11] Seung-Yeong Song, "'Development of Building Technology to Improve the Living Performance Closely Related with Lifestyle to Realize the Housing Welfare', Research Group Report(2-Year)," *Ewha Womans University* 3 (2016).
[12] Ibid.

The most vulnerable location for condensation defects in residential units is the north-facing balcony, which is an unheated, semi-outdoor space in the unit. Based on owners' pre-survey complaint reports on a newly constructed apartment complex in Incheon, Korea, the occupants of 442 units reported condensation complaints during the first four months after construction was complete (October 2015 to January 2016). As shown on Figure 1.2, resorted data by the types of rooms for each unit show that north-facing balconies ranked highest for condensation, according to reported locations. The results were repeated by other researchers in South Korea in 2007. Moon et al.,[13] for example, surveyed the occupants of 466 apartment units who reported a high number of mold complaints and discovered that the area of mold development on the balcony accounted for about 90% of the total. Thus, balcony space in Korean residential buildings is specifically designed to address known condensation problems. Also, the balcony is a critical location for controlling the mold spores which may spread throughout the entire residential unit.

[13] Hyeun Jun Moon and Hwa-Yong Kim, "The Relationships between the Extent of Mould Problems and Physical Building Characteristics in High-Rise Apartment Buildings," *Proceeding of Clima 2007 WellBeing Indoors* 5 (2007).

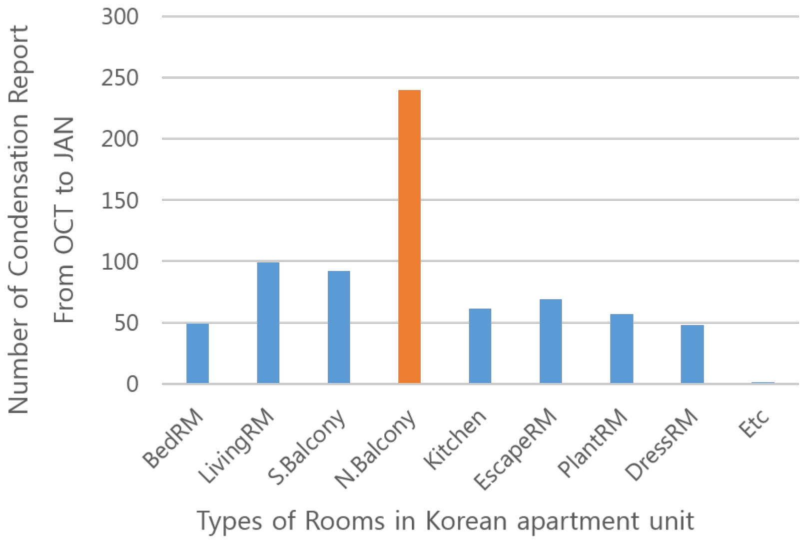

Figure 1. 2. Condensation reports survey by types of rooms in newly constructed apartment units

The report on repeated problems provides information on the same place within each unit of the entire building. The existing solutions for condensation-related problems are suggested as being for applicable during the early design stage, in order to cope with the foreseen occupancy condition. However, after a residential building is completed with the considered design, the dynamics of the indoor condition vary by the occupancy profile of each type of space, and there is the possibility of an early design failure. Moreover, the residential buildings' occupancy schedule and activities are irregular, unlike those of office or commercial types of buildings with a more predictable schedule and with dynamic changes to latent heat. Fortunately, the growing trend of the IoT (Internet of Things) concept provides us with a possibility for overcoming design limitations. The IoT was developed by the proliferation of wireless sensor networks in which where sensors, actuators, and the internet framework are used to form a smart environment.[14] IoT applications have been utilized in many types of equipment such as smart speakers, smart lighting control, air conditioners, refrigerators, and energy meters in home HVAC systems,[15] so there is the possibility of solving the condensation problem with IoT technology concepts.

The aim of this study was to create a condensation-free house by applying a design solution with automation such as IoT technology. The issue of the condensation problem involves a dispute among the different groups in the building industry, from designers to consumers, due to the increased costs of maintenance fees and the impacts of certain design choices on occupants' health. However, research on condensation in buildings has been saturated for decades and its responsibility has been passed down to the practical field. Due to the realization of the power of home automation technologies, the possibility of a different solution for building condensation has opened up; however, the application strategy is up in the air. Therefore, the objective of this study was to review the feasibility of an IoT approach in providing a condensation solution for the balcony space, which is the most problematic location in a residential unit. During the process of the research, the following questions related to the objective were investigated:

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[14] Jayavardhana Gubbi et al., "Internet of Things (Iot): A Vision, Architectural Elements, and Future Directions," *Future generation computer systems* 29, no. 7 (2013).
[15] Margaret Rouse, "Iot Devices (Internet of Things Devices)," (2018).

- Why do Korean balcony spaces have a condensation problem?
- Why is it necessary to apply the IoT approach to solving the condensation problem in residential buildings?
- How to merge IoT technology to the environmental engineering of a building?

1.2. Scope and Method

Within the scope of this work, the overall space was considered rather than one component of the building in order to review the overall impact of condensation. Although there are two types of condensation (surface and interstitial), in this study, only surface condensation was considered in determining the feasibility of the solutions. As mentioned above, the space to be reviewed was targeted to the north-facing balconies, where many condensation problems appear.

The following steps were carried out for the research:

1) **Consideration of existing condensation prevention strategies for unheated spaces (Ch. 2)**

   The existing prevention strategies for unheated spaces in residential buildings, whose conditions are similar to those of Korean balcony spaces, were investigated. Before proposing new condensation control measures for balcony areas, the development of the characteristics of Korean balconies were considered for limitation of the control strategy, and preliminary studies were reviewed. The work was based on the guidelines for required temperatures and humidity levels for condensation prevention, existing solutions and applications in construction companies in Korea, and the results from a literature review.

2) **Investigation of control parameters (Ch. 3)**

   In order to derive the control parameters, diagnosis of the condensation problem on balcony spaces was conducted by field measurement analysis. Long-term monitoring was conducted on the occupied residential units in different seasonal periods. The condensation and measuring point correlations were analyzed for conclusions regarding the control parameters according to the occupancy patterns.

3) **Evaluation of the validity of control parameters (Ch. 4)**

   With the parameters derived from activities in the second step, the control parameters were evaluated for their effectiveness as well as feasibility. The parameters were defined by the occupancy parameters and solid parameters were used to conduct the validation by the site experiment and simulation. During this analysis, it was concluded that it was necessary to apply the occupancy parameters, and that this would require the adoption of real-time control.

4) **IoT application with the development of a control strategy and algorithm (Ch. 5)**

   Applying a real-time control algorithm requires knowing when to operate with the derived parameters established in the second step. The concept of the IoT and the occupancy parameters were interwoven in order to derive the control algorithm for the IoT application. Data generated by the sensors has continually increased the amount of data, which gave rise to the concept of Big Data. To control condensation, it is necessary to process the real-time data that is gathered by the sensors. The control algorithm was derived from the analysis of the field-measured occupancy conditions.

5) **Application of control algorithm based on site experiment results (Ch. 6)**

   The results of IoT control measures employed in typical residential units were evaluated for feasibility.

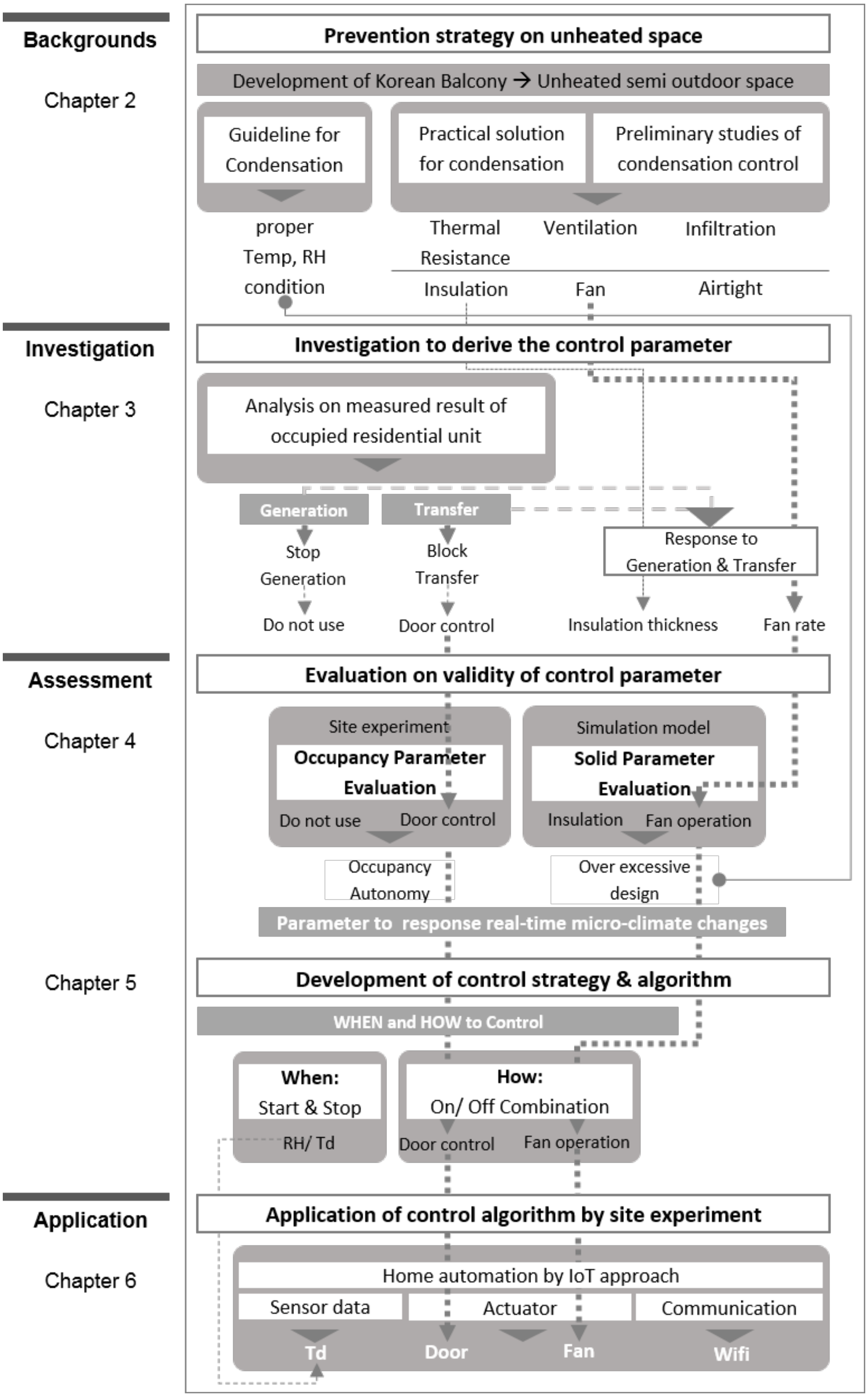


Figure 1. 3. Diagram for research process

Chapter 2. Existing Strategies for Condensation Control

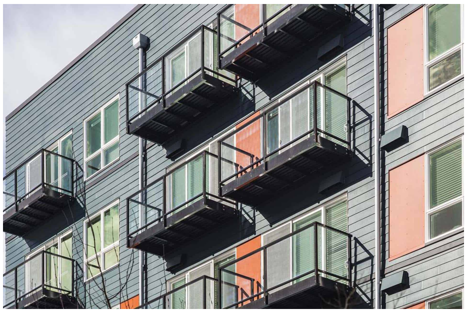
2.1. Conventional Korean Balconies
2.2. Design criteria for condensation control
2.3. The solution application by industry in Korea

2.1. Conventional Korean Balconies

The typical Korean balcony was developed from the traditional lifestyle and real estate situation in Korea. A balcony is defined as “a platform projecting from the wall of a building and enclosed by a parapet or railing.”[16] However, as shown in Figure 2.1 (b) Korean balcony is a part of the residential unit that is enclosed by an exterior wall and window. In Korea, balconies are projected from the residential unit to view the outside, and are defined as a connection between the outdoor and indoor space. The installation of glass windows in balconies was legalized in the early 1990s to reduce noise from the outdoor environment and thermally mitigate the heating space.[17] As shown in Figure 2.2,

[16] Merriam-Webster Dictionary, "Merriam-Webster," *On-line at http://www. mw. com/home. htm* (2002).
[17] CS Park, "Emerging from Customary Design for Balcony Space in Apartment," *J. Archit.*

due to the internal and external divisions, some residents have used their balconies as a laundry area and auxiliary kitchen, with the storage space being used as a pantry, rather than as an area for relaxation and obtaining a view of the outside.[18] Also, in Korea, the balcony space is considered as an additional service area because the entire area of the balcony is not counted with the net floor area of the entire unit; only half of the balcony floor area is counted.[19] Therefore, the balcony space is fully equipped in terms of functionality but it is built without considering it as a part of the living space, and hence it is constructed without any thermal insulation on the wall and without a heating system.



(a) Dictionary definition of Balcony[20]

(b) Korean Balcony[21]

Figure 2. 1. The comparison between a Korean balcony and the dictionary definition of a balcony

Inst. Korea Plan 20 (2004).

[18] Sun-Young Kim and Chan-Ohk Oh, "A Study of Current Status and Residents' Needs of Balcony Extension in Korean Apartment Housing," *Korean Institute of Interior Design Journal* 21 (2012).

[19] Buildling Policy Division (MOLIT), "Enforcement Decree of the Building Act," ed. Infrastructure and Transport (MOLIT) Ministry of Land. http://www.law.go.kr/법령/건축법%20시행령/제119조

[20] https://skylineengineeredaluminum.com/portfolio/balconies/

[21] http://backpackbees.com/wp-content/uploads/2011/03/DSCF1271.jpg

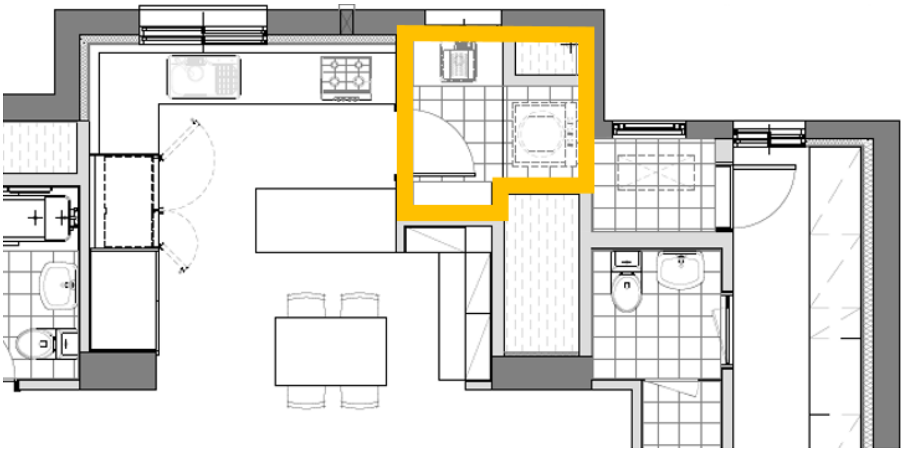


Figure 2. 2. Balcony floor plan designed for service area as laundry room and auxiliary kitchen

Figure 2. 3. Balcony used as laundry room and pantry

2.2. Design criteria for condensation control

In order to provide the proper solution for building condensation control, design results that meet the range of the design criteria must be satisfied. The design criteria provide boundary conditions for deriving the design solution. In this section, an overview is provided relevant to the temperature difference ratio and the moisture balance method used to check whether the boundary condition is appropriate for counting during the creation of a condensation solution.

2.2.1. Temperature Difference Ratio

Most countries, such as Austria, Switzerland, France, the Netherlands, and Japan, use the Temperature Differential Ratio (TDR) of wall and thermal bridges as a design standard for reducing condensation. In the case of France and the Netherlands, there are different temperature ratios for humidity and temperature conditions, unlike other countries that provide a single indoor and outdoor temperature and humidity value for TDR. This follows ISO 10211: Thermal bridges in building construction provides the temperature factor for the thermal bridge area[22].

Similarly, in Korea, the "Design Criteria for preventing condensation in multi-unit dwelling" suggests a TDR for

[22] EN ISO, "10211: Thermal Bridges in Building Construction–Heat Flows and Surface Temperatures–Detailed Calculations (Iso 10211: 2007)," (CEN, 2007); ibid.

condensation reduction.[23] The subjects of TDR are the windows directly contacting doors, wall joints, and the outside air of apartment houses. The outdoor temperature is different depending on the region, but the indoor temperature and humidity (25° C, 50%) is the same in all regions. The TDR value that must be observed in each region is a value that can maintain a temperature higher than the dew point temperature at 25° C and 50%, based on the room temperature and humidity.

2.2.2. Moisture control design

ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineering) standard 160-2009 calls for indoor moisture generation as a default value for designs, with consideration for the effect of moisture.[24] This standard provides criteria for selecting design values for initial moisture conditions, indoor temperatures, indoor humidity, air pressure, airflows, weather data, and rain loads. Its purpose is to provide more precise information on the latent load of the building to calculate the energy load required for the building to be comfortable. The values are mostly collected and measured values, in an effort to standardize the measurement of moisture generation in indoor spaces. Therefore, the design criteria considered for the moisture load may differ according to cultural and social factors.

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[23] Housing Construction Supply Division (MOLIT), "Design Critera to Prevent Condensation in Multi-Unit Dwelling," ed. Infrastrcture and Transport) MOLIT (Ministry of Land (2016). http://www.law.go.kr/행정규칙/공동주택결로방지를위한설계기준

[24] ASHRAE Standard, "Standard 160-2009: Criteria for Moisture Control Design Analysis in Buildings," *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta* (2009).

2.3. Preliminary study of condensation prevention

2.3.1. Preliminary studies on unheated space condensation

The authors of previous studies of condensation-related problems in unheated residential spaces have suggested a different methodology for investigating the movement of water vapor to prevent condensation problems. Gutt[25] investigated attic areas by calculating water vapor transport and diffusion and proved this method using field measurement data. The results showed that moisture is largely transported by airflow, rather than by diffusion through the ceiling, and he suggested blocking the openings and cracks through which it is connected to the living area. Bludau et al. [26] performed investigations using a hygrothermal simulation program (WUFI) on a cool roof, which is effective for lowering the temperature; however, it introduces condensation problems in cold regions. Data on heat and moisture transport through building components have indicated that having a darker color for the roof surface may be better for increase the temperature of roof to prevent condensation. Janssens and Hens[27] presented a sensitivity analysis of the condensation problem in lightweight roof systems used in cold climates. Their results showed that air leakage is a significant cause of condensation and that it is necessary to incorporate building codes for achieving an

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[25] GS Gutt, "Condensation in Attics: Are Vapor Barriers Really the Answer?," *Energy and Buildings* 2, no. 4 (1979).
[26] Christian Bludau, Daniel Zirkelbach, and Hartwig M Künzel, "Condensation Problems in Cool Roofs," *Interface, the Journal of RCI* 27, no. 7 (2009).
[27] A. Janssens and H. Hens, "Interstitial Condensation Due to Air Leakage: A Sensitivity Analysis," *Journal of Thermal Envelope and Building Science* 27, no. 1 (2003).

adequate air barrier system. However, because air leakage control is uncertain in building practices, they also suggested other solutions such as increasing thermal resistance and enhancing the removal of vapor from the inner surface by using a vapor-permeable underlay. Moon et al.[28] used a hygrothermal simulation to analyze the risk of mold growth on the wall of a utility room and balcony space in Korean apartment buildings. The use of appropriate ventilation rates and allowable moisture production activity numbers is suggested for minimizing the risk of mold growth. The leaders of previous studies have diagnose the condensation problem of unheated spaces in residential buildings and provided ideal methods by which to control uncertain air leakage and moisture production, but this restricts the occupants' freedom.

2.3.2. The solution application by Korean industry

Korean construction companies have established and implemented their own design criteria to prevent balcony condensation. For those companies that have confirmed that the balcony condensation prevention design standard is applied, the insulation is installed on the wall facing the outside air, and the detailed standards are different for each company. Some have implemented design standards that combine both insulation and natural ventilation. When the basis for calculating the thickness of

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[28] Hyeun Jun Moon et al., "Evaluation of Mould Growth Risk in Apartment Houses Using Hygrothermal Simulation," *Building Simulation. Sydney, Australia: International Building Performance Simulation Association* (2011).

insulation was presented (company A), the condensation was examined by fixing the balcony's relative humidity to 60%.

The Korean Land & Housing Corporation conducted a study on the construction of a natural ventilation system on the exterior wall of the balcony to reduce the occurrence of condensation on the balcony. The specification defines this as a structural installation ventilation pipe and as being outside of the structure where PVC pipes are buried in the upper and lower parts of the outer wall of the front and back, but for internal use with a rain cap and airflow control device.[29] A vent with a cap is attached to the pipe. The effective area of ventilation is specified to secure more than 35 cm^2, and it is actually applied to new apartment buildings.

Table 2. 1. Insulation strategy for condensation prevention by Korean construction companies

Company	Insulation type and thickness	Significant
A	THK 30 condensation prevention insulation	
B	THK 30 Expanded poly syrol. Type 1-2 (1종 2호)	
C	THK 30 polyurethane foam	
	THK 30 Expanded poly syrol. Type 1-2 (1종 2호)	Ventilation opening (diameter:100mm) 1 location

29 Jong-Yeop; Lee Kim, Jong-Sung; Hwang, Ha-Jin; , "Condensaiton Reduction Test Evalution of Balcony Space," (Land & Housing Corporation, 2006).

	THK 20 Expanded poly syrol. Type 1-2 (1종 2호)	Ventilation opening (diameter: 100mm) 2 location (upper, lower)
D	THK 20 condensation prevention insulation	
E	THK 10 condensation prevention insulation	Surface wall which is indirect to outdoor
	THK 20 polyurethane foam with vapor barrio (type no.1)	Surface wall which is direct to outdoor

2.4. Summary

The balconies in Korean residential building is functioning as utility rooms with constructed as unheated space which constructed without any thermal insulation on the wall and a heating system. There is design criterial for condensation preventing condensation in residential buildings in Korea with the TDR (Temperature Differential Ratio) methods based on ISO 10211. However, this design criteria is not applicable for the balcony spaces since the balcony area is excluded space for the regulation for prevention and the TDR value is driven based on the condition with indoor temperature and humidity as 25° C and 50%.

The existing studies for condensation strategies are controlling the air movement and lessen the heat loss form the cold surfaces. The preliminary studies strategies for condensation on unheated spaces suggested to apply the insulation, prevention infiltration by layering the vapor barrier and restricted the moisture production activities in the unheated spaces. The Korean construction companies established own design criteria to apply insulation to prevent balcony condensation. However, many of the prevention strategies in field is more depends on the temperature control rather than the ventilation strategy, since the ventilation strategy is based on the design criteria of moisture generation rate. This moisture generation rate varies by the cultural and social factors.

Chapter 3. Investigation of the Influence of Condensation by Occupancy Patterns

3.1. Measurement setup
3.2. Causes of condensation in the balcony space
3.3. Control parameters derived from diagnosis

A typical balcony in Korea is designed as a utility room with unheated space. Slight changes to the temperature and humidity easily create condensation on the surface of unconditioned space. For this step in the study, diagnosis of the condensation problem on balconies was performed by using field measurements. From the measurement analysis, the control parameters were derived for the condensation strategy. While the temperature change was stable due to the capacitance of the structure, the moisture changes were dynamic due to the activities inside the balcony space. In order to consider the influence of humidity according to occupancy, field measurements were conducted in the occupied residential units for two different seasonal periods.

3.1. Measurement setup

The onsite monitoring measurement setup was located on the north-facing balcony of a newly constructed, occupied unit. The sensor was located based on the TDR calculation by the design criteria of condensation prevention by the Korean government. The sensor values were data logged and the condensation level was determined by the microprocessor. Some data are missing from the measurement period; however, a reasonable amount was collected for diagnosing condensation occurrence in relation to occupancy behavior.

3.1.1. Monitoring target space

To diagnose the condensation level without the influence of the building's deterioration and water leakage, the onsite monitoring measurement conducted three years after the completion of construction. In order to consider the occupancy influence on the condensation level, the unit selected was a real family home, rather than a vacant unit, as shown in Figure 3.1. The household included two adults with a child and a one-year-old baby. Because of the baby, the unit is actively occupied during the daytime throughout the week. These circumstances made it easy to collect information on the occupants' influence on the condensation data. A brief overview of the unit information is shown in Table 3.1.

The investigation was conducted on a north-facing balcony, which is the most vulnerable location for condensation to occur. As shown in Figure 3.2, the unit is a typical, 84 m2-type plan, which is the standardized national housing floor plan layout in Korea. This type of floor plan has two balcony spaces, a north-facing balcony adjacent to the kitchen, and a south-facing balcony connected to the master bedroom. Compared to south-facing balconies, north-facing balconies easily create condensation due to less direct solar radiation and the effects of moisture generation and transfer from the kitchen activities.

a. The occupied kitchen view   b. The balcony view

Figure 3. 1. The occupied monitoring unit.

Table 3. 1. Information on the monitoring building

Site Location	H apt, Goun-dong, Sejong City, South Korea
Building	Residential Apartment
Building Structure Type	Reinforced concrete structure
Building Completion	2015. 08
Unit floor location	5th floor
Unit Area	84 m^2
Balcony Area	3.57 m^2

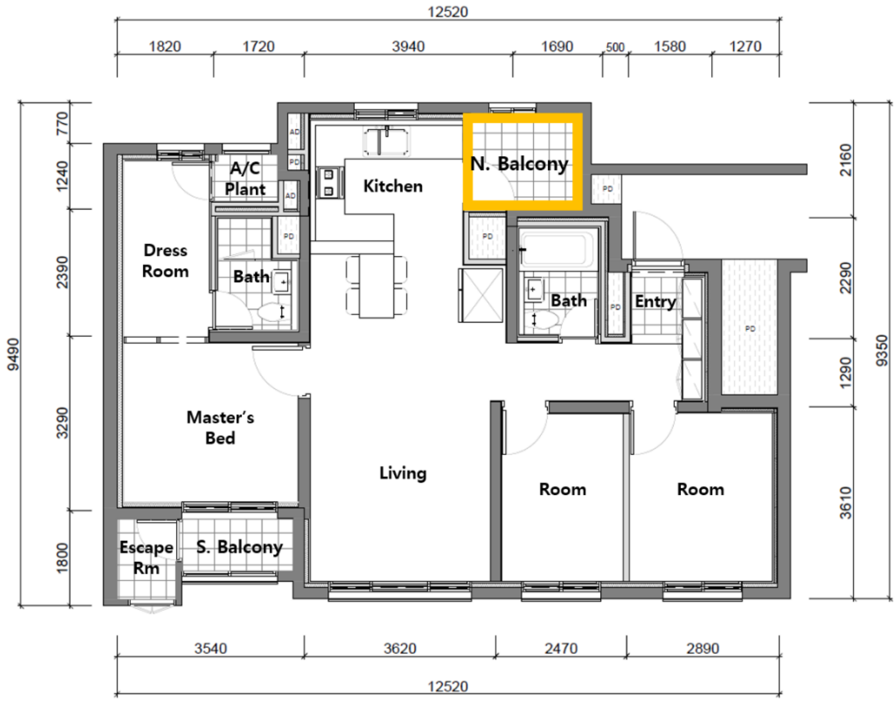

Figure 3. 2. Floor plan of monitoring unit

3.1.2. Data collection points and sensor information

Air temperature and relative humidity sensors and surface temperature sensors were installed in each of four zones to collect environmental measurements. The sensors were connected to the Raspberry Pi microprocessor for simultaneous measurement and functioning as a data logger. Details of the measuring instrument, including sensor accuracy, are shown in Table 3.2.

The monitored measuring points are shown in Figure 3.3. Three zone air sensors were set up in the balcony space and one was in the kitchen to detect micro changes in temperature and humidity in relation to the occupants' activities. As shown in Figure 3.4, the air temperature and humidity sensors were attached to the balcony door frame, balcony window frame, and shelf above the laundry machine so as to not interrupt the flow of traffic. The surface temperature sensors were located in the corner, next to the thermal bridge for heat loss and the designated location for the TDR measuring points (from "Design criteria to prevent condensation in multi-unit dwelling" [30] by the South Korean government).

In order to detect motion information from the balcony entrance and the window (when it was opened for ventilation), magnetic sensors were attached where the frame and opening meets. In order to detect laundry machine use, an electrostatic touch sensor was applied over the laundry machine start button.

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[30] (MOLIT).

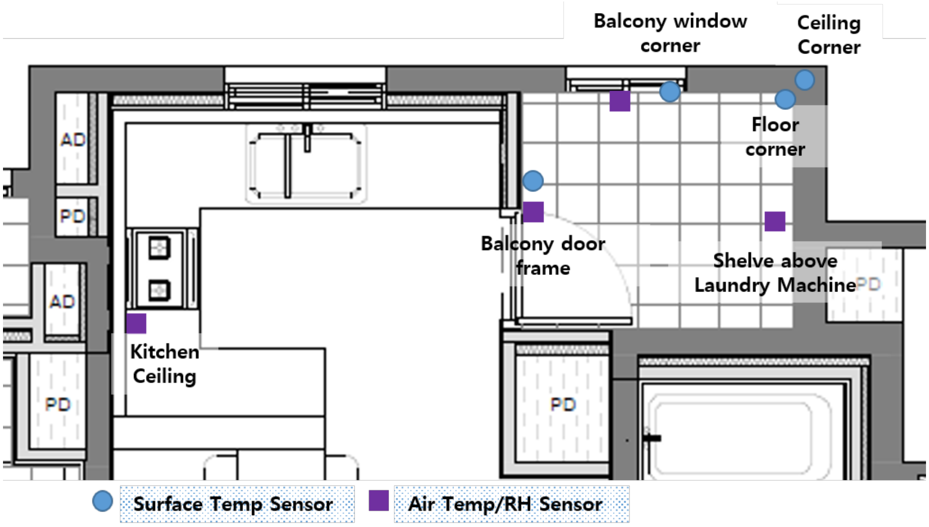


Figure 3. 3. Measurement sensor locations

Table 3. 2. Measurement instrument information

Main Unit Data logger	Micro-processor: Raspberry Pi 3B	
Sensor	Zone Temp, RH	DHT 22[31] Temp: ±0.5°C most uses Humidity: ± 2-5 % most uses
	Surface Temp	K-type Thermocouple [32] (Nickel-Chrominum/ Nickel-Alumel) Temp: ±2.2°C
	Motion Detection	Magnetic proximity sensor - AMS38B 832T Digital Touch Capacity sensor - TTP223B

31 http://www.adafruit.com/product/385

32 https://www.thermocoupleinfo.com/type-k-thermocouple.htm

a. Main board located in balcony space with zone air sensor

b. Window surface and zone air sensor near window

c. Door magnetic sensor with zone air sensor on door frame

Figure 3. 4. The sensor installation on the monitoring unit

3.1.3. Data collection status

The monitoring took place during two seasonal periods: the cooling period (June 8, 2018 to August 29, 2018) and the heating period (December 1, 2018 to February 20, 2019). Measurements were taken every 60 seconds to determine the level of condensation by calculating the dew point temperature from the zone air temperature and the relative humidity sensor value in comparison to the nearby surface temperature. The measured values from sensors and values were calculated by the microprocessor; these were collected for every hour and the data were saved to csv files.

Some data went missing either due to a problem with an individual sensor or with the microprocessor. Because of miscellaneous problems with the sensors, several days' worth of data are missing, as shown in Figure 3.5. However, as shown in Table 3.3, more than 50% of the overall data were successfully collected for diagnosing the balcony's and kitchen's environmental changes related to occupancy activities.

Table 3. 3. Amount of collected data for analysis

Season	*Measured Period (min)*	*Missing Data (min)*	*Proportion of missing data per measured period (%)*
Winter	118081	19094	16%
Summer	119521	48928	40%

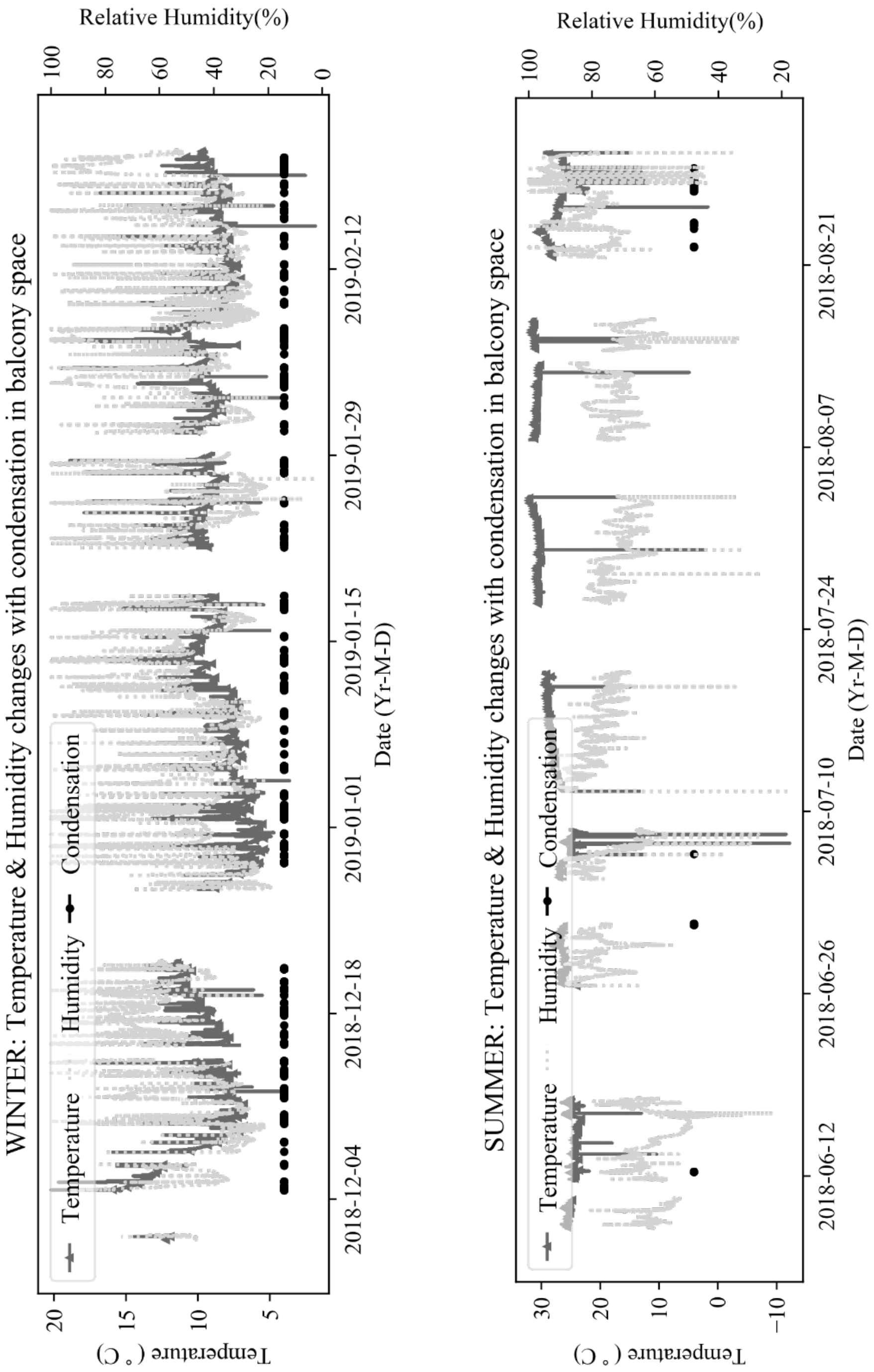


Figure 3. 5. Seasonal monitoring data collection

3.2 Causes of condensation in the balcony space

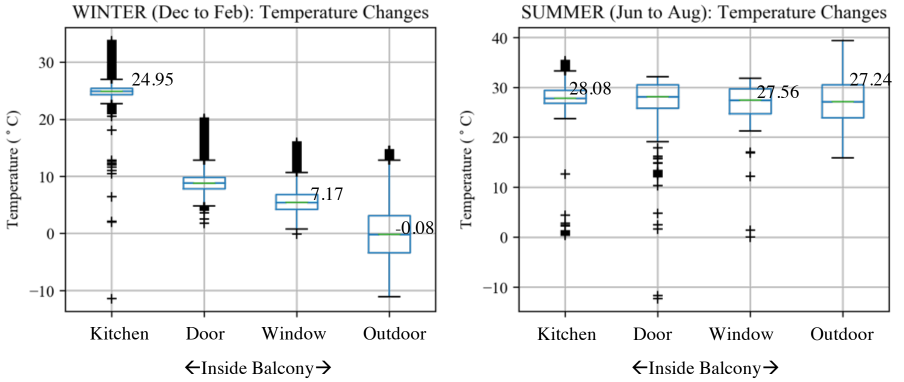
3.2.1. Seasonal influence of condensation

Data from the monitoring taken for two different opposite weather conditions over the course of two seasonal periods show the temperature differences between the outdoor and indoor (conditioned) spaces. Radial floor heating is a conventional feature in Korean residences for use during the heating period, and each room space is individually heated except for the balcony. During the cooling period, a tower-type air-conditioner is operated to cool the indoor space.

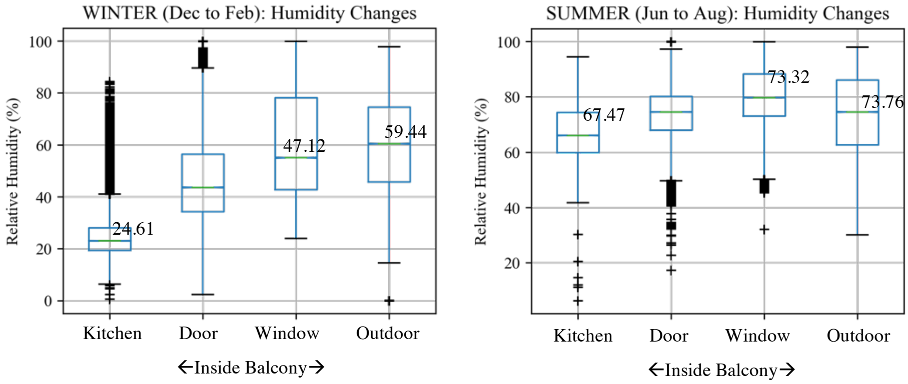
Condensation was detected in the balcony space almost every monitoring day of the winter season, while a few cases of condensation were found during the summer season. The average, measured value of the temperature and humidity of the kitchen (conditioned space), balcony (unconditioned space), and the outdoors was analyzed for the seasonal influence on condensation.

During winter, the average kitchen temperature was 25 °C, which was set up for heating by the radiant floor heating system. The balcony space's environmental condition is influenced by both the indoor, conditioned space and the outdoors. The balcony space was more influenced by the outdoor weather temperature when the average temperature was 7 °C, the outdoor was an average of 0 °C. During the summer, the average temperature and humidity of the three spaces were similar; there was no thermal distinction. As shown in Figure 3.6 (a), the average temperature difference among the three zones during summer was within one degree.

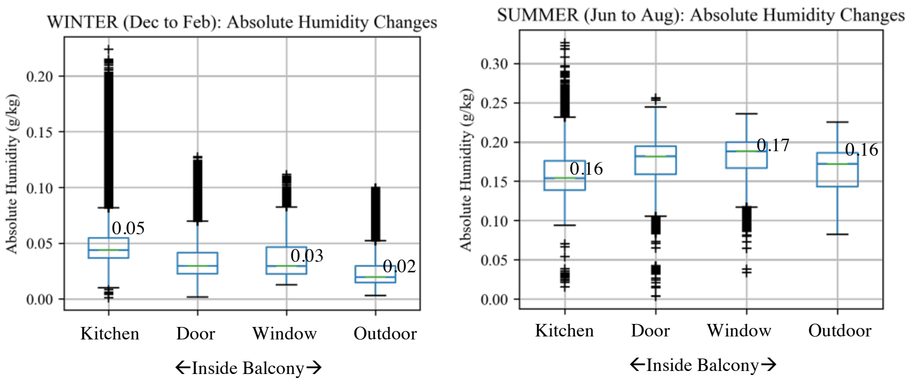
During winter, the average relative humidity became higher from the conditioned space to the outdoors, as shown in Figure 3.6 (b). Since the relative humidity depends on the temperature, it was compared to the absolute humidity. The absolute humidity shows that the water vapor in the conditioned space was higher than the outdoor as shown in Figure 3.6(c).



(a) Temperature Changes



(b) Relative Humidity Changes



(c)Absolute Humidity Changes

Figure 3. 6. Boxplot chart of measured values during winter and summer monitoring period

The temperature and humidity difference between the conditioned and outdoor space was large during the winter season, which easily created balcony space for detecting the condensation. Based on this analysis, it is postulated that the balcony space is influenced by the low outdoor temperatures and vapor pressure is influenced by the conditioned space.

The most vulnerable location for condensation is the window surface of balcony, where condensation frequently occurred even during the summer period. As shown in Figure 3.7 winter condition, condensation was found on the upper corner, lower corner, and window surface during winter while the few cases of condensation only occurred on the window surface during summer, as shown in Figure 3.7 summer condition.

As shown in Table 3.4, the condensation occurrence was larger than any other measured points of the surface since the thermal resistance of the glass was small. As shown in Figure 3.8, the daily surface temperature fluctuations of winter and summer show that the window surface temperature followed the pattern of the outdoor temperature, while the temperature fluctuation of the balcony wall surface changed less.

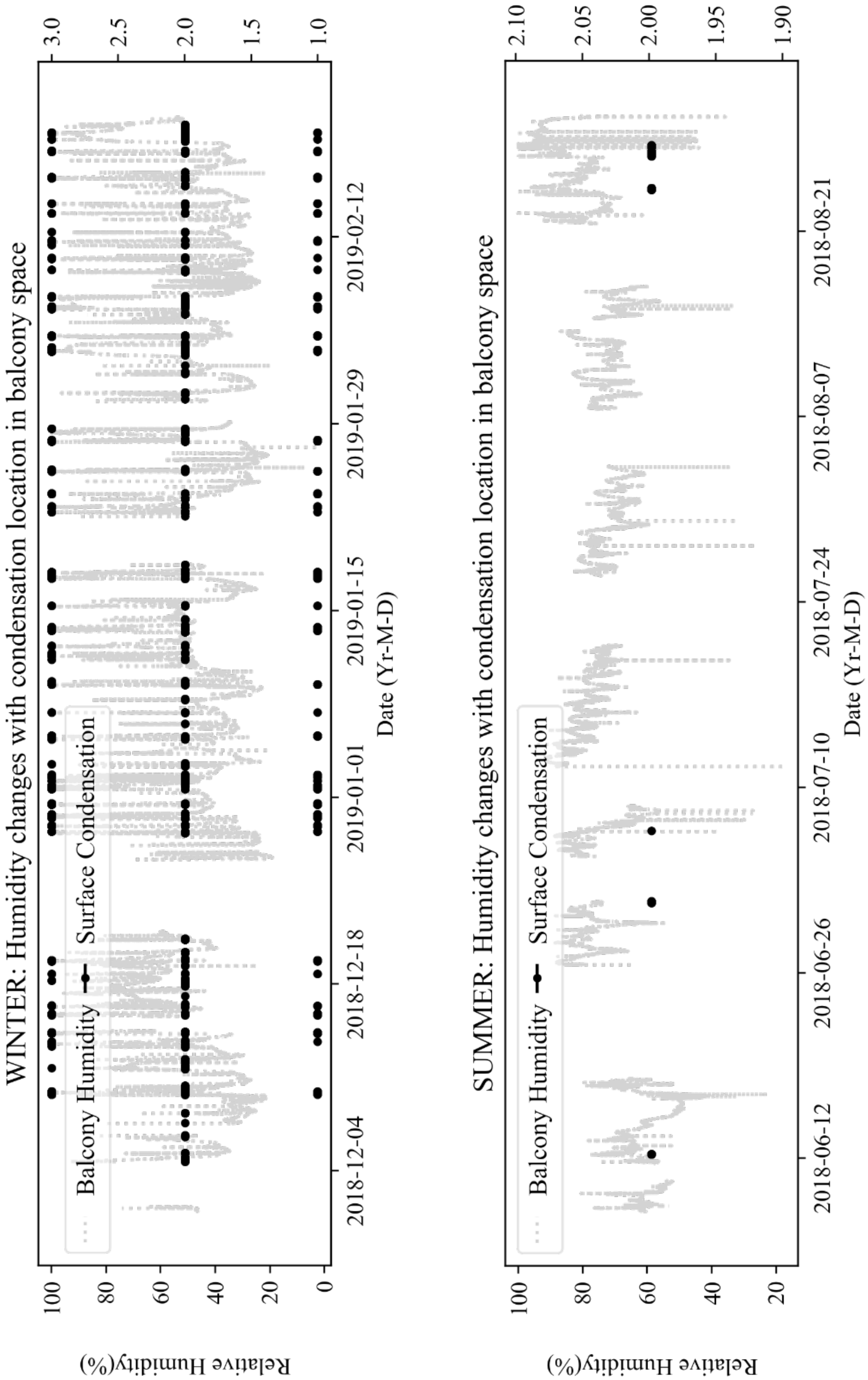


Figure 3. 7. Condensation location on the balcony space during winter and summer

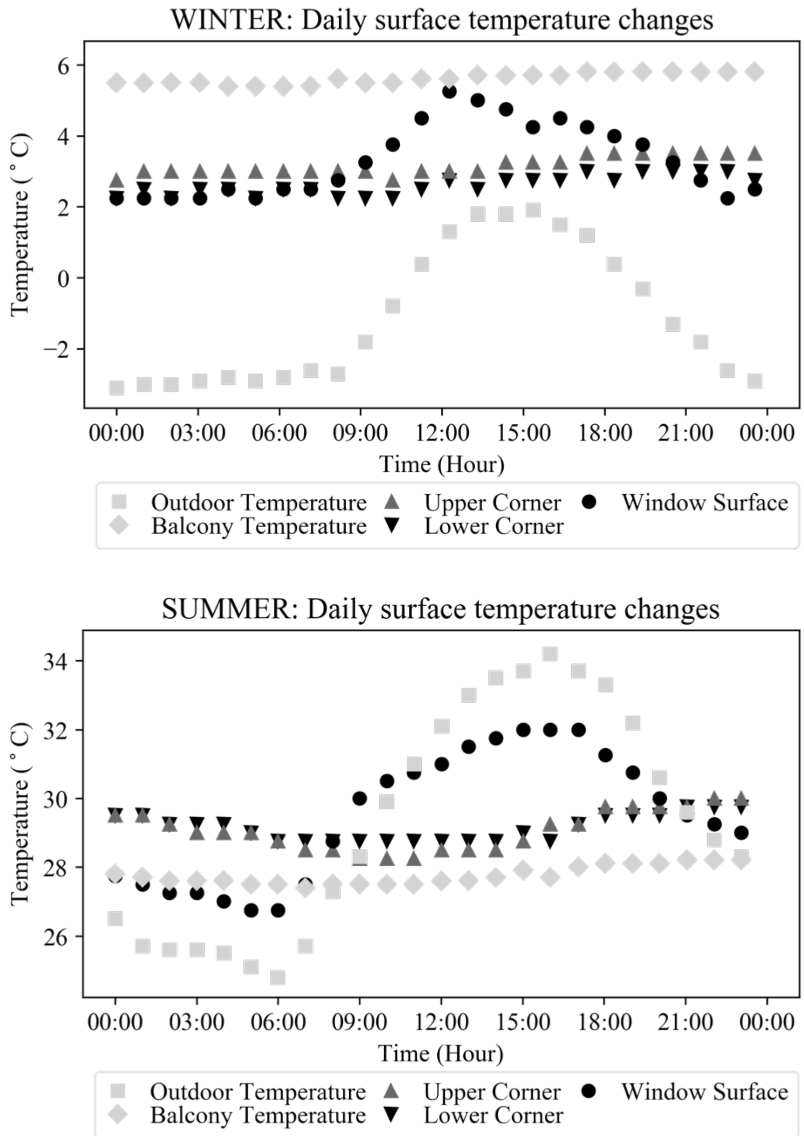


Figure 3. 8. Surface temperature changes in 24 hours

Table 3. 4. Condensation occurrence hours according to surface location

Season	*Lower Corner (hr)*	*Upper Corner (hr)*	*Window surface (hr)*	*Balcony door frame (hr)*	*Total (hr)*
Winter	48.5	36.5	149.8	2.1	163
Summer	0	0	10	0.5	10.5

3.2.2. The influence of the daily schedule on condensation

Along with the long period of monitoring in the occupied apartment unit, there was a daily activity schedule in the kitchen that influenced the condensation in the balcony space. This resulted in an easily recognized pattern that was categorized based on the data relating to condensation occurrence times and the schedule. During the winter monitoring period of 73 days (disregarding the days with missing data), condensation was found on 59 days, which accounts for almost 80% of the monitoring days. In Figure 3.9 an analysis of the daily condensation occurrence times is presented, showing that condensation was frequently detected around seven in the morning.

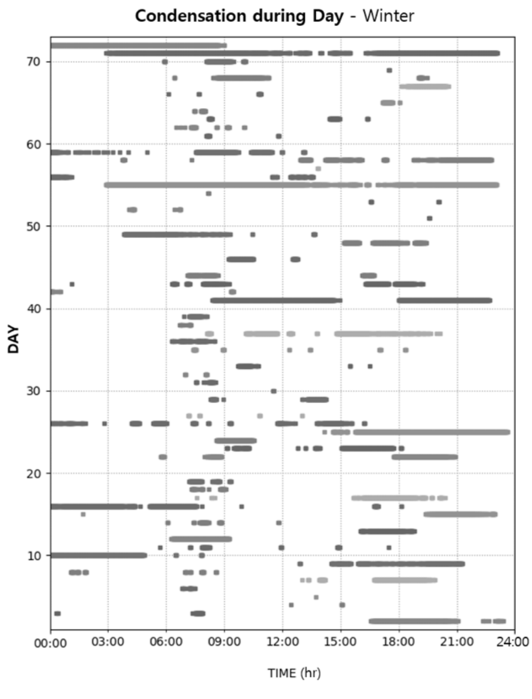


Figure 3. 9. Condensation occurrence by daily schedule according to monitoring period of winter

The balcony condensation had a high correlation with the use of the kitchen, especially when the kitchen was being used to prepare meals for the entire family. Figure 3.10 shows that the condensation usually occurred around seven in the morning (with 16 cases) and six at night (with 14 cases). However, during lunchtime, since the house was occupied by one adult and baby, the activity influence on the condensation problem was less than it was at breakfast and dinner times.

A closer look at the temperature and humidity changes in the morning and night schedule graph showed that the humidity fluctuated in the kitchen space, and when this happened it influenced the humidity of the balcony space. Figure 3.11 and Figure 3.12 represents the case in which the door was opened and the humidity changes by humidity transferred into the space.

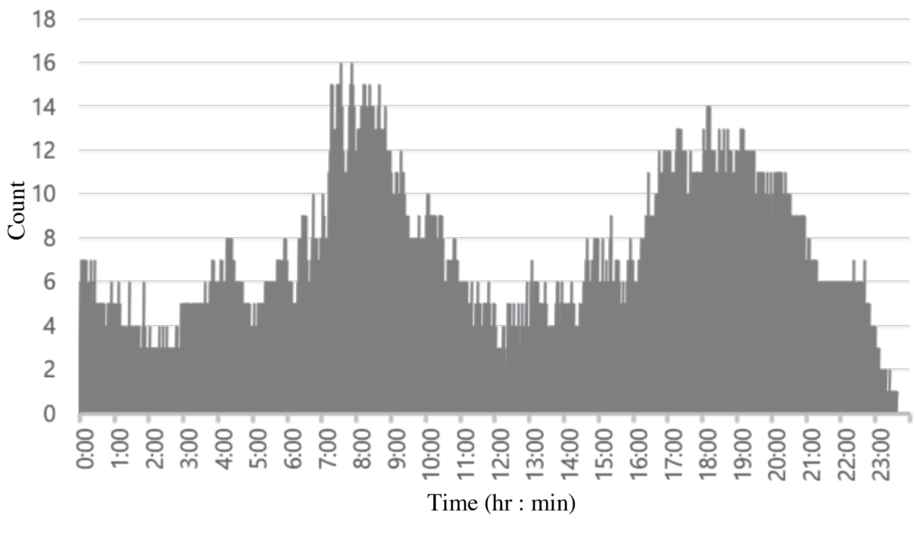
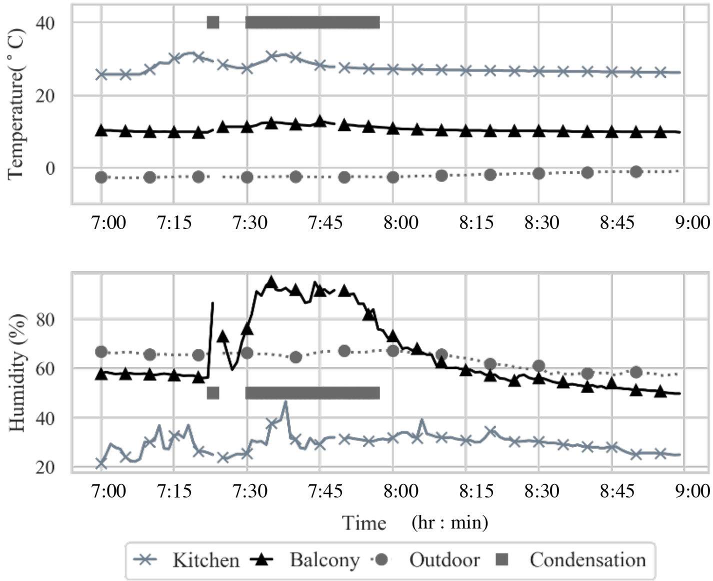
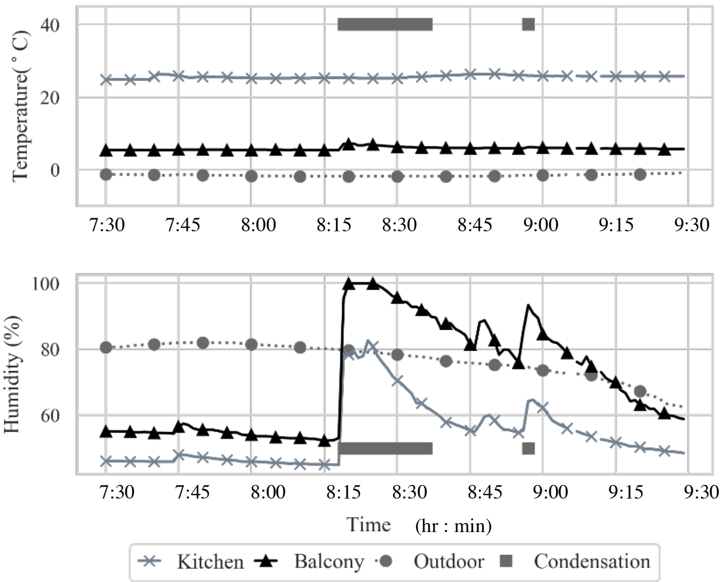


Figure 3. 10. The frequency of the condensation by time

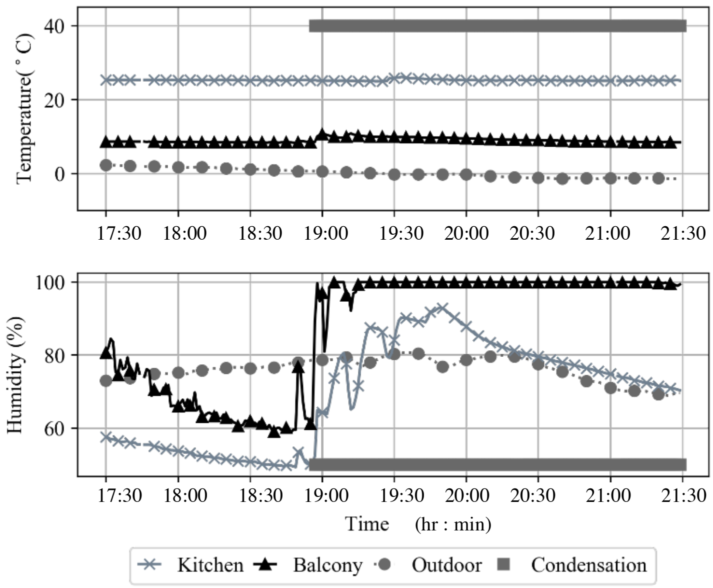


(a) Morning case 1

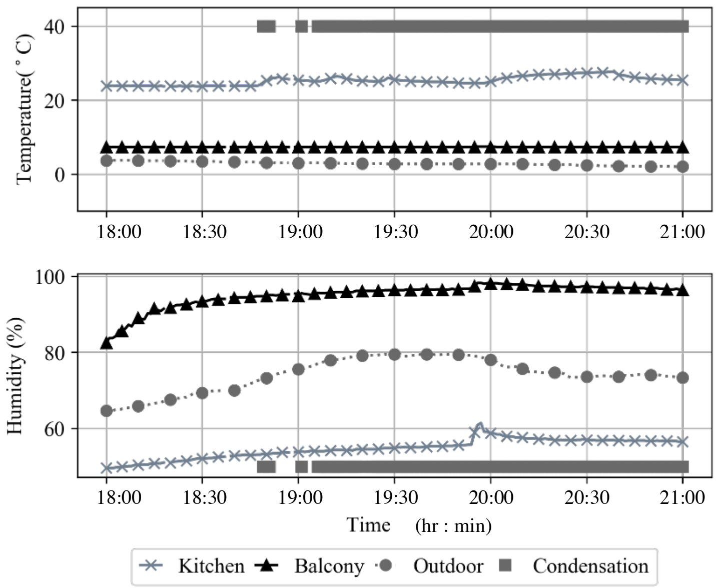


(b) Morning case 2

Figure 3. 11. Condensation occurrence with temperature and relative humidity changes during morning time



(a) Evening case 1



(b) Evening case 2

Figure 3. 12. Condensation occurrence with temperature and relative humidity changes during evening time

3.2.3 The influence of activity on condensation

The moisture generation activity in the balcony and the moisture transfer activity caused the increase of relative humidity, which caused the condensation. During the monitoring period, not only were temperature and humidity monitored but also, human activity in the balcony space was checked the by the sensors. Any time the balcony door opened or the window opened, it was detected by the magnetic sensors. The use of the washing machine located in the balcony space was also detected by the touch sensor applied to the "On" button on the washer. The washing machine was used at least once a week during the measurement period; this occurred mostly during the weekend or on holidays, as shown in Table 3.5. When the laundry touch sensor was touched for machine operation, the relative humidity increased immediately, as shown in Figure 3.13.

The moisture transfer from the kitchen space was caused by the balcony door opening when the warm air from the conditioned space entered the balcony with the high humidity. Although the balcony air temperature was also influenced by the kitchen temperature when the door was open, an increase in temperature was not sufficient to prevent condensation in the space. There were several cases reported for condensation occurring when the balcony door was opened or when there was activity in the area, as shown in Table 3.5. Figure 3.14 also shows that the condensation occurred when the balcony door was opened.

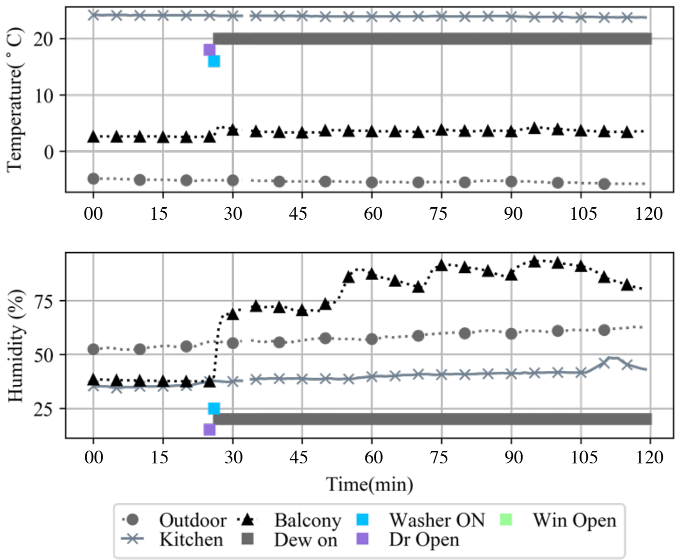


Figure 3. 13. Temperature and relative humidity changes related to equipment (washer machine) use inside the balcony

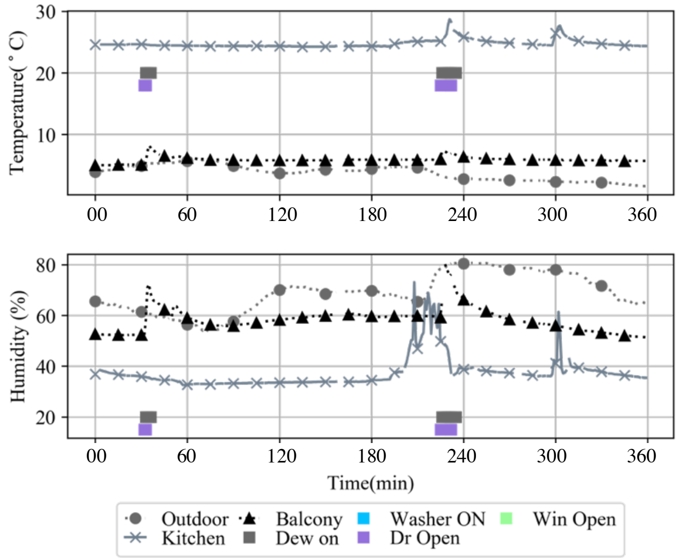
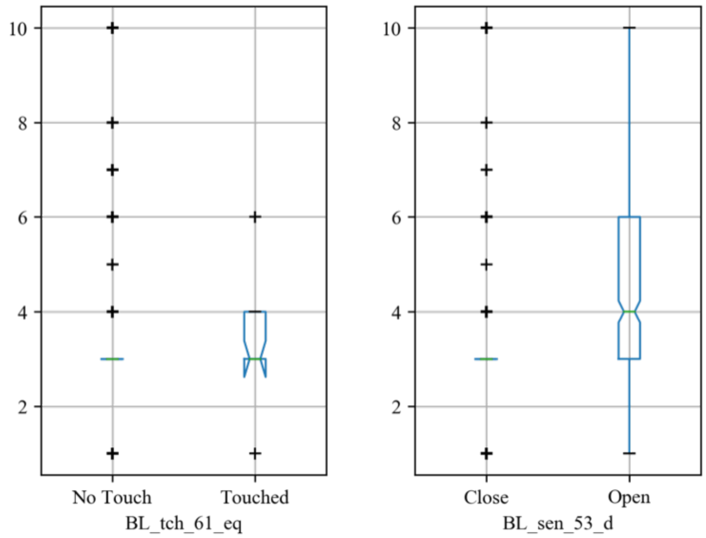


Figure 3. 14. Temperature and relative humidity changes near the door opening, with activity

Based on the data, there was a high correlation between condensation occurrence near the balcony door opening and the use of the washing machine. As shown in Figure 3.15, while condensation occurred, the magnetic sensor at the balcony door reported the door as being open. Also, Figure 3.15 b shows that the condensation occurred while the laundry machine touch sensor was touched for operation.



(a) Washer machine in use (b) Balcony door opened

Figure 3. 15. Boxplot result of condensation occurrence by the occupancy activity

The relative humidity inside the balcony space increased when the door opened and when the washing machine was used. As shown in Figure 3.16, when the sensor was touched and condensation occurred inside the balcony space, the relative humidity also increased in the same area. As shown in Figure 3.17, when the balcony door was opened and the condensation occurred inside the balcony space, the relative humidity also increased in the area.

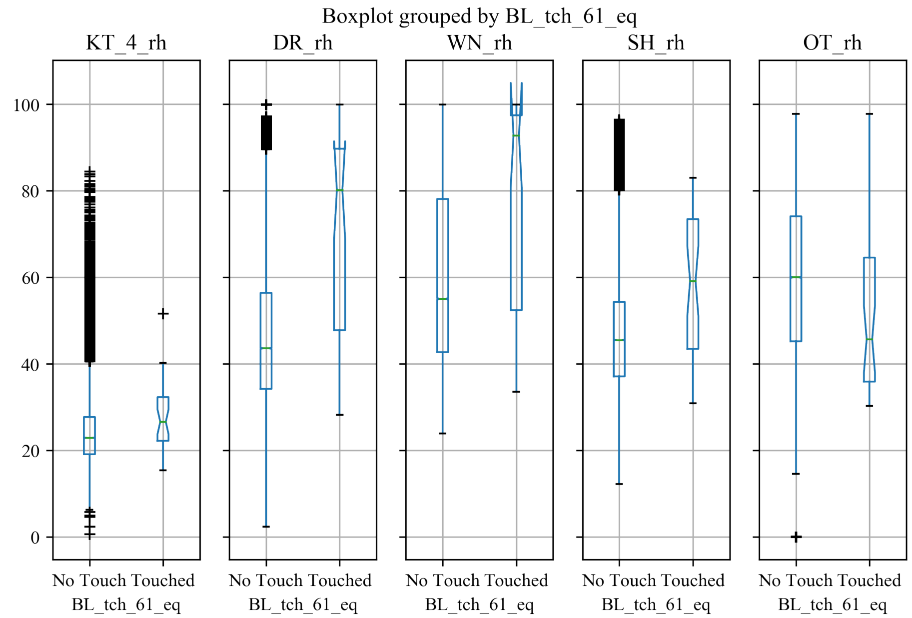


Figure 3. 16. Relative humidity change while the washing machine was in use

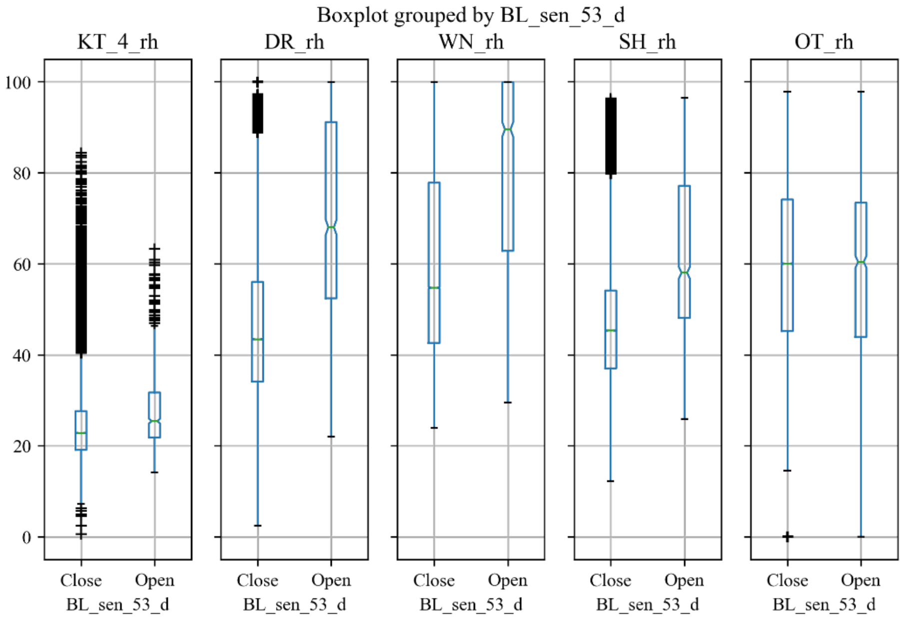


Figure 3. 17. Relative humidity change when it was detected that the balcony door was opened or closed

Table 3. 5. The timing of condensation detection when activities were recorded

	Condensation								
	Balcony door opened			Washing machine in use		Outdoor with high RH	Miscellaneous		
05/12/2018	06:00-09:00								
08/12/2018	06:00-09:00								
09/12/2018	16:00-20:00			20:00 - 00:00					
10/12/2018	00:00-03:00	06:00-09:00							
11/12/2018	14:00-16:00	16:00-18:00				18:00-00:00			
12/12/2018	06:00-09:00					00:00-06:00			
13/12/2018	12:00-13:00	15:00-16:00					05:50 - 06:00	18:00 - 19:00	
14/12/2018	06:00-12:00								
15/12/2018				15:00 - 21:00					
16/12/2018	07:00-10:00	12:00-13:00					06:00 - 07:00		
17/12/2018							02:00 - 03:00	20:00 - 00:00	
18/12/2018	05:30-09:00	17:30-18:30					00:00 - 05:30	10:00 - 11:00	19:00 - 20:00
19/12/2018				16:00 - 22:00			7:00-10:00		
20/12/2018	07:00-10:00								
21/12/2018	6:00-10:00								
28/12/2018									
29/12/2018	6:00-8:00	9:00-11:00		19:00 - 00:00					
30/12/2018				09:00 - 00:00					
31/12/2018				10:00 - 13:00					
01/01/2019				14:00 - 00:00					

	Condensation								
	Balcony door opened			Washing machine in use		Outdoor with high RH	Miscellaneous		
02/01/2019	04:00-10:00	12:00-13:00		00:00 - 04:00	13:00 - 18:00				
03/01/2019	06:00-09:00	13:00-15:00					11:00 - 12:00		
04/01/2019									
05/01/2019	07:00-10:00			12:00 - 16:00					
06/01/2019				11:00 - 13:00					
07/01/2019	06:00-09:00								
08/01/2019							06:00 - 09:00		
09/01/2019	15:00-17:00			09:00 - 12:00			17:00 - 18:00		
11/01/2019	07:00-10:00	12:00-14:00	17:00-20:00				14:00 - 15:00		
12/01/2019	06:00-10:00						06:00 - 07:00		
13/01/2019	08:00-09:30			10:00 - 23:00					
14/01/2019	06:00-18:00								
15/01/2019	06:00-09:00								
16/01/2019									
17/01/2019				09:00 - 18:00	18:00 - 00:00				
18/01/2019	09:00-10:00				00:00 - 03:00				
22/01/2019	06:00-11:00			16:00 - 21:00					
23/01/2019	07:00-10:00	17:00-18:00					17:00 - 18:00		
24/01/2019									
25/01/2019	12:00-15:00			08:00 - 12:00					
26/01/2019									

	Condensation								
	Balcony door opened			Washing machine in use		Outdoor with high RH	Miscellaneous		
27/01/2019				15:00 - 00:00					
28/01/2019	13:00-15:00						00:00 - 09:00		
30/01/2019	18:00-21:00								
31/01/2019	04:00-05:00	07:00-09:00							
01/02/2019	16:00-18:00	20:00-22:00							
02/02/2019							08:00 - 09:00		
03/02/2019				09:00 - 12:00			03:00 - 00:00		
04/02/2019	12:00-15:00			09:00 - 16:00					
05/02/2019	13:00-15:00								
06/02/2019	03:00-09:00	13:00-18:00							
07/02/2019				09:00 - 14:00					
08/02/2019									
09/02/2019	07:00-09:00	11:00-13:00							
10/02/2019	06:00-12:00								
11/02/2019	08:00-09:00	17:00-18:00		14:00 - 18:00					
12/02/2019	07:00-09:00								
13/02/2019				17:00 - 21:00					
14/02/2019	06:00-07:00	08:00-09:00	11:00-12:00						
15/02/2019							18:00 - 22:00		
16/02/2019	19:00-22:00			08:00 - 12:00			06:00 - 07:00		
17/02/2019	17:00-19:00								
18/02/2019	05:00-07:00			08:00 - 12:00					

	Condensation								
	Balcony door opened			Washing machine in use		Outdoor with high RH	Miscellaneous		
19/02/2019							03:00 - 00:00		
20/02/2019							00:00 - 09:00		

3.3. Control parameters derived from diagnosis

The control parameters derived from the diagnosis were categorized for the purposes of developing an application strategy. The author-defined prevention parameters were categorized into two groups: fixed parameters and occupancy parameters. The fixed parameter strategies were related to the existing solutions for condensation prevention, such as increasing insulation thickness and increasing the ventilation rate. Based on the analysis of the field measurements, the fixed parameters must be used in consideration of an increase in humidity inside the balcony. The occupancy parameters are determined by occupancy behaviors, such as controlling the parameters in response to the indoor conditions. With this category it was not necessary to define the limitation of the design criteria. However, occupancy parameters do require real-time responses for stopping the generation of moisture and blocking the moisture transfer.

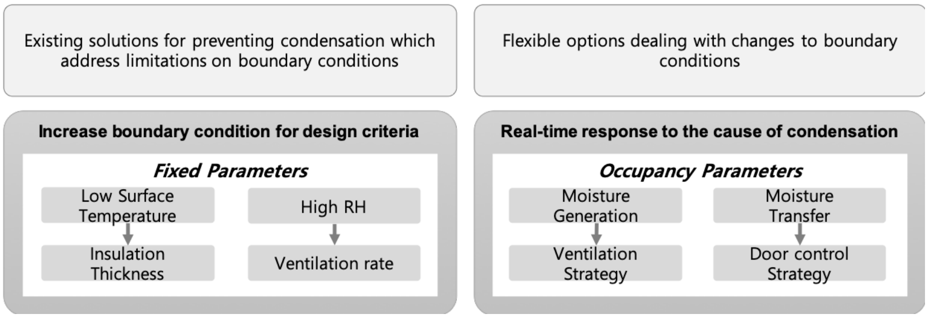


Figure 3. 18. Control parameters categorized as fixed and occupancy parameters

3.3.1. Fixed parameters

Based on a review of the literature related to balconies in Korea, it was found that architectural features as well as used spaces are vulnerable to condensation. Moreover, balcony spaces are not designed for the prevention of condensation based on occupants' activities. During the winter monitoring period, measured data indicated the condensation when the surface temperature value was below the dew point temperature of the nearby sensor.

With regard to applying an insulation panel on the wall adjacent to the outside, although the balcony's air temperature was also influenced by the kitchen temperature when the door was open, an increase in temperature was not sufficient to prevent condensation on the wall surfaces. The temperature of the balcony space was largely influenced by the thermal capacity of the concrete wall; consequently, the temperature quickly returned to the temperature of the space prior to opening the door, as shown in Figure 3.14. This occurred as the result of the influence of activity on rates of condensation.

In terms of providing ventilation to the balcony space, when the balcony door was open, the relative humidity immediately increased within several minutes and thereafter dispersed, as shown in Figure 3.14. However, the moisture content in the balcony space increased after several instances of opening the door, as shown in Figure 3.13; since the balcony is an airtight space, air does not remove the moisture transferred from the kitchen. As shown in the monitoring results balcony space increased the relative humidity more than 90%. Fixed parameter values provided the required amount of CMH value for the space.

3.3.2. Occupancy parameters

The condensation control parameters concluded with the field measurements indicating that the balcony door is an effective mechanism for controlling the occurrence of condensation. As shown in Figure 3.15 (b) cases, condensation was reported when the balcony door was opened. Condensation may be successfully prevented when the door is kept closed while the neighboring space is in use and thereby generating moisture.

Providing ventilation to the balcony space during times of increased relative humidity is necessary. Adequate ventilation, such as can be realized by opening the window or turning on the fan temporarily, reduces the condensation risk. Occupancy parameters require an adequate among of time and the right situation for introducing ventilation.

3.4. Summary

Based on the precedence literature study showed that the balcony in Korea is vulnerable for condensation by architectural feature and how it is used by tenant. Besides the factors of the architectural feature causing the condensation, in this section diagnose the occupancy influence affecting the cause of the condensation on the balcony space to derive the control parameter.

This chapter diagnose the occupancy influence affecting the cause of the condensation on the balcony space to derive the control parameter. Besides the factors of the architectural feature causing the condensation, which is already defined from the precedence literature study, diagnose the moisture influence by the tenant activities. The field measurement taken at the typical Korean apartment unit located in Sejong City, South Korea with occupancy condition.

Seasonal influence – influence by the outdoor condition:

The condensation occurred in balcony space during the monitoring period of winter. However, during summer the frequency of condensation is comparatively minimum than winter period and the condensation only found on the window surface during summer. During winter the temperature and humidity difference among the outdoor and conditioned kitchen space which makes balcony space unstable condition for create condensation.

Occupancy activity influence:

Condensation occurred related with the occupancy activities from the conditioned space. Based on the monitoring analysis, there is correlation between kitchen activities with the condensation occurrence on the balcony space. During the monitoring period, the condensation frequency detected in the morning for breakfast and night for dinner which is the schedule when the kitchen is actively used. Also, the humidity increase situation is also involved with the moisture generation in the balcony space that the relative humidity inside the balcony space increased when the washer machine on/off sensor is touched

Control parameters:

The control parameters derived from the measurement monitoring were categorized into two groups: fixed parameters and occupancy parameters. Fixed parameter strategies were related to the existing solutions for condensation prevention, which includes applying insulation and ventilation. This condensation strategy which address limitations on boundary conditions. The occupancy parameters are determined by occupancy behaviors, such as dealing with changes to boundary conditions to control door and moisture transfer strategy.

Chapter 4. Evaluation of Control Parameters

4.1. Evaluation of fixed parameters
4.2. Evaluation of occupancy parameters
4.3. Limitation of control parameters and occupancy parameters
4.4. Summary

The balcony is designed as an unconditioned space; however, the use of space during the winter period introduces the possibility of condensation, based on the monitoring results. Application of rigorous design criteria for the use of insulation panels or the rate of ventilation is recommended. Also, controlling the opening and closing of the balcony door and windows and removing the moisture inside the balcony space is suggested. These are related to occupants' control. In this chapter, those two categorized condensation strategies are evaluated. The fixed parameters were evaluated by the simulation model and the occupancy parameters were evaluated by the site experiments.

4.1. Evaluation of fixed parameters

In order to find an appropriate design for preventing condensation, the proper parameter values were defined based on the field measurements, and then they were evaluated with a simulation model. It is necessary to know the proper insulation thickness and ventilation rates that were derived, based on previous field measurements of moisture activity gathered daily during the winter.

In this section, the existing strategy, which is to apply insulation panels and employ ventilation, is assessed with respect to humidity produced by occupants' activities. The assumed daily moisture generation rate in the simulation was based on the moisture production rate used in the field measurements for the onsite diagnosis. The assessment was conducted during winter (December to February) to ascertain the effectiveness of reduced condensation occurrence times.

4.1.1. Simulation model setup and validation

The parameters from the onsite diagnosis were evaluated using a simulation model to find an appropriate design value for preventing condensation due to the generation of moisture. We used EnergyPlus 8.6.0 for the simulation model, which was built based on conditions previously obtained through field measurements. The field-measured space was modeled instead of the entire building; the temperatures of the floor and ceiling were assumed to be influenced by the temperatures on the other side of each surface. Furthermore, the balcony and its neighboring spaces (the kitchen, duct space, and plant room) were modeled and connected to allow for the exchange of energy and mass according to the energy balance and mass balance models in Equations (1) and (2)[33] In addition, the unheated spaces, such as the duct space and plant room, were modeled to mimic the influence of buffered exterior temperatures on the balcony space. The mass balance model of Equation (2) includes a term reflecting the diffusion of moisture through the wall; however, this term was excluded because the balcony wall of the studied unit was solid concrete, and thus, this term did not affect the simulation of indoor conditions over a seasonal period.

Each room was connected by an airflow network formed by the air pressure difference. In particular, the kitchen and balcony were connected by an airflow network formed by the door opening, which is given in Equation (3)[34]. Air leakage through the wall between the shaft space and the plant room is almost nonexistent because the wall constructed between these spaces is concrete, which eliminates leakage. The value of the discharge coefficient (C_d) in Equation (3), which is the calibrating coefficient, is between the theoretical value and the actual measurement: We used Riffat's equation[35] shown in Equation (4), to compute the

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33 Energy Plus, "Energy Plus Engineering Reference," *Building Technologies Program, US Department of Energy: Washington, DC, USA* (2013).

34 Ibid.

35 SB Riffat, "A Study of Heat and Mass Transfer through a Doorway in a Traditionally Built House," *ASHRAE Trans* 95, no. 2 (1989).

value of this coefficient. The equation is applicable to natural ventilation conditions and is based on the temperature difference between two rooms:

$$F_i C_{z,i} \frac{dT_{z,i}}{dt} = \sum_{j=1}^{N_{i,g}} F_{gain,j} \dot{Q}_{i,j} + \sum_{j=1}^{N_{i,sur}} h_{i,j} A_j \left(T_{s,j} - T_{z,i}\right) + \sum_{j=1}^{N_{i,\,AFN}} \dot{m}_{AFNi,j} C_p (T_{z,j} - T_{z,i}) + \sum_{j=1}^{N_{i,\,HVAC}} F_{HVAC,j} \dot{m}_{sup,i,j} C_p (T_{sup\,j} - T_{z,i}) \tag{1}$$

$$F_i M_{z,i} \frac{dW_{z,i}}{dt} = \sum_{j=1}^{N_{i,g}} F_{gain,j} \dot{Q}_{i,j} + \sum_{j=1}^{N_{i,sur}} h_{M,j} A_j \left(W_{s,j} - W_{z,i}\right) + \sum_{j=1}^{N_{i,\,AFN}} \dot{m}_{AFNi,j} C_p (W_{z,j} - W_{z,i}) + \sum_{j=1}^{N_{i,\,HVAC}} F_{HVAC,j} \dot{m}_{sup,i,j} (W_{sup\,j} - W_{z,i}) \tag{2}$$

$$\dot{m} = C_d \theta \int_{z=0}^{z=H} \rho v(x) W dz \tag{3}$$

$$\dot{m} = C_d \theta \int_{z=0}^{z=H} \rho v(x) W dz \qquad (4)$$

The simulation model was validated by comparing the field-measured data under the existing, nonactive condition and those under the moisture-generation condition. The field-measured data were collected at night (11:00 p.m. to 6:00 a.m. local time), and the results from the simulations agreed well with the measured data, as shown in Figure 4.1. The energy balance simulation refers to the measured result, almost the same as that shown in Figure 4.1(a). The humidity results showed a difference range of 10% relative humidity, as indicated in Figure 4.1(b). The mass balance simulation model was based on the result of a one-node, fully mixed condition, while the actual humidity changes were due to local air pressure and air temperature differences. However, the simulation results of humidity changes followed the tendency of the measured results, and the difference was within 10% relative humidity, thus validating their use in simulation.

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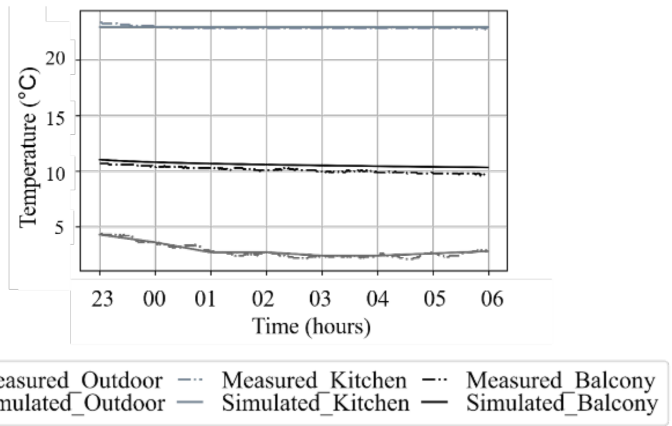
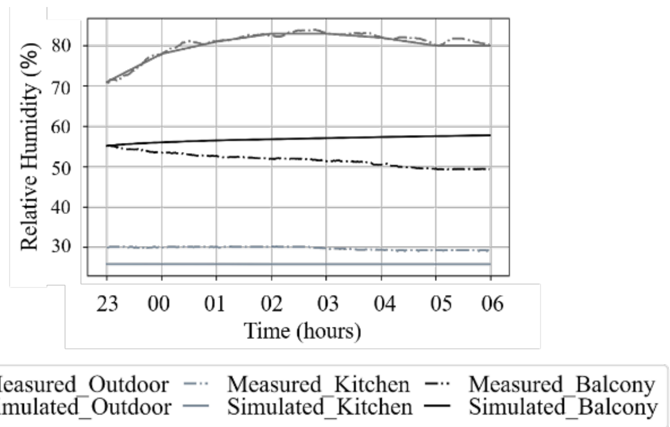


(a) Temperature for validating the energy balance model



(b) Humidity for validating the mass balance model

Figure 4. 1. EnergyPlus model validation

The moisture transfer simulation was validated. Moisture generation was simulated using steam equipment inputs in EnergyPlus 8.6.0, which allows for adjusting the ratio of sensible heat and latent heat to provide the moisture production rate. Steam equipment operation in the kitchen zone occurs by the schedule file applied in the same manner as with the measurement experiment. As shown in Figure 4.2, moisture was transferred to the balcony space, increasing the absolute humidity inside the area during times when the door was open.

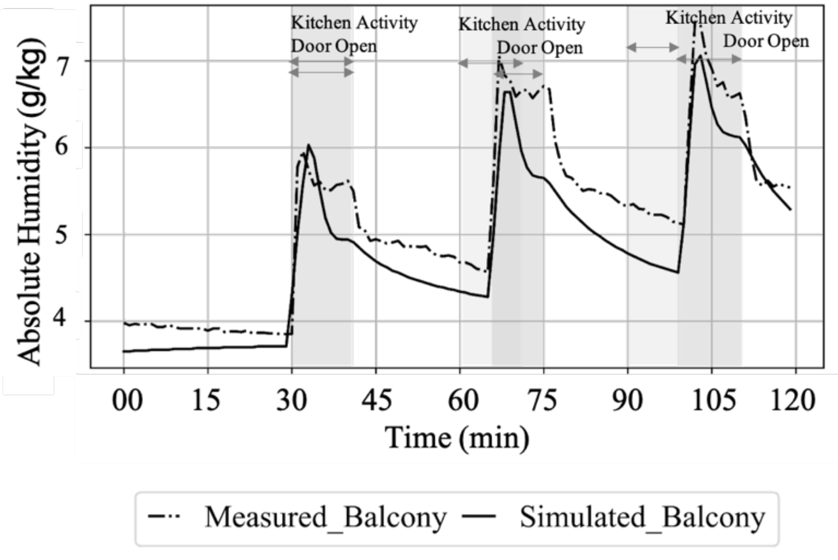


Figure 4. 2 . Absolute humidity for validating the moisture transferred by the airflow network

4.1.2. Insulation thickness evaluation

The application of insulation panels reduced the influence of the exterior temperature on the wall when applying the same properties of the insulation panel to the conditioned space. As shown in Figure 4.3, the reduction effect ceased to increase when the insulation thickness exceeded 80 mm. The tested insulation material was a polystyrene insulation panel with a conductivity of 0.032 W/mk that is popularly used in Korean buildings; moreover, the indoor air-conditioned spaces at the field measurement site were equipped with this type of insulation, with a thickness of 85 mm. However, condensation was still observed on window surfaces.

As shown in Figure 4.4, using a ventilation strategy in the balcony space was effective for both the wall and the window in reducing the duration of condensation. Ventilation rates ranging from 0 CMH to 120 CMH were applied during the evaluation; 90 to 110 CMH is the conventional range of ventilation rates applied to bathrooms in Korean residential buildings. The results revealed that higher ventilation rates may eliminate the condensation risk in the balcony space.

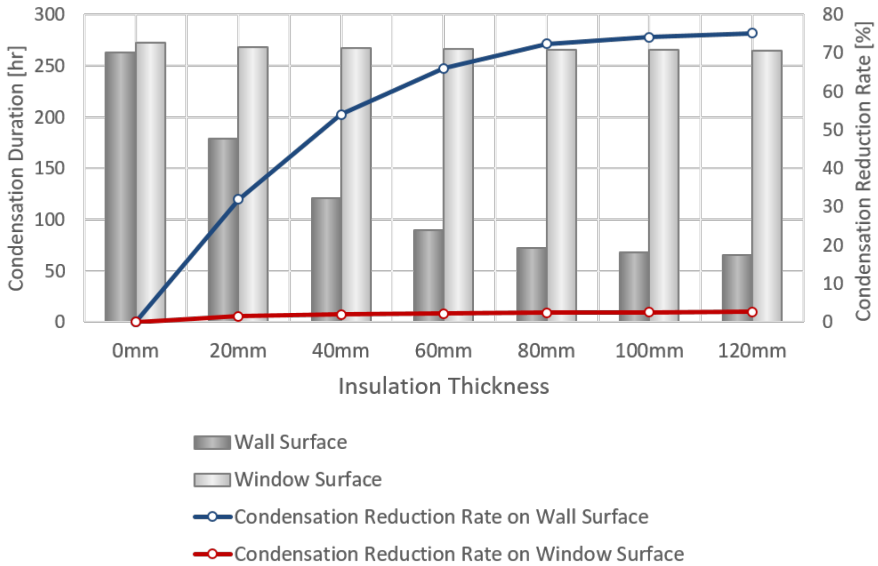


Figure 4. 3. Influence of insulation thickness on condensation duration (in hours) on the north-facing wall surface and window surface during winter, and the condensation reduction success rate.

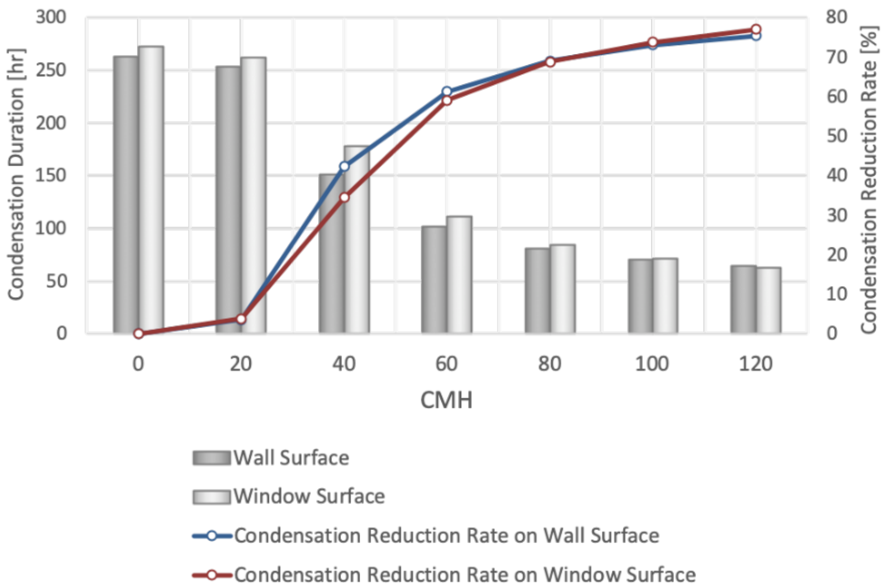
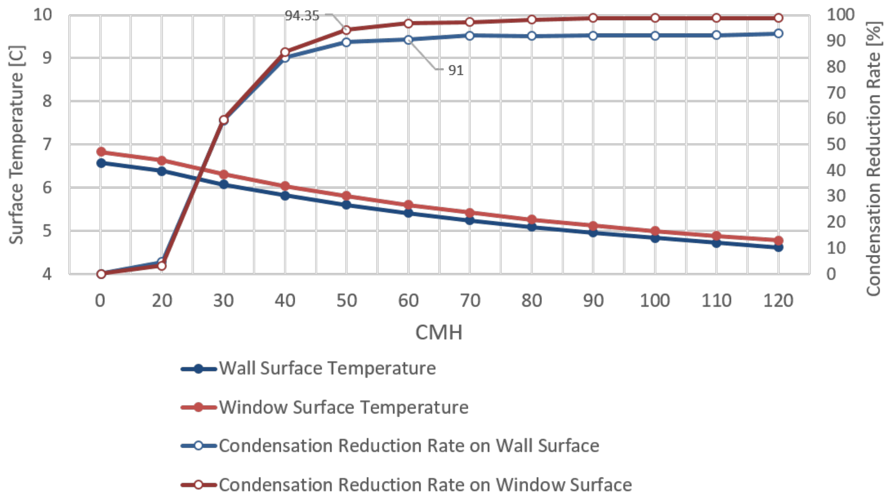


Figure 4. 4. Ventilation rate influence on condensation duration (in hours) on the north-facing wall surface and window surface during winter, and the condensation reduction success rate.

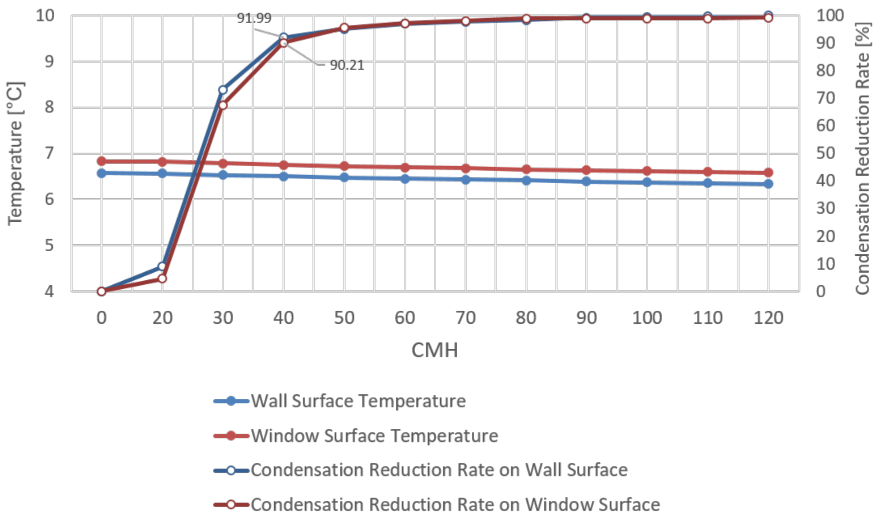
4.1.3. Ventilation rate evaluation

A simulation was also conducted to examine the effectiveness of the proposed condensation prevention method and to investigate the changes in surface temperature due to continuous or intermittent ventilation. Intermittent ventilation was scheduled to begin upon the transfer of moisture. As shown in Figure 4.5 (a), the surface temperature dropped when the constant ventilation rate increased, but as shown in Figure 4.5 (b) intermittent ventilation did not cause a decrease in the surface temperature.

While continuous ventilation uses the lower outdoor temperature to cool down the surface of the balcony wall, intermittent ventilation thermally separates the outdoor space and the balcony. To achieve a 90% comprehensive reduction in condensation by the use of continuous ventilation, a ventilation volume of 60 CMH was the result of simulation for the window and wall, as shown in Figure 4.5 (a). With intermittent ventilation, 40 CMH was the result of the simulation for both the wall and the window, to achieve the same condensation prevention effect, as shown in Figure 4.5 (b).



(a) Constant ventilation



(b) Intermittent ventilation

Figure 4. 5. North-facing wall surface and window surface temperatures during winter with condensation reduction success rate

4.2. Evaluation of occupancy parameters

The occupancy parameters evaluation was done by using the site experiment to determine its effectiveness. There was a limitation to the evaluation with the use of the simulation model because the simulation model review excluded the balcony door control parameter. The reason was, it was not a countable parameter value for building physical models during the design stage, and it was difficult to provide a meaningful result using the forward simulation model, which would have required the consideration of unpredictable occupancy patterns. This experiment was set up to imitate the effectiveness of controlling the door for moisture transfer and vapor removal by the ventilation.

4.2.1. Onsite experiment setup

The investigation was conducted on a north-facing balcony during a period of heating. During the experiment, the temperature of the indoor living space, including the kitchen area, was set to 25 °C, while the outdoor average temperature was approximately 4 °C. Temperature and humidity were measured every 60 seconds during the investigation; information on the sensors employed in the experiment and data on the accuracy of the measuring instruments are shown in Table 4.1. The layout of the measuring points is shown in Figure 4.7 Surface temperatures were measured on the window surface, the north-facing wall, the corner joint of the north wall, and the wall surface adjacent to the outer door. Condensation was determined by the dewpoint temperature, which was calculated from the measured temperature and humidity in the balcony space and then compared with the measured temperature on the lowest surface. In this step of the process, we considered the influence of moisture when moisture was produced due to either the neighboring space or the balcony space being used. To mimic the influence of occupants' behaviors in the vacant unit used for this simulation, a portable gas stove was used to boil water in the kitchen, while the humidifier was located in the balcony space.

Table 4. 1. Measurement instrument information

Measured Element	Field Measurement Instrument	
	Main Unit	Sensor
Zone Air	Data Logger Model SK-L200THIIa	SK-LTHIIa-2 w/Sensor cord Temp: ± 0.5 °C at 15.0 °C to 35.0 °C Humidity: ± 3% relative humidity at 15.0 °C to 35.0 °C (30% to 90% relative humidity)
Wall Surface	National Instrument Device	T-type (Copper/Constantan) Thermocouple

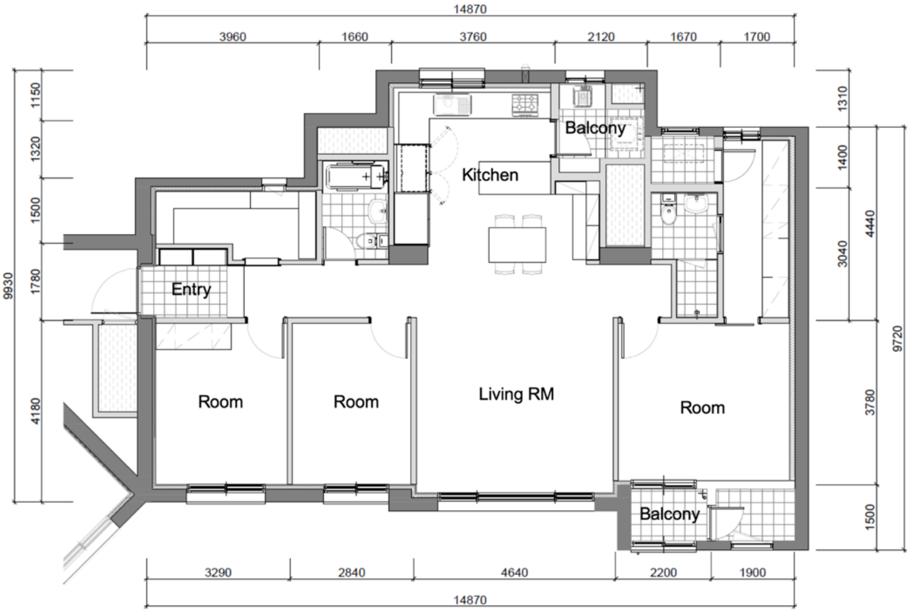


Figure 4. 6. Floor plan of the field experiment unit in Incheon, Korea

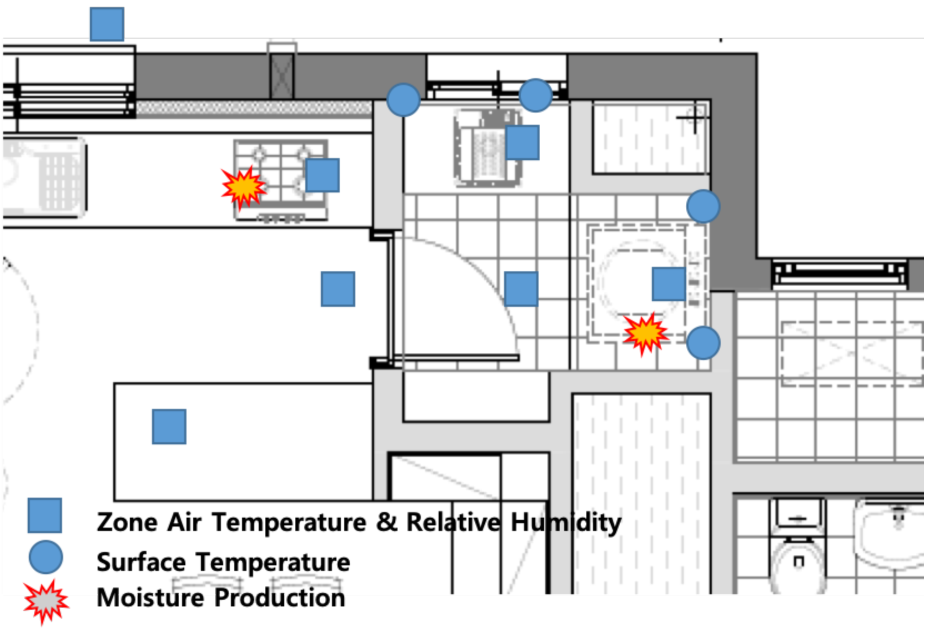


Figure 4. 7. Sensor and moisture generation equipment location for onsite experiment

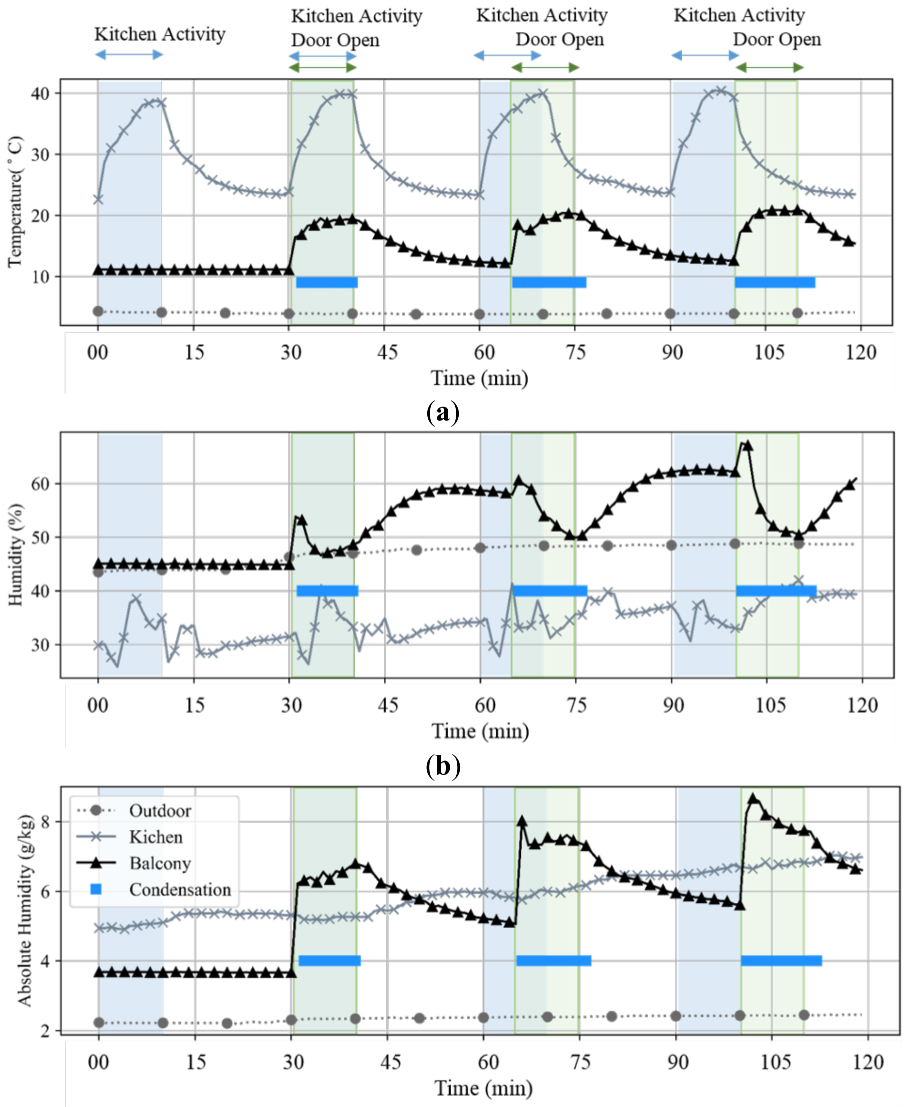
(a) (b)

Figure 4. 8. Experiment set up with sensors (a) Field measurement site view to balcony; (b) Field measurement site view to Kitchen

4.2.2. Moisture transfer control evaluation

In this experiment examined how the transfer of moisture from kitchen activities influenced the balcony space according to whether the balcony door was open and closed. In all the cases shown in Figure 4.9 (a) and (b), the temperature and relative humidity on the balcony were not influenced by whether the balcony door was closed. However, as shown in Figure 4.9 (b), when the balcony door was open during the times of kitchen activity, the relative humidity increased within three minutes and was dispersed; condensation was then reported. The moisture content in the balcony space increased after several door opening activities, as shown in Figure 4.9 (c); the balcony is an airtight space that does not flush out the moisture which is transferred from the kitchen.

The balcony air temperature is also influenced by the kitchen temperature when the door is open. However, the increase in temperature is not high enough to prevent condensation on the surface wall. The zone air temperature increased rapidly, and the increase became gradual until the door was closed to cut off the influence from the kitchen space, as shown in Figure 4.9 (a). The temperature of the balcony space was influenced more by the thermal capacity of the concrete wall component, and the temperature immediately went back to the initial temperature, which existed prior to the activities for which the door was opened.



(c)

Figure 4. 9. Moisture transfer by door control experiment to evaluate condensation prevention: (a) temperature; (b) humidity; and (c) absolute humidity.

4.2.3. Moisture removal evaluation

Korean balconies are designed as a sub-kitchen and laundry room, and moisture production activities causes the problem of condensation in the balcony space. However, even with a moisture-generating activity, providing adequate ventilation by opening the window or turning on the fan may reduce the condensation problem. As shown on Figure 4.10, when moisture was generated inside the balcony space, the relative humidity increased from 45% to 95%. However, as shown on Figure 4.10, opening the window was an effective way to reduce the condensation problem within the space. When the window was opened, the dew point temperature decreased as the influence of the window infiltration on relative humidity decreased. However, at the same time, when the window was opened, the surface heat coefficient was temporarily influenced by the outdoor condition, indicating the possibility of reducing the surface temperature by constant ventilation.

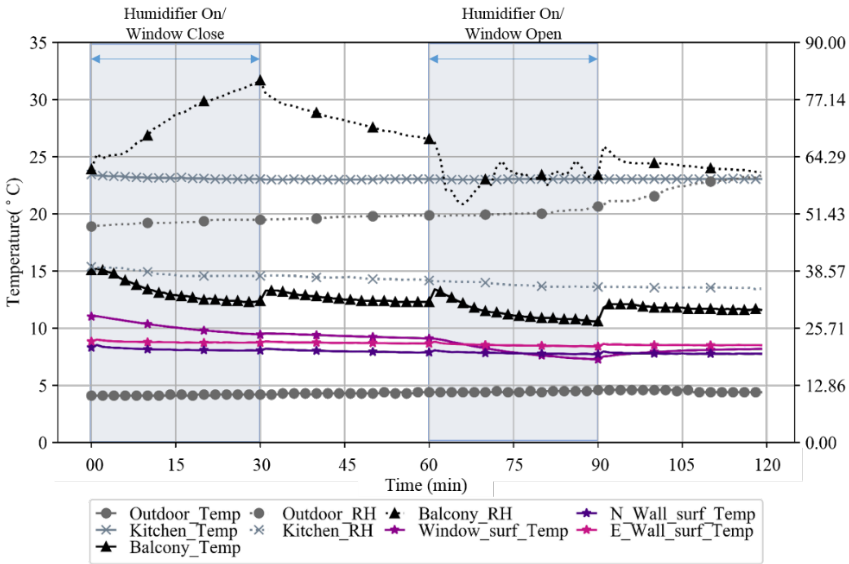


Figure 4. 10. Moisture generation and removal by natural ventilation experiment

4.3. Limitations of control parameters and occupancy parameters

Designing a balcony space with the determined fixed parameters values will successfully prevent condensation in the balcony area. Ventilation is more effective than insulation. In addition, the intermittent ventilation strategy was more effective than continuous ventilation. The assumed daily moisture generation rate in the simulation was based on the moisture production rate used in the field measurement for the onsite diagnosis. The existing condensation prevention strategies involving insulation and ventilation are typically considered during the early design stage for coping with foreseen occupancy conditions. Nevertheless, many unknown factors are related to occupancy that limit the average moisture generation rate; hence, the design parameters may not be reliable or may require further adjustment according to different households and lifestyles. Therefore, the required insulation thickness and ventilation rate will vary based on the dynamics of the occupancy pattern.

The condensation control parameters diagnosed from the field measurements indicated that controlling the opening and closing of the balcony door is an effective mechanism for reducing the occurrence of condensation. Additionally, the parameters determined via the simulation showed that intermittent ventilation is more effective than continuous ventilation. These two settings can be handled by a unit's occupants. However, occupancy parameters with these solutions cannot be suggested as design solutions. The reason is, it is difficult to guarantee constant results because occupants may sense things differently (and sometimes incorrectly), and thus, intermittent condensation may occur. Nevertheless, the IoT is able to collect data from sensors to determine the situation for implementing this strategy.

4.4. Summary

This chapter evaluates the control parameters for validation of condensation prevention strategy. The fixed parameter strategies are conventional way of designing the condensation free building strategy in building engineering. On the other hand, the occupancy parameters are required for tenants to change their habits of lifestyle for prevent the condensation. In this chapter those two different categorized parameters are assessed by the EnergyPlus simulation model and onsite experiments.

The result of solid parameter performance – Insulation Thickness:

The simulation model result provides that increasing the thermal resistance is effective for reducing condensation on the north-facing wall. The condensation reduction effectively slows down when the insulation thickness reaches up to 80mm which requires a similar standard of insulation thickness as the heated space of the site. The application of the insulation panel reduces the influence of the outdoor space on the wall, thereby reducing condensation; however, the problem remains on the window surface.

The result of solid parameter performance – Ventilation Rate:

The ventilation strategy both effectively reduce the condensation risk on the wall and window surface. The ventilation rate is applied from 0 CMH to 120 CMH to perform the simulation evaluation. Ventilation rate of 90 to 110 CMH is the conventional size applied on the bathrooms in Korean residential buildings. In the case simulation with the accessed space requires up to 120 CMH for reduce the condensation occurrence times.

The simulation also conducted to examine the effectiveness of the continuous or intermittent ventilation of balcony space. The intermittent ventilation thermally separates the outdoor space and the balcony while continuous ventilation lowers the surface temperature while plashing out the moisture to the outdoor space.

The result of occupancy parameter performance – Controlling the door and remove generated moisture:

The occupancy parameters are confirmed its effectiveness of reducing the risk of condensation by the experiment measurement of balcony door control. When the balcony door was open during the time of kitchen activity, the relative humidity increased to create condensation inside the space. Although the kitchen space is in use for moisture production activities with door closed case shows that the balcony space is safe from condensation. Also, the experiment confirmed that moisture removal activity with natural ventilation while the balcony space is used for moisture generation, reduce the risk of condensation.

Both of the fixed and occupancy parameter strategies shows the result of reducing the condensation risk inside the balcony space. Nevertheless, many unknown factors are related to occupancy to varies the moisture generation rate which may cause fail of fixed parameter solution. Since the occupancy parameter control connects with the moisture production rate by the occupancy activity that the strategy ensures to reduce the risk of condensation.

Controlling of the occupancy parameter provides the result effectively reduce the risk of condensation with occupant's awareness. Unless there are engineering design solution connectivity between the occupancy parameter control and occupant's awareness the occupancy parameter strategy cannot be suggested as design solution. However, there is the Internet of Things which able to connects the occupancy parameters to control the parameters by automation and without occupancy awareness.

Chapter 5. Application of the Internet of Things for condensation control

5.1. Application of the Internet of Things
5.2. The Internet of Things experiment setup
5.3. The algorithm based on the occupancy parameters
5.4. Summary

5.1. Internet of Things (IoT) application

The growing trend of IoT technology provides us with a new approach for improving the quality of indoor environments. The IoT was developed with the proliferation of wireless sensor networks in which sensors, actuators, and the internet framework were used to form a smart environment. Recently, many researchers have tried to apply IoT techniques and applications to uses in residential and commercial buildings to investigate its effectiveness and potential for more widespread use.

5.1.1. The concept of the Internet of Things

The concept of the IoT, which involves everyday objects in our surroundings, is one that includes the ability to continuously collect data for understanding the complexity of the environment. Meanwhile, humans are incapable of doing the same, based on the limits of time, interest, and accuracy. The IoT provides the potential for analysis of the overlooked surrounding conditions and suggesting a solution.

IoT was first introduced by Kevin Ashton in 1999 as part of an application for supply chain management.[36] It has been further developed and extended beyond the scope of radio frequency identification (RFID) technologies[37]. Although the term "the Internet of Things" has become more and more widely used, there is fuzziness about the definition and subsequently, a lack of understanding about it. This is because its variations are the result of the blurring of products and technologies involved. Terms which are used interchangeably with "the Internet of Things" include "ambient technology," "ubiquitous technology," "sensor web," "sensor network," "wireless sensor networks," "smart dust," "smart cities," "smart data," "smart grid," "cloud data," and "Object Naming System."[38] As technology has evolved, the definition of "the Internet of Things" has changed, but its main goal of understanding information on a computer without human intervention is the same.[39] As shown in Figure 5.1, the IoT is implemented through information transmission, analysis, and

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36 Gubbi, J., et al. (2013). "Internet of Things (IoT): A vision, architectural elements, and future directions." Future generation computer systems **29**(7): 1645-1660.

37 Felix Wortmann and Kristina Flüchter, "Internet of Things," *Business & Information Systems Engineering* 57, no. 3 (2015).

38 E Anzelmo et al., "Discussion Paper on Internet of Things, Commissioned by the Institue for Internet and Society," (Berlin, 2011).

39 Gubbi et al.

application using the existing internet standards and information acquisition methodologies as well as interactions with the physical world through detection of the surrounding environment involving a network of interconnected objects.

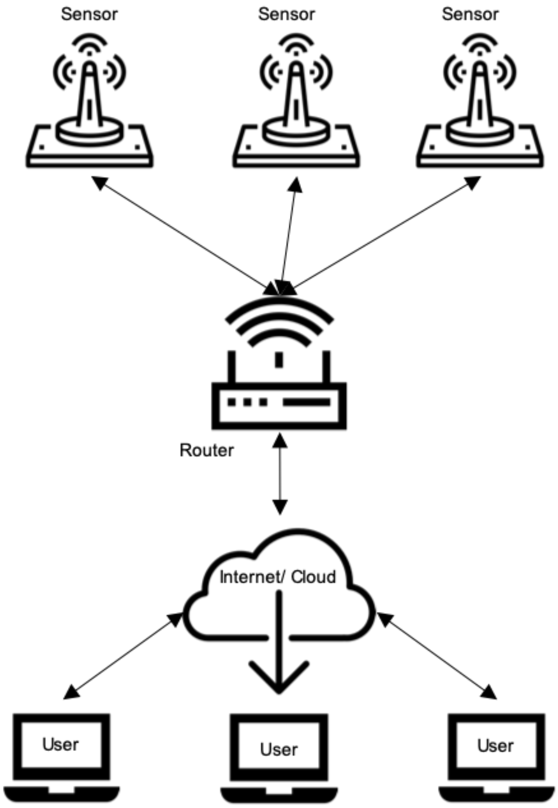

Figure 5. 1. Concept diagram of Internet of Things

5.1.2. Application cases involving the Internet of Things

The use of the IoT has been inclusive, covering a wide range of applications in healthcare, utilities, transport, etc. Sensor technologies provide possibilities for coping with and remedying building uncertainties by collecting measured data. In particular, the IoT is developing rapidly due to the proliferation of wireless sensor networks.[40] The IoT makes it possible to analyze massive amounts of data and to control the environment. Recently, the threshold for constructing ubiquitous sensors was lowered to establish an IoT concept of the measured environment, which enabled researchers to customize their own devices. Moreno et al.[41] presented a building automation platform to monitor energy consumption based on occupants' behaviors. Bashir and Gill[42] demonstrated a control strategy for oxygen pumps, fire alarms, and lights with virtual sensors using Python code, which can be implemented in real oxygen pumps and fire alarms in the future. Pocero et al.[43] presented an IoT metering device for school buildings and applied an open-source IoT infrastructure to develop a low-cost solution for monitoring energy consumption in indoor environments. Tang et al.[44] presented a smart home

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[40] Gubbi, J., et al. (2013). "Internet of Things (IoT): A vision, architectural elements, and future directions." Future generation computer systems **29**(7): 1645-1660.

[41] Moreno, M., et al. (2014). "How can we tackle energy efficiency in iot basedsmart buildings?" Sensors **14**(6): 9582-9614.

[42] Bashir, M. R. and A. Q. Gill (2016). Towards an IoT big data analytics framework: smart buildings systems. 2016 IEEE 18th International Conference on High Performance Computing and Communications; IEEE 14th International Conference on Smart City; IEEE 2nd International Conference on Data Science and Systems (HPCC/SmartCity/DSS), IEEE.

[43] Pocero, L., et al. (2017). "Open source IoT meter devices for smart and energy-efficient school buildings." HardwareX **1**: 54-67.

[44] Tang, S., et al. (2017). "Development of a prototype smart home intelligent lighting control architecture using sensors onboard a mobile computing system." Energy and buildings **138**: 368-376.

lighting system with the ability to leverage sunlight to conserve electricity; the system was developed and evaluated using an Arduino-controlled luminaire with a Raspberry Pi main board controller.

5.2. The Internet of Things experiment setup

Sensors, actuators, and the internet framework are used to form a smart environment; this is referred to as the IoT.[45] We implemented the IoT strategy experiment in a typical third-floor Korean apartment, shown in Figure 5.2. Radiant floor heating is conventionally used in Korean residences, and each apartment unit is individually heated by this system, excluding the balcony area. The temperature of the indoor living space, including the kitchen area, was set as 25 °C while the outdoor average temperature was about 4 °C during the experiment.

5.2.1. Microprocessor device setup with wireless communication

Author used a Raspberry Pi 3 Model B as a microprocessor to create own sensor device and actuators. As shown in Figure 5.3, three microprocessors were used for communicating the data from the sensors. The experimental control was based on a home internet gateway, which provided access from different locations anywhere internet WiFi was available. Unlike the previous occupancy monitoring measurements, this experiment was

[45] Gubbi, J., et al. (2013). "Internet of Things (IoT): A vision, architectural elements, and future directions." Future generation computer systems **29**(7): 1645-1660.

performed remotely using automatic controls. Most of the time, the experimental unit was accessed remotely from a university office located 46 km from the site.

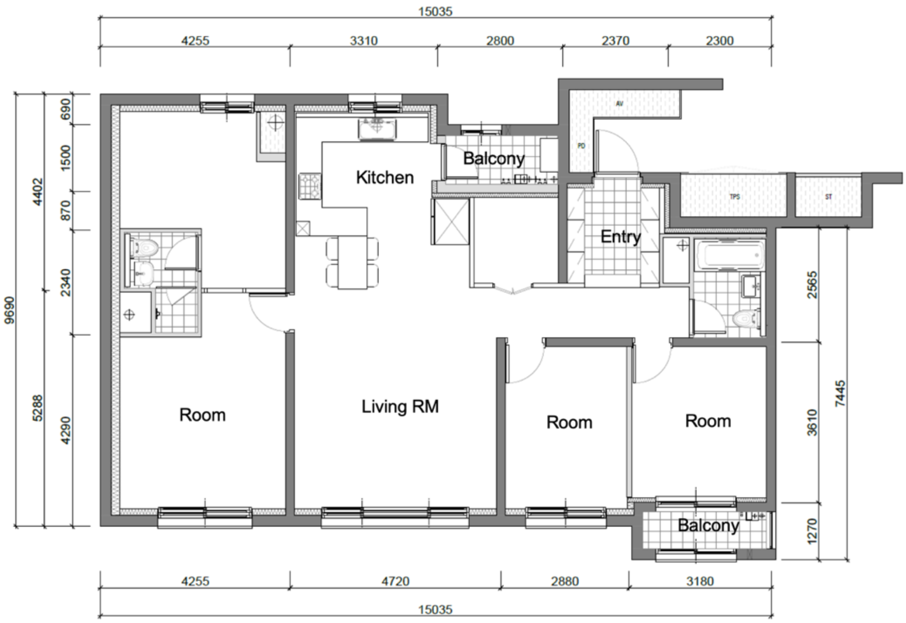


Figure 5. 2. Floor plan of the site experiment unit in Kyungi-do, Uljungbu, Korea.

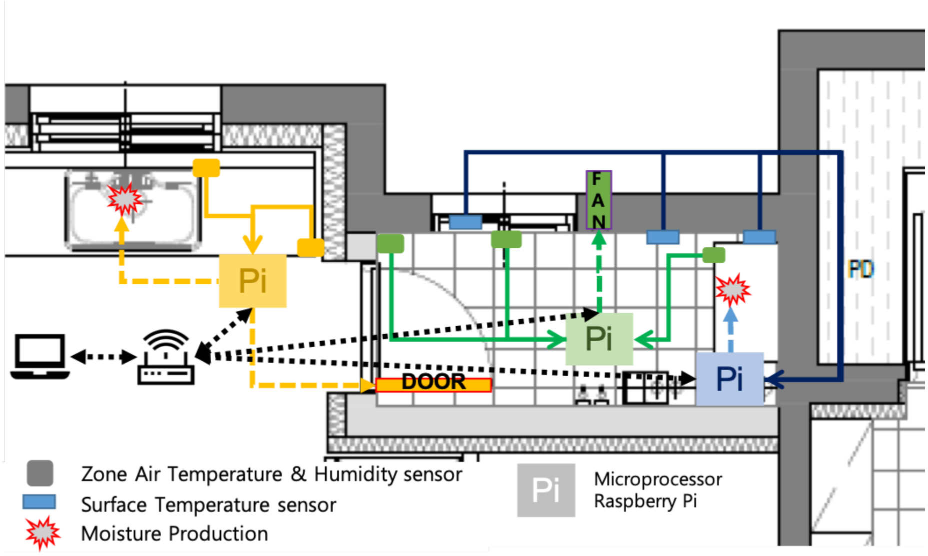


Figure 5. 3. The IoT experimental setup showing the sensor, actuator, and microprocessor locations.

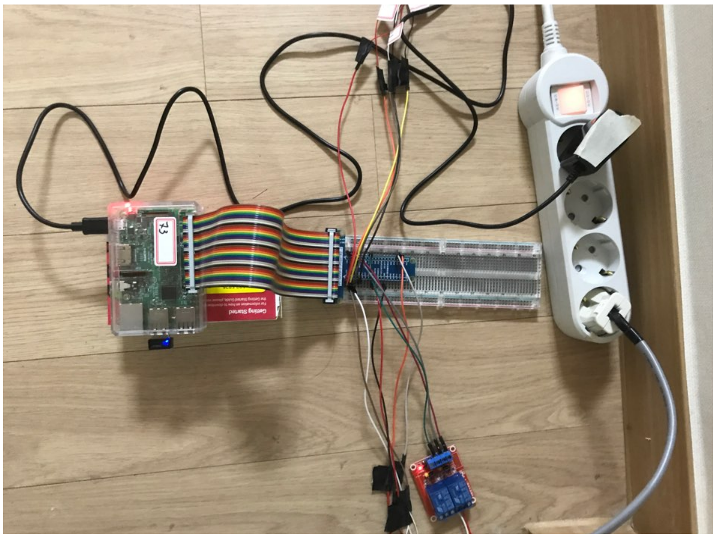


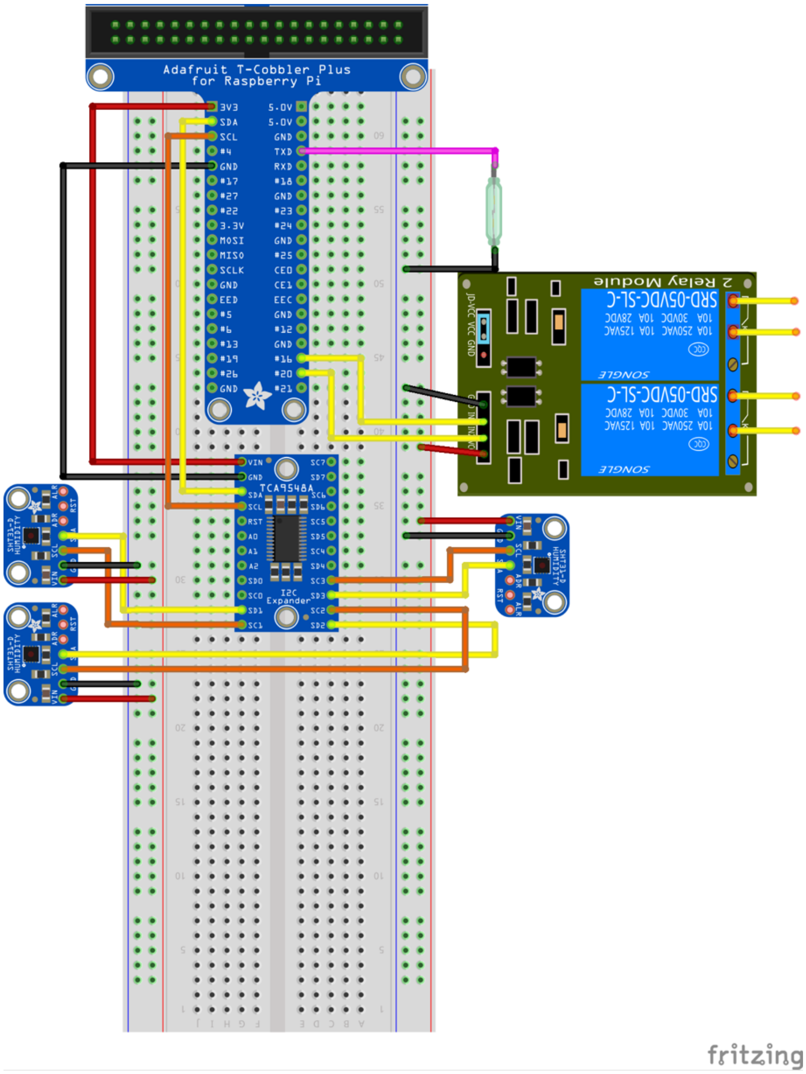
Figure 5. 4. Micro-processor (Raspberry Pi 3B) used for onsite experiment

Table 5. 1. Measurement instrument information

Measure Element	IoT Experiment Instrument	
	Main Unit	Sensor
Zone Air	Raspberry Pi 3 Model B	Adafruit Sensirion SHT 31-D Temp: ± 0.3 °C most uses Humidity: ± 2% relative humidity most uses
Wall Surface		Thermocouple Amplifier MAX31856
		T-type (Copper/Constantan) Thermocouple

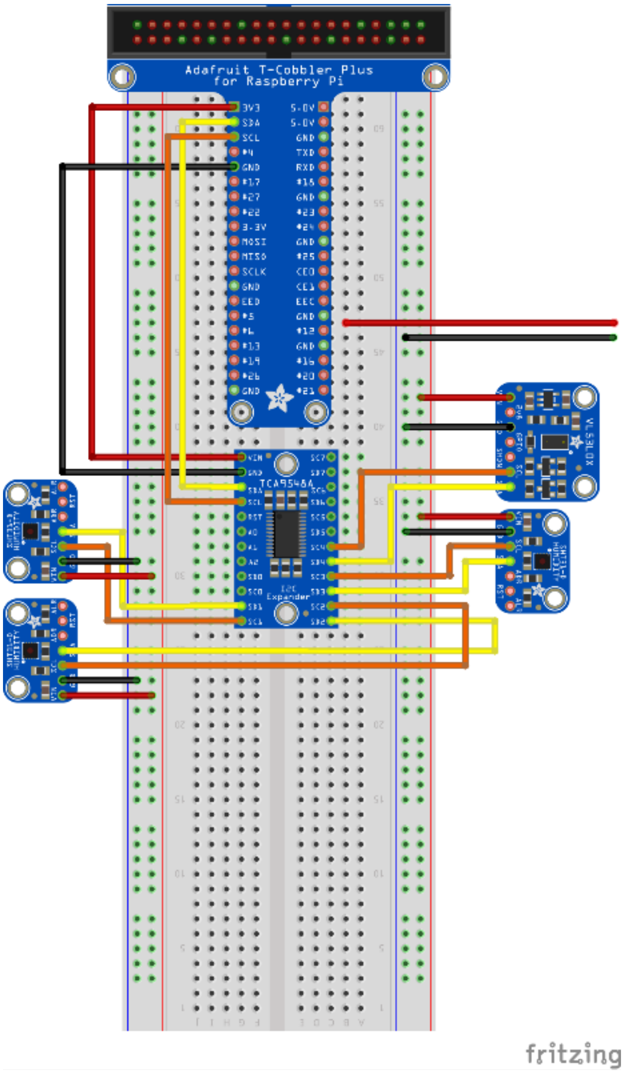
5.2.2. Sensor and actuator connection with the physical element

The actuators were controlled by an on/off relay connected to the Raspberry Pi's general-purpose input/output (GPIO) board, as shown in Figure 5.4. During this assessment, a swing door actuator was installed on the balcony door, and ventilation was provided by installing a constant airflow fan (of 150 CMH) on the balcony ceiling, as shown in Figure 5.8 and Figure 5.9. To imitate occupancy, the kitchen faucet was connected to a solenoid valve, and the automatic swing door controller on the balcony door was operated to generate and transfer water vapor. Moisture was generated in the balcony area by a humidifier, whose relay on/off operation was controlled by a microprocessor. The sensor and actuator connection to the GPIO board is shown on Figure 5.5, Figure 5.6 and Figure 5.7.



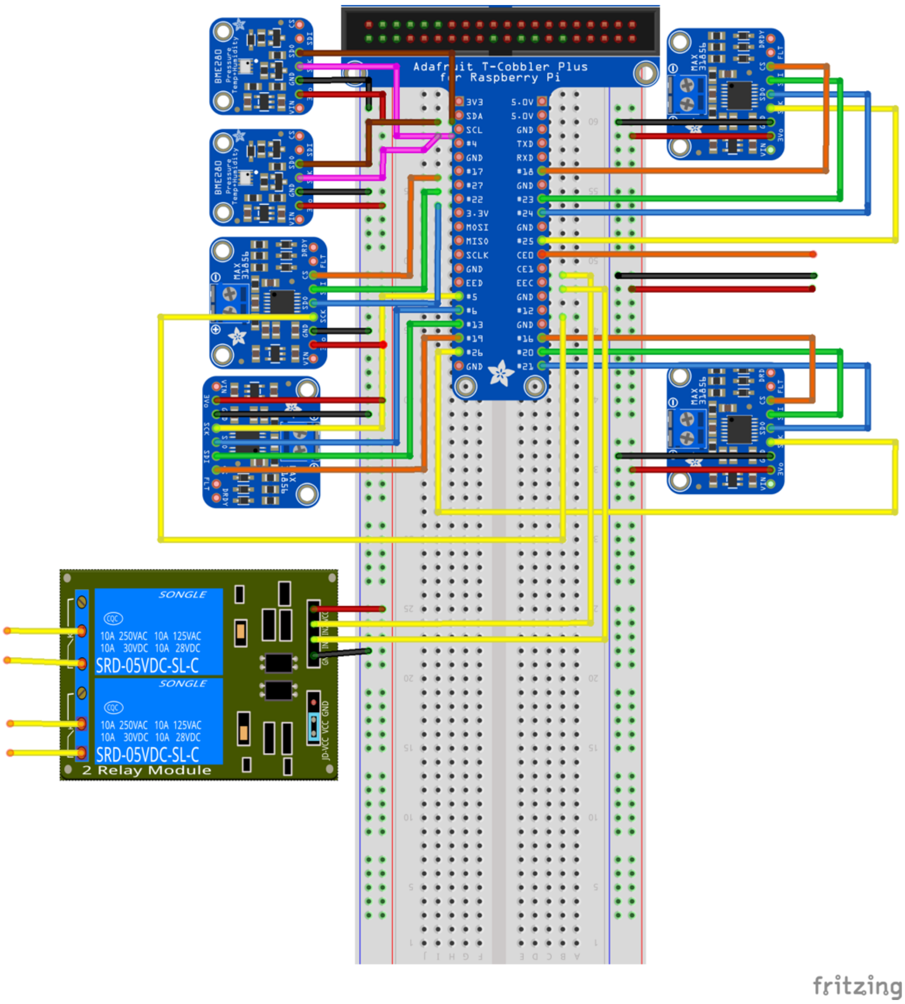
Temperature/Humidity Sensor			Actuator	Door open detection	
SHT	Location	TCA	Relay	Magnetic sensor	
T1/H1	Balcony Door	1	Swing Door	Door	14
T2/H2	Kitchen Sink	2	Sink Solenoid		
T3/H3	Living Room	3			

Figure 5. 5. GPIO board sensor arrangement located in Kitchen



Surface temperature sensor			Window open detection	
MAX	Location	(clk, cs, do, di)	Magnetic sensor	
T1 /H1	Upper Corner	5, 19, 6, 13	Balcony Window	16
T2/H2	Lower Corner	25, 18, 24, 23		
T3/H3	Window Surface	12, 17, 22, 27		

Figure 5. 6. GPIO board sensor arrangement located in balcony 1



Temperature/Humidity Sensor			Actuator	Door open detection	
SHT	**Location**	**TCA**	**Relay**	**Laser sensor**	
T1 /H1	Window	1	Fan	Window Distance	7
T2/H2	Shelves	2	Humidifier		
T3/H3	Balcony door	3			

Figure 5. 7. GPIO board sensor arrangement located in balcony 2

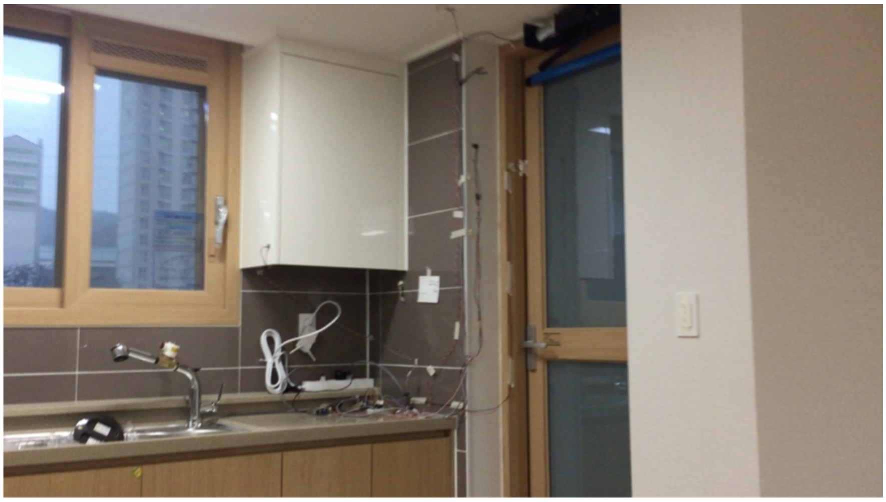


Figure 5. 8. Solenoid valve connected on kitchen faucet and swing door operator installed on balcony door

Figure 5. 9. Ventilation fan attached on balcony ceiling and humidifier located on balcony to imitate moisture production

5.2.3. Condensation determination

The condensation determination is calculated based on the comparing the surface temperature and dew-point temperature of the air. The location of the surface temperature is measured most vulnerable spot where the thermal bridge is created with directly neighbor the outdoor. This spot is also requirements to achieve the safe factor condensation prevention based on Design criteria for apartment building in Korea.

The dew-point temperature are calculated based on the air temperature and relative humidity value. The dew-point temperature calculation is based on the ASHRAE Fundamental standard[46]. As shown on the equation (1) and (2) the dew-point temperature is driven by water vapor partial pressure. The water vapor partial pressure is driven from the saturation pressure which is calculated with the temperature as shown on the equation (3).

$0 \le T < 93$:

$$t_d = C_{14} + C_{15}\alpha + C_{16}\alpha^2 + C_{17}\alpha^3 + C_{18}(p_w)^{0.1984} \qquad (1)$$

$T < 0$:

$$t_d = 6.09 + 12.608\alpha + 0.4959\alpha^2 \qquad (2)$$

$$\alpha = \ln(p_w)$$

46 ASHRAE Handbook, "Fundamentals, Ashrae–American Society of Heating," *Ventilating and Air-Conditioning Engineers* (2017).

$$p_w = p_{ws} * RH/100 \tag{3}$$

C_{14} = 6.54

C_{15} = 14.526

C_{16} = 0.7389

C_{17} = 0.09486

C_{18} = 0.4569

$-100 \leq T < 0$:

$$\text{In}p_{ws} = C_1/T + C_2 + C_3/T + C_4/T^2 + C_5/T^3 + C_6/T^4 + C_7 InT$$

C_1 = −5.6745359E+03

C_2 = 6.3925247E+03

C_3 = −9.6778430E−03

C_4 = 6.2215701E−07

C_5 = 2.0747825E−09

C_6 = −9.4840240E−13

C_7 = 4.1635019E+00

$0 \leq T < 200$:

$$\text{In}p_{ws} = C_8/T + C_9 + C_{10}/T + C_{11}/T^2 + C_{12}/T^3 + C_{13}/T$$

C_8 = −5.8002206E+03

C_9 = 1.3914993E+00

C_{10} = −4.8640239E−02

C_{11} = 4.1764768E−05

C_{12} = −1.4452093E−08

C_{13} = 6.5459673E+00

When the surface temperature is lower than dewpoint temperature, then considered as the condensation is occurred. The surface temperature is compared with the nearest temperature and humidity sensor location which is shown on the Figure 5.10.

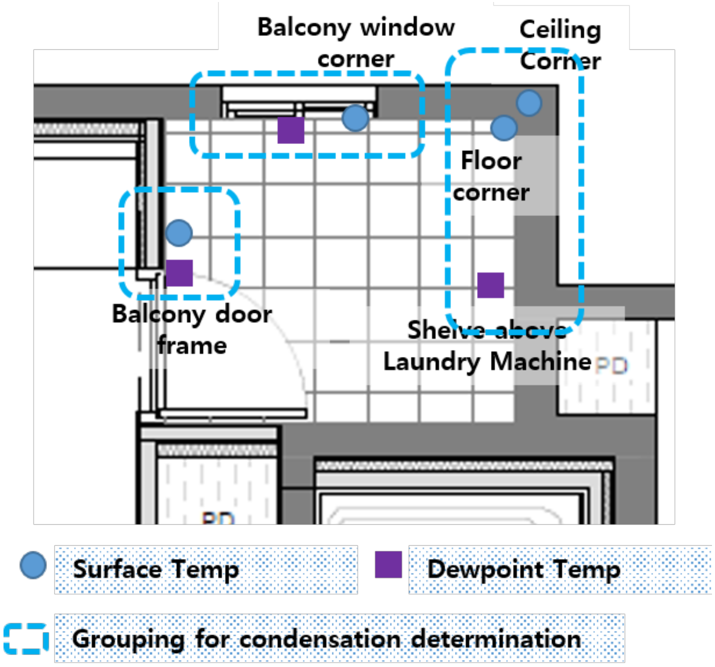


Figure 5. 10. Group of surface and air sensor location for comparing the condensation determination

5.3. The algorithm based on the occupancy parameters

In order to apply the IoT as a condensation prevention solution, it was necessary to embed the occupancy parameters control algorithm in the processor. With the earlier-derived occupancy parameters (described in Chapter 3), the control algorithm had to interpret real-time data received from sensors and it had to actuate the occupancy parameters feature to adequately deal with the occupancy condition.

The algorithm was created with the aim of minimizing excessive moisture inside the balcony space so as to reduce the possibility of condensation occurring on the surface with the lowest temperature. As noted in Chapter 3, it was necessary to remove the generated moisture by ventilation and to block the transfer of moisture from the conditioned space by using the door control. The algorithm was necessary for determining when to start and stop the ventilation fan and the closing of the door based on information from the sensors.

5.3.1. Activity detection-based control

The occurrence of condensation is related to occupants' activities, as described in Chapter 3. Moisture-generating activity in the balcony and moisture transfer activities cause the increase of the relative humidity, which causes condensation. Moisture generation was caused by the use of the washing machine at the monitoring site. In the measured unit, the machine was used at least once a week during the measurement period, mostly during the weekend or holidays. Whenever the machine's on/off switch was detected for touch, an increase in relative humidity occurred, as shown in Figure 5.11. Therefore, the washing machine's condition (on or off) was found to be related to the condensation prevention parameters.

However, there were several cases in which it was shown that even with the equipment in the on position, condensation did not immediately occur. As shown in Figure 5.12, the relative humidity inside the balcony space increased slowly so there was a time lag between the touch sensor detection and the actual time of condensation. Therefore, it was unnecessary to connect the equipment directly to the on/off situation with the occupancy parameters operation.

The transfer of moisture was caused by the balcony door opening from the kitchen space. There were several cases in which condensation was found when the balcony door was open. As shown in Figure 5.13, when the balcony door was opened, condensation was detected and it stopped after the door was closed. However, even when the door was closed, there were times when the condensation remained for a longer period. As shown in Figure 5.14, the opening of the door caused the problem.

The kitchen humidity was an influence on the condensation in the balcony space while the balcony door was open. Even when it was open, there were times when condensation was not found in the balcony space, as shown in Figure 5.15. Therefore, it is necessary to control the occupancy parameters with the use of something in addition to the simple detection of activity. It is also necessary to interpret the received data values in light of the activity conditions. There are some times when moisture generation and transfer are happening at the same time, as shown on Figure 5.16. The complexity of the activity control may simply be solved by the sensor value-interpreted control.

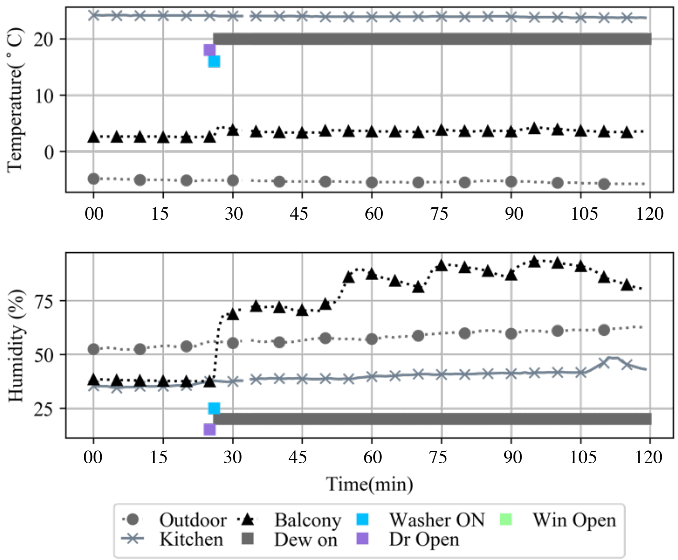


Figure 5. 11. Condensation detected after washer equipment starts to operate inside the balcony space

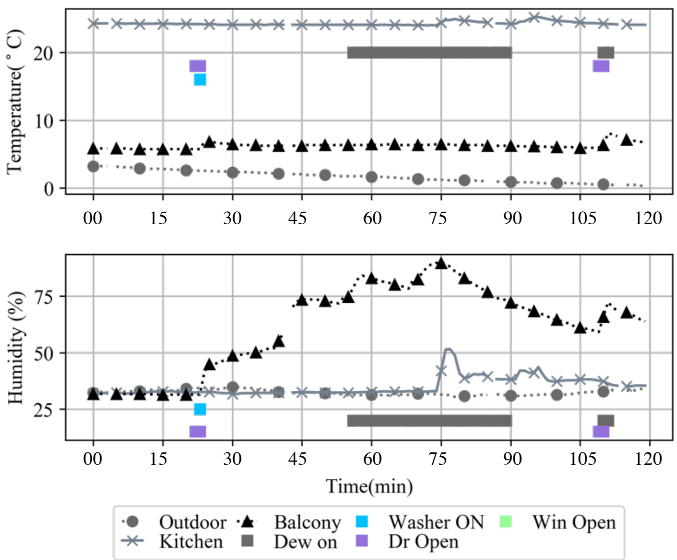


Figure 5. 12. Condensation detected middle of the washer equipment operation inside the balcony space

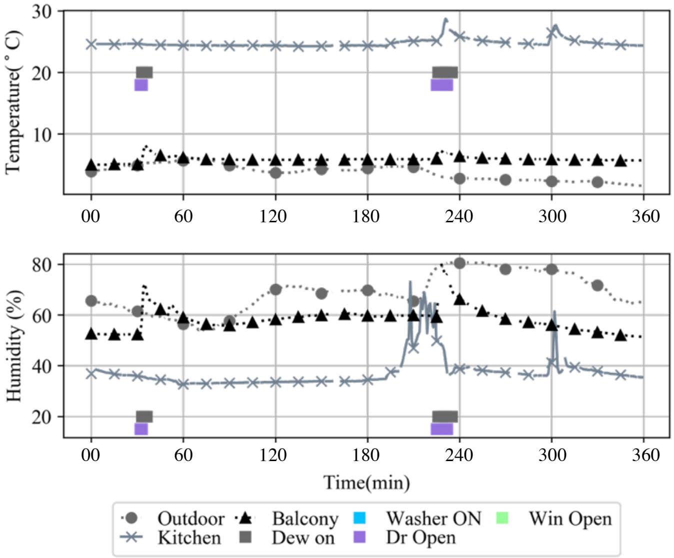


Figure 5. 13. Condensation detected during the door opening activity

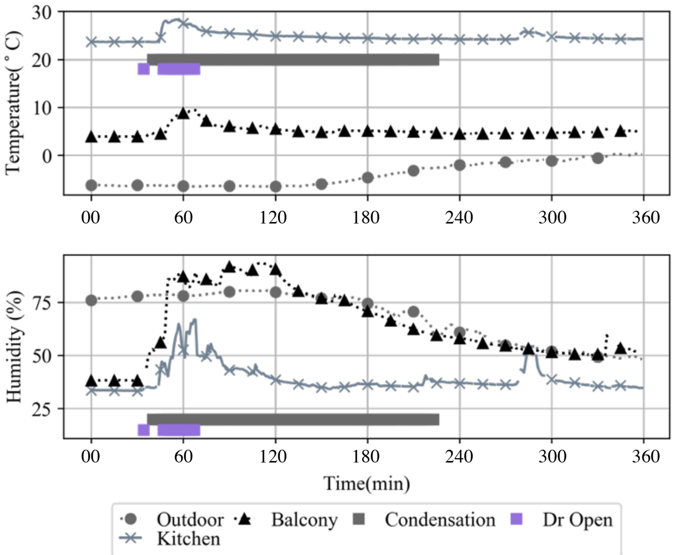


Figure 5. 14. Condensation remained after the door opening activity

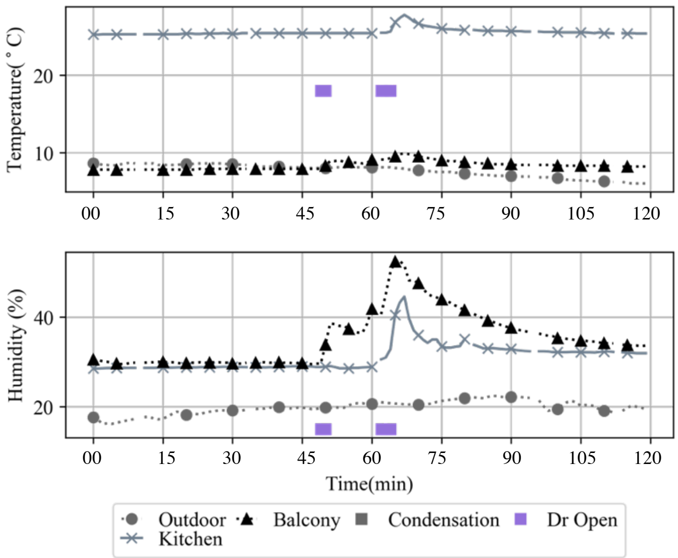


Figure 5. 15. Non-condensation detected during the door opening activity

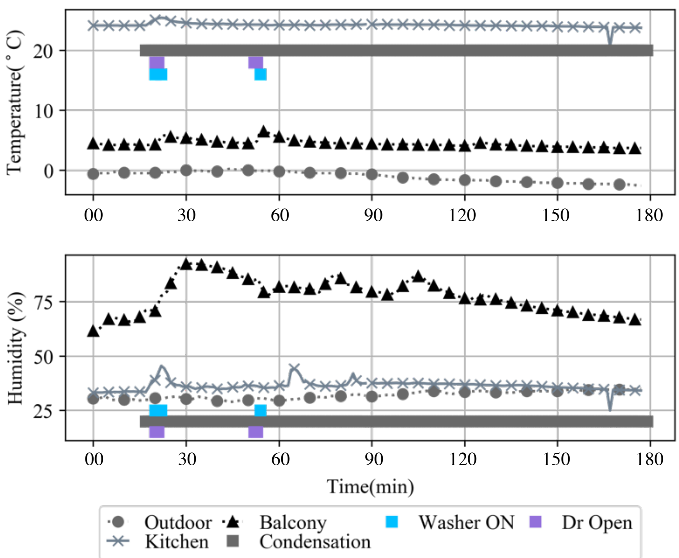


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Figure 5. 16. Multiple activities increased the possibility of condensation duration time.

5.3.2. Sensor value-interpreted control

The balcony door and the intermittent ventilation schedule are the main parameters for controlling the condensation risk. The balcony door connected to the IoT system can be operated by the measured sensor value of relative humidity of the kitchen or the relative humidity near the balcony door.

Data shown in Figure 5.17 are the results of the relative humidity distribution during the measured months, which was dependent on the condensation that occurred due to the balcony door opening. Compared with the condensation and non-condensation monitoring case, the kitchen humidity slightly increased in the condensation case, on average, between 40% and 48% relative humidity while the non-condensation case was 36% to 40% relative humidity. However, the difference between the condensation and non-condensation situation with the kitchen relative humidity doesn't shows the significant difference.

This was due to cooking and the door opening, which did not simultaneously happen; it happened in the same general time range but often, both activities were happening simultaneously. Also, moisture generation is high near the stove when it is being used for cooking, since the kitchen and living area are opened up and the moisture may be dispersed. Based on the data values, it is difficult to control with regard to the humidity value of the kitchen.

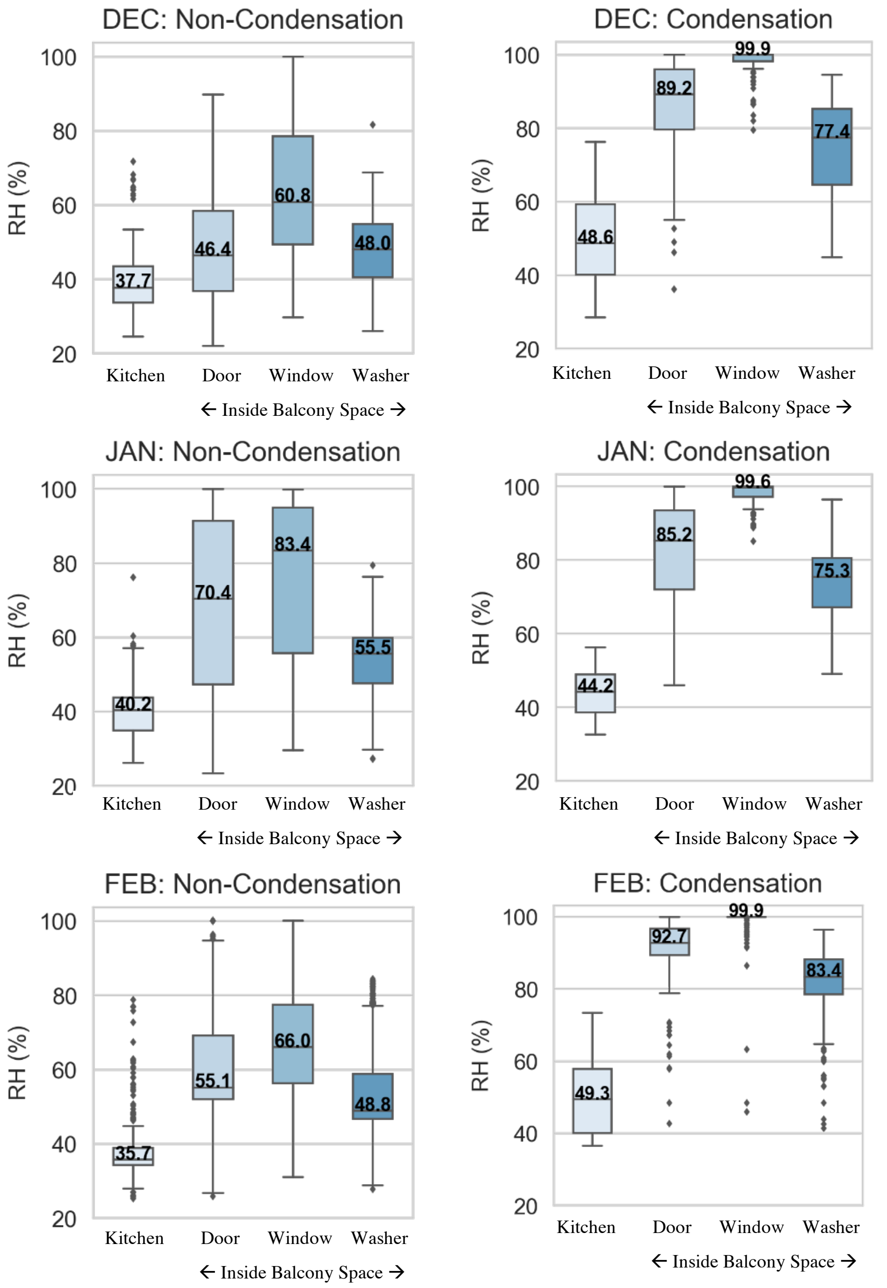


Figure 5. 17. Relative humidity values of measured locations by non-condensation and condensation during balcony door opening activity

In order to determine the door control condition, it is necessary to consider the relative humidity distribution while the condensation is found in the balcony with the door open, as shown in Figure 5.18. As can be seen in 5.18 (a), the kitchen's relative humidity is in the proper range for comfort while the balcony door is open and condensation is occurring. Therefore, having the door open is not related to the kitchen's relative humidity in terms of balcony condensation. Condensation occurs when the relative humidity is mostly above 80% as detected at the balcony door (b); above 90% near the window; and (c) above 80% near the laundry machine shelf (d). Although condensation did occur above 80% relative humidity, there is the possibility that condensation found in the balcony space was when the area near the door and the laundry machine had less than 80% relative humidity. Therefore, it is necessary to determine the door control situation for relative humidity at 70%.

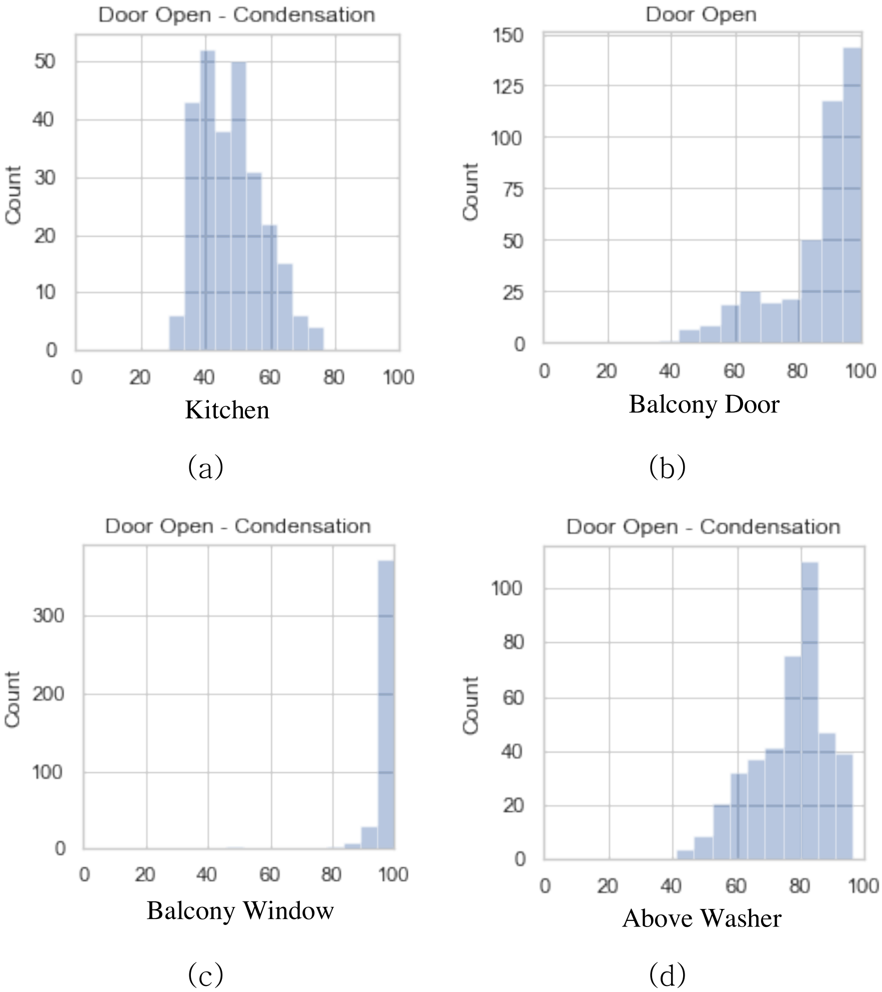


Figure 5. 18. Relative humidity values of measured locations by condensation during balcony door opening activity

When applying the control algorithm, it is possible to make calculations and auxiliary judgements based on 70% relative humidity, but it is difficult to use them as absolute control points due to the local congestion and influence of the airflow. The balcony is a non-conditioned space in which it is impossible to completely prevent the occurrence of condensation. The programmed control algorithm in the microprocessor is based on comparing the surface temperature with the air temperature of the nearby zone to determine the occurrence of condensation. When condensation is detected on any of the measured surfaces by the dew point temperature calculation, a combination of door and fan operations are performed, as shown in Figure 5.19 which is a control algorithm embedded in a Raspberry Pi.

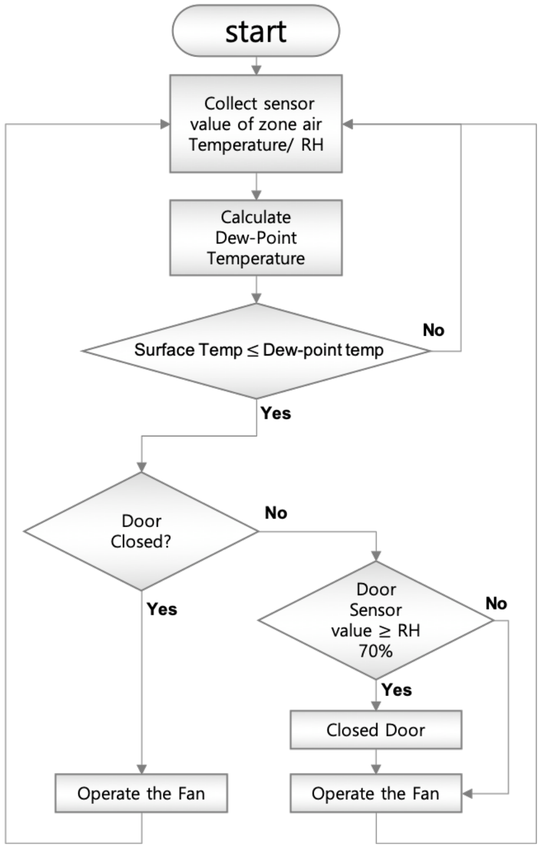


Figure 5. 19. Algorithm for IoT strategy of condensation prevention

5.4. Summary

Applying the concept of IoT

In this chapter the concept of the IoT and the occupancy parameters were interwoven to derive the control algorithm for the IoT application. The concept of the IoT is one in which objects can sense the surrounding conditions and exchange information related to it, while offering complexity data and responding immediately.

The proliferation of devices with communicating-actuating capabilities is bringing us closer to the vision of an IoT. Various applications for microprocessors have been developed with the manufacturers' movement and development of sensors that brought about price reductions, enabling the creation of the IoT. The IoT model was used as a real-time reaction control experiment in this study, as a solution for the condensation problem. As described in this chapter, automated actuators, sensors, and pieces of wireless communication equipment were set up at a typical Korean apartment unit in Uljung-bu City, Korea.

Control algorithm populated by processing of real-time data

The data generated from the IoT sensors can be extracted and analyzed in real time or near-real time for energy efficiency, health, safety, and the comfort of residents. Data generated by the sensors has increased to the point that it has given rise to the concept of Big Data. Therefore, it is necessary to know how to process the real-time data read by the sensors for controlling the condensation.

The complexity of the activity control may be simply solved by the sensor value-interpreted control. When applying the control algorithm, it is possible to make calculations and auxiliary judgements based on 70%, but it is difficult to use them as absolute control points due to the local congestion and the influence of the airflow. Therefore, the control algorithm embedded in Raspberry Pi follows: When condensation is detected on any of the measured surfaces (as indicated by the dew point temperature calculation), the combination of door controls and fan operations are performed.

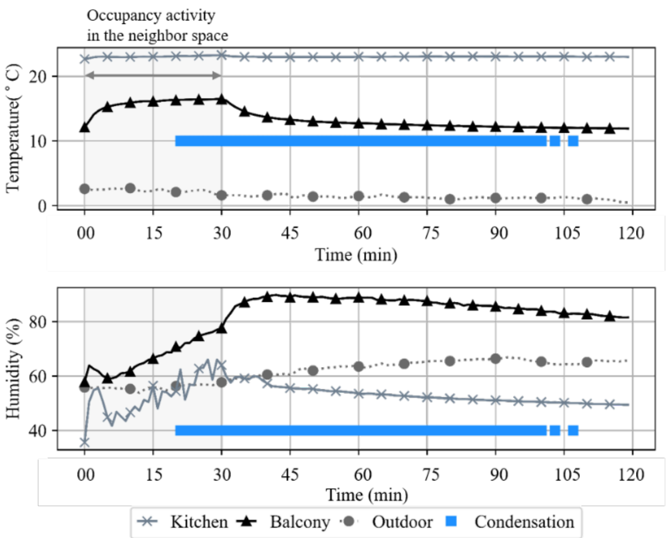
Chapter 6. Feasibility of IoT application at Home

6.1. Result of the onsite IoT experiment
6.2. Level of application with feasibility
6.3. Summary

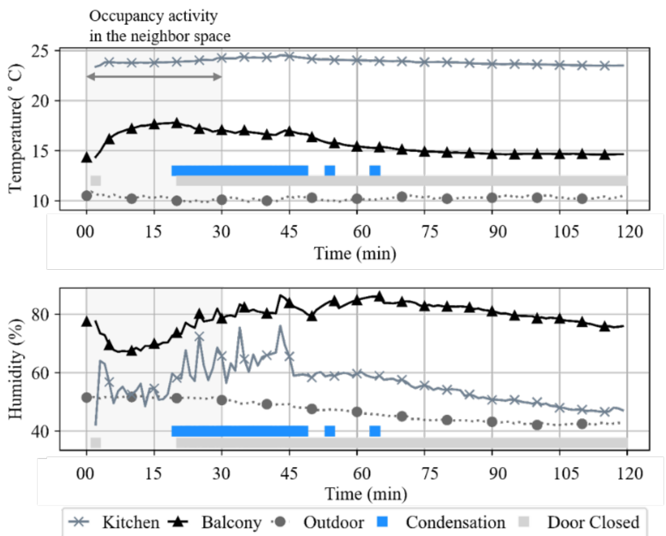
6.1. Result of the onsite IoT experiment

6.1.1. Door control for preventing moisture transfer by condensation detection inside balcony

The balcony door was closed to block the moisture transfer from the kitchen. The generation of moisture by the occupants through kitchen activity was imitated by automatically controlling the opening of the balcony door (using a balcony door actuator) and the solenoid faucet in the kitchen. The door was closed when one of the balcony surface temperatures was lower than the calculated dew point temperature as shown on the Figure 6.2. During the imitation of kitchen activities (due to occupants opening the door), the condensation lasted for an hour inside the balcony, as shown in Figure 6.1 (a). The finding in Figure 6.1 (b) shows that successful results were obtained for operating the door control to block the moisture transfer and reduce the duration of condensation.



(a) Condensation remaining time by moisture transfer to the balcony



(c) Door swing actuator controlled by condensation detection inside

Figure 6. 1. Automatic control strategy for moisture generation case

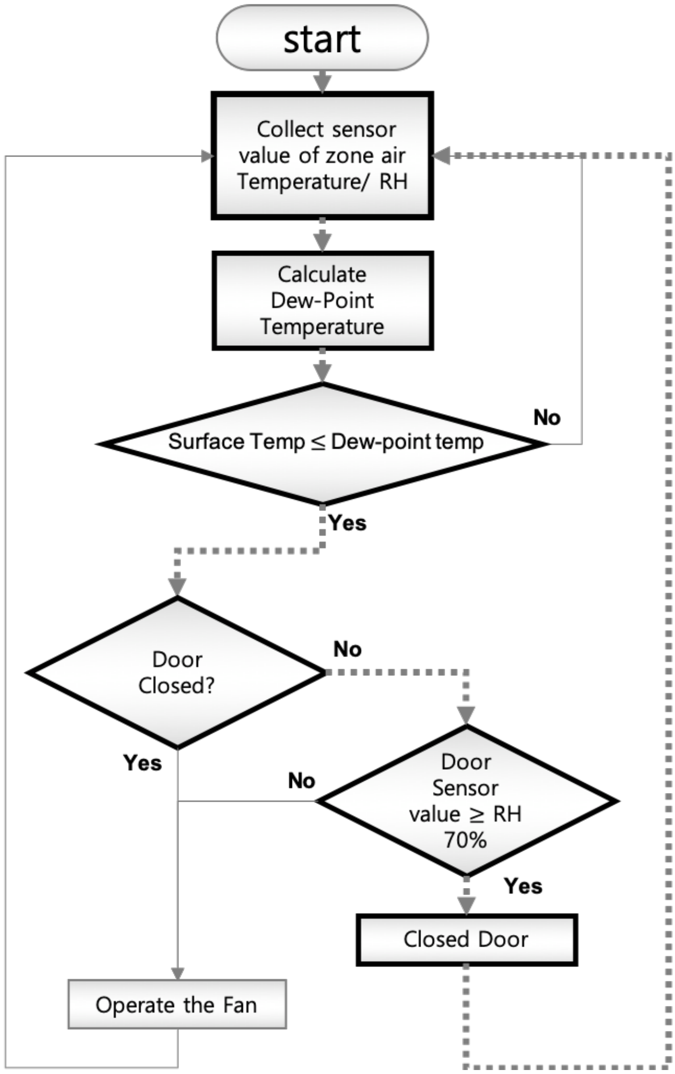
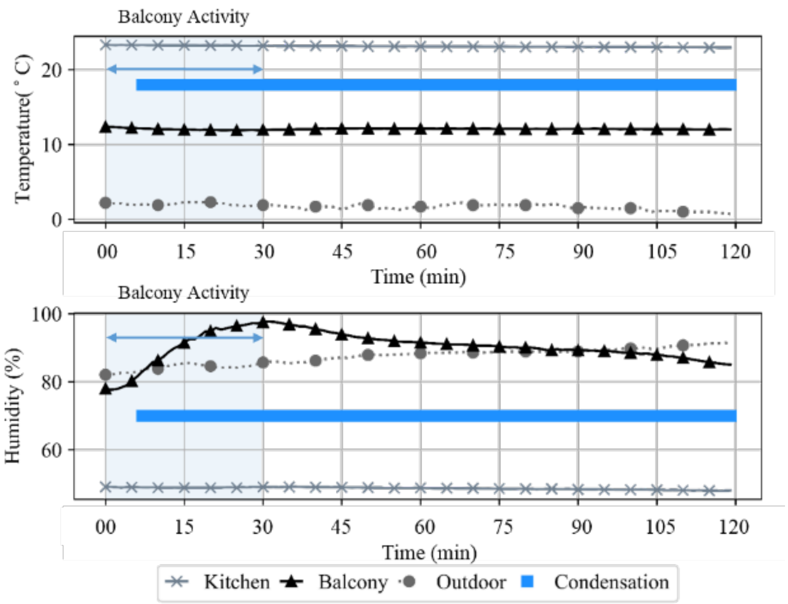


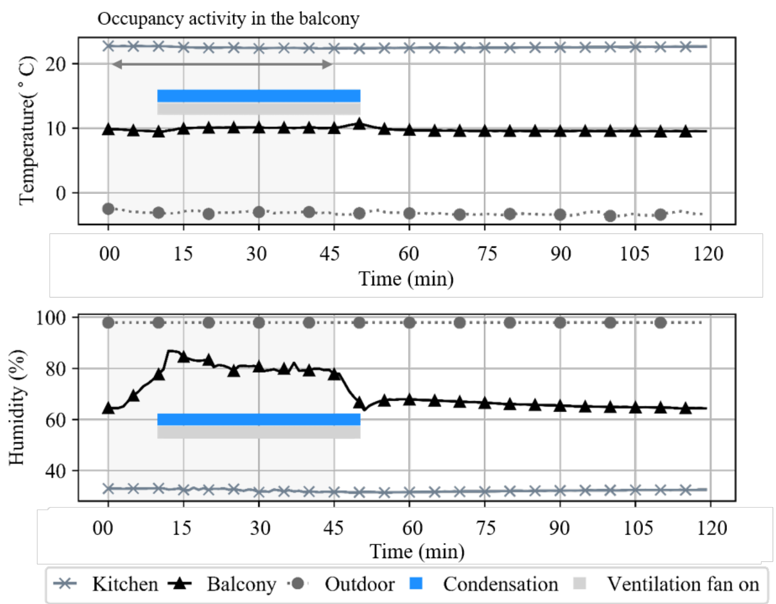
Figure 6. 2. Algorithm process of balcony door control

6.1.2. Intermittent fan operation by condensation detection inside balcony

The ventilation fan is turned on automatically when the door is closed without an occupant in the balcony space when moisture is generating. The control algorithm follows the fan in the situations shown in Figure 6.4. During this assessment, ventilation is provided by installing a constant airflow fan at150 CMH on the ceiling of the balcony, as shown in Figure 6.3 (b). The moisture generation in the balcony was imitated by running the humidifier inside the balcony. As shown in Figure 6.3 (a), without the condensation control, the 30 minutes of moisture generation causes two hours of condensation. When condensation is detected due to moisture generation, the fan is turned on to reduce it. Sensing with automatic control is effective when the balcony space is used for moisture-generating activities that occur without the presence of occupants.



(a) Condensation remaining time by moisture generation inside the balcony space



(d) Ventilation fan controlled by condensation detection inside

Figure 6. 3. Automatic control strategy for moisture generation case

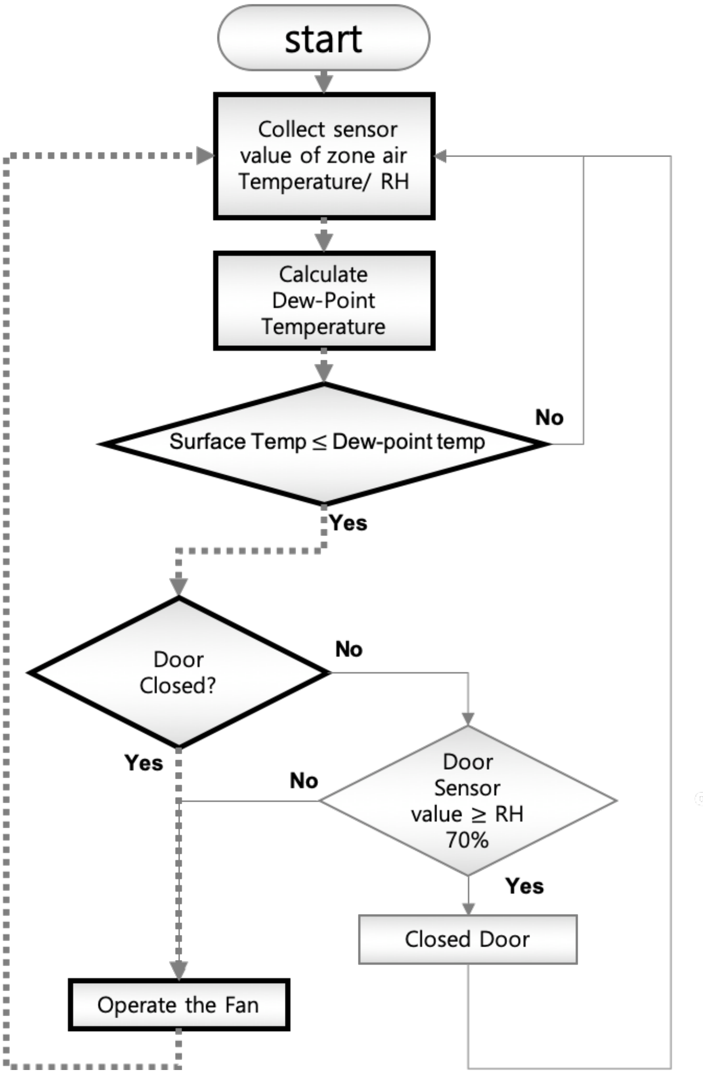


Figure 6. 4. Algorithm process of ventilation fan control

6.1.3. Control algorithm by combining and applying different parameters

Based on the IoT experiment results, the balcony door and ventilation fan successfully became part of the IoT. Each object reacted to real-time data related to balcony condensation by actuating for prevention, which provided the free-parameter objects to be operated by various combinations depending on occupancy patterns. There may be situations in which the occupant might want to keep the balcony door open for various reasons, when it is necessary to ventilate the transferred vapor.

Figure 6.5 shows that leaving the balcony door open and operating only the ventilation is effective for reducing the condensation. Also, the combination of parameter operations improves the condensation prevention strategy by the balcony door being closed to block the moisture transfer from the kitchen; simultaneously it ventilates the transferred moisture inside the balcony as shown in Figure 6.6.

Either of the control parameters actuate based on the real-time data of the indoor condition, effectively making the balcony space much less likely to have condensation. The building parameters then become flexible by adopting the IoT techniques, comparing with the application of solid parameters.

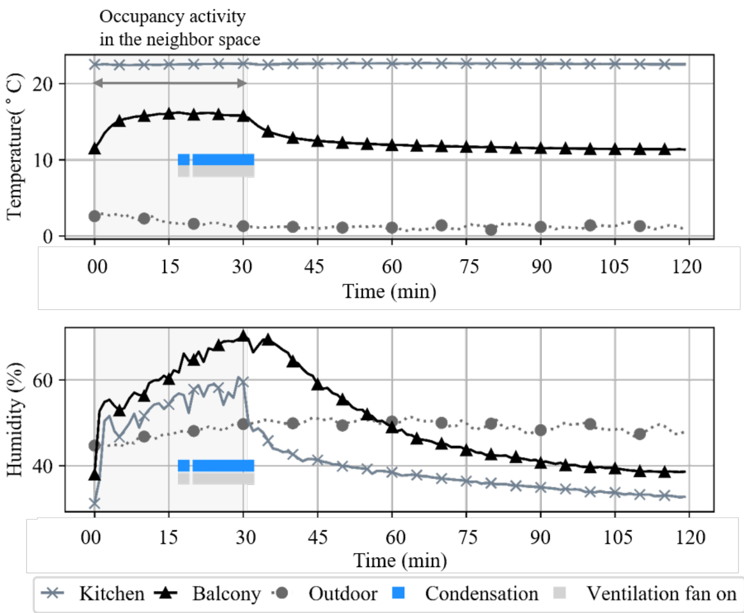


Figure 6. 5. Experiment result of fan operation

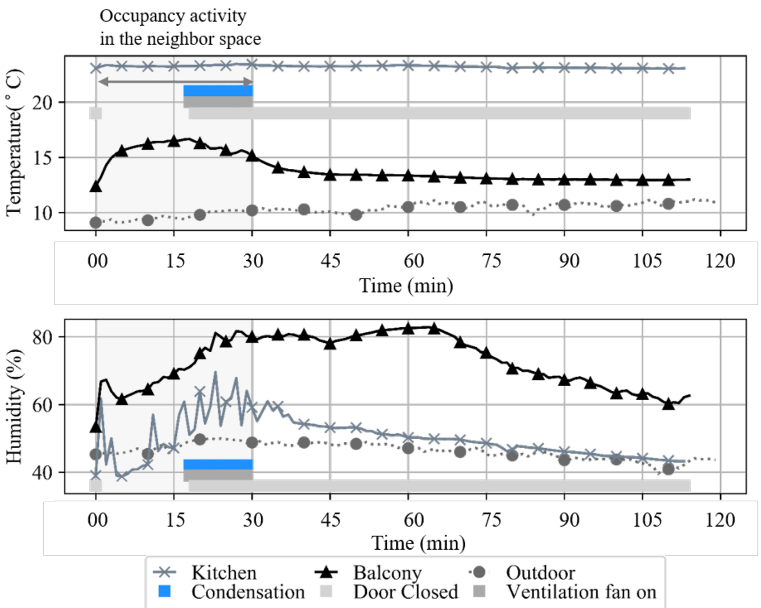


Figure 6. 6. Experiment result of both fan and balcony door operation

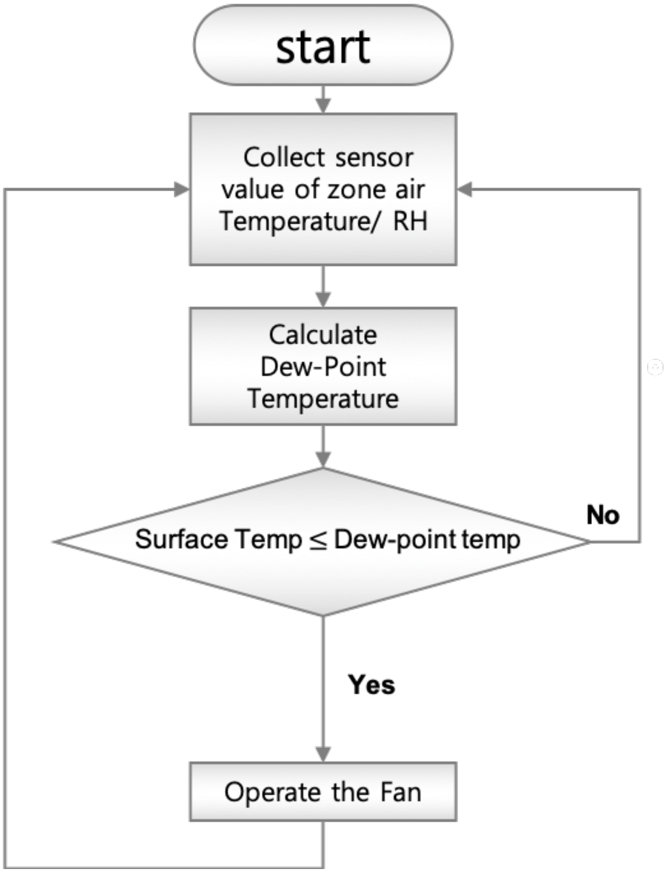


Figure 6. 7. Algorithm process of ventilation fan control

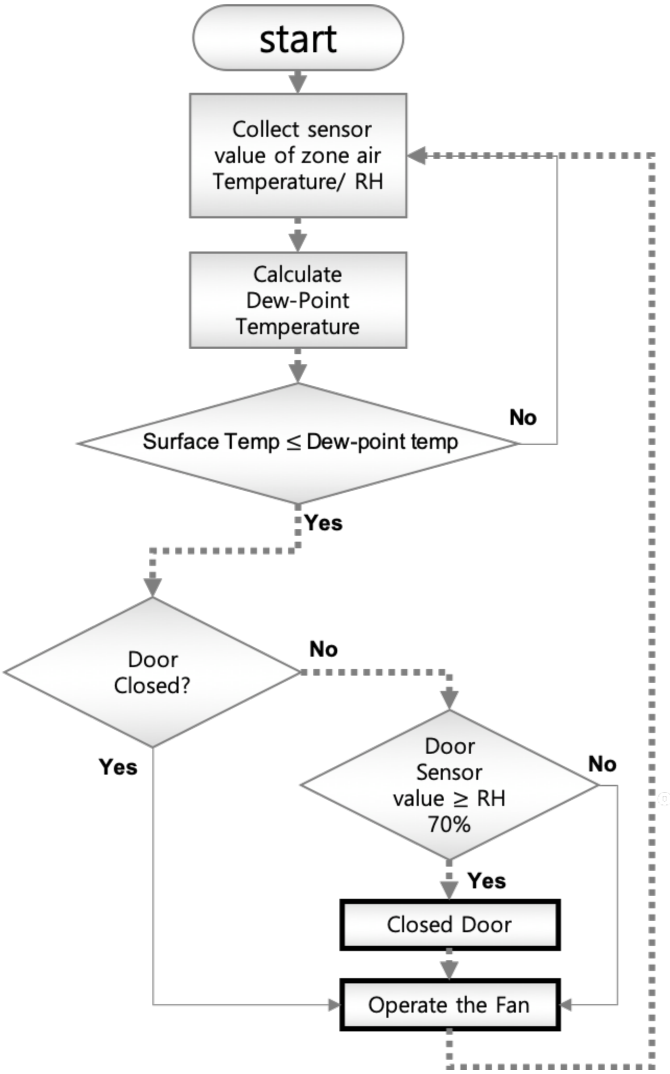


Figure 6. 8. Algorithm process of ventilation fan and balcony door control

6.2. Levels of application with feasibility

6.2.1. The IoT application level for condensation control

The proliferation of devices with communicating technologies, the price of the sensors, and the making of a device based with the Raspberry Pi microprocessor makes it easy for people to adopt. Therefore, the application can vary not only by the algorithm but also by the combination of the device selections. The site application case is the most expensive in order to include all of actuations and maximum number of sensors, but in order to achieve condensation control, the device and algorithm can be made simpler by the user's adaptability.

The levels can be classified into four steps, as shown in Table 6.1. All four levels have the identified numbers of receiving sensors that create the difference in output reaction in tandem with the actuator. With Level 1, instead of auto actuating, it is designed to produce a warning alarm to inform the tenant that action needs to be taken to introduce ventilation. Levels 2 and 3 involve application of either automatically turning on a fan or automatically controlling the door. Both of them are unlikely candidates for most residents, based on the price of the actuator, since the swing actuator (which is for commercial purposes) is much higher than the ventilation fan which is for residential buildings. The detailed price information is attached in the appendix.

Table 6. 1. The sensors and parts requirements for create different levels of IoT devices

Material for IoT control device			Total No.	Level 1	Level 2	Level 3	Level 4
Data Measurement Device	Processor	RPi	2	♦	♦	♦	♦
	Data Storage	SD card	2	♦	♦	♦	♦
Sensor	Surface temperature	T-type Amp	3	♦	♦	♦	♦
	Temperature and humidity	SHT-31	4	♦	♦	♦	♦
	Door opening	Magnetic	2	♦	♦	♦	♦
Actuator	Alarm Notice	Magnetic Buzzer MAB-GEC05S	1	♦			
		LED light	3	♦			
	Ventilation fan	TA-C150 (150CMH)	1		♦		♦
	Swing operator	TOT-901	1			♦	♦
Relay	For Ventilation fan	3-channel	1		♦		♦
	For Swing operator	3-channel	1			♦	♦

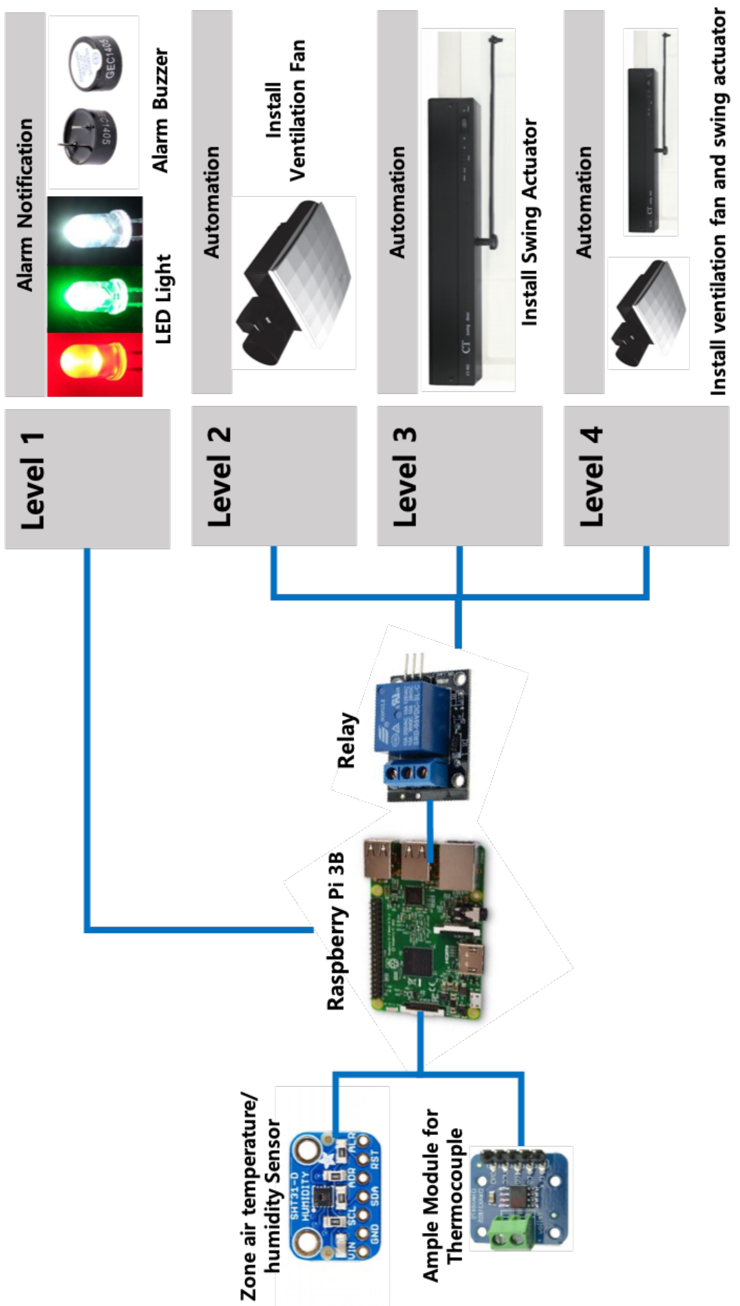


Figure 6. 9. Combination of control device by different levels of output

6.2.2. The effectiveness of condensation reduction among the different levels

In this section we will compare the feasibility of the different levels of the application. Level 1 is the alarm sensor control, which is the most economical. The tenants are notified with a sound or LED light that tells the occupant it is time to introduce ventilation in order to control condensation. However, it rapidly provides information on the condition of the house and can tell the tenant when to act on the condensation prevention control measures that are available. Hence, the actuation output is changed to an alarm, with the reaction based on the alarm algorithm as shown in Figure 6.10. Since the output is the alarm, it is much easier to build by itself and there is no extra construction work involved to connect the actuation for home automation. The faulty part of this solution is that it is a hassle to act when internal condensation occurs when the balcony door is closed and moisture-generating activity is happening.

Levels 2 and 3 are for either selecting the fan automation or balcony door automation for output actuation. This solution is for the units in which either one of the solutions are applicable. Although the door swing operation is more expensive than the fan operation, actuating only by the fan is much more effective for removing condensation than controlling the balcony door to block the moisture transport, as shown in Figure 6.11. Level 4 is the case which was examined and applied in the previous section. The advantage of this solution is effectively solving the condensation problem by blocking the moisture transfer and reducing the humidity inside the balcony. The alternative controls are also possible.

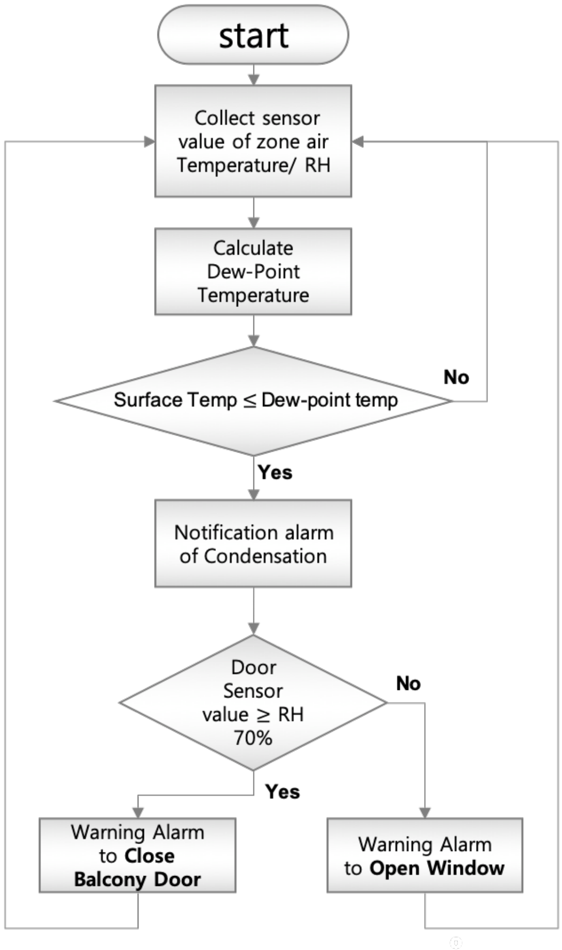
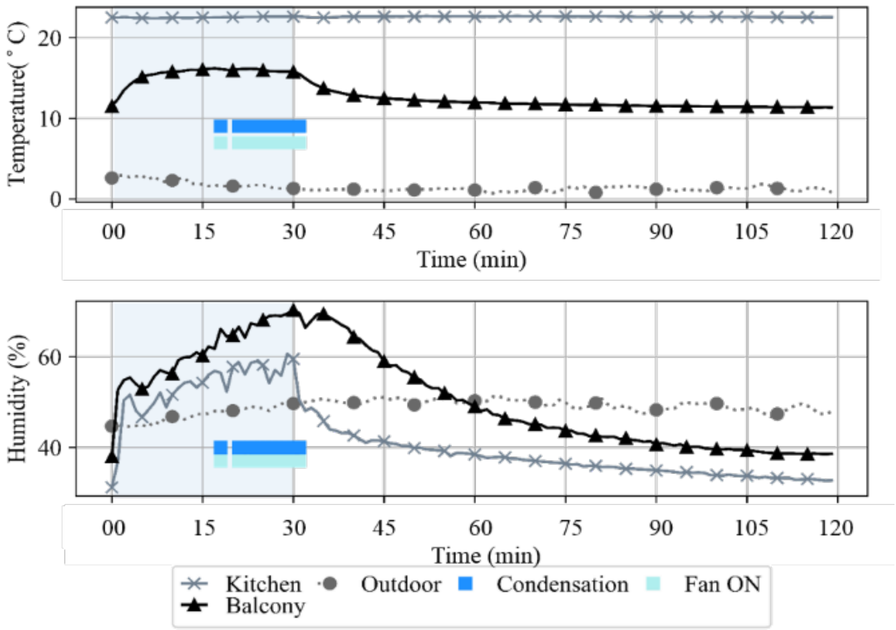
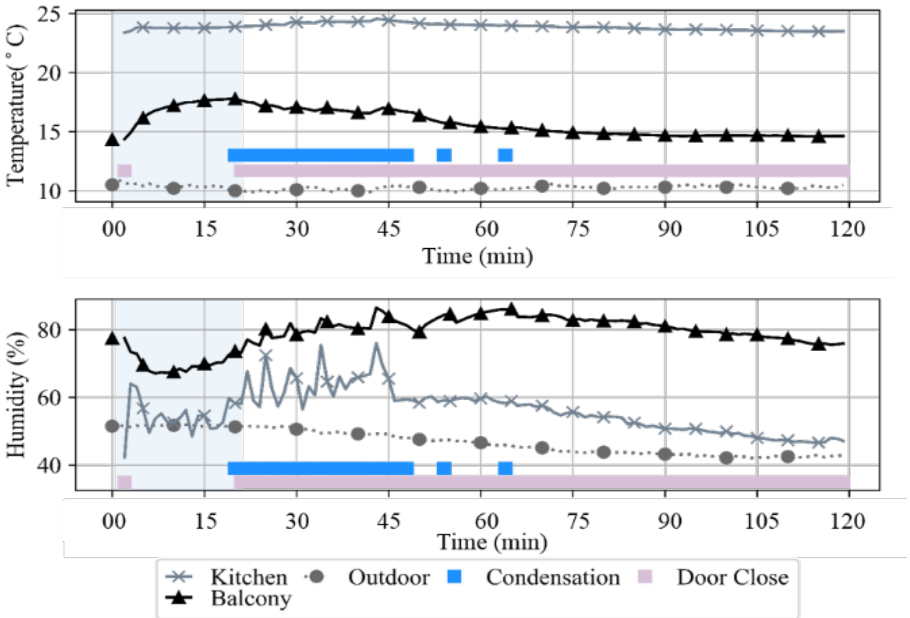


Figure 6. 10. Control algorithm for sensor alarm notification as an output



(a) Level 2 : Actuation connected to the ventilation fan



(b) Level 3: Actuation connected to the swing door

Figure 6. 11. Result of condensation reduction by applying level 2 or level 3

6.4 Summary

Various applications for microprocessors have been developed with the manufacturers' movement and development of sensors that brought about price reductions, enabling the creation of the Internet of Things (IoT). The IoT model was used as a real-time reaction control experiment in this study, as a solution for the condensation problem.

Results of the Application

With regard to the algorithm, in this section, the possibility of adopting the IoT techniques to control and prevent condensation in the balcony space is assessed. Author examined the various control applications to examined the combination of the different operations being manipulated via remote access to the internet.

The application cases involved: Door control for preventing moisture transfer by condensation detection inside the balcony; and Intermittent fan operation by condensation detection inside the balcony. All of the algorithm cases of auto-controlling showed that successful results were obtained in order to reduce the duration of condensation. Also, there still exists the possibility of altering the combination to adopt a different algorithm for control.

Feasibility of application by the control level

The proliferation of sensor development, the price of the sensors, and the making of a device based with the Raspberry Pi microprocessor makes it easy for people to adopt. Therefore, the occupancy parameter control by the IoT application can be implement by tenants. Author have compared the feasibility of application by the levels which classified by the number of sensors and actuator connection.

Each of the levels were classified into four categories, with each level possessing a specified number of receiving sensors that work together to create an output reaction with the actuator. These levels are as follows:

Level 1: This is an alarm sensor control, which is the most economical option. The occupants participate by controlling the door and introducing ventilation when the sensors produce an alarm or LED light indicating it is time for condensation control. This presents an inconvenience to the dweller, who becomes responsible for responding to the alarm when moisture-generating activity is happening.

Levels 2 and 3: These levels are classified by either selecting the fan automation or balcony door automation for output actuation. Although the swing door operation is more expensive than the fan operation, actuating by use of the fan is much more effective for removing the condensation inside the balcony, as opposed to controlling the balcony door to block the moisture transport.

Level 4: The advantage of this solution is effectively solving the condensation problem by blocking the moisture transfer and reducing the humidity inside of the balcony simultaneously.

Chapter 7. Conclusion

The aim of this study was to solve the problem of balcony condensation in Korean apartments. In addition to providing a solution, by considering the changes in the physical parameters of the building, new approaches were suggested which involve the adoption of IoT techniques.

Condensation inside a building contributes to the growth of molds and the deterioration of the surface of materials, which indicates inadequate indoor air quality. Moisture accumulation on building materials causes biological activities which bring about the deterioration. The built environment is developed with the aim of providing a comfortable indoor condition. Most of the building guidelines such as ASHRAE, CIBSE, ISO, etc., suggest an appropriate range of values that can accomplish a healthy and comfortable indoor building condition. These suggestions are also considered during the early design stages in order to cope with the foreseen occupancy condition.

After building construction is completed according to the considered design, the dynamics of the indoor condition vary depending on the occupancy profile of that space; as such, there is always the possibility of early design failures. In particular, problems related to moisture in the building create condensation due to complex and subtle changes in humidity and temperature. However, the increasing use of wireless sensor networks with real-time data open the possibility of immediately controlling the indoor conditions to cope with such subtle changes. The growing trend of the IoT technology provides us with a new approach for improving the quality of the indoor environment. The IoT was developed by a proliferation of wireless sensor networks to form a smart environment using sensors, actuators, and the internet system.

The phenomena of the condensation and attendant control strategies are well-known; however, the condensation problem still exists due to various unpredictable reasons. In this study we defined the occupancy pattern as one of the more unpredictable variables contributing to condensation. The design of a condensation-free house with solid parameters may fail because of different occupancy patterns. Therefore, instead of providing fixed or standardized design values for building environments, it is necessary to consider controlling the environments with home automation technologies such as the IoT.

Author first diagnosed the phenomenon of condensation, which is repeatedly found in Korean residential balcony spaces, by long-term monitoring the occupied unit. It was found that balcony spaces are constructed without any insulation or heating system; however, the space is influenced by the moisture transfer from the kitchen and any moisture-generating activity in the balcony. Based on this monitoring result, it was seen that this unheated space needs door control and ventilation to prevent the transfer of generated moisture, and it also needs insulation on the lowest surface of the wall.

The control parameters derived from the field measurements were reviewed using an EnergyPlus simulation model and an experimental field measurement. The fixed parameter value was derived from the simulation model by applying different insulation thicknesses and ventilation rates. With the occupancy parameters, author examined the balcony door control for blocking the moisture transfer from the neighboring space; also examined the natural ventilation to eliminate the produced moisture. The provision of a fixed parameter value for insulation thicknesses and ventilation rates has limitations that are difficult to deal due to unexpected moisture production depending on the occupancy profile.

Developing techniques related to IoT, the limitations of fixed values and uncertainty of occupancy activities were overcome. By detecting the sensor measurement value, it was possible to control objects such as the door, which is not possible with the traditional methods for controlling the indoor environment. Also, instead of setting up a fan operation schedule for ventilation, the fan can be operated whenever condensation is detected by the sensor.

The traditional way of providing a fixed design parameter value is also important and necessary, as it requires a standardized guideline or default condition. Apart from the default conditions, an active control methodology or algorithm needs to be applied to solve the problems caused by the various occupancy patterns and outdoor conditions. The design solution using the IoT needs to be optimized through further studies with occupancy behavior prediction or weather forecasts.

There were limitations to this study; author could not consider every possible reason for condensation issues caused by micro-climate conditions, nor was it feasible to investigate the myriad types of condensation. In this study we only considered surface condensation due to the problematic surface of the balcony wall, which is composed of just one layer. Simulation performances were reviewed to considered full zone mixing.

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국 문 초 록

사물 인터넷을 활용한 주거용 건물에서의 결로 해결 방안

IoT strategy to solve condensation problem in residential building

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Ph.D. Dissertation

Department of Architecture

Graduate School of Seoul National University

Advised by Prof. Yeo, Myoung Souk

2020. 8.

건물은 거주 공간의 의도치 않은 수분 침투 및 발생으로 인한 피해를 최소화 하기 위한 방향으로 기술 발전 되어 왔다. 특히 결로와 관련된 연구 및 관련 건축 기술로는 단열 및 환기 등의 적절한 조합을 통해서 적용 될 수 있는 방안들이 활발히 검토되었다. 그럼에도 불구하고 여전히 공동주택 건설현장에서는 결로와 관련된 하자 분쟁 및 민원이 끊이지 않고 있는 실정이다. 이러한 결로 문제를 해결하기 위해서 단열과 환기와 같은 결로 방지 설계 기준을 높이려고 하지만, 다양하고 복합적인 요소들의 구성체인 건물에서 단순히 결로 만을 위한 조건을 상향 시킬 경우 건물 내에서 의도치 않은 다른 환경변화를 야기 할 수 있다. 따라서 본 연구에서는 복합적인 환경변화 요소들을 고려 할 수 있는 사물 인터넷 기술을 활용하

여 주거공간에서의 결로 문제를 해결하는 방안을 새롭게 제안하고자 하였다.

주거공간 내 결로 문제 해결 방안 도출은 다음과 같이 진행되었다. 결로 발생 원인 파악을 통한 결로 방지 전략 도출을 위해서 주거 공간 내 결로 피해 문제가 심각한 비확장 발코니 공간을 대상으로 장기 모니터링을 진행 하였다. 모니터링 결과 발코니의 시공요소로 인한 원인과 재실 행위에 의해서 결로가 발생하는 것으로 분석되었고 이러한 요소들의 제어를 통한 결로 방지 효과를 EnergyPlus 시뮬레이션 모델(단열, 환기 방안)과 현장 실험(재실 행동 제어 방안)을 통해서 검토하였다. 시뮬레이션 모델과 현장 실측 검토 결과 기존의 결로 방지 방안인 단열 및 환기 전략 보다는 재실 행동 제어 방안을 통해서 즉각적이고 효과적으로 결로 발생을 방지 하는 것으로 나타났다.

재실 행동을 제어하는 방안을 결로 방지 해법으로 제시하기에 공학적 측면에서 그 효과를 담보 할 수 없지만 사물 인터넷 개념과의 기술 결합을 통해서 실현 가능한 것을 확인하였다. 실시간 데이터 값 처리 및 분석 알고리즘을 통해 발코니 문 자동 구동체와 발코니 내부에 추가 설치한 환기 팬을 결로 발생 조건에 따라 작동되도록 마이크로 프로세서(Raspberry Pi)와 연결하였고 해당 기기는 와이파이로 접근 가능하도록 실제 현장에 구현하였다. 실험 결과 사물 인터넷과 결합한 결로 방지 제어를 통해서 결로 발생 시간이 적용 전과 비교하여 단축되는 효과를 확인하였다.

본 연구에서는 건물에서의 결로를 해결하기 위한 방안으로 설계단계에서의 대응과 재실 단계에서의 대응으로 구분하였다. 설계단

계에서는 건물에서의 결로 발생 가능성 등을 종합적으로 고려하여 단열 조건 및 환기량이 설계에 반영되는 방안으로 현존하는 건물 설계 방법이었다면, 건물 사용단계에서 재실 활동에 따라 수증기 이동 차단 및 발생된 수증기를 배출하는 방안을 사물 인터넷 기술을 활용하여 실내 환경 변화에 따라서 능동적으로 대응 할 수 있도록 새롭게 제안하였다. 기존에는 건물 완공까지의 상황만을 고려하고 이후의 재실 및 사용에 따른 건물 내의 환경 변화에 대응하는 설계는 고려 대상이 아니었다. 건물 사용에 대해서는 재실자의 자율성에 맡겨두었다면 본 연구를 통해서 건물 완공 이후 건물이 사용되는 상황을 제어하는 설계의 가능성을 엿볼 수 있게 되었다.

주요어 : 결로, 공동주택 아파트, 비확장 발코니, 사물 인터넷, 마이크로 프로세서(Raspberry Pi)
학 번 : 2013-30934

Appendix

Appendix 1. Cost for IoT device level 1: Alarm Sensor Notification

Material for IoT control device			Total	unit price	Level 1
Data Measurement Device	Processor	RPi	2	₩64,020	₩128,040
	Data Storage	SD card	2	₩5,643	₩11,286
Sensor	Surf Temp	T-type Amp	3	₩25,058	₩75,174
	Temp& Humidity	SHT-31	4	₩22,517	₩90,068
	Door Openness	Magnetic	2	₩2,820	₩5,640
Actuator	Alarm Notice	Magnetic Buzzer MAB-GEC05S	1	₩760	₩760
		Led light	3	₩300	₩900
	Ventilation Fan	TA-C150 (150CMH)	1	₩80,000	
	Swing operator	TOT-901	1	₩660,000	
Relay	for Ventilatoin fan	3-channel	1	₩19,800	
	for Swing operator	3-channel	1	₩19,800	
					₩311,868

** The price information based on 2019.02

Appendix 2. Cost for IoT device level 2: Ventilation Fan Control

<table>
<tr><th colspan="3">Material for IoT control device</th><th>Total</th><th>unit price</th><th>Level 2</th></tr>
<tr><td rowspan="2">Data Measurement Device</td><td>Processor</td><td>RPi</td><td>2</td><td>₩64,020</td><td>₩128,040</td></tr>
<tr><td>Data Storage</td><td>SD card</td><td>2</td><td>₩5,643</td><td>₩11,286</td></tr>
<tr><td rowspan="3">Sensor</td><td>Surf Temp</td><td>T-type Amp</td><td>3</td><td>₩25,058</td><td>₩75,174</td></tr>
<tr><td>Temp& Humidity</td><td>SHT-31</td><td>4</td><td>₩22,517</td><td>₩90,068</td></tr>
<tr><td>Door Openness</td><td>Magnetic</td><td>2</td><td>₩2,820</td><td>₩5,640</td></tr>
<tr><td rowspan="4">Actuator</td><td rowspan="2">Alarm Notice</td><td>Magnetic Buzzer MAB-GEC05S</td><td>1</td><td>₩760</td><td></td></tr>
<tr><td>Led light</td><td>3</td><td>₩300</td><td></td></tr>
<tr><td>Ventilation Fan</td><td>TA-C150 (150CMH)</td><td>1</td><td>₩80,000</td><td>₩80,000</td></tr>
<tr><td>Swing operator</td><td>TOT-901</td><td>1</td><td>₩660,000</td><td></td></tr>
<tr><td rowspan="2">Relay</td><td>for Ventilatoin fan</td><td>3-channel</td><td>1</td><td>₩19,800</td><td>₩19,800</td></tr>
<tr><td>for Swing operator</td><td>3-channel</td><td>1</td><td>₩19,800</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>₩410,008</td></tr>
</table>

** The price information based on 2019.02

Appendix 3. Cost for IoT device level 3: Swing door actuator control

Material for IoT control device			Total	unit price	Level 3
Data Measurement Device	Processor	RPi	2	₩64,020	₩128,040
	Data Storage	SD card	2	₩5,643	₩11,286
Sensor	Surf Temp	T-type Amp	3	₩25,058	₩75,174
	Temp& Humidity	SHT-31	4	₩22,517	₩90,068
	Door Openness	Magnetic	2	₩2,820	₩5,640
Actuator	Alarm Notice	Magnetic Buzzer MAB-GEC05S	1	₩760	
		Led light	3	₩300	
	Ventilation Fan	TA-C150 (150CMH)	1	₩80,000	
	Swing operator	TOT-901	1	₩660,000	₩660,000
Relay	for Ventilatoin fan	3-channel	1	₩19,800	
	for Swing operator	3-channel	1	₩19,800	₩19,800
					₩990,008

** The price information based on 2019.02

Appendix 4. Cost for IoT device level 4: Door & Ventilation fan control

Material for IoT control device			Total	unit price	Level 4
Data Measurement Device	Processor	RPi	2	₩64,020	₩128,040
	Data Storage	SD card	2	₩5,643	₩11,286
Sensor	Surf Temp	T-type Amp	3	₩25,058	₩75,174
	Temp& Humidity	SHT-31	4	₩22,517	₩90,068
	Door Openness	Magnetic	2	₩2,820	₩5,640
Actuator	Alarm Notice	Magnetic Buzzer MAB-GEC05S	1	₩760	
		Led light	3	₩300	
	Ventilation Fan	TA-C150 (150CMH)	1	₩80,000	₩80,000
	Swing operator	TOT-901	1	₩660,000	₩660,000
Relay	for Ventilatoin fan	3-channel	1	₩19,800	₩19,800
	for Swing operator	3-channel	1	₩19,800	₩19,800
					₩1,089,808

** The price information based on 2019.02