Master's Thesis of Engineering

Study on the Applicability of Low-temperature Heating System for Maintaining Thermal Comfort and Reducing Heating Energy in High-Insulation, High-Tightness Apartment Houses

고단열、고기밀 공동주택 온열쾌적 유지 및 난방에너지 저감을 위한 저온난방시스템 타당성에 관한 연구

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Graduate School of Engineering
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A Study on the Applicability of Low-temperature Heating System for Maintaining Thermal Comfort and Reducing Heating Energy in High-Insulation, High-Tightness Apartment Houses

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Abstract

According to relevant statistics, residential buildings such as apartments in buildings account for 43.4% of the energy consumption of the entire building sector. In addition to the energy consumption of the electrical system, the next most important energy consumption system is the heating system.

By examining and analyzing the literature of related studies, this thesis discovered that, while the thermal insulation and tightness of apartment building envelopes have greatly improved in recent years, the heating load has been reduced to a relatively low level. Regardless of whether individual or district heating is used, hot water at a higher temperature is still used to transfer heat for the room through radiant floor heating panels to meet the indoor heating load.

The strengthening of the thermal insulation of the envelope has led to a continuous decrease in the heating load of apartments, which provides theoretical possibilities for the application of low-temperature heating systems in residential buildings.

Therefore, in this thesis, two low-temperature heating systems using individual gas boilers as heat sources and three low-temperature district heating systems were constructed by referring to the forms of related existing heating systems.

To analyze the applicability of low-temperature heating systems in high - insulation high-tightness apartment buildings, a model of the relevant building and heating system was created using the dynamic simulation software EnergyPlus 9.5 as a research tool. For assessing the applicability of the low-temperature heating system, an assessment strategy was constructed from three perspectives: heating performance, thermal comfort, and energy consumption. Finally, according to the evaluation system, by comparing with the existing heating systems.

The main results of this study are as follows.

(1) It was confirmed that all low-temperature heating systems can meet the indoor heating demand. Floor surface temperatures and room temperatures tend to be lower than those of existing heating systems. And the floor surface temperature does not exceed the upper limit 29℃ required in the ASHARE HANBDBOOK.

(2) Both low-temperature individual heating systems can improve the heating performance, low temperature individual heating system that use outdoor reset control to regulate water temperature can further improve heating performance. In the assessment about low-temperature district heating systems, it was found that the low-temperature district heating systems with HIU equipment has the most significant improvement in heating performance.

(3) As the supply water temperature decrease, the low-temperature heating systems often require longer operating times to meet the indoor heating load. That is why individual low-temperature heating systems with outdoor reset control and district low heating systems with HIU have the longest operating times. In contrast to the runtime scenario, however, energy savings in the study period of the two longest-running low-temperature heating systems that use different heat sources are the most significant.

Keyword : Heating System; Radiant Floor Heating System; Low-Temperature Heating System;
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Chapter 1. Introduction

1.1. Study Background and Purpose

According to the statistics[1] on energy consumption of buildings by the Ministry of Land, Infrastructure and Transport of Korea in 2021, it was found that residential buildings such as apartment houses (43.3%) and detached houses (16.3%) accounted for about 60% of the total building sector. Though electricity accounts for more than half (52%) of the total energy use in the building sector, the urban gas (41%) and district heating (7%) are as followed. Meanwhile, urban gas (52%) accounted for the largest proportion of residential energy consumption.

In residential buildings, such as apartments, space heating is an essential component for good indoor air quality (IAQ), especially in terms of delivering occupant comfort. In fact, in some jurisdictions heating is a regulatory requirement for landlords and building owners.

The space heating system supplies heat more than the amount of heat loss to each home in the building to maintain the heated space at the desired temperature, and the ideal goal of the heating facility is to supply the amount of heat required per unit time to the heated space.

When heat different from the required heat per unit time is supplied, heating may be unpleasant due to insufficient or excessive heat supply, operating efficiency may be reduced, and energy may be wasted due to unnecessary heat supply. Therefore, in terms of heating and energy performance, supplying the required amount of heat per unit time is a priority, but there are also factors that make this difficult. Therefore, in terms of heating and energy performance, supplying the required amount of heat per unit time is a priority, but there are also factors that make this difficult.

In the 1980s, a European floor heating system was introduced and spread nationwide. So far, radiant floor heating systems have become an integrated facility in Korean residential buildings.

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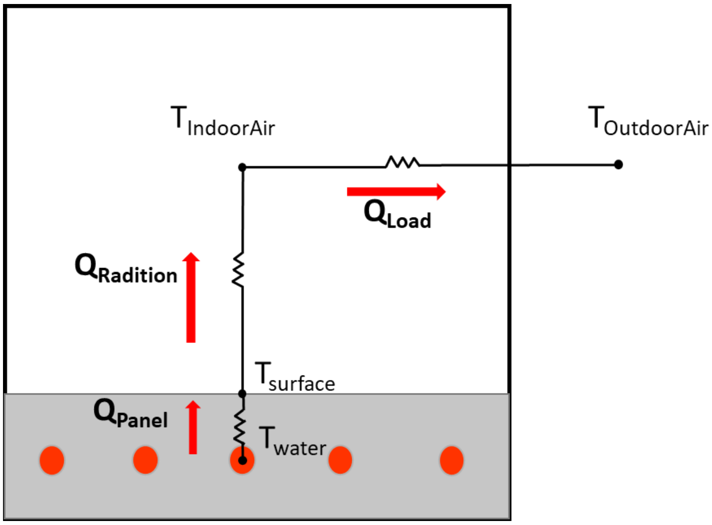
[1] Yo, Ing -Yu. "Building energy use has been on the decline over the past three years". *KHARN* 6 June 2021.Web. Accessed 10 Apr 2022.

Following the recent significant increases in energy savings and emission reduction, demand for improving energy efficiency in various fields has been increasing since it is utilized as a traditional residential heating method in Korea. According to the "Construction Criteria for Energy-Saving Environment-Friendly Housing residential buildings", a high-efficiency heating system is also an infrastructure for environment-friendly residential buildings. Many system enhancements have been implemented, including the development of energy-saving control algorithms and control devices, as well as the addition of an integrated hot water distributor with actual flow control and temperature control functions.



[Figure 1.1] Heat Transfer Network with Floor Radiant Heating System

The heat transfer network graph for a space with a radiant floor heating system installed is shown in [Figure 1.1], T_{water}, $T_{surface}$, $T_{IndoorAir}$, $T_{OutdoorAir}$ stands for the temperature of the hot water delivered to the radiant floor heating panel, the floor surface temperature, the indoor air temperature, and the outdoor air temperature. Q_{Panel} expresses the heat transfer from hot water in the water pipes to the floor surface, $Q_{Radition}$ expresses the heat transfer from the floor surface to the indoor air, and Q_{Load} is the heat loss from the building due to the temperature difference between the interior and exterior.

Due to the heat storage properties of the structural body of the floor, the heat delivered by the radiant floor heating panels must be more than the heat loss of the building at the same time to keep the indoor temperature within the predetermined comfort range. However, if too much heat is given, because the Q_{Panel} is too large, the ground temperature and $Q_{Radition}$ will be overly, causing excessive heat to be transmitted from the floor surface to the indoor air temperature, the room temperature will be outside the comfort range. High indoor temperature will enhance the heat exchange between indoor and outdoor, thus causing more heat loss. In order to maintain a comfortable indoor thermal climate while also improving energy economy, it is critical to install a radiant floor heating system with properly heating capacity.

The relevant geometric factors, such as the diameter, the installation spacing, the length of the pipe is first determined according to the heating load and the heating area of the room when planning floor radiant heating panels. Once these geometric factors are determined, the actual water supply temperature and flow rate during operation determines the instantaneous heat output of the radiant floor heating panels. Consequently, operating with the suitable hot water temperature and flow rate can make the heating system achieve good heating performance and energy efficiency. At as well, the heat loss of the building is constantly changing, and the heat output needs to be adjusted by the control system to match the actual heating demand of the building.

In summary, to improve the heating performance and energy performance of the heating system, this thesis examines the currently existing heating system in Korea, collates the heat source equipment for producing hot water and the control method of radiant floor panels with a view to analyzing the problems in the existing system. A proposal for a solution to shift to a low-temperature heating system with appropriately lowered supply water temperatures in high-insulation, high-tightness apartment buildings, and its applicability is investigated.

1.2. Research Approach and Scope

To investigate the applicability of low temperature heating systems in apartments, this study discusses the heating performance and energy performance of low-temperature heating systems, mainly by comparing them with existing heating systems. Individual heating systems using individual boilers and district heating systems operating under low temperature conditions were examined separately.

For simulation research, a 20-story apartment building with a maximum design load of about 32.5 W/m2 was created with reference to the boundary conditions of an existing building. To conduct a simulation study on district heating systems, the model contains three floors, the uppermost floor, the middle floor, and the lowermost floor, with three families on each floor. Since the two households adjacent to the middle household are the same, only the middle household and one of the households adjacent to it are simulated and analyzed. The model has six households and one of them is selected for the study where the individual heating system is used.

In this dissertation, firstly, the changes in the thermal characteristics of the envelope of Korean residential buildings and the resulting changes in the heating load under the requirement of energy saving and emission reduction are analyzed. Then, by compiling the relevant literature, it was analyzed that the current water temperature is too high even though the heating load decreases continuously, and the heat output of the heating system is not regulated in time during operation. For district heating, the design of the heating equipment based on specific conditions and the customary application without considering the actual situation of each household separately. Afterwards, studies related to low-temperature heating systems were compiled. In purpose of studying the applicability of low temperature heating systems, relevant building models, HVAC models by EnergyPlus and assessment systems were also developed. At the end, the simulation results were used to evaluate the heating performance and energy performance of individual heating systems and district heating systems operating at low temperatures, respectively.

(1) The study of heating load and heating facilities about apartment in Korea and Low-Temperature heating system.

In the first step, the heating load characteristics and heating facilities of apartments were studied. The composition of existing heating systems of apartment employing individual boiler and district heating sources, as well as the status of heating panel and heating control methods that have been commonly utilized in domestic apartment buildings, were studied next. It has been found that current heating systems, whether individual boilers or district heating, operate in a condition where proper supply water temperature is ignored and in favor of straightforward convention.

The improved insulation of buildings and heating equipment has enabled low-temperature heating systems with lower water supply temperatures to be used in residential buildings. The outlet temperature of individual gas boilers set up within households can be adjusted manually or automatically according to the actual heating demands of each home, so the two types of low-temperature district heating were examined, direct and indirect method. For indirect system, HIU (Heat interface unit) equipment can be used to control the temperature of the water supply entering the family. Thereby allowing radiant floor panels to response well to changes in indoor heating load.

(2) Research Subjects and Assessment strategy

To investigate the applicability of low temperature heating systems in apartments, evaluation factors were selected to evaluate heating performance, thermal comfort, and heating energy consumption characteristics were proposed. Meanwhile, simulation conditions such as subject apartment, heating system, and simulation period were determined.

(3) Study of the applicability of low-temperature heating systems

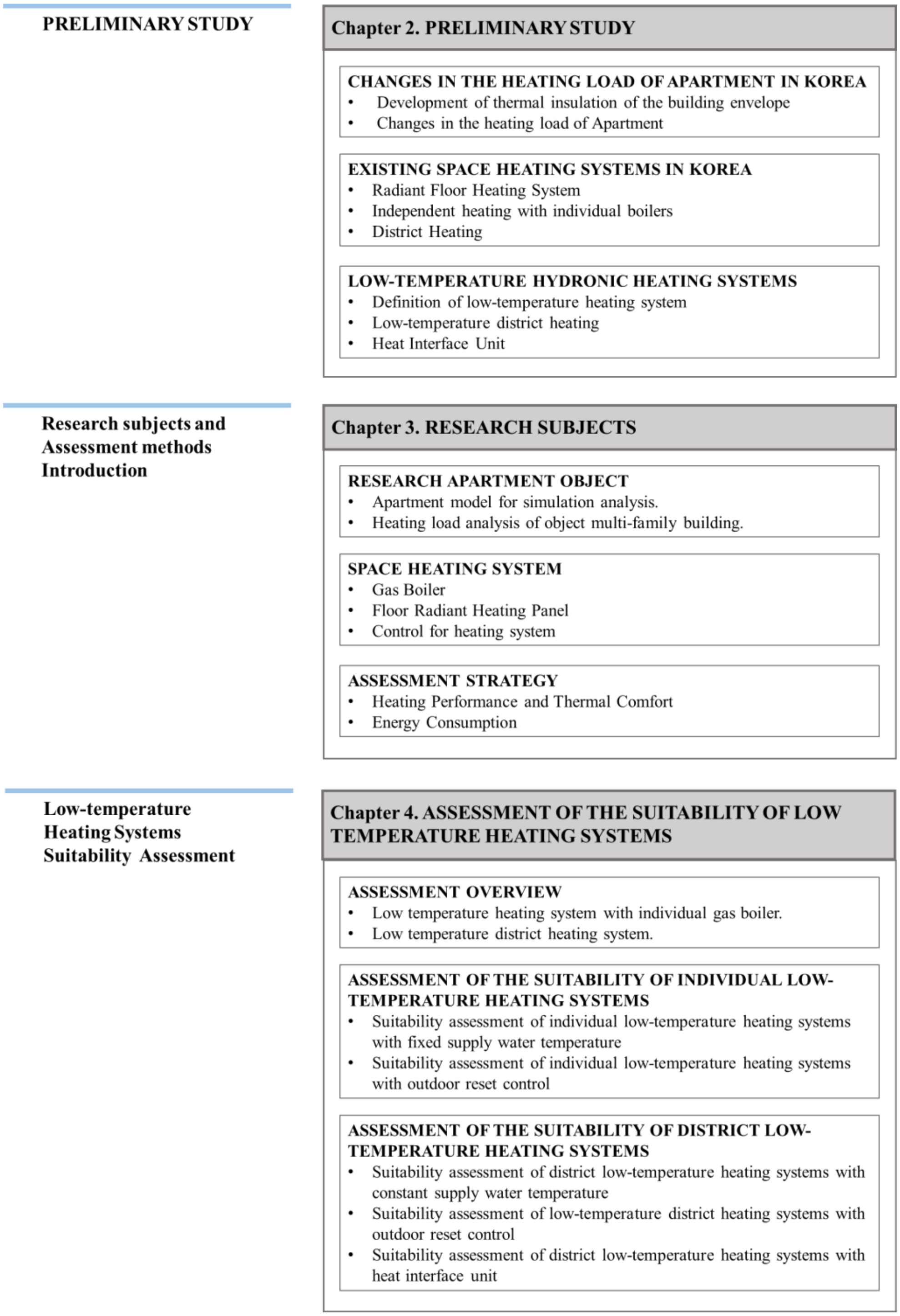
Space heating systems in Korea mainly use individual gas boilers and district heating as heat sources. Therefore, in purpose of evaluating the suitability of low-temperature heating systems in the high-insulation and high-tightness apartment building, the heating operation characteristics, heating system performance and energy consumption performance of different low-temperature heating systems and existing heating systems were compared.

Both the existing system and each low temperature system were simulated using EnergyPlus software, and the related suitability was discussed and analyzed according to the analysis interval and the different heat sources.

In the case of analyzing individual low temperature heating systems, there are three analysis intervals set according to the outdoor temperature distribution, which are the interval where the outdoor temperature is low and stays below zero all the time, the interval where the outdoor temperature varies widely with both above and below zero, and the interval where the outdoor temperature is relatively high, and the outdoor temperature stays above zero.

In the case of analyzing district low-temperature heating systems, there are two analysis intervals set according to the outdoor temperature distribution, which are the interval where the outdoor temperature is low and stays below zero all the time and the interval where the outdoor temperature is relatively high with the outdoor temperature stays above zero.

In the summary, the research flow of this thesis is shown in [Figure 1.2].



[Figure 1.2] Research Flowchart

Chapter 2. Preliminary Study

Space heating systems are designed to satisfy the thermal comfort requirements of building occupants. The planning of any space heating system is based on the heating load characteristics of the building it serves.

Investigation and study of the heating load characteristics of current buildings and the space heating systems used are necessary if a further optimization of space heating systems and reduction of heating system energy consumption are desired. A well-grounded view of the current situation can help to identify the existing problems in the space heating system and propose solutions.

Therefore, in this chapter, the variation in heating load of the building is examined first, then the utilization of heat source equipment for space heating systems and radiant floor panels, which are used extensively in Korea as end-use devices to transmit heat to the room, are examined separately.

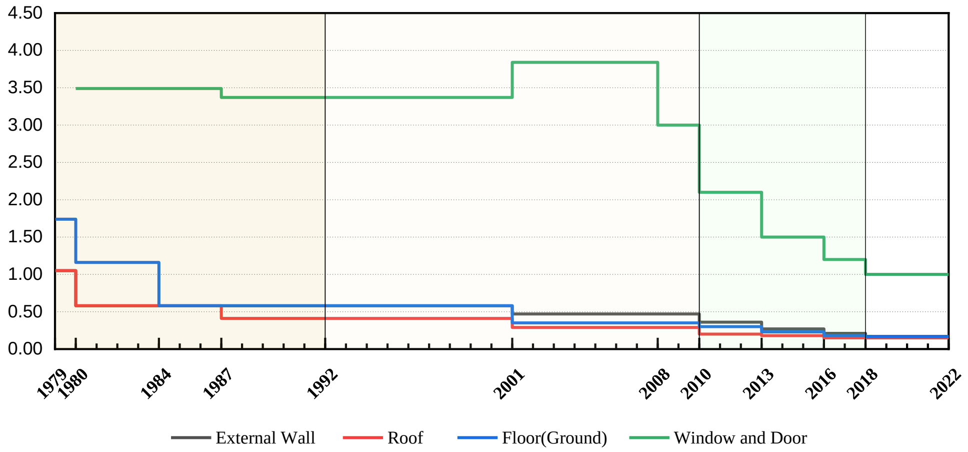
2.1. Changes in the heating load of apartment in Korea

2.1.1 Development of thermal insulation of the building envelope

The heating load is the amount of heat energy that would need to be added to a space to maintain the temperature in an acceptable range, determined by the heat loss of the building. Heat loss caused by heat transfer through the envelope structure accounts for the majority of total building's heat loss. So that the trend of heating load is consistent with thermal transmittance(U-Value) of the envelope are consistent

Reviewing design standards related to thermal insulation performance of buildings in Korea, the standards were transferred to the "Regulations on Building Facility Standards" in 1992 from "Building Regulation" implemented since 1979. As the importance of building energy management emerged in line with the national policy stance of low-carbon green growth, the "Energy Saving Design Standards of Buildings" was enacted separately in 2008. Eventually, "Energy Saving

Design Standards of Buildings" operated as a uniform standard that can be referred to plan thermal insulation of buildings from September 2013.



[Figure 2.1] Design criteria for apartments in Seoul (Floor heating)

The change in U-Value of the building envelope structure with time is shown in [Figure 2.2] and <Table 2.2>, As related technologies are still being developed, the insulation performance of buildings will continue to increase, and it is necessary to further improve the heating system in order to adapt to this tendency.

2.1.2 Changes in the heating load of apartment

Design indicators are often taken as over-valued, so they will differ from the actual heating load of buildings. However, the design heating load for each period can be a representative reflection of the general building’s heating load in that period. In order to investigate regions, the variation of building heat load with the increasing thermal insulation of buildings, this study studied the Korean literature related to heating loads in buildings since the introduction of radiant floor heating in Korea in the 1970s.

In 1977, when radiant floor heating had only entered the Korean space heating market and the relevant standards had not been fully developed, according to a study[2] on apartment heating systems by lee et al. mentioned that the heating load at that time was in the range of 123-150 W/m^2. Following the release of the new standard in 1992, Park Seok-bong conducted load calculations for an apartment building[3] that met the relevant standard in 1996, and the results showed that the load was 65 ~ 100 W/m^2 depending on the location of each family.

Entering the new century, Lee, Youn-Jung et al. published an article[4] on the characteristics of heating loads in residential buildings, in which they used the data specified in the standards implemented in 2001 and 2010 to build building models by simulation software and analyzed the heating loads of the subject buildings. The analysis shows that at the beginning of the 20th century, the heating load was 36-65 W/m^2. In 2010, the heat load range is reduced to 30-60 W/m2.

Referring to the latest standard use released by the Korea District Heating Corporation, the heat load per unit area of an apartment according to the size of the room is shown in <Table 2.1>[5], where apartments of all sizes with design heating loads of no more than 45 W/m^2.

<Table 2.1> Unit heating load reference for residential

	Area	heating load unit [W/m^2]			
		A	B	C	D
Apartment	above 85	48.7	44.9	41.0	38.3
	60-85	50.0	45.8	42.1	39.2
	below 60	52.0	47.7	43.8	41.0

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2 Lee, gon et al. "Design of Radiant Heating System for Housing". *The Magazine of the Society of Air-Conditioning and Refrigerating Engineers of Korea*.Vol.6, No.2, (1977):110-124.
3 Park, Seok-bong. "To accept the space of balcony as non-heating space of indoors = Study on Heating Load of Multiple Dwelling Units". *Industrial technology research*. Vol.6, (1996):39-42.
4 Lee, Youn-Jung et al. "Design of the Radiant Floor Heating Panel Considering Heating Load of Residential Building". *Journal of Architectural Institute of Korea*. Vol.27, No.9, (2011): 349-357.
5 Korea District Heating Corp. 2020, Standard of Heating Facility Standard.

<Table 2.2> Changes in design criteria for apartment envelopes in Seoul (Floor heating)

		Building Regulation[6]				Regulations on Building Facility Standards[7,8,9]				Energy Saving Design Standards of Buildings[10]		
		1979	1980	1984	1987	1992	2001	2008	2010	2013	2016	2018
External Wall	direct	1.05	0.58	0.58	0.58	0.58	0.47	0.47	0.36	0.27	0.21	0.17
	indriect						0.64	0.3	0.49	0.37	0.3	0.24
Roof	direct	1.05	0.58	0.58	0.41	0.41	0.29	0.29	0.2	0.18	0.15	0.15
	indriect						0.41	0.41	0.29	0.26	0.22	0.21
Floor (Ground)	direct	1.74	1.16	0.58	0.58	0.58	0.35	0.35	0.3	0.23	0.18	0.17
	indriect						0.52	0.52	0.43	0.35	0.26	0.24
Floor		-	-	-	-	-	0.81	0.81	0.81	0.81	0.81	0.81
Window and Door	direct	-	3.49	3.49	3.37	3.37	3.84	3	2.1	1.5	1.2	1
	indriect	-	-	-	-	-	5.47	4.3	2.8	2.2	1.6	1.5

[6] Ministry of Construction, Building Regulation, 1979/1980/1984/1987.
[7] Ministry of Construction, Regulations on Building Facility Standards, 1992.
[8] Ministry of Construction and Transportation, Regulations on Building Facility Standards, 2001.
[9] Ministry of Land, Transport and Maritime Affairs, Regulations on Building Facility Standards, 2008/2010.
[10] Ministry of Land, Infrastructure and Transport, Energy Saving Design Standards of Buildings, 2013/2016/2018.

2.2. Existing space heating systems in Korea

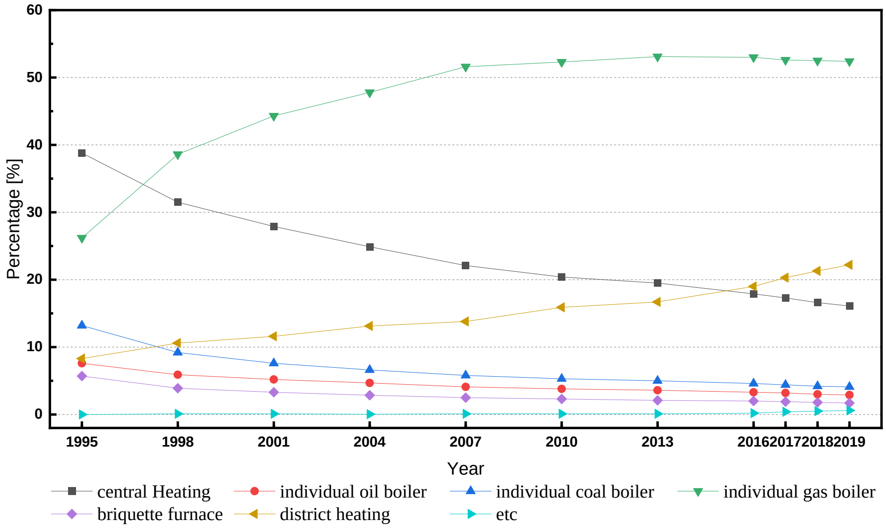
In Korea, the traditional ondol is a principle of heating air by setting fire in a kitchen furnace and circulating under the floor. The heated air transfers heat to the gutter, and then the floor heated by high-temperature air heats the air in the room. In fact, this method is a healing method used not only in traditional houses but also apply for space heating in residential-type buildings since the development of hot water heating boilers in the 70s.

Unlike the past heating method that used high-temperature air to heat the floor, the most common space heating method in Korea today would be hot water(hydronic) radiant floor heating. From ordinary apartments to detached houses, many of our living spaces utilize hydronic radiant floor heating. This method, as its name suggests, is a method of heating the space with radiation by flowing hot water to pipes embedded in the floor at a constant temperature. Hot water floor heating solved the problem of carbon monoxide poisoning in traditional ondol at once. It also has the advantage of being able to generate a pleasant environment. Radiant floor panels have become essential over all apartment buildings for every family.

The heating system in an apartment can be divided into individual heating with an independent boiler for each household, and central heating with hot water produced by equipment installed in the mechanical room of the building and delivered to each household through the building's hydronic distribution system, depending on the method of installation of the heat source. A large-scale heat production facility with sophisticated anti-pollution technology, such as a co-generation, generates central heating with hot water efficiently and economically.

District heating systems are comparable to central heating systems, but unlike central heating systems, the equipment for producing hot water is placed in a heat production plant managed by the district heating corporation rather than inside the building. District heating systems are an important aspect of greening the heating industry because they enable the integration of flexible and clean energy sources into the energy mix.

According to the National Statistical Office, since the second half of the 1990s, the share of furnished apartments with individual gas boilers has constantly increased due to the growth in demand for indoor comfort and the improvement of gas boiler industry technology. Simultaneously period, the proportion of apartments with a central heating system and the proportion of apartments with district heating as the hot water source have been trending in different directions.



[Figure 2.2] Heat Source of Korea Apartment[11]

At present, the individual gas boilers and district heating are used as the main source of hot water in apartment buildings in Korea, with water-based radiant floor heating panels as the end-use equipment to form the space heating system. The position of the boiler, supply of hot water, system administration, and user control of indoor temperature are all significant considerations in Korea's two most popular apartment heating systems.

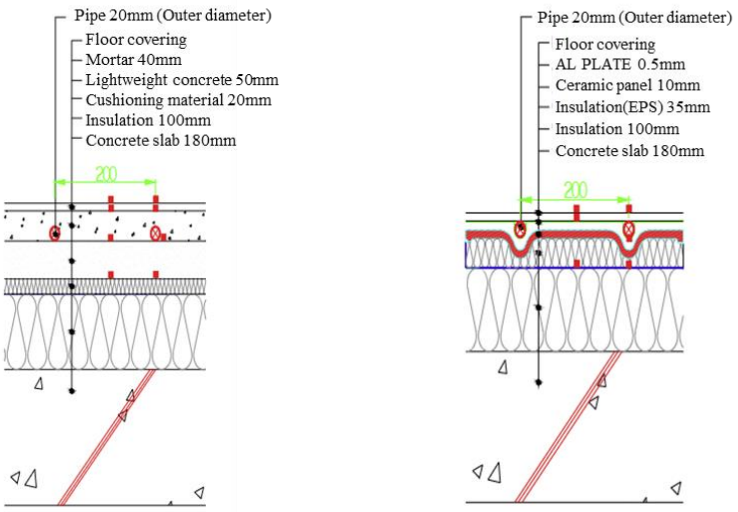
This chapter covers the status of apartment heating systems to better respond to the tendency of continuously reducing building heat loads and improving the energy efficiency of heating systems.

[11] KOSIS National Statistical Portal, kosis.kr

2.2.1 Radiant Floor Heating System

A radiant heating system usually includes emitting equipment like radiators or radiant floor panels, heat supply, distribution, and control systems. As the terminal equipment of the whole heating system, the thermal output of radiant heating panels set in the room is fundamental to space heating for most Korean households.

Underfloor heating systems applied to apartment households in Korea for space heating can be divided into two types according to the installation method, the wet type which is mostly used in new buildings, and the dry type which is widely used in renovation projects, and its general composition is shown in the [Figure 2.3]



[Figure 2.3] Wet ondol (left) and dry ondol (right) sections[12]

(1) The thermal output of radiant floor heating panel

For heating panels of the above configuration, the specific thermal output of a radiant heating panel is determined by the following parameters[13]:

12 Jung, Hae-Kwon et al. "Comparative Analysis on the Heat Transfer Characteristics between Dry and Wet Ondol Systems." *JOURNAL OF THE ARCHITECTURAL INSTITUTE OF KOREA Planning & Design*. Vol.25, No.11, (2009): 315-322.
13 DIN EN 1264-2, "Water based surface embedded heating and cooling systems - Part 2: Floor heating: Methods for the determination of the thermal output using calculations and experimental tests", 2021.

- Pipe spacing.
- Thickness and heat conductivity of the layer above the pipe.
- Heat conduction resistance of the floor covering.
- Pipe external diameter.
- Contact between the pipes and the screed.

Meanwhile, the specific thermal output is proportional to the temperature difference between the heating medium and the room temperature. When the above geometry factors are determined, the heat output of the panel can be expressed by the following characteristic curve.

$$q_H = K_H \cdot \Delta\theta_H$$

In which

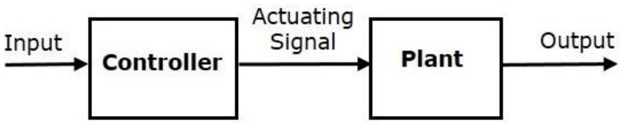
$$\Delta\theta_H = \frac{\theta_{supply} - \theta_{return}}{ln\frac{\theta_{supply} - \theta_{room}}{\theta_{return} - \theta_{room}}}$$

The characteristic value K varies according to the design of the panel and is determined by relevant experiments.

To summarize, when the indoor installation of a floor heating panel is determined, the heat output of the entire space heating system is closely related to the difference between the heat medium and the indoor temperature. In addition to this, the total heat output during the actual operation of the hot water floor heating panel is also affected by the flow mass rate of hot water.

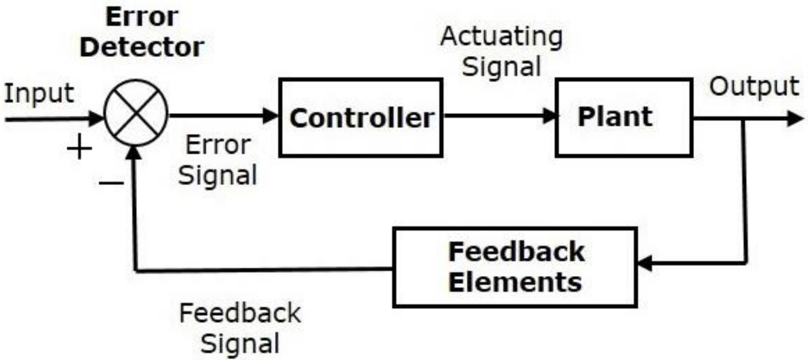
(2) The control of radiant floor heating panels

A control system is a system that provides the desired responses through the controlled outputs. The following figure shows a simple block diagram of the simplest control system with actuating plant. Here, an input signal is applied to a controller, then the controller's built-in control algorithm will generate an actuating signal or controlling signal. This signal is given as an input to a plant or components which is to be controlled.



[Figure 2.4] Typical open-loop control system

The major purpose of the control system of the radiant heating panel is to ensure the comfort of the indoor thermal environment, which is currently set up mainly to maintain the indoor temperature at the indoor set point. This means that the room temperature is used as a feedback object in the control system to determine what control action to take. And the control system with a feedback mechanism like [Figure 2.5] is called a closed-loop control system.



[Figure 2.5] Typical closed-loop control system

The current control system of a floor radiant heating panel is mainly to maintain the indoor temperature at a setpoint or comfortable range. Based on the closed-loop control system formation, equipment with the Feedback signal and Actuating signal, the variables associated with the control system in the entire radiant floor heating panel system are organized in <Table 2.3>.

A variety of control methods have been proposed so far, and a classification of each method according to the control factor, i.e., the object to be controlled, can be obtained as <Table 2.4>.

As we can see controlling the flow or temperature of the water supply are relatively easy to be achieved in the actual control process, the control method to manage these two variables is also the mainstream of radiant heating floor panel nowadays. While the ultimate purpose of the control system is to maintain room temperature, this is achieved by controlling the heat output.

<Table 2.3> Control factor of floor radiant heating system[14]

Control Factors	***Variable***	***Measuring/regulating device***
Input signal	Outdoor air temperature ; Indoor air temperature ; Return water temperature;	Temperature sensors and Integrated controller
Actuating signal	Supply water temperature	Boiler water supply temperature controller, temperature adjusted valve, 3-way/4-way mixing valve
	Supply water flow rate	On-off valves, pulse control valves, 2-way control valves, variable flow pumps
	Heating energy	Boiler with the certain heat output
	Heat source operation mode	On-off valves, Operation and shutdown of constant speed pump

[14] Yeo, Myoung Souk and Lyong Ryoo Seong. "Control Method of Hot Water Ondol Heating System in Residential Buildings". *Magazine of the SAREK*. Vol.34, No.8, (2005): 33-42.

<Table 2.4> Control methods for radiant floor heating systems[14]

Control parameters			Water temperature		Heat flux
			Constant temperature	Variable temperature	
Water flow rate	Continuous flow	Constant flow	-	Outdoor reset control	flux control
				Outdoor reset control with indoor temperature feedback	-
		Variable flow	P, PI, PID, fizzy control	-	-
	Intermittent flow	Two position Control	On/off Control	Outdoor reset + On/off Control	-
		Pulse-width modulation	On/off Pulse-width modulation	Outdoor reset + On/off Pulse-width modulation	-

The heat output of an installed hot water radiant floor heating panel can be calculated from equation 2 and is a function of the hot water flow rate and the difference in supply and return water temperature. The linear relationship between hot water temperature and heat output for a hot water floor heating system is shown in [Figure 2.6 a], while as shown in [Figure 2.6 b] the correlation between flow rate and heat output constitutes a non-linear ratio.

$$Q_{output} = M_{flow} \cdot C_p \cdot \Delta T$$

Which

$Q_{output} -$ *radiant floor heating panel heat output* $[W]$

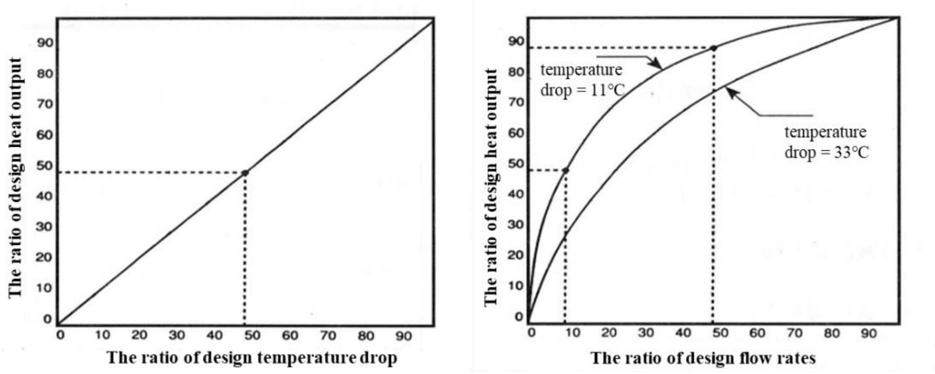
$M_{flow} -$ flow mass rate [kg/s]

$\Delta T -$ *difference of supply water temperature and return water temperature*

$C_p -$ *Specific heat capacity of hot water* $[J/kg]$

While there is an everlasting debate about proportional control of water supply flow, the majority of households in South Korea still use constant flow valves to govern the flow of hot water through the heating coil due to the characteristics of the valve and the non-linear relationship between flow and heat supply. In comparison with proportional control with variable flow valves, the case of a constant flow valve is typical on/off control. As a result, the supply of heated water is intermittent and therefore the room air temperature always fluctuates over time.

In particular, the temperature of the hot water in space heating systems in South Korea is often set at a constant state, so that when the temperature of the water supply is high, the overshooting of the interior temperature, exceeding the upper limit of the interior temperature, is a serious problem, which can lead to a reduction in the energy efficiency.



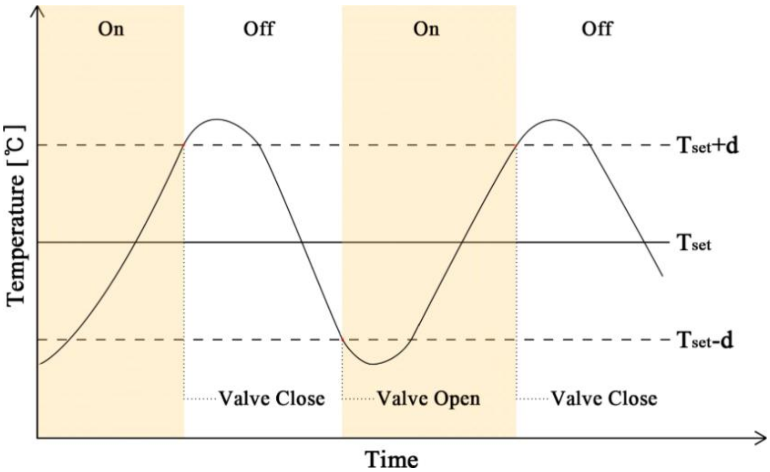
[Figure 2.6] control characteristics of (a) temperature and (b) flow rate[14]

Supply hot water flows control is a method of adjusting the flow rate to control the heat supply under the condition that hot water is supplied at a constant temperature and can be divided into intermittent on/off control and continuous variable flow control.

The on/off control method is a method of supplying or shutting off flow by controlling an on/off valve according to the control algorithms. The variable flow control method is a process of controlling the flow of hot water supplied by controlling a valve that operates in proportion to the difference between the set room temperature and the actual room temperature, thereby allowing the heat supply to be controlled.

The on/off control, the simplest form of feedback control, is currently the most widely applied control method in common residential space heating systems in Korea. An on/off controller simply drives the manipulated variable from fully closed to fully open depending on the position of the controlled variable relative to the setpoint. The temperature control in a domestic heating system is a common example of On/Off control. When the temperature is below the thermostat setpoint the heating system is switched on and when the temperature is above the setpoint the heating switches off.

As shown in [Figure 2.7] consider room temperature as the setpoint, even if the valve is closed when the control action of the off is performed which means supplying heat to space is stopped, the indoor temperature still increases for some time due to the thermal storage characteristics of the floor structure. In addition, for the same reason, when the room temperature decreases below the lower operating limit, the valve turns on immediately, but the room temperature starts to increase after some decrease instead of rising immediately. In such situations that occur, an error that deviates from the setting interval when control action is executed is called an overshoot or an undershoot. In this way, when the On/Off control is applied to the floor radiant heating system, the range of fluctuations in room temperature and floor temperature is large.



[Figure 2.7] Control characteristics of On/Off control[15]

The supply hot water temperature control is an approach to control the heat output via controlling the temperature of supply water at a constant flow rate. Considering the assignment of the space heating system to maintain indoor thermal comfort, an ideal system would continually and instantaneously adjust its rate of heat delivery to match the heat loss of the building it serves. The indoor air temperature would remain rock stable. There would be no difference in comfort regardless of outside conditions. However, hydraulic heating systems developed so far, but no hydronic heating system can claim to meet this ideal. Instead, interior air temperatures cycle up and down (albeit less than with most forced air systems) as heat is delivered in "spurts" rather than as a smooth continuous process. This is the result of water being supplied to the space heating system like

[15] Seunghyun M. Design and Control Method of Radiant Floor Heating System by Reducing Heating Load of Apartment House Using District Heating Source. 2019. Seoul National University, Master.

a floor radiant heating system at the same (design) temperature regardless of the current heating load. As the heat load varies mainly depending on the outside temperature, the control method to control the rate of heat supplied by adjusting the supplied hot water temperature according to the outside temperature is outdoor reset control. In a few words, outdoor reset controls use outside air temperature as the basis for determining an ideal "target" water temperature to be supplied to the floor radiant heating panel. It sends out cooler water to the system during the warmer outdoor temperatures. And sends warmer water to the building in cooler outdoor temperature. The proposal for outdoor reset control is based on two basic heat transfer principles:

- ✧ The heat loss of a building Q_{loss} is proportional to the difference between indoor and outdoor air temperature.

$$Q_{loss} = \mathrm{U} \times (T_{indoor} - T_{outdoor})$$

- ✧ The heat output of radiant heating panels Q_{output} is approximately proportional to the difference between the supply water temperature and the room air temperature.

$$Q_{output} = \mathrm{k} \times (T_{supply} - T_{indoor})$$

When the rate of heat output and heat loss are equal, the two equations are combined, and the following relationship can be derived:

$$T_{supply} = T_{indoor} + \frac{U}{k}(T_{indoor} - T_{outdoor})$$

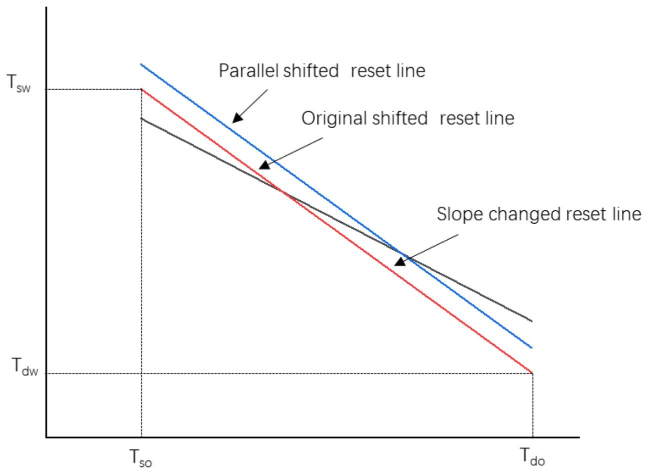
Once the indoor temperature is assumed to be the design temperature, the equation represents the linear relationship between the water supply temperature and the outdoor temperature.

After determining the maximum water supply temperature T_{sw} by referring to EN1264, ASHRAE Handbook, or other relevant materials based on the design load, the reset ratio can be calculated. The minimum water supply temperature T_{dw} and temperature setpoint for heating system start-up T_{do} is often set to the equivalent of the design value of the room temperature. According to the current design standards, the design outside temperature T_{so} of Seoul is 11.9 ℃.

$$RR = \frac{T_{sw} - T_{dw}}{T_{so} - T_{do}}$$

$$T_{supply} = RR(T_{indoor} - T_{outdoor})$$

In general, the thermal characteristics of each building and its radiant heating panels are different, so the reset ratio and heating curve calculated solely on the basis of design conditions are often too large, resulting in an avoidable energy consumption increase. Fine adjustment is a method of adjusting the set room temperature to maintain an accurate value by changing the slope of the straight line or moving it in parallel, as shown in [Figure 2.7].

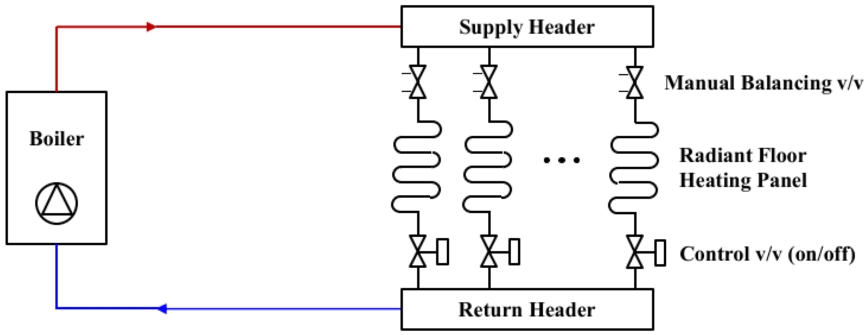


[Figure 2.8] Heating Curve and Fine adjustment

2.2.2 Independent heating with individual boilers

In the 80s, when small gas boilers for domestic use first began to be distributed in Korea, most of them were imported and sold from Europe. However, the European boiler, which opened Korea's gas boiler market, disappeared from the domestic market with many problems. Since then, the boiler industry has developed boilers suitable for space heating with ondol culture through steady technology.

When applying an individual heating method to an apartment house in South Korea using an individual gas boiler, the representative heating facility configuration is shown in the system shown in [Figure 2.9]. The entire heating facility consists of a gas boiler with a circulation pump and an expansion tank, a hot water distributor including a manual balancing valve and a control valve, and a radiant floor heating panel including heating pipes.



[Figure 2.9] Radiant Floor Heating System supplied by the individual gas boiler.[16]

Since individual gas boilers are generally used for domestic hot water and space heating at the same time, their capacity is commonly calculated based on the domestic hot water load or according to the space heating area. As the capacity of the gas boiler is determined, the circulation pump is also determined according to the specified standard without calculating the fitting flow rate.[17]

When calculating the hot water supply and heating load of a building, the capacity of the boiler is determined based on 100%, but 99% of the actual operating time is operated under partial load. In particular, since 50% of the total boiler operation time is less than 50% of the boiler's maximum load, the energy-saving effect can be maximized only by considering the minimum load rate of the boiler and the stable operation in the low load operation section.

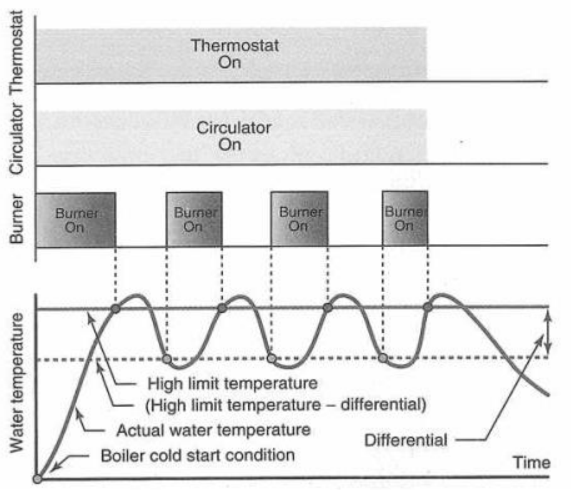
The operation of individual gas boilers can be divided into the operation of burners and pumps, which are performed by sensing indoor temperature and the heating water temperature control of the boiler. During heating operation, the boiler is operated if the room

16 Jeong, Chang Ho. Handling Strategies of Hydronic Thermal Energy System for Heating Demand on Low Energy Residential House. 2017. The Seoul National University, Doctorate.

17 Yoo, Mi Hye. Analysis of Effectiveness with Improved Alternative for Individual Heating Systems Using Flow Bypass. 2013. The Seoul National University, Master.

temperature falls below the set temperature and heating demand occurs in the room, and if the room temperature is higher than the set temperature, the boiler is stopped.

Most conventional gas boilers applied in Korea control the heating water temperature by turning on/off the burner with constant thermal output. As shown in [Figure 2.10], when the supply temperature or return temperature reaches the lower limit of the set temperature, the burner ignites and heats the heating water flowing through the heat exchanger, and when the heating water temperature reaches the set temperature limit, the operation of the burner stops and the heating water temperature drops again.



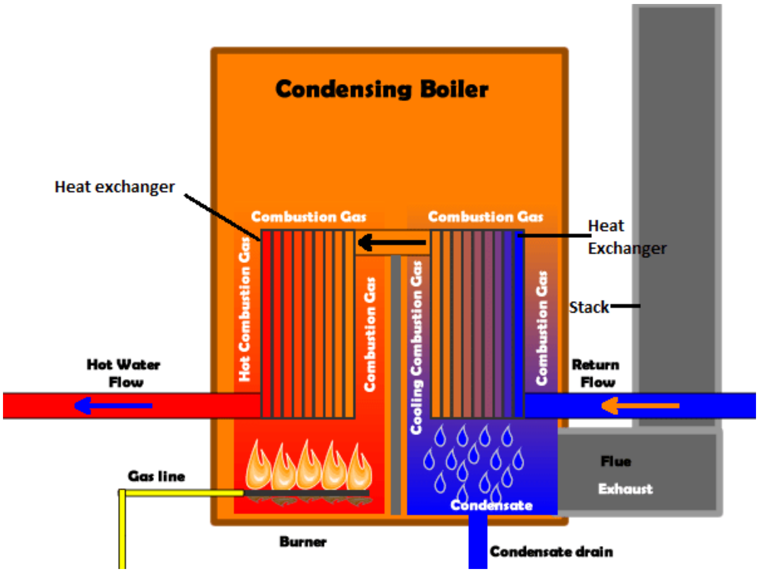
[Figure 2.10] Diagram of individual boiler operation scheme[18]

The existing on/off control method, in which the maximum amount of gas is ejected and digested during combustion leads to a short combustion time. The repeated ignition may also cause noteworthy unsafety, short boiler life, and difficulty in obtaining a stable and comfortable water supply temperature is also an issue that needs to be improved.

Consequently, more energy-efficient and eco-friendly condensing boilers furnished with proportional control are gradually coming into prominence and have begun to take the place of conventional boilers

[18] John Siegenthaler, P.E. MODERN HYDRONIC HEATING for residential and light commercial buildings. 3rd edition, DELMAR, 2012. p.381.

as a better individual hot water source. In 2005, it became law that all new gas boilers installed in domestic properties in the UK must be condensing boilers[19]. Condensing boilers for individual household hot water production also emerged in South Korea as early as 1989[20]. The exit flue gas temperature of conventional gas boilers is always high, and a large portion of the heat energy within exhaust gas is dissipated into the environment. Condensing boilers are designed to recover both sensible and latent heat by adding a condensing heat exchange, its components are shown in the [Figure 2.11].



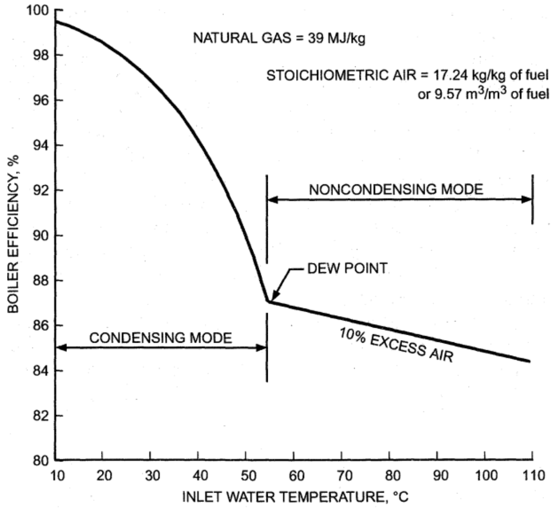
[Figure 2.11] Diagram of individual boiler operation scheme[21]

Return water from the space heating system or domestic hot water system is applied as the cooling medium of the heat exchanger positioned on the condensing side. In the cool-down process of the exhaust gas, the water itself is also heated by the high-temperature gas to achieve a preheating effect. Therefore, condensing boilers can

[19] The Boiler (Efficiency) Regulations 1993, SI (1993) No 3083, as amended by the Boiler (Efficiency) (Amendment) Regulations 1994, SI (1994) No 3083.
[20] Cho, Heung-won, "Energy Conservation and Environmental Improvement Effects of Condensing Boiler", *Boiler Equipment,* No.92, (2001):112-114.
[21] Satyavada, Harish, and Simone Baldi. "A novel modelling approach for condensing boilers based on hybrid dynamical systems." *Machines* 4.2 (2016): 10.

achieve better heat exchange efficiency when return temperatures from the heating system are lower.

Furthermore, when the temperature is below the dew temperature of the exhaust gas that allows recovering the latent heat of water vapor in the gas, so as to achieve obviously higher efficiency levels than conventional boilers. The key point in applying condensing technology to gas boilers is to maintain a high-temperature difference between supply and return water. When this condition is not maintained, the boiler will operate in a non-condensing mode[22]. It is able to notice that characteristics of condensing boilers make them more efficient when the boiler supply temperature is set at a lower point, resulting in further savings in fuel consumption.



[Figure 2.12] Effect of return (inlet) temperature on condensing boilers efficiency.[23]

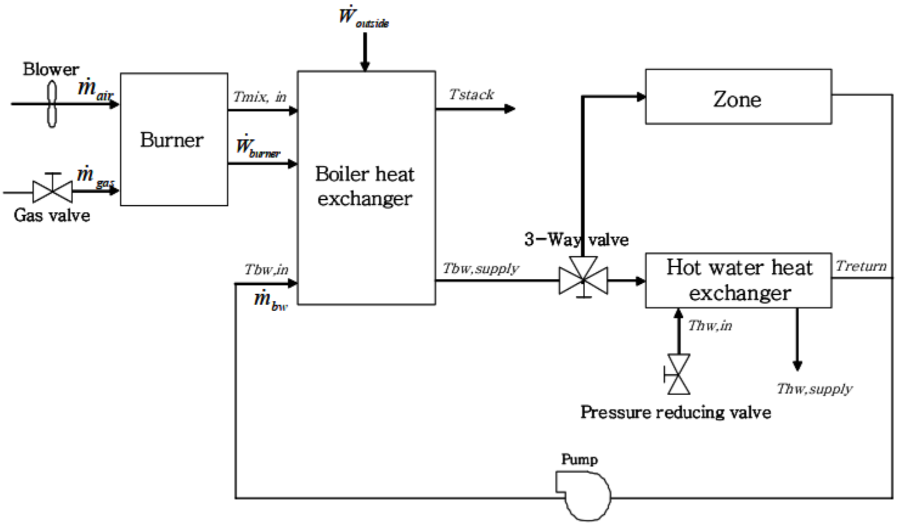
Better than conventional boilers, condensing boilers usually adopt a proportional control system to produce hot water at a set temperature. Proportional control is a method that automatically measures the setting temperature set by the user, then the boiler's hot water temperature is controlled by using a proportional rotation DC fan and a proportional control solenoid valve to match the ratio of

[22] Lee, Seung-ro, Sung-Min Kum, and Chang-Eon Lee. "Performances of a heat exchanger and pilot boiler for the development of a condensing gas boiler." Energy 36.7 (2011): 3945-3951.

[23] American Society of Heating, Refrigerating and Air Conditioning Engineers ASHRAE. ASHRAE handbook HVAC systems and equipment; 2020.

combustion air and gas in the entire range.

[Figure 2.13] shows a block diagram of a condensed gas boiler system. As shown in the figure, in the condensed gas boiler system, the heat generated from the combustor is transferred to the water through a direct alternating current boiler heat exchanger and a latent heat exchanger. Then the hot water discharged from the boiler heat exchanger provides heat to the thermal zone through radiant floor heating panels and hot water heat exchanger.



[Figure 2.13] A condensing gas boiler system.[24]

The control system of a condensing boiler involves three main devices, which are the supply fan, the gas supply valve, and the burner. when the boiler is operated, a gas combustion process is performed, and the temperature of the water (heating water) inside the boiler increases. At this time, when the temperature of the heating water exceeds the preset temperature by the user, the gas combustion process stops, and when the temperature reaches the set temperature, the gas combustion process proceeds again. The present invention relates to a gas supply amount control method for maintaining a heating water temperature constant according to a predetermined

[24] Han, Do-Young, and Sung-Hak Kim. "Effective dynamic models for the development of control algorithms of a condensing gas boiler system." Korean Journal of Air-Conditioning and Refrigeration Engineering 20.6 (2008): 365-371.

temperature without stopping a gas combustion process by reducing a gas supply amount suitable for the current temperature before the heating water temperature reaches a predetermined temperature. The notable advantage of gas-FAN is that the amount of gas is adjusted according to the heating or domestic hot water load so that the hot water temperature can satisfy the user's set temperature range as much as possible despite the fluctuation of the load.

In recent years, the heating load is decreasing due to improved insulation and tightness of buildings, but the radiant floor heating panel is still empirically applied in accordance with the practice without considering the reduction of the heating load. The supply flow rate applied to the panel is calculated by using the heating load and the supply-return temperature difference, but the supply water temperature is usually 55 to 60°C for individual heating, and that does not vary over time also exists. Other than that, from the catalog of the latest condensing boilers currently in circulation, the supply temperature range generated by the condensing boilers is roughly 40-83°C, and the return water temperature is between 30℃ and 65 ℃ [25]. The actual operating temperature of the water supply is determined by the users' settings.

In summary, the current apartment space heating system uses individual gas boilers, although a large number of condensing boilers have been installed there are still some households using non-condensing boilers. Also, regardless of the type of boiler that families selected when designing space heating systems using individual heat sources for each household in South Korea, compared to the maximum heating load(the space heating design load), larger capacity boilers are usually selected to produce hot water due to the need to use heat sources in combination with domestic hot water systems, which means that the boilers operate at a lower partial compliance rate most of the time. The last but not least, the current boiler output temperature is at a high level relative to the decreasing heat loss of the buildings, and

[25] Kyungdong Navien Product Comprehensive Catalog, http://en.kdnavien.com/index. Accessed 20 Apr 2022.

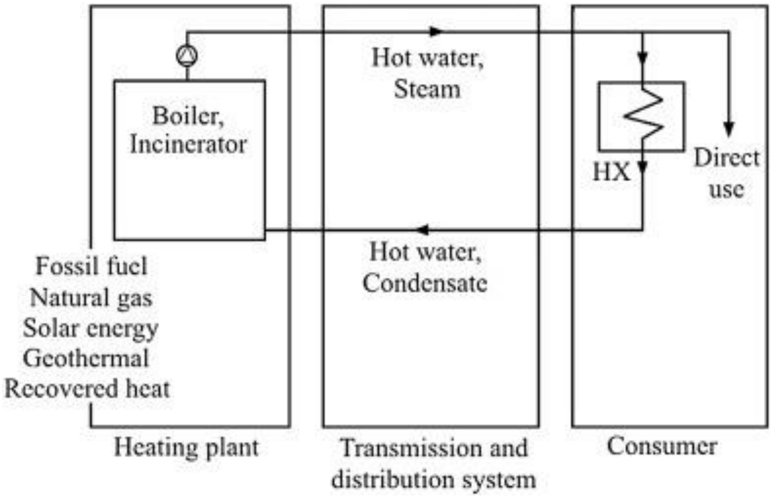
the high temperature of the hot water supplied for radiant heating can lead to overheating of the indoor air, resulting in worse indoor thermal comfort and decrease in energy efficiency.

2.2.3 District Heating

Domestic district heating was first introduced in November 1985 in Mok-dong, Seoul, as part of a plan to save energy in the heating and power sectors under high oil prices in the 1980s.

In the case of the central heating system using district heating heat sources, the floor radiant heating panel, which is a terminal facility used for space heating is the same as the individual heating method. There is only a slight difference between the heat source facility, the hot water from the plant will be distributed to each household through the hydronic network located in the building.

Unlike the individual heating method, which produces hot water for each household using individual gas boilers, the district heating is an advanced heating system that does not install individual heat production equipment in apartments but supplies to large areas heat (hot water) produced economically in a large-scale heat production facility such as a cogeneration plant.



[Figure 2.14] Major components of district heating system[26]

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[26] Ioan Sarbu, Calin Sebarchievici, "Chapter 5 - Solar Water and Space-Heating Systems," *Solar Heating and Cooling Systems*, Academic Press,

As [Figure 2.14] shows that the district heating system is composed of three fundamental components: the heating plant, the transmission and distribution network, and the user system. The heat energy that can be produced by a central plant (district heating station) can be any combination of boilers, solar, geothermal sources, or simply a by-product of power generation. At the same time, hot water is an attractive medium for transporting heat for systems that primarily serve residential and commercial buildings.

The last part of the whole district heating system is the consumer system, which contains all kinds of in-building equipment. When the hot water from the central plant is supplied to the building, it may be used directly by the building HVAC systems or indirectly where isolated by a heat exchanger.

District heating systems are important solutions for decarbonizing the heating sector in the Net Zero Emissions by 2050 Scenario. Modern networks with low operating temperatures can integrate 100% renewable sources to supply energy-efficient buildings, especially in areas where decentralized solutions would not allow the direct integration of available clean energy sources or efficient operations, for example, due to space or infrastructure constraints.

The primary side of the in'-build heat exchanger is the side that is connected to the distribution network, and the secondary side is the side that is connected to the building HVAC system. According to the thermal utility standards issued by the Korea District Heating Corporation and modified in 2020, when the space heating method on the secondary side is radiant heating, the design water supply temperature on the first side is 115°C, and the design temperature difference between the supply and return water is 60°C.

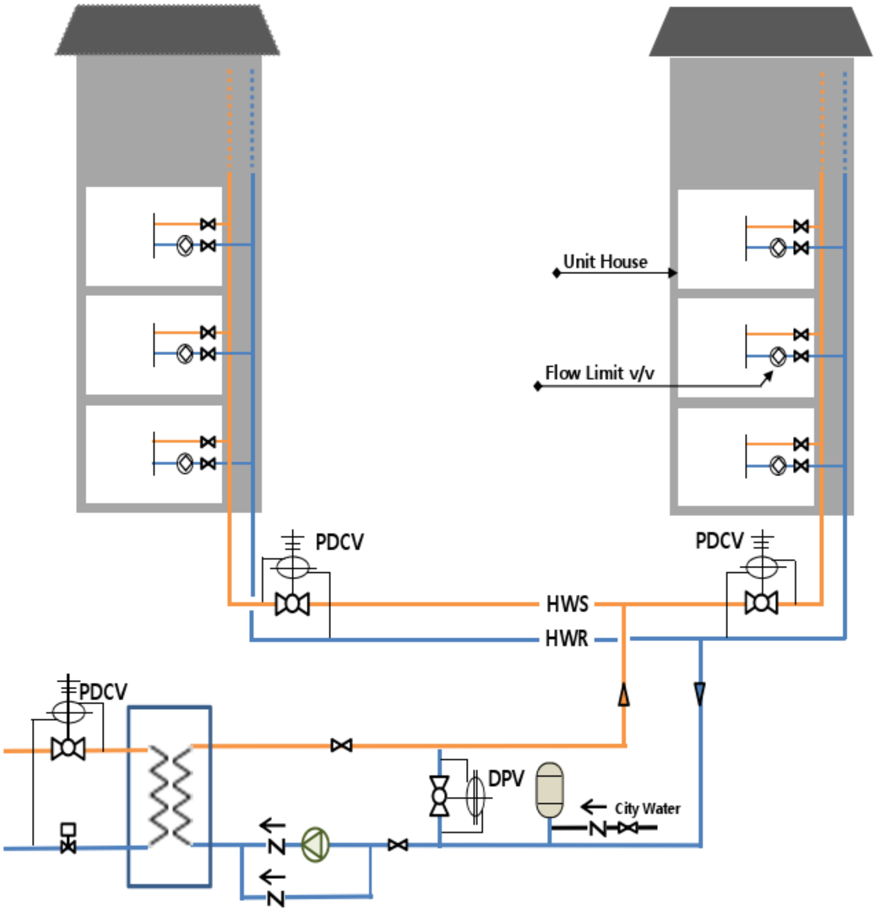
Moreover, in an investigation of the district heating network in the Seoul area, it was shown that the average annual supply temperature of the distribution network ranges from 95 to 110°C, and the annual average return water temperature is approximately 60°C.[27]

2017. 139-206. ISBN 9780128116623

[27] Kwag, Hyun Ju, et al. "Transition to the 4th Low Temperature District Heating Systems in SEOUL District Heating System." *Transactions of the*

Because of the high temperature of the hot water produced in the current district heating system using CHP etc. equipment, and so for better use in space heating and domestic hot water of apartment households, a common distribution facility is installed to supply heating water from the central machine room to each household. The heating water supplied to each household has a similar water supply temperature.

Therefore, due to the characteristics of the hydronic network that supplies heating water to multiple households by the centrally installed circulation pump, a maximum flow limit valve that limits the maximum flow rate to the household is added for each generation.



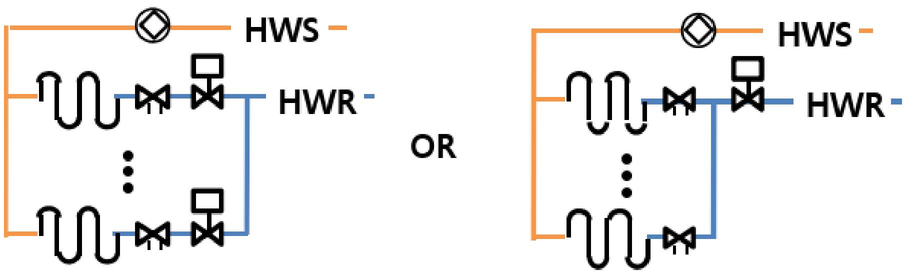
[Figure 2.15] District Heating System for Space Heating.[16]

Korean Society of Mechanical Engineers. B45.12 (2021): 691-699.

There are two main methods of water supply temperature control on the secondary side of heat exchange installed in apartment buildings, one is set-point control, and the other is outdoor reset temperature control.

The Korea District Heating Corporation recommends the temperature of heating hot water supplied to each household from the center heat exchanger at 60°C, so for apartments using the first control scheme, 60°C is usually chosen as the setpoint. The hot water at this temperature is supplied to each household through a distribution network inside the building, even at the coldest times, which is excessive for most homes with good insulation and infiltration properties. On the other hand, some apartments try to apply outdoor reset temperature control for reasons such as reducing heating energy, but most of them supply heating hot water at fixed temperatures due to complaints related to comfort and energy consumption during actual operation.

In common with space heating systems that use individual boilers as the heat source, most households in apartment complexes that use district heating heat sources control room temperature by simple on/off control like [Figure 2.16], and switching valves are installed on the supply or return pipes of households to control flow rates.



[Figure 2.16] Systematic diagram of heating system in household[28]

The fine flow control valve in the household is a manual balancing valve, and the design flow rate determined by each room is set to flow when the entire room in the household is heated.

[28] Jin, Hua Guo. Characteristics and Improvement of Hot Water Supply in Apartment Housing using District Heating Source. 2013, The Seoul National University, Master.

Related research documents were considered to understand the heating control method and operation status currently applied in apartment houses using local heating heat sources.

Choi Chang-sik and four others[29] surveyed the operation status of the heat source and distribution system using drawing analysis, in-depth interviews with managers, and resident surveys for a total of 10 complexes in the Gangseo and Yangcheon areas. As a result of the survey, most apartment complexes were equipped with the function of outdoor reset control. However, the possibility that the use of outside reset control may cause a slow temperature rise after turning on the heating system, most apartment choice to supply high-temperature hot water. In addition, even if outdoor reset control is applied, in fact maximum supply water temperature is about 53 to 60°C, which is higher than the actual required temperature.

A study by Lee et al.[30] investigated the supply temperature of heating circulation water for 4,000 households in Korea where adopt the district heating method, and in the case of the intermittent heating method, hot water is supplied in the temperature range of 56 to 60°C, and in the case of continuous heating method, hot water is supplied in the temperature range of 51 to 55°C.

Meanwhile, the supply temperature of heating hot water according to the outside temperature presented by SH Group Energy Business is shown in <Table 2.5> below.

<Table 2.5> Definition of temperature ranges for heating designs[31]

outdoor air temperature [°C]		-12	-5	0	10
supply water temperature [°C]	Normal	60	50	47	35
	Economy	53	47	42	32

[29] Choi, Chang-Sik et al. "Analysis on the heat source and the distribution system operation of apartment house complex using a district heating source." *Proceedings of the SAREK Conference* (2015): 545-546.
[30] Lee, Tae-Won, and Kim. Yong-Ki. " A Study on the Operating Conditions for the Demand Side Facilities of the District Heating System." *Proceedings of the SAREK Summer Conference* (2011): 533-538.
[31] Seoul Housing & Communities Corporation, Facilities Manager Technical Textbook.

2.3. Low-temperature Hydronic heating systems

According to the study of existing heating systems in Korea, the hydronic heating system is currently the only option for apartment houses, compare to forced air systems in that they heat the circulating liquid thermal medium, which in turn heats the environment air in the building or room. In a forced-air system, the air is warmed directly and mixed with the ambient air in the building to reach the requested temperature.

Hydronic heating systems typically consist of three basic elements: a heating system for the generation of hot water, a distribution system for transporting hot water, and a heat exchange system for heat transfer to space. With radiant floors, the most common heat exchange system of space heating in Korean apartment buildings, once the geometric factors of the radiant floor heating panels mounted in the room have been clearly determined, the heating performance of the system during its operation is completely contingent on the working conditions of the thermal fluid flowing through it.

Despite the current improvements in the insulation and tightness in buildings, the hot water temperature of the existing heating system has not significantly changed in comparison to about 20 years ago. Though the operation scheme is different from the previous plan of supplying hot water to each household with a fixed water temperature simply by the schedule, there is a house-by-house and room-by-room control method mainly based on ON/OFF control, the overshoot phenomenon of indoor air temperature is still unavoidable due to the high-level water temperature.

While condensing boilers capable of producing lower temperature hot water have been used extensively in Korean homes and as individual heating systems, the outlet water temperature can easily be controlled manually or automatically, which can be a challenge for district heating systems. Accordingly, this chapter mainly examines low-temperature heating systems with district heating as the heat source.

2.3.1 Definition of low-temperature heating system

For Hydronic heating systems, various options for each subsystem exist. Depending on the heat source to be used for the entire heating system, both district heating systems, and individual heating systems are currently used in apartment houses in Korea. As an alternative, the heating system can also be categorized based on the temperature of the hot water delivered in the distribution system.

According to the related research, the heating system may be divided into a high-temperature heating system, medium-temperature heating system, low-temperature heating system, and very low-temperature heating system respectively in accordance with the temperature of the heat medium. The supply and return water temperature of each type of system is generally shown in <Table 2.6>.

<Table 2.6> Definition of temperature ranges for heating designs[32]

System	Supply Flow	Return Flow
High temperatures (HT)	90℃	70℃
Medium temperatures (MT)	55℃	35-40℃
Low temperatures (LT)	45℃	25-35℃
Very low temperatures (MT)	35℃	25℃

The level of water temperature supplied to the radiant floor heating panel in households plays a major role in primary energy consumption and environmental impacts. As more and more buildings are becoming energy-efficient due to better thermal insulation, less infiltration, and more efficient heating and ventilation systems, heat losses from buildings are decreasing. All these changes could be the reasons to reduce the need to supply the heating system with water at a temperature as high as previously.

A low-temperature heating (LTH) systems implementation program in buildings program conducted by Netherlands Agency for Energy and the Environment mentioned that the primary objective of

[32] BOERSTRA, Atze et al. “The health, safety and comfort advantages of low temperature heating systems: a literature review”. *In: Proceedings of the 6th international Conference on Healthy Buildings*. 2000, p.629-634.

reducing the supply water temperature of space heating systems are able to use Low Valued Energy as a heating source. Major savings in energy consumption can be realized by fully utilizing the potential of Low Valued Energy.

Besides the Argument savings in energy supply, there are additional benefits in the fields of[33]: Indoor Air Quality, Thermal Comfort and Energy Consumption. The hydronic heating system already creates better indoor air quality because of fewer mites and fewer airborne particles than forced-air systems. Not only that low-temperature heating system with a lower water supply temperature also maintains the indoor temperature at a relatively low level, thus preventing negative effects on the health of the occupants when the indoor temperature fluctuates in a wide range. In case the space heat exchange equipment is using radiant heating panels, the low hot water temperature can diminish vertical temperature gradients, less radiant heat asymmetry, more comfortable floor temperatures, and also reduce draft risk[32].

In terms of energy saving, the convenience of utilizing high-efficient and low carbon-emitting heat sources cannot be ignored. Air exhaust and geothermal heat pumps have been successfully used in residential buildings in European countries, and the heat pump units are able to operate at higher COP when the heat medium temperature is lower.[34] As a particular technique to reduce or eliminate the primary energy consumption, a solar-assisted heat pump system reduces CO_2 emission with the substitution of renewable-based energy sources, which technology has the potential of providing an effective alternative heat source for LDH[35]. While the apartment house is in the district

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[33] Eijdems, H. H. E. W., A. C. Boerstra, and P. J. M. Op't Veld. "Low temperature heating systems: Impact on iaq, thermal comfort and energy consumption." vol. Annex 37 (2000).

[34] Hesaraki, Arefeh, and Sture Holmberg. "Energy performance of low temperature heating systems in five new-built Swedish dwellings: A case study using simulations and on-site measurements." B*uilding and Environment* 64 (2013): 85-93.

[35] Buker, Mahmut Sami, and Saffa B. Riffat. "Solar assisted heat pump

heating network, waste heat from industrial processes also can be used as the heat source to generate hot water there is a much higher potential for using waste heat from industrial processes and from cooling processes in commercial buildings e.g., supermarkets[36]. About the individual heating case, condensing boilers, which currently occupy a larger share of the market, also perform better at low return and supply temperatures and steady energy consumption.

Not only does the use of lower water temperatures for space heating reduce energy consumption and non-renewable energy use on the heat source side, but it also decreases heat losses from the heat production unit and from distribution pipes as the temperature of the hot water flowing through the distribution network. In apartment buildings the distribution and emission losses were significantly higher than in detached houses and compared to low-temperature heating curves with 45/35℃, the conventional 70/55℃ curve remarkably increased the losses[37].

Many pilot projects have demonstrated that local heating supply temperatures slightly above 50°C can meet end-user indoor heating (SH) and DHW demand in central Northern Europe.

Based on the relevant domestic study[27], Hyun Ju Kwag et.al identified the potential of the current district heating system transition to LTDH in Seoul, Korea. The study found that reducing the supply and return water temperature from 100°C to 90°C, from 60°C to 50°C respectively reduces the distribution network heat loss by 17%, and 4GDH level of supply/return temperature reduction (70°C/40°C) reduces the annual heat loss of the distribution network by 56%.

In view of the fact that the water supply temperature in the existing heating system in Korea is often set at a high level and there

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systems for low temperature water heating applications: A systematic review." *Renewable and Sustainable Energy Reviews* 55 (2016): 399-413.

[36] Cooper, Samuel JG, et.al. "Potential for use of heat rejected from industry in district heating networks, GB perspective." *Journal of the Energy Institute* 89.1 (2016): 57-69.

[37] Maivel, Mikk, and Jarek Kurnitski. "Low temperature radiator heating distribution and emission efficiency in residential buildings." *Energy and Buildings* 69 (2014): 224-236.

are cases where the heating system is controlled and regulated without considering the change in space heating demand, there is a need for discussion and research on low-temperature heating systems in response to the progress of low carbonization in the country and the world, and as the building, thermal insulation performance becomes better and better.

2.3.2 Low-temperature district heating

The district heating system has a very important role in the Korean energy system. The conventional district heating system is based on water or steam flowing through pipes which are usually placed under the ground or above in some cases. Water is used as a heat carrier medium which has many fetching characteristics. Water is relatively cheap, accessible, and not special corrosive or toxic.

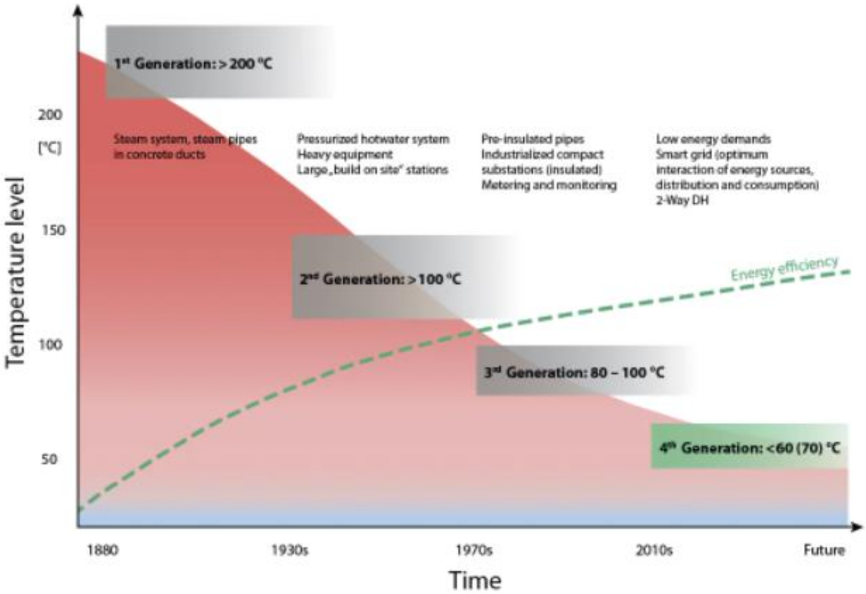
The first generation of district heating was introduced in the USA in the 1880s where scalding steam at 300 °C was used as the heat carrier. The second generation of district heating characteristic is the transition from steam into hot, pressurized water with a temperature often higher than 100°C. The third generation of district heating systems was introduced in the 1970s, but it took a large share of extensions until 1980s. The different in this generation is the temperatures in the supply lines are below 100 °C, which provides more efficient and lean material to be used for these systems

On the basis of the previous section on the current status of the district heating system in Korea, the current district heating system is still in the 3rd generation of supplying medium temperature water.

Throughout the generation, the temperature of the district heating network is gradually decreasing as the better insulation of buildings result in required heat load is reduced. The 4th generation district heating is called Low Temperature District Heating (LTDH) as the user temperature level is lowered to 50 to 70°C.

The current domestic district heating system only sets up a large heat exchange heat preparation in the mechanical room of the building to obtain the warm water supplied to the occupants. This approach ignores the actual heating needs of the households compared to the boiler which can adjust the water supply temperature according to the demand.

Even if low-temperature water is used as the heating medium and a fixed supply temperature is supplied to the space heating system, the heating system is still unable to respond to changes in heating load, resulting in energy waste. As a result, outdoor reset control is used in a large number of low-temperature heating systems in energy-efficient houses. In order to control supply water temperature, while LTDH is applied to multi-storey buildings, a decentralised solution with flat stations is used in Danish. The system schematic is shown in [Figure 2.18]

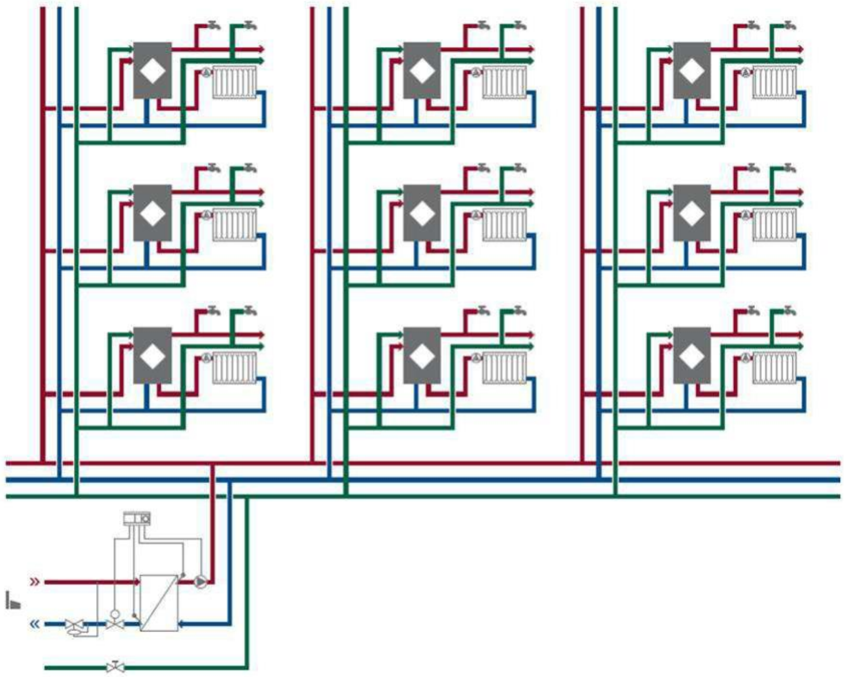


[Figure 2.17] The development process of district heating[38]

By preparing the hot water in the flat station according to the actual requirements of consumers, not only does it reduce room temperature overheating caused by high water supply temperatures, but it also improves energy efficiency. The flat station concept is individual metering of each flat heat consumption and complete control over space heating preparation. Depending on the product, there are

[38] Lund, Henrik, et al. "The status of 4th generation district heating: Research and results." Energy 164 (2018): 147-159.

many names for the flat station that based on water-water heat exchangers like Plate heat exchangers (PHEX)[39], Heat interface unit (HIU)[40]. In this article I will represent this device with HIU.



[Figure 2.18] The development process of district heating[40]

2.3.3 Heat Interface Unit

In existing district heating systems, the temperature of the supply water entering different households is almost the same because the heat exchanger is often located only in mechanical rooms to obtain the desired temperature of hot water. Moreover, the design supply temperature is usually determined according to the representative room with the highest heating load for the whole building or directly set based on building manager experience. In fact, due to the different orientation, location, and other factors of each household, the demand for heating is different from one household to another at every moment,

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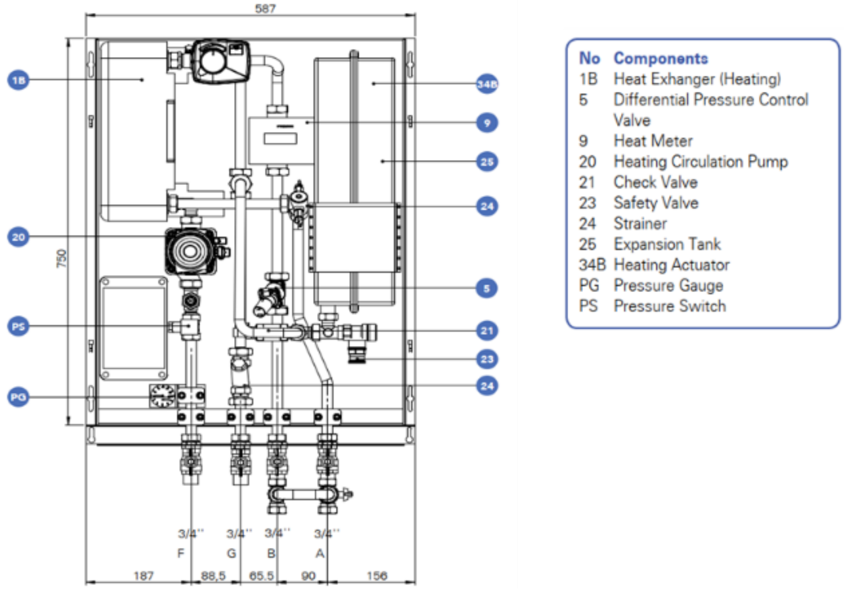
[39] Teskeredzic, Armin, and Rejhana Blazevic. "PLATE HEAT EXCHANGER MODEL AS PART OF INDIRECT HEATING SUBSTATION." *Annals of DAAAM & Proceedings* (2019): 709-717.
[40] Olsen, Peter Kaarup, et al. "Guidelines for low-temperature district heating." *EUDP-DEA. Denmark* (2014).

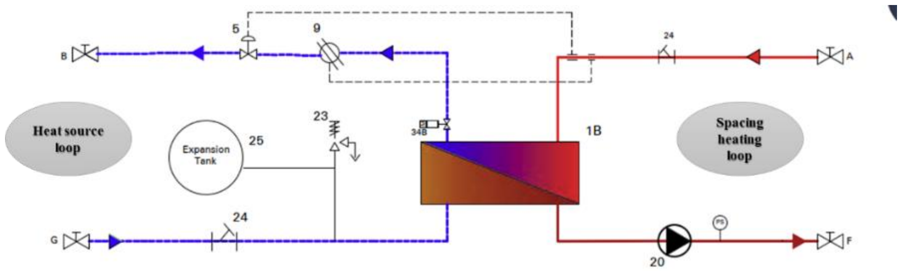
so with the same water temperature, the overshoot of the room temperature is still serious in the rooms with smaller heating loads.

The Heat interface unit (HIU) is used in a direct heat exchange method in Europe and receives low temperature (60°C or less) hot water to supply heating and hot water within a generation and transmit sector-specific metering data to an integrated control center. A heat interface unit basically fulfills the same function as a gas boiler in a property when used as part of a communal heating network. A central plant room (either a gas boiler or a renewable energy source) will generate heat which is distributed through a network of pipes to each separate property in the building. Each home or apartment has its own HIU installed, which uses heat distributed from the central network to provide heating and domestic hot water (DHW) for use in the home, completely replacing the requirement for individual boilers in each property. To the end-users, it is just like having a boiler as normal but without the flame. HIU can be classified into those specialized in domestic hot water, space heating and both according to their functions. This section summarizes product information related to space heating systems.

A typical HIU for space heating only consists mainly of a small heat exchanger and associated controlling components, the other components are shown in [Figure 2.19]. The system of single heating HIU is shown in [Figure 2.20], with HIU's heat exchange equipment, it can facilitate the application of individual control methods for controlling the water supply temperature in real time such as outdoor reset control during the actual operation of the heating. The potential to further reduce energy consumption compared to existing district heating systems that do not allow for individual water temperature control.



[Figure 2.19] The components process of single heating HIU[41]



[Figure 2.20] The system of single heating HIU

[41] Emmeti UK, Heat Interface Units Communal Heating Schemes.

2.4 Summary

This chapter analyzes the variation of heating loads in residential buildings in Korea, the composition of heating systems currently applied in apartment buildings and their control methods, etc., mainly through literature review. Finally, it also examines the relevant development trends and applications regarding low-temperature heating systems.

(1) As the building insulation performance is continuously strengthened, its heating load is also in constant decline. At present, in the design process of heating system, Seoul region often adopts a heating load of about 40w/m2 as the design index.

(2) Presently, district heating and individual gas boilers are mainly used as the heat source for heating systems. Almost all apartment residents have installed radiant floor heating panels as the indoor end of the heating system.

(3) Most systems simply use a simple ON/OFF control to turn the radiant floor heating panels turned on and off to control the room temperature. Although adjusting the supply temperature of radiant floor heating panels can effectively regulate the heat output, the temperature of the water supply to the heating system is always constant. At the same time, whether using a boiler or district heating in the current widely used heating systems, the supply water temperature is high, often exceeding 50°C. This temperature does not differ from the period when buildings were less well insulated. Whereas in some apartments with district heating an outdoor reset control is used to regulate the temperature of the water supply on the secondary side, the heating curve on which the control is based is often determined by convention. The fluctuation range of room temperature will be larger when the water supply temperature of radiant floor heating system is not suitable due to the characteristics of ON/OFF control.

(4) High insulation, high tightness residential building allows the heating load to be maintained at a low level throughout the heating season, which creates the conditions for the application of low temperature heating systems. The current research on district heating systems is mainly focused on the 4th generation district heating systems, i.e., district low temperature heating systems. This low-temperature district heating network will deliver hot water below 60°C to all types of consumers.

(5) The water supply temperature is the same for each household in the current district heating system, and individual control of the supply water temperature for each household is difficult to achieve. In Europe, there are equipment called Heat interface unit (HIU) with a small heat exchanger as the core component installed in each household to achieve individual control like using individual boiler.

Chapter 3. Research Subjects

With the aim of comparing with the existing heating system and exploring the applicability of the low-temperature heating systems in existing buildings, building models and HVAC models were constructed for application in simulation analysis. Simultaneously, relevant heating performance evaluation systems were built to better analyze the space heating performance of radiant floor heating panels when their water supply temperature is low.

3.1. Research Apartment Object

3.1.1 Apartment model for simulation analysis

The building model used for simulations is based on an existing apartment building with high thermal insulation and high tightness. The Thermal transmittance of its envelope is shown in <Table 3.1>. Given that the apartments were built with high-insulation performance, the thermal design of the exterior walls, roof, and the structure of the lowermost floor of the building in contact with the ground meets the design standards for energy-efficient buildings introduced in 2018. The retrofitting of windows is easier to achieve than that of the envelope, and the windows in this apartment are highly insulated with a heat transfer rate of less than 1.50 W/m^{2}K, which also meets the latest energy-saving design requirement.

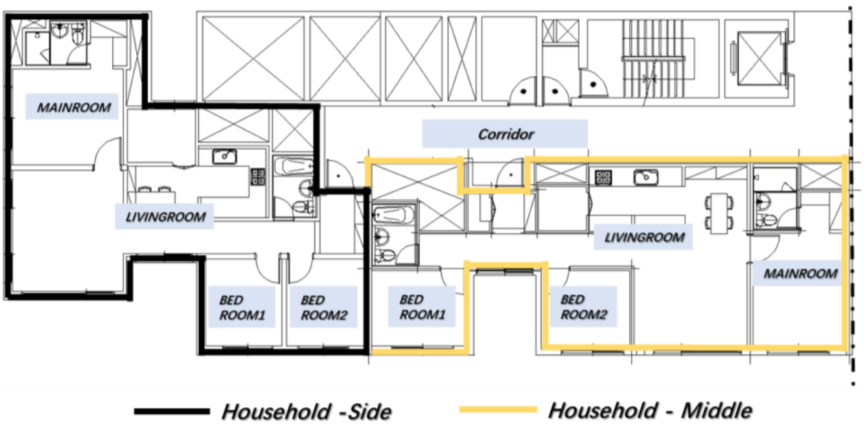
<Table 3.1> Thermal transmittance of the study object envelope

Structures		**Thermal transmittance(U-value)**
Exterior Wall		0.16 W/m^{2}K.
Exterior Roof		0.16 W/m^{2}K.
Floor	Ground	0.20 W/m^{2}K.
	Middle	0.60 W/m^{2}K.
Window		0.79 W/m^{2}K.

The apartment houses have 3 units on each floor, which are distributed axially symmetrically with the central axis of each floor. To simplify the model, only the west unit as a representative of the family on the side and the center as a representative of the family in the middle were modeled. Moreover, in order to examine the differences in the heating loads of households in different locations. The building model also includes the lowermost floor in contact with the land, as well as the middle floor which ignores the heat transfer between upper/lower households, and the uppermost floor where the roof is in direct contact with the outdoor.

The geometry of the building model and the layout of households on the standard floor are shown in the [Figure 3.1], and the layout of rooms within the household is shown in [Figure 3.2]. There are two house types on each floor, and each house consists of four heating zones: living room, main bedroom, bedroom 1 and bedroom 2. The non-heated areas were also modeled under the same envelope conditions, and the corridor temperature was set at a fixed 15°C

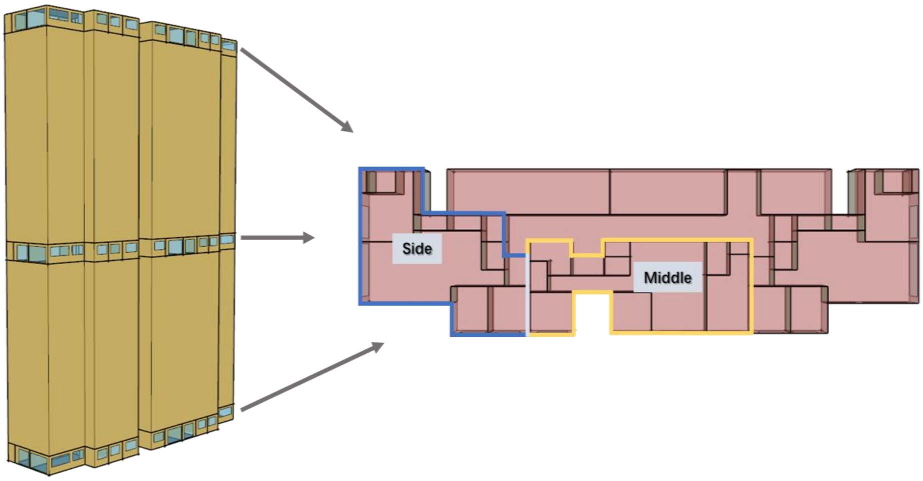
The thermal load of a building is not only linked to the thermal characteristics of the building envelope but is also constantly influenced by the outdoor air temperature, solar radiation, indoor air temperature setpoint, internal heat gains and the external air introduced into the room. Outdoor air temperature and solar radiation ate from 2015 meteorological data for the Seoul area, and the indoor air temperature setpoint is 21°C.



[Figure 3.1] The building model layout of household and standard floor

The thermal load of a building is not only linked to the thermal characteristics of the building envelope, but is also constantly influenced by the outdoor air temperature, solar radiation, indoor air temperature setpoint, internal heat gains and the external air introduced into the room.

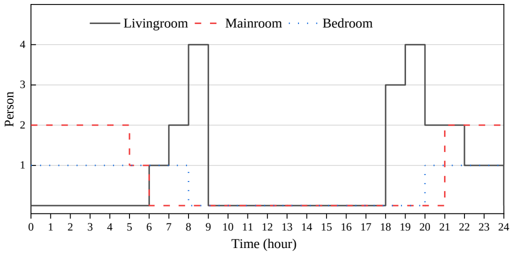
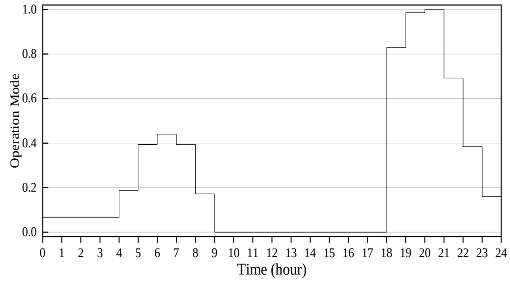
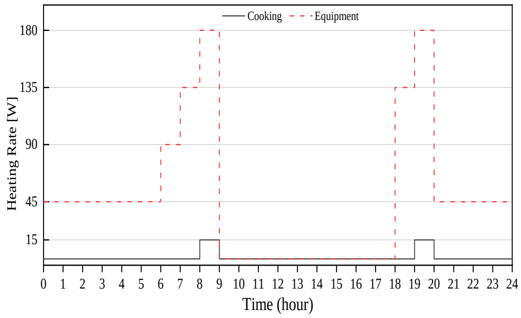
In this study, three internal heat gains were simulated. Based on ASHARE data, it was assumed that people in the room were seated and only lightly active, and the human heat generation was 70 W/Person for sensible heat and 45 W/Person for latent heat. There are up to four people in the Livingroom at the same time, two people in the main bedroom, only one person in the bedroom. The heat output unit from lighting equipment is 6.46 W/m2 and the maximum heat output from mechanical equipment is 180 W. The schedule of internal heat gains is set as shown in the <Table 3.2>. Although the air entering the room can be divided into two parts: air exchange and infiltration, the minimum air exchange is set to 0.2 ACH based on the recent studies and surveys related to the infiltration in the apartment.[42]



[Figure 3.2] The building model layout of household and standard floor

<Table 3.2> Simulation conditions of the object building for analysis

[42] Mun, Jung-Hyon, Lee, Jong-Ik, and Kim, Min-Sung. "Study on Estimation of Infiltration Rate (ACH natural) using Blower Door Test Results." *Proceedings of Korean Institute of Architectural Sustainable Environment and Building* 14.6 (2020): 687-698.

<table>
<tr><th>Input Object</th><th colspan="3">Value</th></tr>
<tr><td>Weather Dataset</td><td colspan="3">Seoul - 2015</td></tr>
<tr><td>Infiltration</td><td colspan="3">0.2 ACH (Minimum)</td></tr>
<tr><td rowspan="8">Internal Heat Gain</td><td rowspan="4">People</td><td>Sensible Heat:</td><td>70W/Person</td></tr>
<tr><td>Latent Heat:</td><td>45W/Person</td></tr>
<tr><td>Activity:</td><td>Seated, very light work</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td rowspan="2">Light</td><td>Sensible Heat:</td><td>6.46W/m2
convction:0.28
radiation: 0.72</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Equipment</td><td colspan="2">
</td></tr>
<tr><td>Indoor Air Temperature</td><td colspan="3">21℃</td></tr>
<tr><td>Simulation Period</td><td colspan="3">1~3, 11-12</td></tr>
</table>

3.1.2 Heating load analysis of object multi-family building.

The heating load is the thermal energy that needs to be added to the space to keep the temperature within an acceptable range. There are four types of heat loss within any building. Heat loss can be due to either convection, conduction, radiation, mass transfer, or a combination. Heat loss in buildings without ventilation system in winter mainly includes heat loss through the building envelope caused by the temperature difference between indoor and outdoor, and air infiltration, cracks within the joins or underneath the door can cause heat to move out of the building.

The situation of the above influential factors is varying from room to room in different locations. The main factors affecting heat loss in buildings are the following:

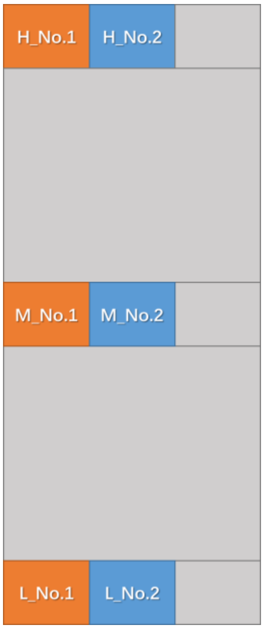
- ✧ Insulation of the envelope
- ✧ Area of the envelope
- ✧ Temperature difference
- ✧ Air change rate
- ✧ Exposure and orientation

Even for family on the same floor at the same height, the family in the middle and the family on either side have completely different envelope exposures. Not to mention in different floor, after all, height will affect the outdoor wind speed, wind pressure and temperature which can also affects both the heat transfer of the envelope and air infiltration rate.

To account for the heating load from the air exchange, each home in the apartment is equipped with a mechanical ventilation system. When fresh air is delivered to the room, it will first pass through a total heat exchanger to exchange heat with the room exhaust air for the purpose of preheating the fresh air. This total heat recovery ventilation system will provide the required airflow according to the occupants in the room, which is 20 cfm per person according to ASHARE HANDBOOK.

In this section, to discuss the differences in heating loads at various locations and to design space heating systems for each household, the heating loads for the five months from November 1 to March 30 were calculated using simulation software EnergyPlus 9.5, and the load characteristics were compared by location of the families.

The study was conducted on an apartment building, and only two households of the same type in the same location on the uppermost, middle, and lowermost floors were selected for the heating load analysis. Each household is divided into unheated and heated zones according to whether heating is required. Although the middle household and the two sides of the household do not have exactly the same household type, they all have 4 heating zones, living room, main bedroom, bedroom 1 and bedroom 2. The floor areas of the four heating zones are 40m^2, 15m^2, 9m^2 and 8m^2 respectively. The schematic diagram of the study object can be referred to [Figure 3.3]. The household on the side of each floor is household #1 and the middle household is household #2.



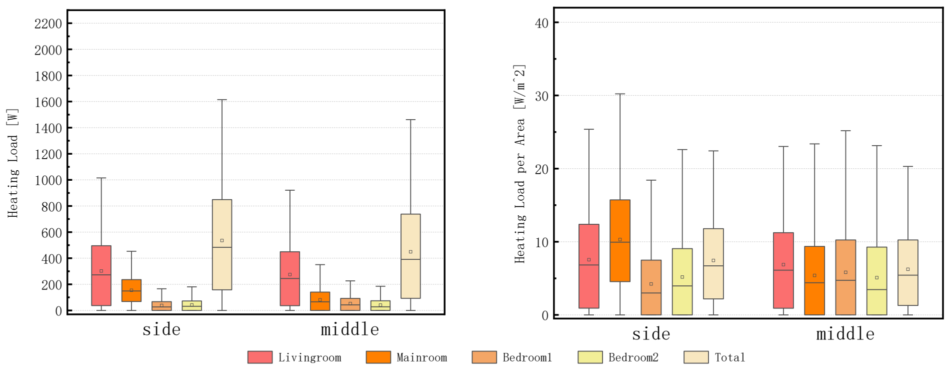
[Figure 3.3] Schematic diagram of the research object

1) Heating load of the lowest floor

The floors of the lowest layer are in direct contact with the land but considering that the heating system is a radiant floor heating system, the boundary conditions of the floor in the heating area are adiabatic during the simulation analysis, i.e., the heat exchange between the floor and the land is not considered.

[Figure 3.4] shows the distribution of heating loads for the two lowest research objects studied during the simulation period. The lines indicate the range of the heating load, 75% of the heating load is in the range of the bar height.

The figure reflects that the bedroom load is relatively small, whether household No.1 or household No.2, mainly concentrated in 0~120W, and the unit area load is 0~10W/m^2. The main bedroom, which has a more extensive envelope and a larger heating load than the bedrooms. The heating load of No.1 main bedroom is mainly distributed between 100W and 250W, while the No.2 main bedroom is mostly less than 200W. Therefore, the unit load area also varies, from 5W/m^2 to 15 W/m^2 and 0 W/m^2 to 10 W/m^2. The heating load in the Livingroom of two households is the largest, with No.1 exceeding 1000W and No.2 a whopping 900W. The maximum unit area load is 25 W/m^2 and 22.5 W/m^2 respectively.

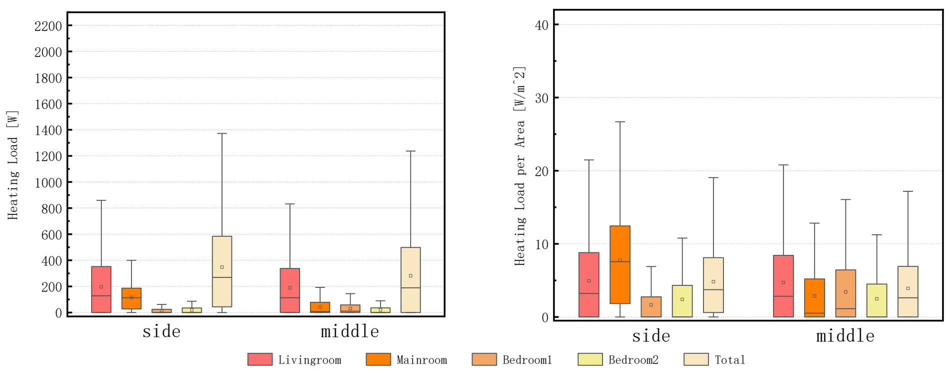


[Figure 3.4] Heating load of the lowest floor

2) Heating load of the middle floor

In the calculation of the heating load of the middle floor, the heat transfer between the floors of all rooms is ignored. [Figure 3.5] shows the distribution of heating loads for the two research objects located in middle floor studied during the simulation period.

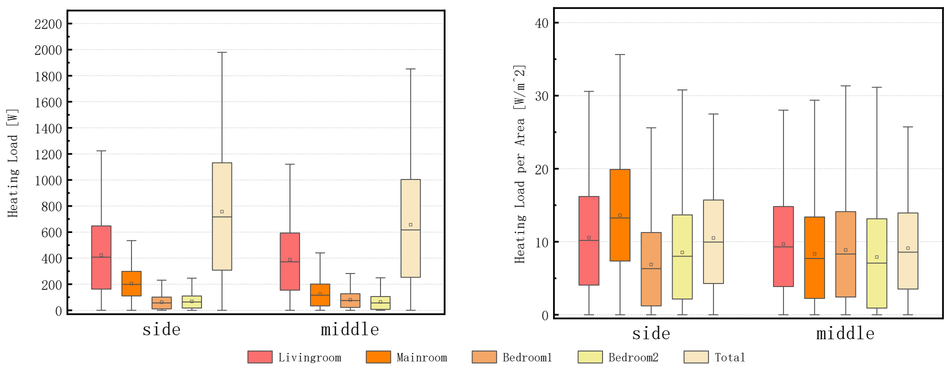
As in the case of the lowest floors the smallest heating load of each household is in the bedroom, followed by the main bedroom, and the largest is Livingroom. Bedroom 2 in the middle household is not in contact with any non-heating zone and only exchanges heat with surrounding through two external walls, so the heating load per unit area does exceed 5W/m2 most of the time, while No.2 bedroom 1 is adjacent to the non-heating area so the heating load compared to bedroom 1 of No.1 increases. This makes the difference in heating load between the No.2 two bedrooms obvious. At the same time, the maximum heating load is in the living room, where the heating demand is the greatest, and no more than 22W/m^2. The differences in heating load per unit area between the living room of the middle family and the side family are smaller.



[Figure 3.5] Heating load of the middle floor

3) Heating load of the highest floor

In the calculation of the highest floor, the roof is a boundary condition in direct contact with the outdoors, ignoring the inter-story heat transfer through the floor structure. The distribution of heating loads for the two research objects located in middle floor studied during the simulation period are showed with [Figure 3.6].



[Figure 3.6] Heating load of the highest floor

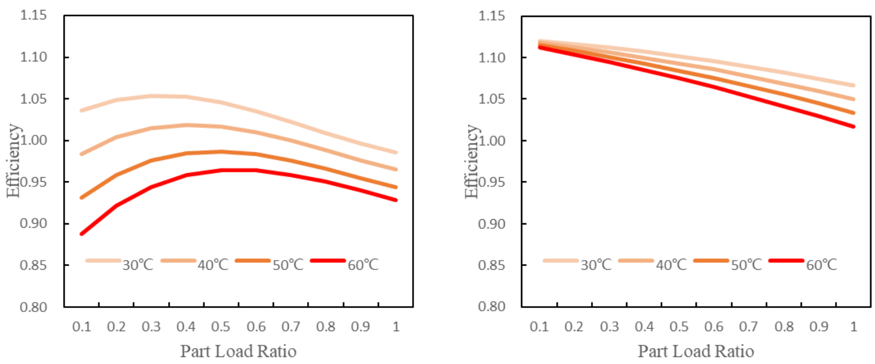
It is clearly seen from the graph that most of the time the heating load of all the rooms in the upper floors of the study is larger than the heating load of the other floors. The maximum heating load in the living room can reach 31W/m^2, while the main bedroom can reach 36W/m^2. However, there is almost no difference in the heating load of homes located on the same floor.

3.2 Space Heating System

In this study, space heating systems using individual boilers and district heating as heat sources were established separately for the simulation analysis. The equipment such as floor radiant heating panels and gas boiler associated with this heating system is described in detail in this chapter.

3.2.1 Gas Boiler

Two gas boiler plants were used in this suitability study for low-temperature heating systems. The first is a conventional boiler capable of producing low-temperature water but without a condensing unit, and the other is a condensing boiler with a condensing unit. Both boiler models are sourced from the EnergyPlus example files named boilers.idf that can be found in the online database of EnergyPlus.

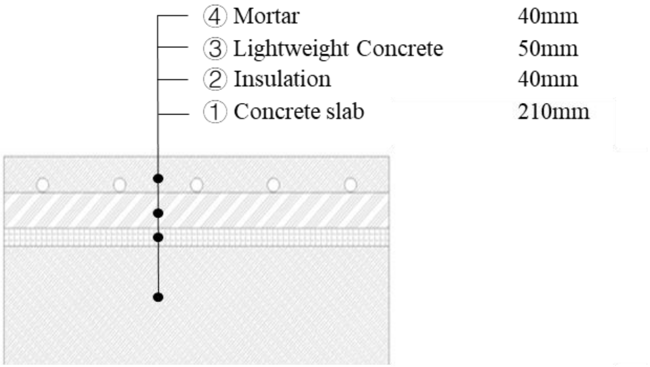


[Figure 3.7] Efficiency curve of non-condensing(left) and condensing boiler(right)

Condensing boilers can recover more latent heat from condensate when outlet temperature is low43, so they are more efficient at lower PLRs than regular boilers. Therefore, as shown in Figure [3.7], Part load efficiency curve of non-condensing and condensing boiler, boiler efficiency tends to increase as PLR decreases, and it is expected to be suitable as a heat source for low-energy apartment houses with a relatively high frequency of partial load.

3.2.2 Floor Radiant Heating Panel

The composition of the floor radiant heating panel follows the standard floor structure [44] proposed by the Ministry of Land, Infrastructure and Transport for blocking floor impact sound between floors, and the details of the cross-section and its reference values are shown in [Figure 3.8]. There are 6 households in this study, each with 4 heating zones, so there are 24 radiant floor heating panels set up in the whole model, all as shown above.



[Figure 3.8] Configuration of radiant floor heating panels

In comparing existing heating systems with low-temperature heating systems, there are two operating conditions, high-temperature and low-temperature conditions. As the hot water temperature decreases, there is a possibility of a thermal comfort problem due to

[43] Satyavada, Harish, and Simone Baldi. "Monitoring energy efficiency of condensing boilers via hybrid first-principle modelling and estimation." *Energy* 142 (2018): 121-129.
[44] Ministry of Land, Infrastructure, and Transport, Structural Standards for Blocking Floor Impact Noise between Floors for Noise Prevention, 2018

the horizontal temperature difference on the floor surface, so the pipe space is reduced to 150mm. The pipe embedded in the mortar has an outside diameter of 16mm, a thickness of 1.5mm and a heat transfer coefficient of 0.35 W/mk. The geometric specifications of radiant floor heating panels are organized in the <Table 3.3>.

<Table 3.3> Geometry of heating pipes

Condition	Space	diameter	thickness	Conductivity
High temperature	230mm	16mm	0.15mm	0.35 W/mk
Low temperature	150mm			

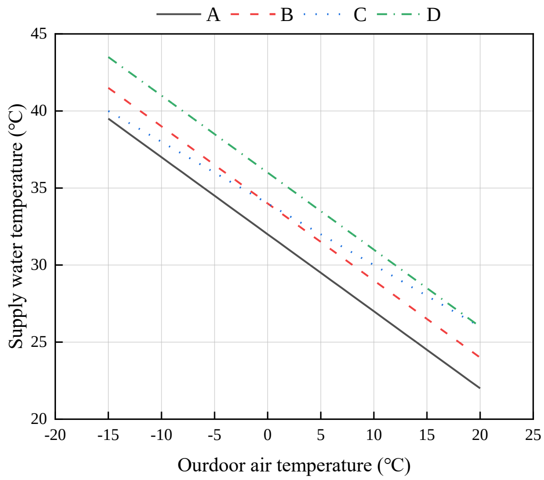
3.2.3 Control for heating system

In accordance with Chapter 2 on the collation of heating system control methods, hot water temperature control mainly uses outdoor reset control, while flow control uses a two-position control method ON/OFF control. The purpose of this thesis is to investigate the applicability of low-temperature heating systems in existing buildings, and the application of low-temperature heating systems with outdoor reset control is an effective measure to further improve the energy performance of low-temperature heating systems.

In this dissertation, the heating curve for each room was determined and revised based on the load characteristics of the reference room of each household and organized into <Table 3.4> and [Figure 3.9]. Since the heating load of the living room is always the largest regardless of the room location, the living room is selected as the reference room for the calibration of the heating curve.

<Table 3.4> Heating Curve for each household

Floor	Household	Reference Room	Heating Curve	#
Lowest	No.1	Livingroom	Tsupply = 34 – 0.5 Toutdoor	A
	No.2			
Middle	No.1		Tsupply = 33 – 0.5 Toutdoor	B
	No.2		Tsupply = 32 – 0.5 Toutdoor	C
Highest	No.1		Tsupply = 36 – 0.5 Toutdoor	D
	No.2			



[Figure 3.9] Heating Curve for each household

Although the use of outdoor reset control allows for timely adjustment of the water supply temperature according to outdoor weather conditions, the indoor temperature can still be outside the comfort range due to the heat storage nature of the floor structure and the fact that the heating curve used is determined without regard to solar radiation and internal heat generation.

As a result, the ON/OFF signal with the indoor air temperature as the feedback signal and the outdoor reset control form the control system of the low-temperature heating system. 6 households with a total of 24 radiant floor heating panels with flow ratios all interchanged between the values 0 and 1 depending on the room temperature. If the indoor temperature exceeds 22°C, the radiant heating panel will stop working and the flow rate will be 0. When the temperature drops below 21°C the radiant heating panel will immediately operate at the designed flow rate.

It is to be noted that for the purpose of discussing the heating performance and energy consumption performance of low temperature heating systems, there are also fixed temperature heating systems where the flow rates are only controlled by ON/OFF control method.

3.3 Assessment Strategy

In this section, an assessment strategy for space heating systems is constructed to estimate the performance of low-temperature heating systems in maintaining a comfortable indoor thermal environment and energy consumption.

3.3.1 Heating Performance and Thermal Comfort

Essentially, the performance of the heating system can be said to be the ability of achieving and maintaining the setpoint of indoor temperature. If heat larger than the heating load is supplied from the heating facility, the indoor temperature will exceed the set temperature range, and if heat smaller than the heating load is supplied from the heating facility, the indoor temperature will fall below the set temperature range. The set temperature of this study is 21.5°C, and the adjustment range of the control system is 0.5°C. By means, if the indoor temperature is below 21°C, heating will start, and if it exceeds 22°C, heating will stop. In summary, in order to evaluate the heating performance of low-temperature system, the ability to achieve the set temperature (21℃) of the indoor temperature and maintain the set temperature range (21℃ to 22℃) of the indoor temperature are evaluated.

Thermal comfort results from a combination of environmental factors and personal factors. This research only focuses on the performance of low-temperature heating systems in keeping a comfortable indoor thermal environment, so it will neglect the effect of the indoor thermal environment due to the occupants. And the main factors affecting indoor thermal comfort are air temperature, air velocity, radiant temperature, relative humidity.

These two factors, air velocity and relative humidity, will not be considered in the process of evaluating indoor thermal comfort because the heating equipment set in the room involved in this study is radiant floor heating panels without convection heating system and almost without any latent heat exchange.

Radiant temperature is the temperature of a person’s surroundings including surfaces, heat generating equipment, the sun, and the sky. This is generally expressed as mean radiant temperature, a weighted average of the temperature of the surfaces surrounding a person. For floor radiant heating system, the room temperature and the heat transfer coefficient between the floor and the walls almost both keep the same during heating, the floor surface temperature is the most important parameter which affects the heating capacity of the system. In addition, considering the comfort and condensation, the floor surface temperature of radiant floor system should be kept in certain temperature ranges during heating.

Internationally, the floor surface temperature should not be lower than 19℃ and higher than 29℃[45]. Therefore, in the design and the operation of the radiant floor system, the floor surface temperature is one of the most important parameters.

In this study, indoor temperature and floor surface temperature were selected as representative indicators for evaluating indoor thermal comfort.

3.3.2 Energy Consumption

At the individual household level, the heating energy input to the heat source for fruit production can be classified according to the method of supplying the heating heat source. In the case of individual heating, most apartment houses install gas boilers with instantaneous heating as heat source, so heating energy can be determined by the total gas consumption supplied to the gas boiler. In the case of the district heating system, since multiple generations share the heat source, it is unreasonable to evaluate the heating energy consumption at the individual generation level simply by the amount of primary energy invested in the heat source facility. Therefore, it is reasonable to evaluate the heating energy consumption based on the heat supplied to the household by floor radiant heating panels.

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[45] Olesen, Bjarne W. "Radiant floor heating in theory and practice." *ASHRAE journal* 44.7 (2002): 19-26.

3.4 Summary

Building models and HVAC models were created for use in simulation analysis with the goal of comparing them to the existing heating system and exploring the applicability of low-temperature heating systems in high-insulation , high-tightness buildings. Concurrently, a relevant heating performance evaluation system was built to better analyze the space heating performance of radiant floor heating panels when the temperature of their water supply is low.

(1) A model of an apartment building with an envelope thermal conductivity that meets the latest design rules for energy-efficient buildings was developed. The building has 20 floors, with three households distributed on each floor. Considering that the heating loads of households at different locations of the building are different, detailed models are established for the lowest floor in contact with the ground, the middle floor where heat transfer from above and below is ignored, and the uppermost floor where the roof is in contact with outdoor air.

(2) The heating loads of households in different locations from November to March were analyzed. The heating load of the uppermost layer of the household is generally larger, the middle layer is smaller due to the neglect of the heat transfer between the upper and lower layers, and the bottom layer is in the middle value.

(3) A model of the equipment used in the space heating system is presented. Firstly, two types of gas boilers, one condensing and the other non-condensing, used in this study to evaluate the suitability of low temperature individual heating systems are described. The composition of the radiant floor heating panels as defined by the national codes used in this study is also presented. The heating curve for each study household was calculated by simulation correction since the application of outdoor reset control was also involved in this study.

(4) An assessment scheme for heating systems based on heating

performance, thermal comfort and energy consumption is designed. The heating performance is evaluated by the ability of the heating system to maintain the room temperature within the set range (21℃-22℃), and the thermal comfort is evaluated by the indoor air temperature and the floor surface temperature. When evaluating the energy consumption of individual heating systems, the natural gas energy consumption of individual boilers is used as an index for evaluation. In contrast, when assessing the energy consumption of district heating systems, the heat output of radiant floor heating panels is used as an evaluation indicator.

Chapter 4. Evaluation of the suitability of low temperature heating systems

Since the introduction of floor radiation (ondol) heating using hot water in the 1970s, heating facilities in domestic residential buildings have been conventionally applied without significant changes in their composition and design variables. The application of heating system without considering the thermal characteristics change due to reduction of heating load is one of the main factors in heating performance, comfort, and energy consumption.

As an example of heating system considering the actual heating requirements of high-insulation, high-tightness residential buildings, the lower heating load in such residential buildings increases the possibility of achieving heating requirements and thermal comfort while using low-temperature hot water.

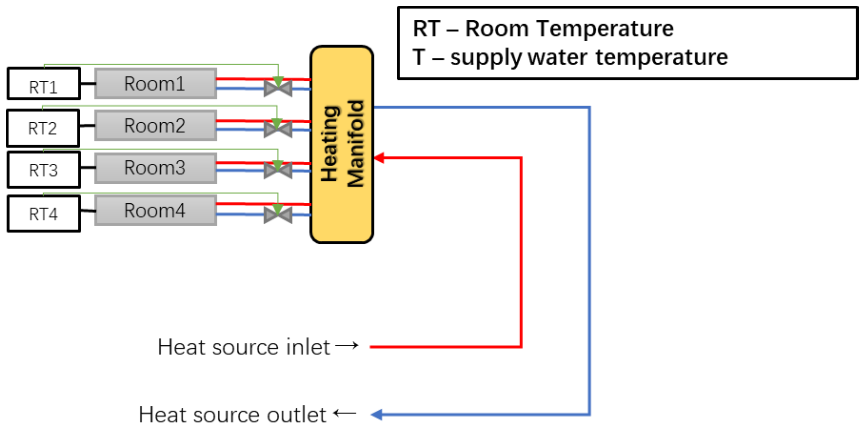
Given that heating systems in apartment buildings mainly use individual gas boilers and district heating as hot water supply equipment, the composition and operation scheme of low-temperature heating systems using both heat sources separately are planned in this chapter. In the process of building the operation method not only set the necessary ON/OFF control in the radiant floor heating panels but also adopted the control method of regulating the water supply temperature on the heat source side, not only considering a certain water supply temperature but also using the control method that the water supply temperature changes with the outdoor temperature to improve the operation strategy of the heating system. In this chapter, to study the applicability of low temperature heating systems in high-insulation, high-tightness existing buildings, the low temperature heating systems are analyzed in terms of heating performance, thermal comfort assurance and energy consumption under different operating conditions in comparison with the existing heating systems.

4.1 Assessment Overview

In this thesis, to assessment the applicability of low-temperature heating systems in apartment buildings, a relevant existing heating system model and low-temperature heating system was developed based on the contents and conclusions of the literature survey in Chapter 2, after referring to the composition of heating systems using individual gas boilers and district central heating, respectively.

The individual boilers currently used in apartment homes often produce fixed temperature hot water and deliver it to the radiant floor heating panels, which then control the opening and closing of the ON/OFF valves set on the manifold by signal changes of temperature sensors set in the rooms according to a control algorithm to maintain the room temperature.

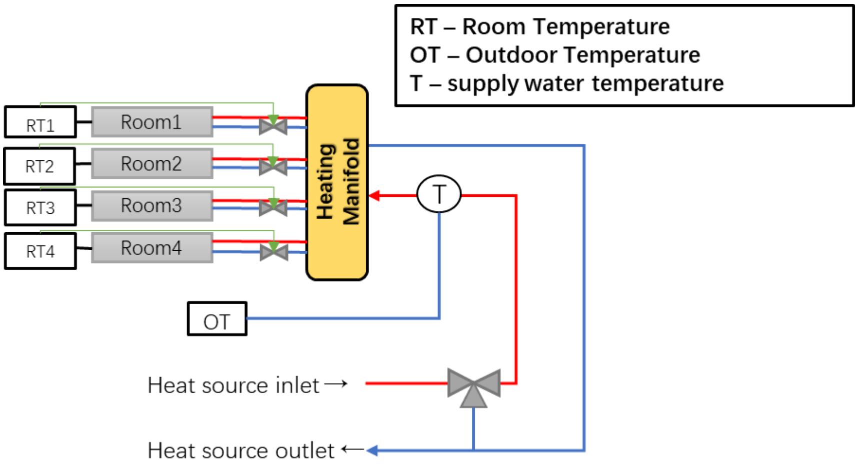
Thus, the system diagram of the existing individual heating system using individual boilers in this study is shown in Figure 4.1, and the water supply temperature is constant at 50°C during the operation of the entire heating system.



[Figure 4.1] Individual heating system with constant supply water temperature

For low-temperature heating systems, two operation schemes are analyzed in this chapter, using fixed-temperature hot water and using outdoor reset control which the supply temperature varies continuously with the outdoor temperature.

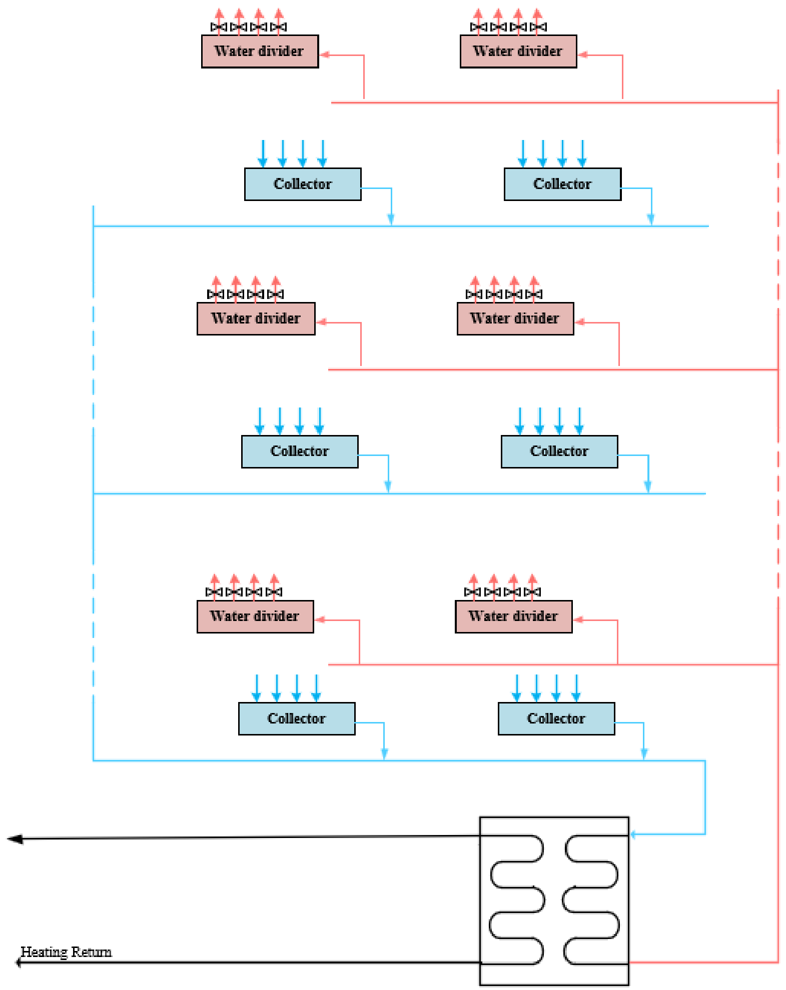
The system of the low temperature heating system with a fixed supply temperature is the same as the existing reference system, while the supply temperature is 38°C, which is the maximum temperature of the heating curve applicable to the household subject of individual heating system. Because of the function to adjust the supply water temperature, the system diagram of the low temperature heating system with outdoor reset control is shown in [Fig. 4.2]. The temperature of the water supply to the radiant floor heating panels is determined by the outdoor temperature and heating curve calculated in section 3.3.



[Figure 4.2] Individual heating system with Outdoor Reset Control

As the temperature of the hot water delivered from the existing district heating system to buildings through the distribution network from the hot water production plant is too high, apartment buildings that currently use hot water provided by the district heating network have heat exchangers in mechanical rooms located on the ground floor of the building. With a heat exchanger, it is then possible to use the high temperature hot water from the primary side to obtain the required supply water temperature for the secondary side, often above 50°C according to the study in chapter 2.2.

Like individual heating system, the existing district heating system with fixed water temperature is set up for the reference case with the system diagram shown in Figure 4.2, secondary side water supply temperature is set to 50℃. The indoor temperature is controlled by an ON/OFF valve set on each household manifold.

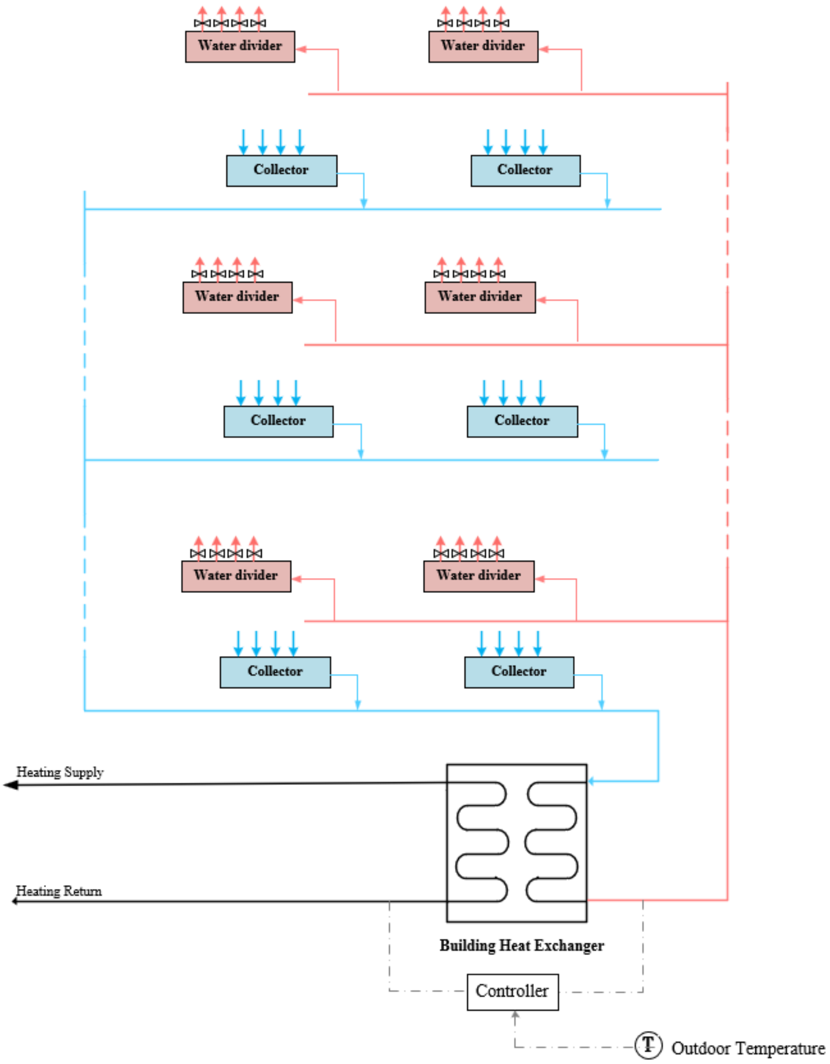


[Figure 4.3] District heating system with constant supply water temperature

For low-temperature district heating systems the operation of the building's heating system varies due to the drop in hot water temperature in the district heating network.

The low-temperature district heating systems which building heating system have the same connection with district heating network as in the existing heating system, while the secondary side can obtain a lower water supply temperature through the heat exchanger installed in the mechanical room as the primary side of the water supply temperature decreases.

Considering this situation, the system composition is the same as the existing system, only the supply water temperature is different. In this chapter two operating cases of this type of low temperature district heating system are considered, one with a fixed water temperature on the secondary side and the other with the use of outdoor reset control to regulate the secondary side supply water temperature. The system diagram for fixed water supply temperature on the secondary side is the same as the one in [Figure 4.3] for the existing heating system, while the system for applying outdoor reset control is shown in [Figure 4.4].



[Figure 4.4] District heating system with outdoor reset control

Due to the energy saving and emission reduction potential of district heating, the use of district heating as building heating is constantly increasing. In the case of setting up the heat exchanger in the mechanical room to connect to the district heating network, the water temperature on the secondary side of this integrated heat exchanger is often determined by the maximum heating load of the entire building, but in reality, the heating load, i.e. the heating demand, is completely different for families in different locations in the building.

Hence, according to the difference in heating demand of individual household units, distribution facilities that can be individually adjusted are required which can adjust supply water temperature for each household. Referring to the application of low-temperature heating systems abroad, setting up a heat interface unit (HIU) with a small plate heat exchanger in each household can achieve the goal of individually regulating the water temperature in each household.

<Table 4.1> Condition for Individual Heating System

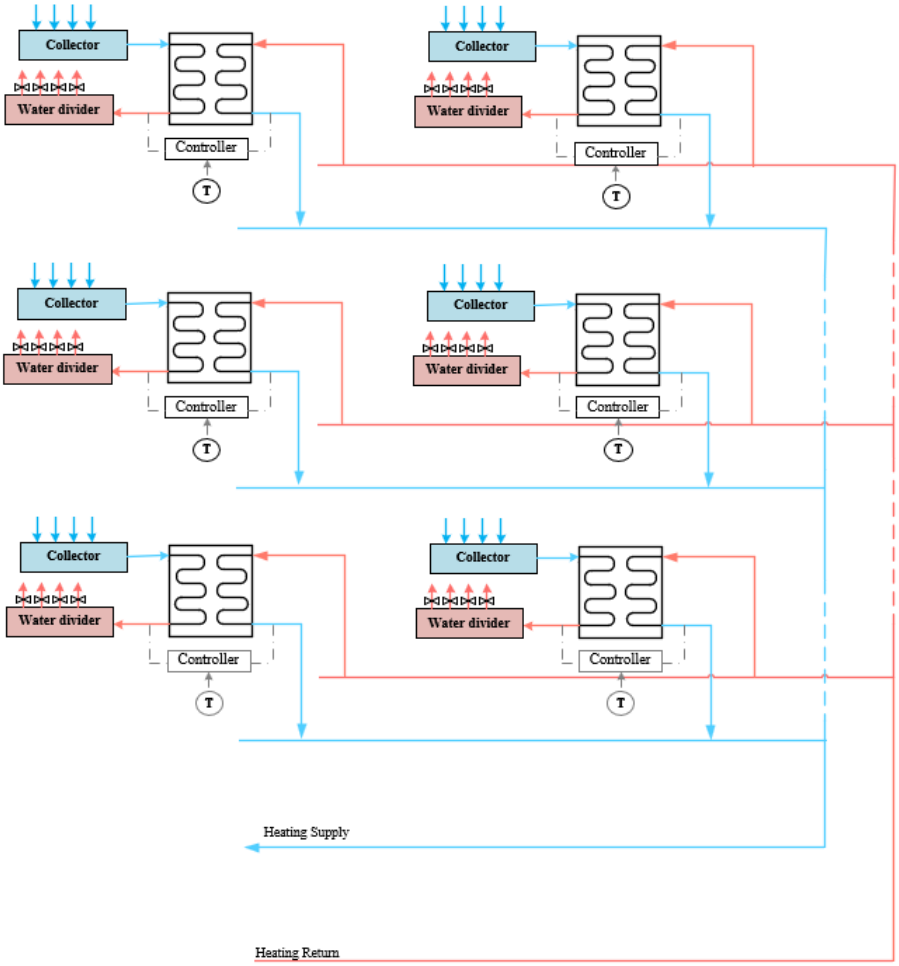
Individual Heating System	Supply Water Temperature	
	Operation Condition	Value
Existing Condition	Fixed	50 ℃
Low temperature Condition ①	Fixed	38 ℃
Low temperature Condition ②	Outdoor reset control	heating curve of household subject

<Table 4.2> Condition for District Heating System

District Heating System	Primary side water Temperature	Secondary side supply Water Temperature	
		Operation Condition	Value
Existing Condition	100℃	Fixed	60℃
Low temperature Condition ①	60℃	Fixed	43℃
Low temperature Condition ②	60℃	Outdoor reset control	heating curve of household with maximum load
Low temperature Condition ③	60℃	Outdoor reset control	heating curve of each household

In purpose of studying the applicability of the low temperature heating system using HIU equipment, a heating system was established as shown in [Figure 4.5]. All six household unit subjects were installed with heat exchangers, the primary side of which was directly connected to the low temperature district heating network, and the secondary side water temperature was determined by an outdoor reset control algorithm of each household.

In summarizing the above, to analyze the applicability of low-temperature heating systems in low heating load apartments, individual heating systems using individual boilers and central heating systems using district heating were established. Their existing operating conditions and low-temperature operating conditions are arranged in <Table 4.1> and <Table 4.2>.



[Figure 4.5] District heating system with HIU

4.2 Assessment of the suitability of individual low-temperature heating systems

In considering the applicability of low-temperature heating systems using individual heat sources, the heating performance, thermal comfort, and energy consumption characteristics of two low-temperature heating systems were analyzed by comparing them with existing operating conditions.

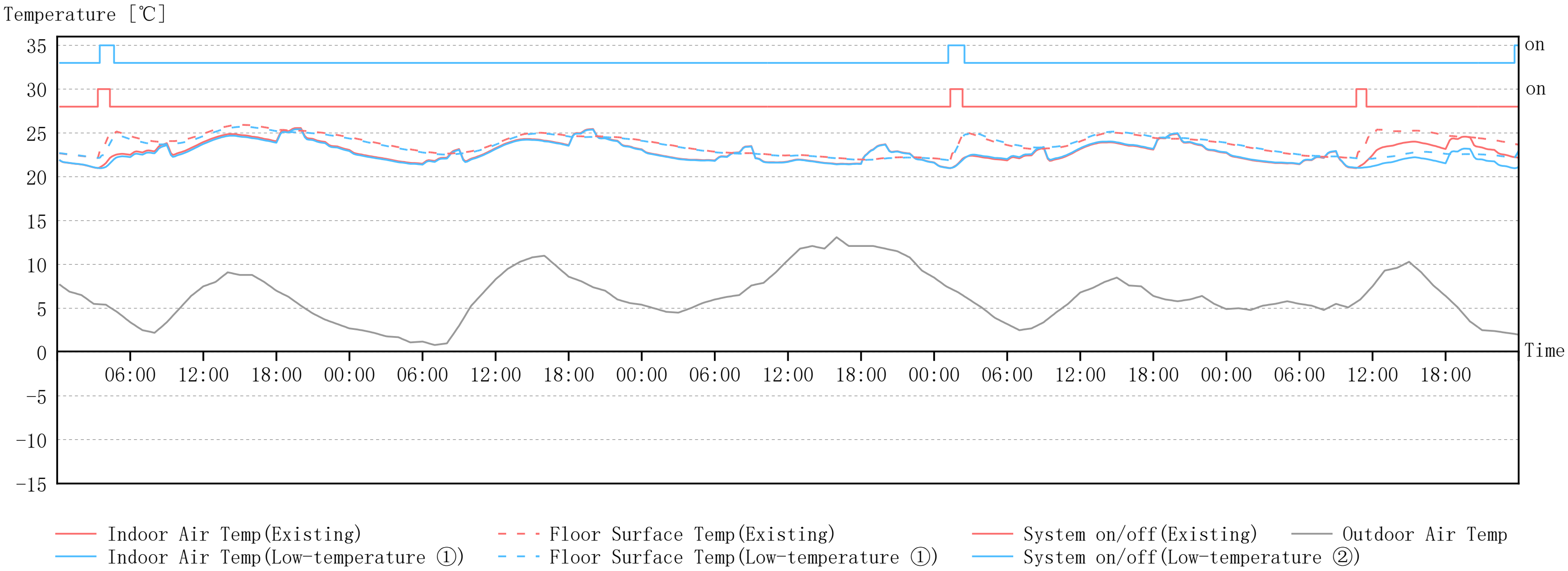
For the analysis of the simulation results, since the determination of the supply water temperature under low temperature conditions is based on the living room, the room with the largest heating load, the living room is chosen as the representative room in the analysis of heating performance and thermal comfort. The whole household simulation results are used to analyze the boiler gas consumption.

The operation of the radiant floor heating panels is controlled by the ON/OFF control algorithm only, regardless of the existing operating conditions or the low temperature operating conditions, all in a continuous operation mode.

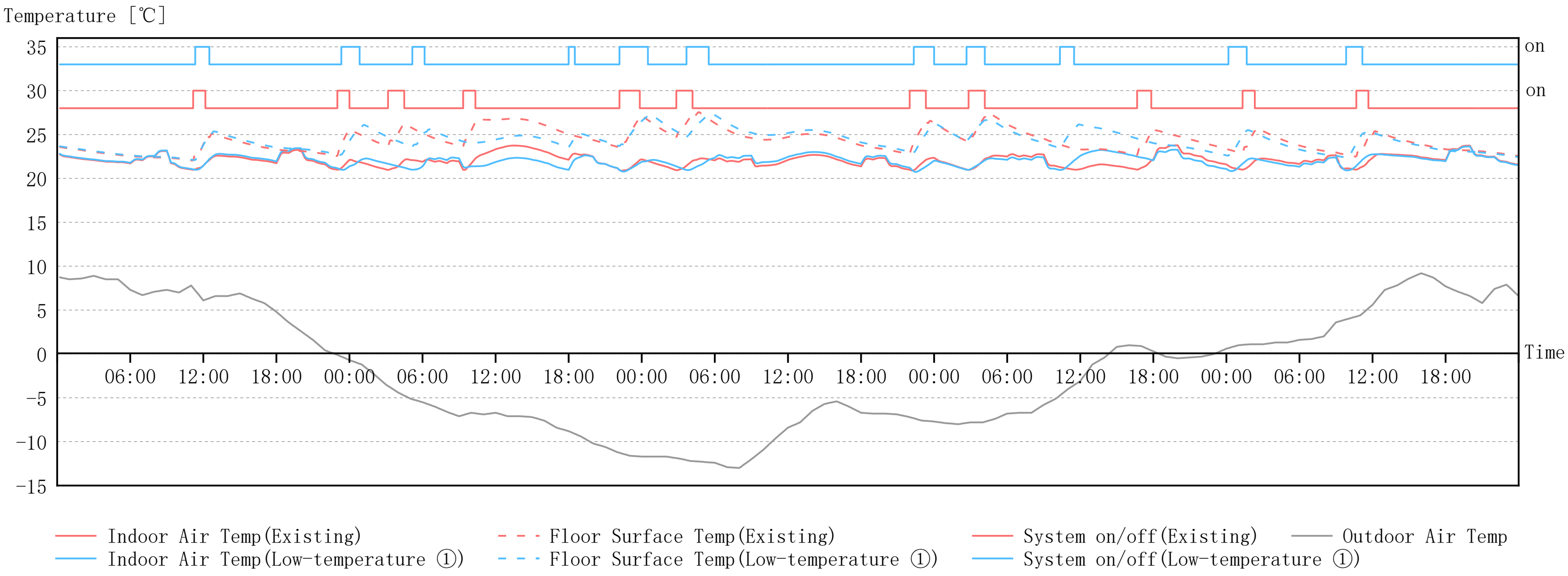
4.2.1 Applicability evaluation of individual low-temperature heating systems with fixed supply water temperature

In the comparison of low temperature heating systems with constant supply water temperature and existing heating systems, three analytical periods were set according to the outdoor temperature conditions. Each period is 5 days, January 1 to January 5, when the outdoor temperature is relatively low, is period ①. The outdoor temperature in period ① is maintained below 0℃. The outdoor temperature in period ② from January 1 to January 5, on the other hand, is relatively high, remaining above 0°C. In addition to this there is a large variation in outdoor temperature in period ③, from January 1 to January 5.

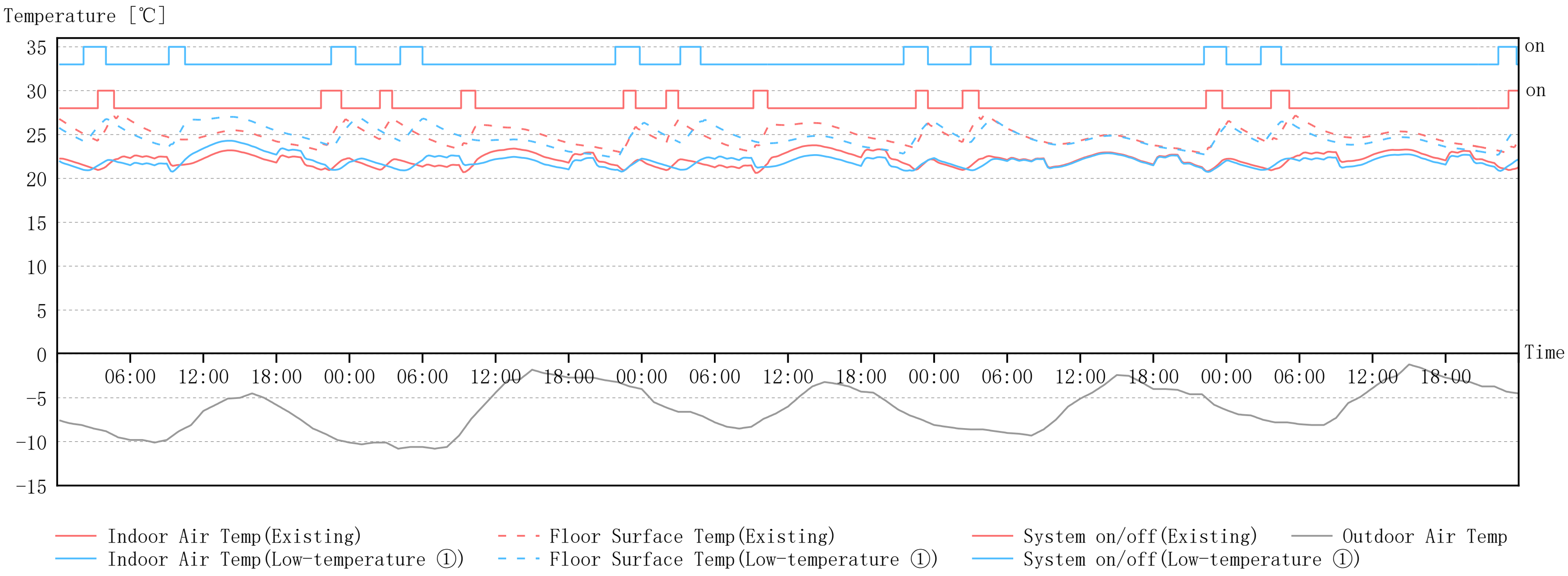
[Figure 4.6] ~ [Figure 4.8] shows the outdoor temperature, indoor temperature, floor surface temperature and operation status of the floor radiant heating system for each period according to the change in the heating load.



[Figure 4.6] Heating operation characteristics with relatively high outdoor temperature



[Figure 4.7] Heating operation characteristics with wide-range outdoor temperature



[Figure 4.8] Heating operation characteristics with relatively low outdoor temperature

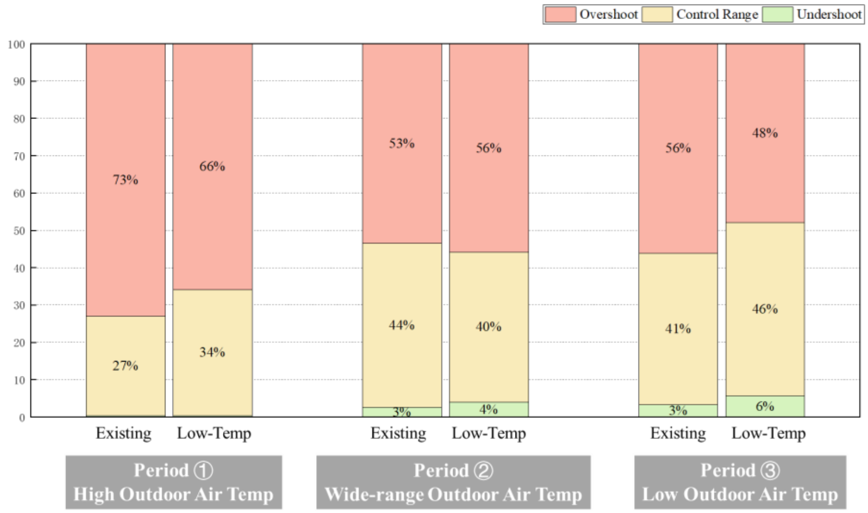
In the period when the outdoor temperature is high and the heating load is low, we observe in <Figure 4.6> that the use of a lower supply temperature based on the maximum heating load of the study subject can still maintain the indoor temperature within the set range and maintain a small fluctuation range compared to the conventionally used supply temperature. In fact, the heating load demand at this time is much less than the maximum heating load used to determine the supply temperature, which results in an operation process that is almost consistent, although the supply temperature has been reduced compared to the hot water in the existing heating system.

As shown in [Figure 4.8], even when the heating load is high, using a lower water temperature still allows the room temperature to reach the set-point and keeps the fluctuation of the room temperature within a small range. We can also see that when the existing system and the fixed water temperature low-temperature heating system are started at the same time under the same initial conditions, the floor surface temperature and room temperature of the existing system are often higher than the low-temperature heating system.

The low temperature heating system with certain water supply temperature also has good heating performance when the outdoor temperature varies widely, maintaining above the set temperature value throughout the interval and keeping the appropriate fluctuation range. At the same time, although the supply water temperature is reduced, the distribution of the floor surface temperature of the low-temperature heating system with fixed water temperature did not differ much from that of the existing heating system by comparing the two heating characteristics in the period ③ where the outside air temperature exists both above and below zero, regardless of whether the heating load is small or large.

The ability to maintain the indoor temperature within the set range is an important indicator to evaluate the performance of the heating system. [Figure 4.9] statistically analyzes the ratio of time below the lower limit 21°C of the set rang and the ratio of time above the upper limit 22°C for the existing heating system and the low-temperature heating system with constant water temperature for each period, and the middle bar part indicates the ratio of time when the room temperature is within the set range.

Lowering the water supply temperature when the outdoor temperature is high or low allows more time for the indoor temperature to be within the control range, thus improving the heating performance. However, simply lowering the supply water temperature over a wide range of outdoor temperatures period did not have a positive effect on heating performance.

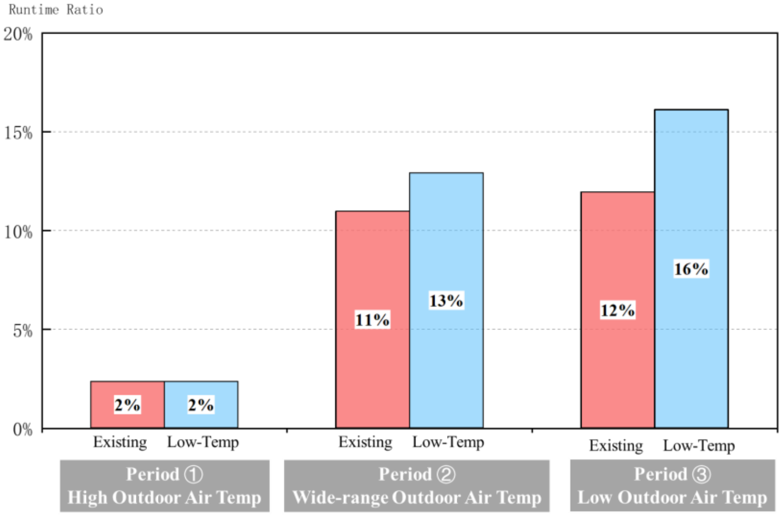


[Figure 4.9] Assessment of heating performance at different condition

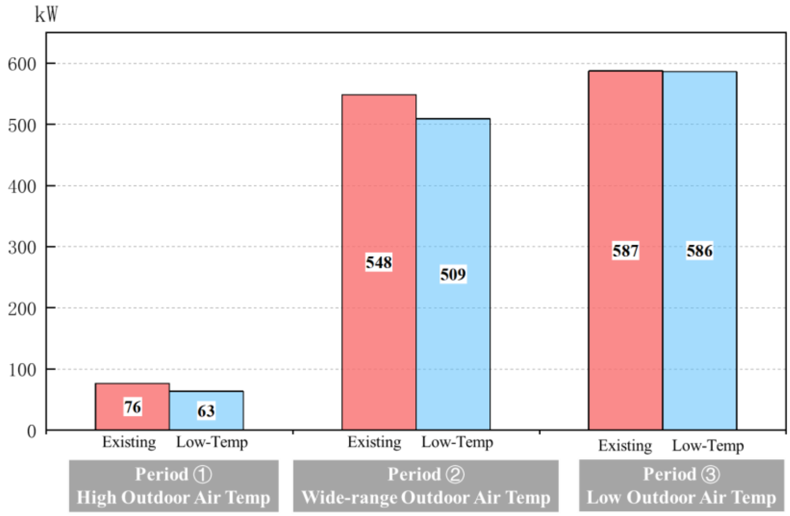
The heating characteristics of each period show that the low temperature heating system runs for a longer time after each start compared to the existing heating system. And the number of start-ups of the two heating systems in the three-simulation period selected for this study is similar, so the ratio of heating operation time to the whole heating period were calculated in [Figure 4.10].

There is no difference in the running time of the two systems when the outdoor temperature is high. In the other two periods, lowering the supply water temperature extended the system runtime.

At the end, the energy performance of the existing heating system and low-temperature heating system with the constant water temperature were evaluated by comparing their natural gas consumption rate in different periods, as shown in [Figure 4.11].



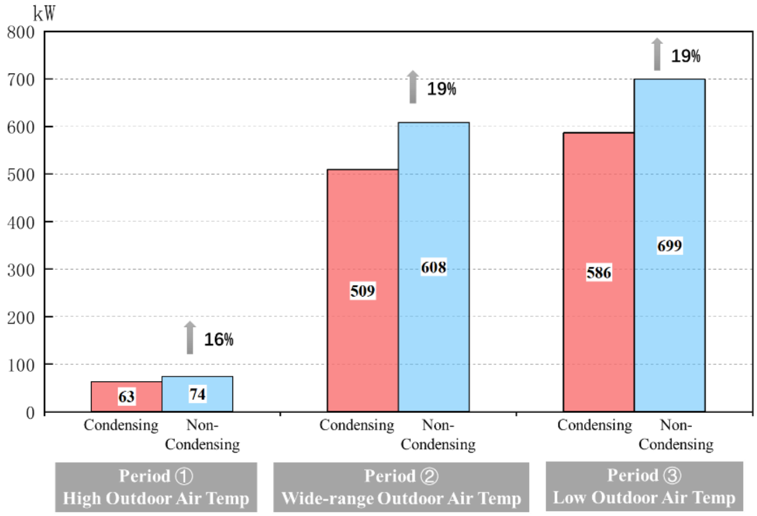
[Figure 4.10] Operation time ratio at different condition



[Figure 4.11] Natural gas consumption at different condition

The use of low temperature heating systems can reduce natural gas consumption by approximately 17% when the outdoor temperature is high and the heating load is low, though its running time is quiet. 7% energy savings in period with large outdoor temperature differences, even though the operating time for low temperature conditions is higher than the existing conditions. In addition, when the outdoor temperature is low, the natural gas consumption did not increase, although the operation time of the low temperature condition is longer.

The current small gas boilers for residential use are mainly divided into condensing boilers and non-condensing general boilers, which were simulated in this chapter using mainly the condensing boilers introduced in Chapter 3.3. In this chapter, the gas consumption of low-temperature heating system with constant supply water temperature simulated using condensing boilers and non-condensing boilers. The consumption of natural gas using different boilers in the same simulation period shown in [Figure 4.12]. The gas consumption of low temperature heating systems increased when using a general boiler, by more than 15%.



[Figure 4.12] Natural gas consumption of different boilers at different condition

4.2.2 Applicability evaluation of individual low-temperature heating systems with outdoor reset control

Similar to section 4.2.1, three analysis periods were established in accordance with the outdoor temperature conditions for the comparison of low temperature heating systems with outdoor reset control and existing heating systems. The first period, which lasts for five days from January 1 to January 5, is when it's relatively cold outside. In period 1, it is kept below 0 degrees Celsius outside. On the other hand, the outside temperature during period 2 from January 1 to January 5 is relatively high and stays above 0°C. In period 3, from January 1 to January 5, there is a significant change in the outside temperature.

The supply temperature is lower when the outdoor temperature is higher compared to a low temperature heating system with a constant supply temperature because the outdoor reset control is used to modify the supply temperature according to the outdoor temperature.

Looking at [Figure 4.13], when the low-temperature heating system with outdoor reset control was turned on at the same time as the existing heating system, it increased the indoor temperature and the room temperature simultaneously, but at a slower rate, and the highest point of the floor surface temperature was a little cooler than it was with the existing heating system.

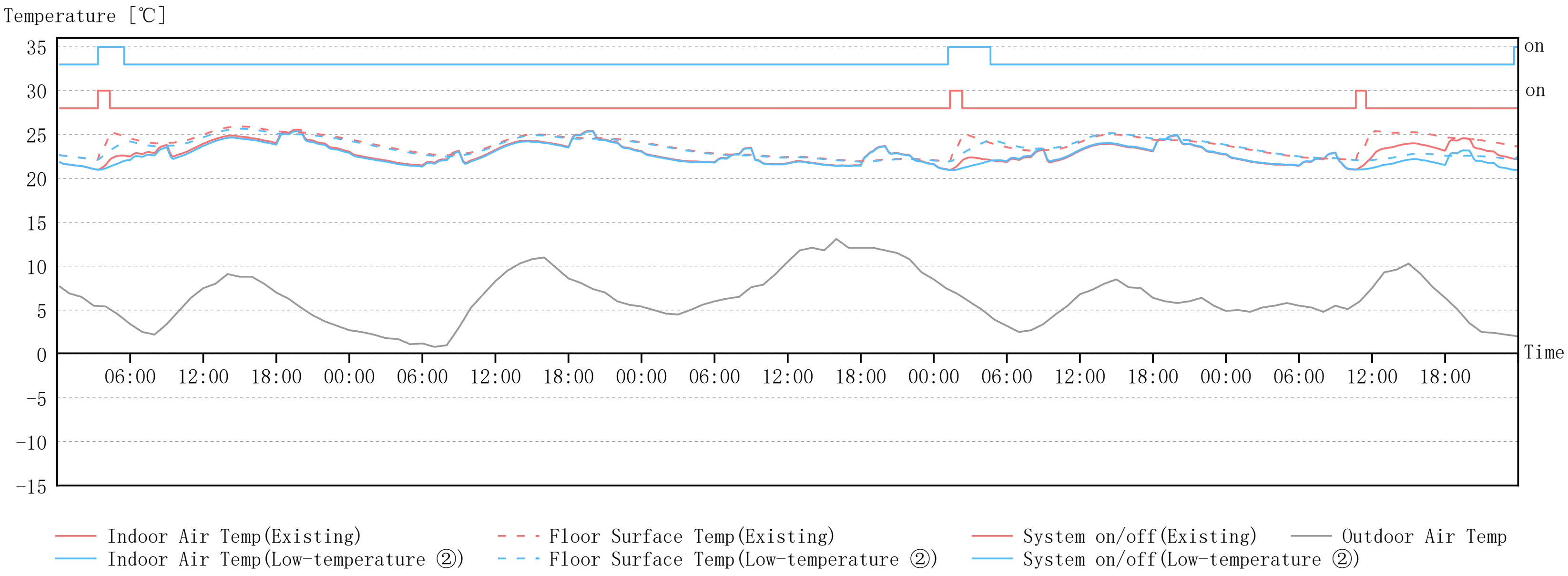
The low temperature heating system with outdoor reset control, which maintains indoor air temperature within the set temperature range during the interval and keeps the proper fluctuation range, also has good heating performance when the outdoor temperature varies quite substantially. Comparing the two heating characteristics in the period ② where the outside air temperature exists both above and below zero, regardless of whether the heating load is small or large. It is revealed that although the supply water temperature is reduced, the distribution of the indoor air temperature of the low-temperature heating system with outdoor reset control did not differ significantly from that of the existing heating system. The low temperature heating system can meet the indoor heating demand and raise the floor surface temperature to roughly the same temperature as the existing heating system at larger heating loads, albeit running longer.

As seen in [Figure 4.14], utilizing a lower water temperature still enables the room temperature to meet the set-point and maintains the variation of the room temperature within a small range even when the heating load is always large. The floor surface temperature and room temperature of the existing system are frequently greater than those of the low-temperature heating system with outdoor reset control when the two systems are started simultaneously under the same initial conditions. The slow rise in floor surface and indoor temperature of the low-temperature heating system can also be seen in the graph.

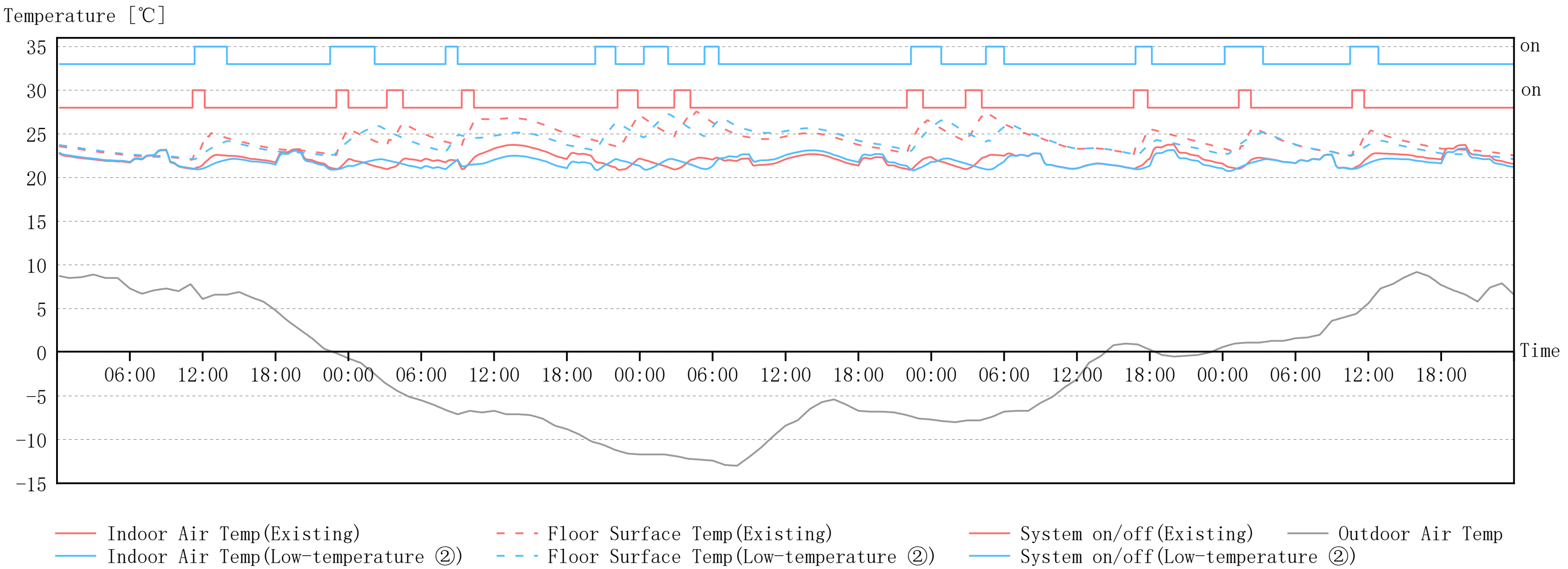
An essential metric for assessing the performance of the heating system is the capacity to keep the interior temperature within the predetermined range. For the existing heating system and the low-temperature heating system with outdoor reset control for each period, [Figure 4.15] statistically analyzes the ratio of time below the lower limit of the set range of 21°C and the ratio of time above the upper limit of 22°C. The middle bar portion shows the ratio of time when the room temperature is within the set range.

[Figure 4.16] shows that lowering the water supply temperature when the outdoor temperature is relatively high or low allows more time for the supply water temperature to be within the control range, thus improving the heating performance., simply lowering the supply water temperature over a wide range of outdoor temperatures period did not have a positive effect on heating performance.

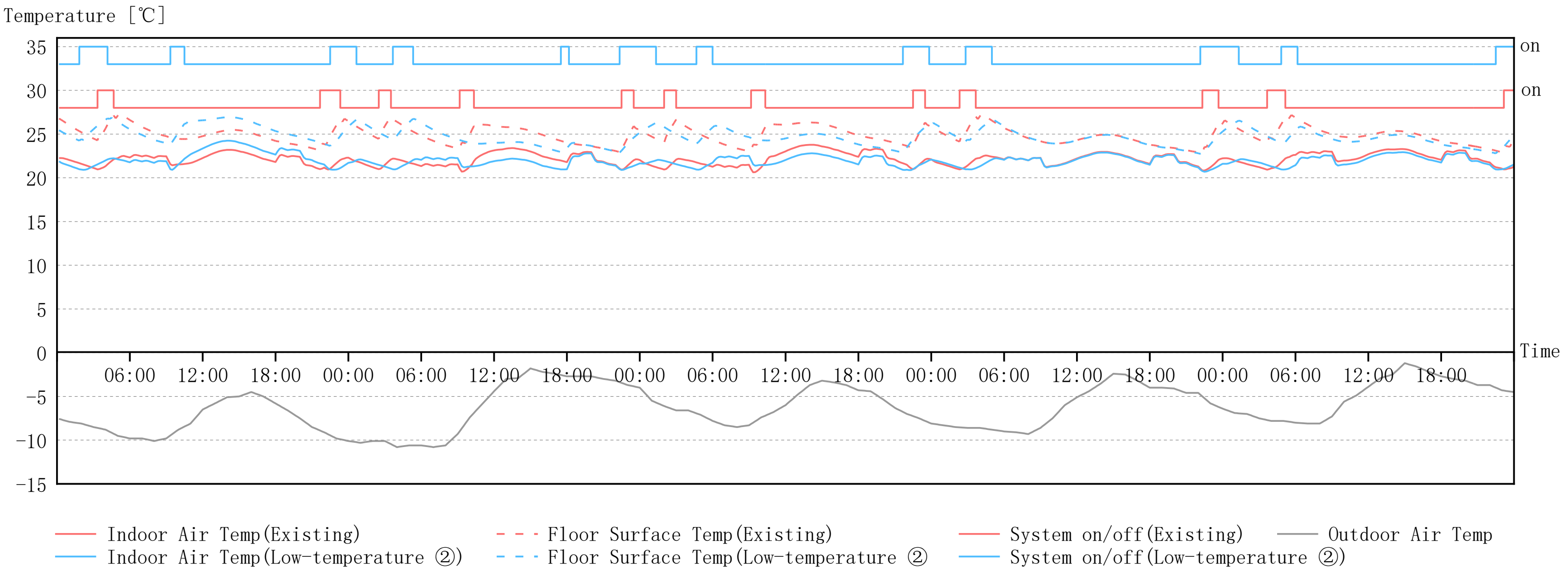
The amount of time that the indoor air temperature is kept within the predetermined range during wide-ranged outdoor temperature period does not increase when a low-temperature heating system with constant water temperature is used. On the other hand, employing a low-temperature heating system with outside reset control can efficiently keep the inside temperature within the desired range for more than 56% of the time.



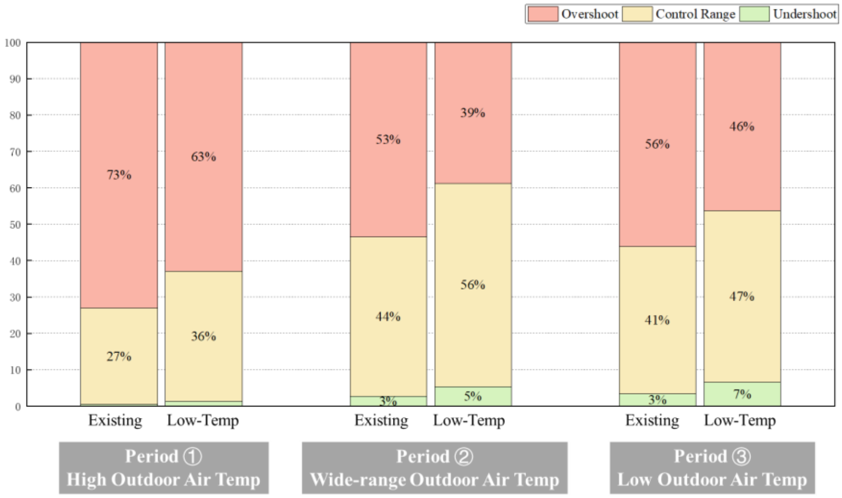
[Figure 4.13] Heating operation characteristics with relatively high outdoor temperature



[Figure 4.14] Heating operation characteristics with wide-range outdoor temperature

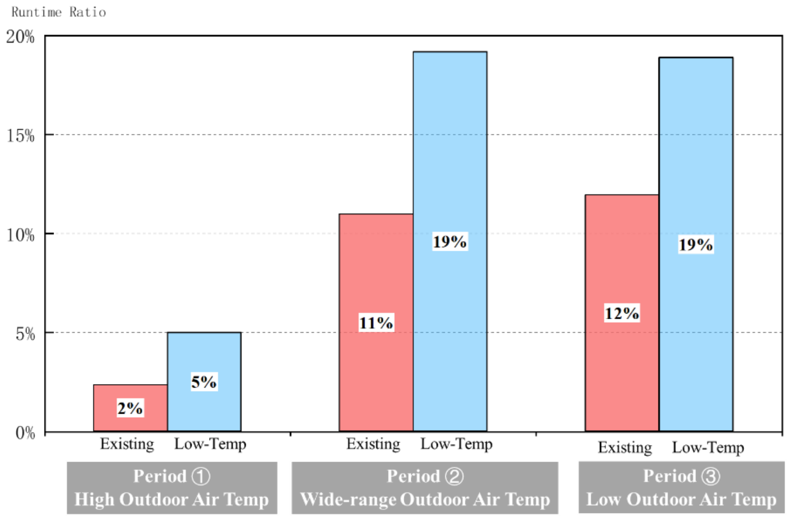


[Figure 4.15] Heating operation characteristics with relatively low outdoor temperature



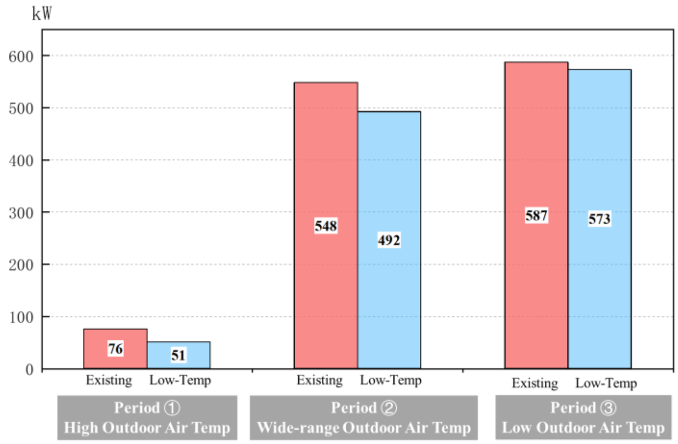
[Figure 4.16] Assessment of heating performance at different condition

When compared to the current heating system, the low temperature heating system runs longer after each start, according to the heating characteristics of each period. The ratio of heating operation time to the entire heating duration is computed in [Figure 4.17] since the number of starts-ups of the two heating systems in the three-simulation period used for this study is also similar.



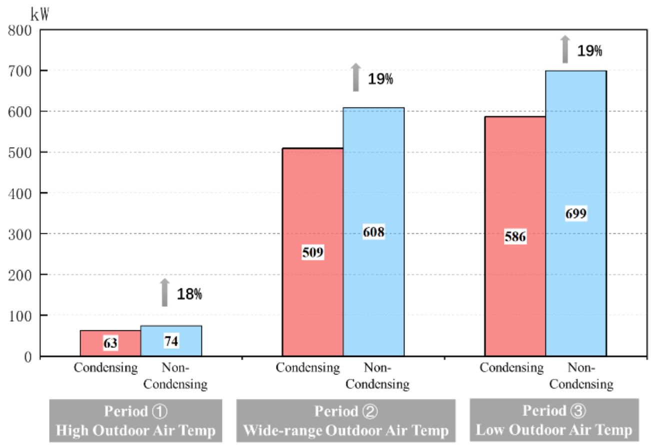
[Figure 4.17] Assessment of runtime ratio performance at different condition

The use of low temperature heating systems with outdoor reset control can reduce natural gas consumption by approximately 33% when the outdoor temperature is high and the heating load is low, though its running time is longer. 10% energy savings in period with large outdoor temperature differences, even though the operating time for low temperature conditions is higher than the existing conditions. In addition, unlike low-temperature heating systems with constant water temperature, low-temperature heating systems with outdoor reset control can also save natural gas consumption when the outdoor temperature is lower, and the load is higher.



[Figure 4.18] Assessment of heating performance at different condition

In this chapter, the gas consumption of low-temperature heating system with outdoor reset control are simulated using condensing boilers. The consumption of natural gas using different boilers in the same simulation period is shown in [Figure 4.19]. The gas consumption of low temperature heating systems is increased when using a general boiler, by about 18%.



[Figure 4.19] Natural gas consumption of different boilers at different condition

4.3 Assessment of the suitability of district low-temperature heating systems

In considering the applicability of low-temperature district heating systems, the heating performance, thermal comfort, and energy consumption characteristics of three low-temperature district heating systems were analyzed by comparing them with existing operating conditions.

The existing district heating secondary side water temperature is often determined based on the convention or the room with the largest heating load in the entire building. For rooms in a building with a smaller load, the water supply temperature determined in this way is clearly unreasonable. Therefore, to explore the effect of different water supply temperature conditions on the rooms with small heating loads, the middle floor middle house with the smallest heating load in the whole building was selected as the object of study and analysis.

Furthermore, when using the HIU equipment, the relevant water supply temperature and heating curve are determined based on the living room, which has the largest load in a household. So, the living room will be used as a representative room for the analysis of the heating system characteristics. The operation of the radiant floor heating panels is controlled by the ON/OFF control algorithm only, regardless of the existing operating conditions or the low temperature operating conditions, all in a continuous operation mode.

In the comparison of district low-temperature heating systems with and existing district heating systems, two analytical periods were set according to the outdoor temperature conditions. Each period is 5 days, period ① is from Nov. 11 to Nov. 15 when the outdoor temperature is relatively high. The outdoor temperature in period ① is maintained above 0℃. The outdoor temperature in period ② from January 9 to January 13, on the other hand, is relatively low, remaining below 0°C. This section studies district low-temperature heating systems in various types independently, much as the research of low-temperature heating systems employing individual heat sources.

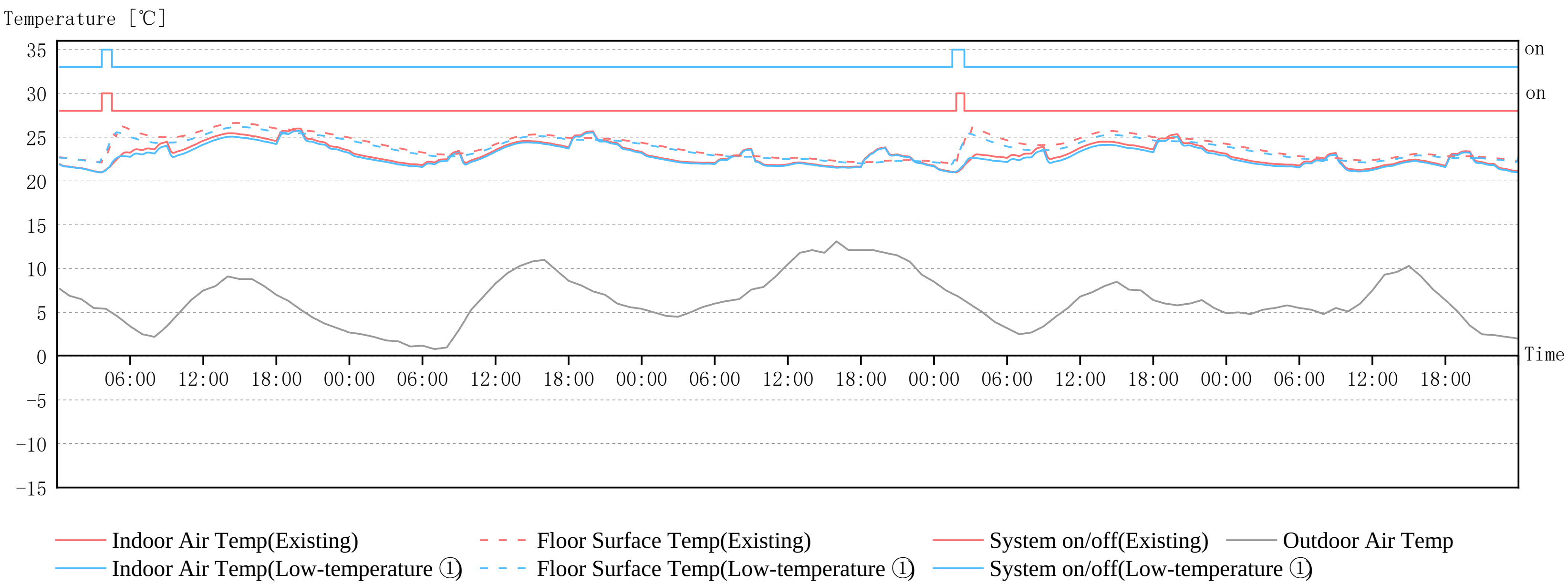
4.3.1 Applicability evaluation of district low-temperature heating systems with constant supply water temperature

The same system form as the district heating system currently used in Korean apartments can be used to connect the low-temperature district heating system to the building's heating system by installing a heat exchanger in the mechanical room of the building in an indirect connection.

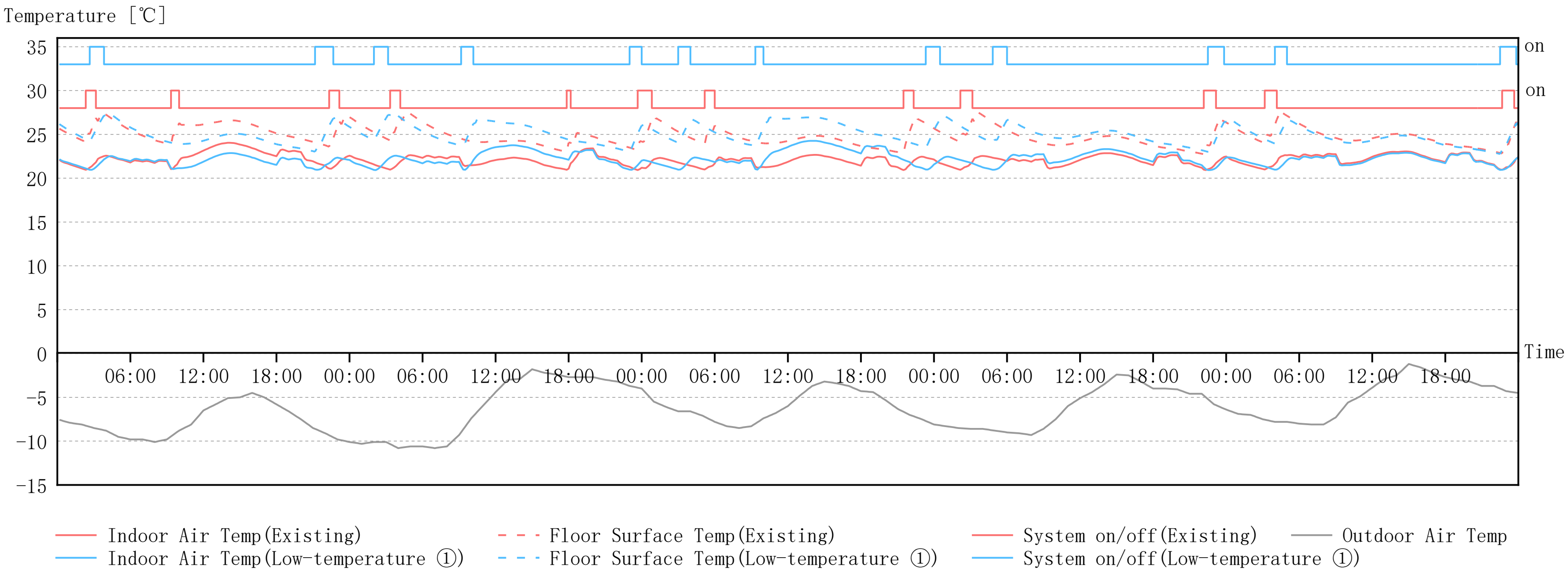
Two methods, constant supply water temperature control and outdoor reset control, are primarily used to regulate the secondary side hot water temperature of the heat exchanger installed in the mechanical room. This section compares existing district heating systems to assess the suitability of district low temperature heating systems with constant supply water temperature in high-insulation, high-tightness apartments.

The maximum heating load of the study apartment occurred in the uppermost corner room, so the secondary side water supply temperature set point was determined to be 43°C based on the maximum load of this room with reference to the design standard EN1264 for radiant floor heating systems represented by the uppermost side home of the study apartment with the maximum heating load and is determined to be 43°C with reference to EN1264, the standard for setting up radiant floor heating systems.

In the period when the outdoor temperature is high and the heating load is low, we observe in <Figure 4.20> that the use of a lower supply temperature determined by the apartment household with maximum heating load can still maintain the indoor temperature within the set range and maintain a small fluctuation range compared to the conventionally used supply temperature. It is observed that when the water supply temperature is low, the room temperature and the floor surface temperature are lower during the operation of the radiant floor heating panels.



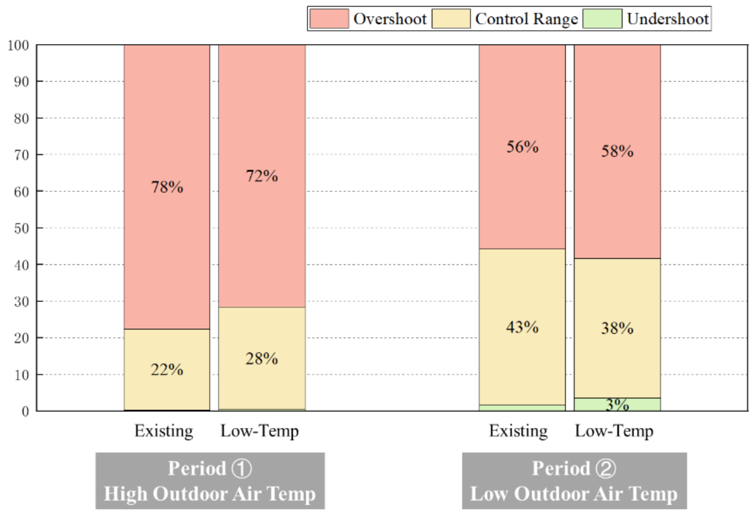
[Figure 4.20] Heating operation characteristics with relatively high outdoor temperature



[Figure 4.21] Heating operation characteristics with relatively low outdoor temperature

As shown in [Figure 4.20], even when the heating load maintain high level, using a lower water temperature still allows the room temperature to reach the set-point and keeps the fluctuation of the room temperature within a small range. It follows from the graph that when the supply water temperature is at a lower level, when the room temperature drops below the lower limit of the set range is the time that the system is on and running time is always longer than the existing district heating system with a higher water supply temperature on the secondary side.

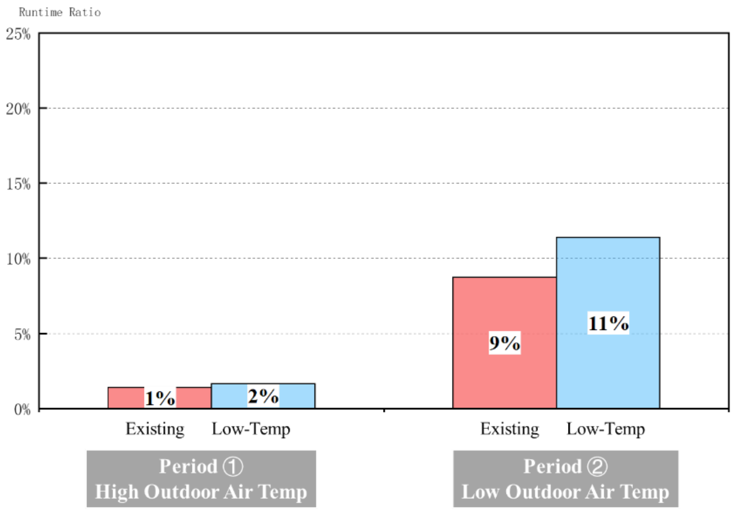
[Figure 4.21] statistically analyzes the ratio of time below the lower limit 21°C of the set rang and the ratio of time above the upper limit 22°C for the existing district heating system and the low-temperature district heating system with lower constant water temperature for each period, and the middle bar part indicates the ratio of time when the room temperature is within the set range.



[Figure 4.21] Assessment of heating performance at different condition

[Figure 4.21] shows that lowering the water supply temperature when the outdoor temperature is relatively high allows more time for the supply water temperature to be within the control range, thus improving the heating performance. However, simply lowering the supply water temperature over low outdoor temperatures period did not have a positive effect on heating performance. The indoor temperature variation in the operating characteristics of the low temperature district heating system for this period also shows that there are some time periods when the indoor temperature is higher than the indoor temperature of the existing district heating system, and the time ratio of both Undershoot and Overshoot increases due to the slower temperature rise process of the low temperature district heating system.

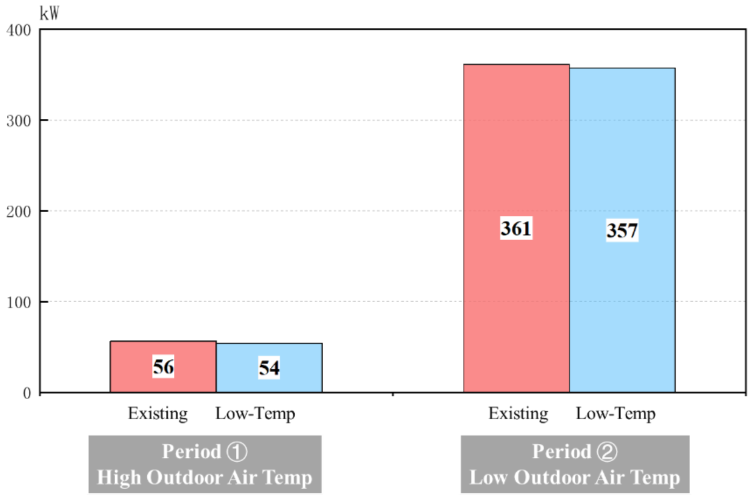
The heating characteristics of each period show that the low temperature heating system runs for a longer time after each start compared to the existing heating system. And the number of start-ups of the two heating systems in each simulation period selected for this study is similar, so the ratio of heating operation time to the whole heating period is calculated in [Figure 4.22].



[Figure 4.22] Operation time ratio at different condition

At the end, the energy performance of the existing heating system and low-temperature heating system with the constant water temperature was evaluated by comparing their heating energy rate in different periods, as shown in [Figure 4.23].

The heating energy rate of the radiant floor heating panels is decreased when a low-temperature district heating system is used, both in the period with greater heating loads and period with lower heating loads. The drop in heating energy rates is not significant because of the relatively similar operation of the heating systems in the two study intervals.



[Figure 4.23] Heating energy rate of radiant heating panel at different condition

4.3.2 Applicability evaluation of low-temperature district heating systems with outdoor reset control

The previous section covered the suitability of low-temperature district heating systems with lower constant secondary-side water supply temperature in a similar configuration to the current district heating systems. In fact, in apartments with heat exchangers in the mechanical room, there are situations where outdoor reset control is used to regulate the temperature of the secondary side water supply.

This section compares existing district heating systems to assess the suitability of district low temperature heating systems with outdoor reset control in high-insulation, high-tightness apartments. According to the literature review, even when outdoor reset control is used for heating hot water temperature regulation in existing district heating systems, a prescribed or customary heating curve is often used to determine the water supply temperature set point.

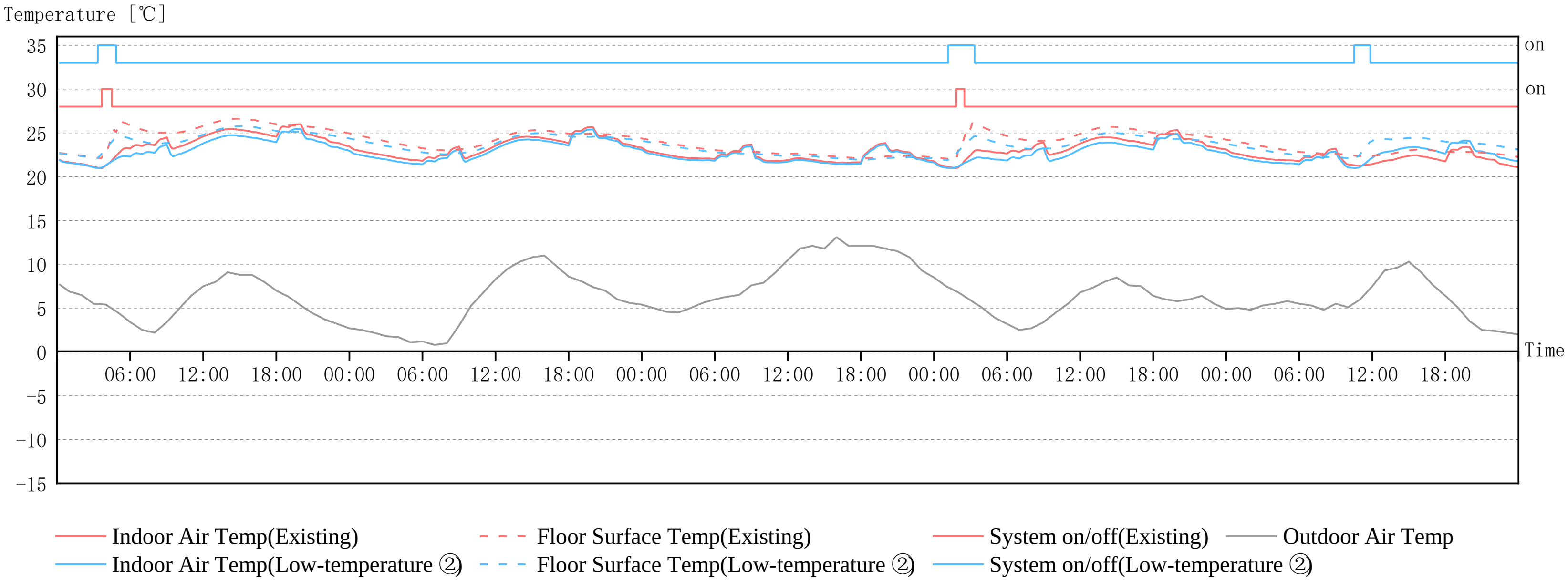
To construct a low-temperature district heating system using outdoor reset control, the heating curves of maximum heating load household was applied. The maximum heating load of the study apartment occurred in the uppermost corner room, so the secondary side water supply temperature set point was determined by heating curve of this household decided by multiple simulation corrections.

In the period when the outdoor temperature is high and the heating load is low, we observe in <Figure 4.24> that the use of a lower supply temperature determined by the apartment household with maximum heating load can still maintain the indoor temperature within the set range and maintain a small fluctuation range compared to the conventionally used supply temperature. It is observed that when the water supply temperature is low, the room temperature and the floor surface temperature are always lower during the operation of the radiant floor heating panels.

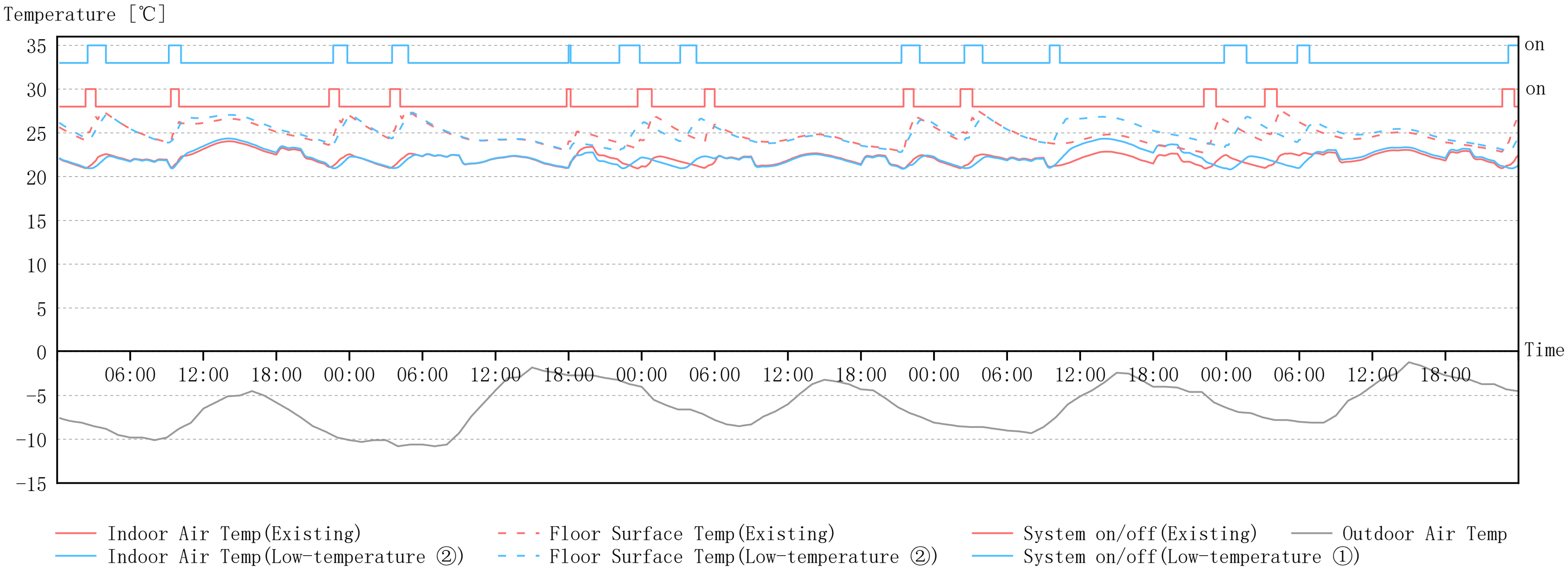
As shown in [Figure 4.25], even when the heating load maintain high level, using a lower water temperature still allows the room temperature to reach the set-point and keeps the fluctuation of the room temperature within a small range. The two district heating systems with different water supply temperatures have slightly different operating period, but the variation in room temperature is very similar most of the time. It follows from the graph that when the supply water temperature is at a lower level, when the room temperature drops below the lower limit of the set range is the time that the system is on and running time is longer than the existing district heating system with a higher water supply temperature on the secondary side.

[Figure 4.26] statistically analyzes the ratio of time below the lower limit 21°C of the set range and the ratio of time above the upper limit 22°C for the existing district heating system and the low-temperature district heating system with outdoor reset control for each period, and the middle bar part indicates the ratio of time when the room temperature is within the set range.

Lowering the supply temperature by outdoor reset control can effectively improve the performance of the heating system when the outdoor temperature is high. However, low supply water temperature over low outdoor temperatures period did not have a positive effect.



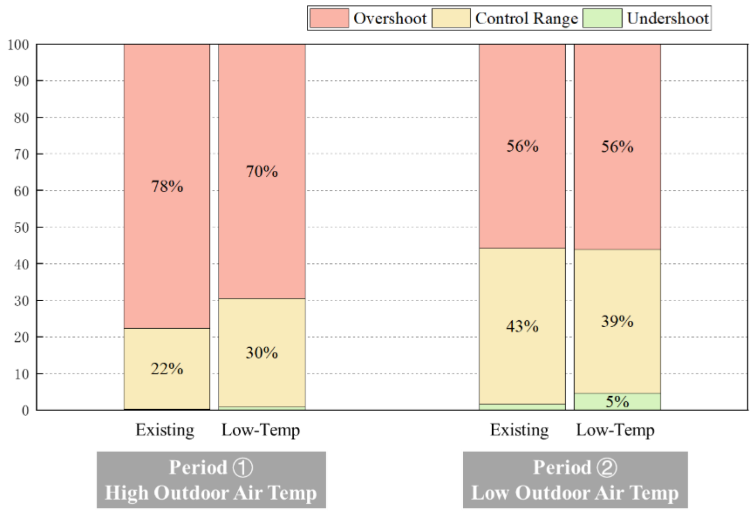
[Figure 4.24] Heating operation characteristics with relatively high outdoor temperature



[Figure 4.25] Heating operation characteristics with relatively low outdoor temperature

According to the statistics given in [Figure 4.27], despite the fact that the overshoot time did not increase, the undershoot time increased because the outdoor reset control acted to maintain the water supply temperature at a level well below the 60°C supply temperature of the existing district heating system.

The indoor temperature variation in the operating characteristics of the low temperature district heating system with outdoor reset control for this period also shows that there are some time periods when the indoor temperature is lower than the indoor temperature of the existing district heating system, and the temperature rise process of the low temperature condition is slower. It is why the time ratio of undershoot increased.

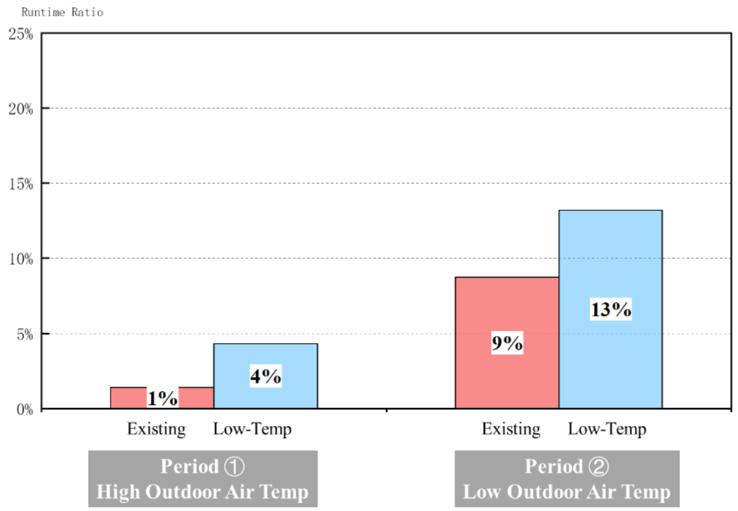


[Figure 4.26] Assessment of heating performance at different condition

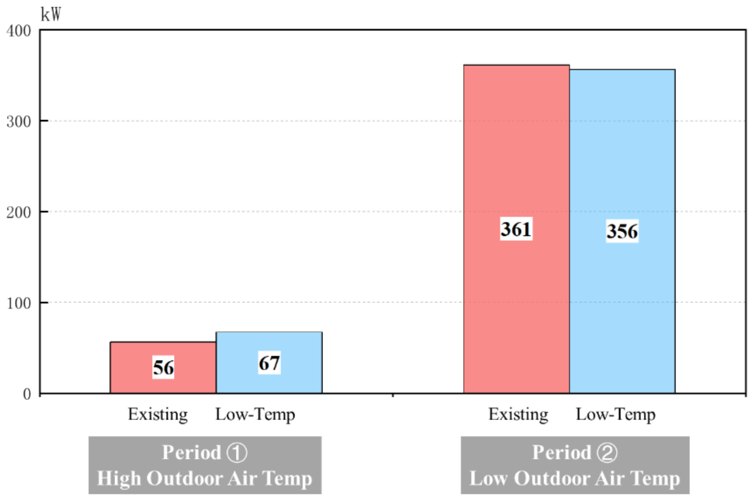
The heating characteristics of each period show that the low temperature heating system runs for a longer time when start compared to the existing heating system. And the number of start-ups of the two heating systems in each simulation period selected for analysis periods is almost similar, so the ratio of heating operation time to the whole heating period is calculated in [Figure 4.27].

At the end, the energy consumption of the existing heating system and low-temperature heating system with the constant water temperature are evaluated by comparing their heating energy rate in different periods, as shown in [Figure 4.28].

When a low-temperature district heating system is employed, the radiant floor heating panels' heating energy rate slightly decreased within periods of high heating demand. The situation does become different when the outdoor temperature is high level.



[Figure 4.27] Operation time ratio at different condition



[Figure 4.28] Heating energy rate of radiant heating panel at different condition

The characteristics of heating operation when the outdoor temperature is high, it can be noticed that when using the low temperature district heating system with outdoor reset control discussed in this section, the indoor air temperature with the low temperature condition drops below the lower control limit at some point. And the indoor temperature is always lower compared to the existing heating system, the indoor air temperature with the existing heating system remains in the control range. Since a heating system needs to run for a period after start-up to make the room temperature exceed the upper limit of the control range before it is turned off, the extra running time when using low temperature conditions causes excess heat consumption.

4.3.3 Applicability evaluation of district low-temperature heating systems with heat interface unit

The previous section covered the suitability of low-temperature district heating systems with lower constant secondary-side water supply temperature in a similar configuration to the current district heating systems, and the suitability of low-temperature district heating systems with outdoor reset control.

The supply water temperature setting point for these low temperature district heating systems, or the heating curve applied to the outdoor reset control is determined by a representative family of the entire building. The establishment of those operating parameters is closely related to the chosen design heating load.

But as in the results obtained from the analysis of the heating loads of the families in different locations in Chapter 3, it can be concluded that there are differences in the heating loads in different locations. And so, the heating curve determined by representing the household is clearly not the most suitable for households with small heating loads.

In district heating systems, instead of installing large heat exchangers in mechanical rooms, HIU equipment can be installed in each home, allowing for the same individual heating system control as when using individual boilers.

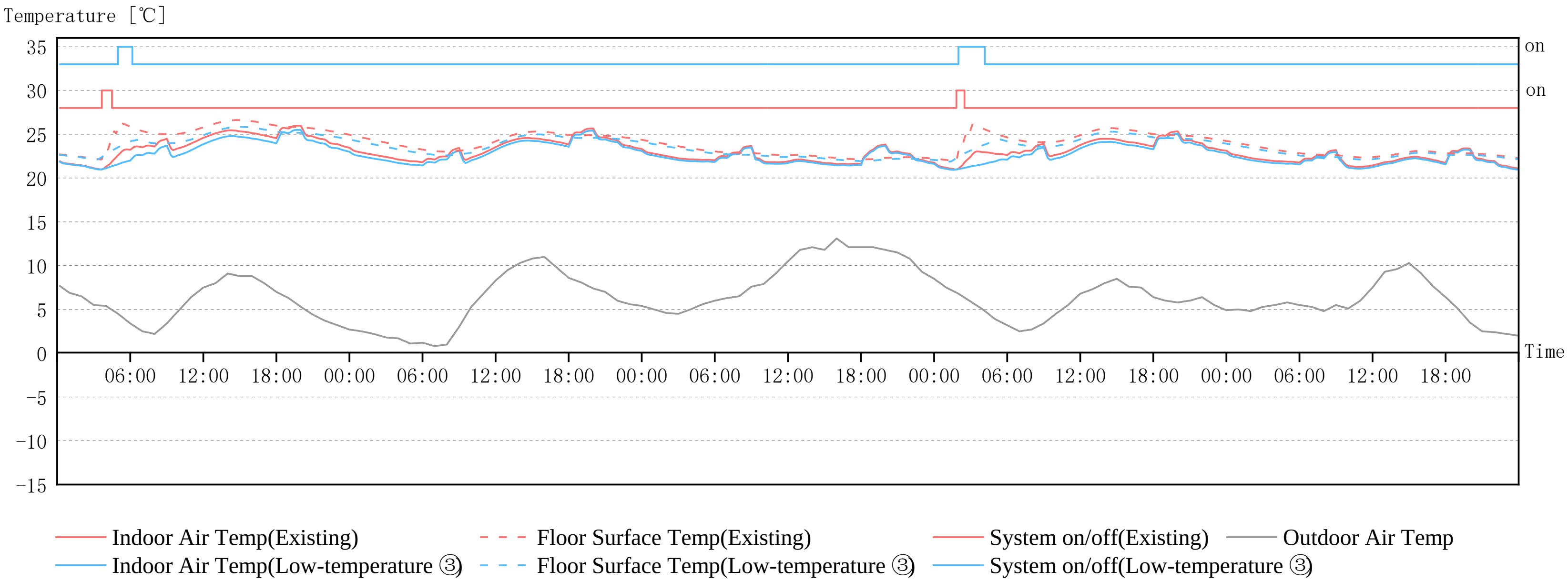
This section compares existing district heating systems to assess the suitability of district low temperature heating systems with HIU in high-insulation, high-tightness apartments. The outdoor reset control is also used to regulate the temperature of the HIU outlet water, and the heating curve is modified by simulation for the household located in the middle of the building, where the heating load is the most different from that of the whole building's representative homes.

In the period when the outdoor temperature is high and the heating load is low, we observe in [Figure 4.29] that the use of a lower supply temperature determined by the apartment household with HIU and fixed heating curve can maintain the indoor temperature within the set range and maintain a small fluctuation range compared to the conventionally used supply temperature. It is observed that when the water supply temperature is low, the room temperature and the floor surface temperature are always lower during the operation of the radiant floor heating panels. It is clear from the graph, that during the operation of a low-temperature district heating system with HIU equipment, both the floor surface temperature and the room temperature rise more slowly, and the maximum value is always lower than with the existing district heating system.

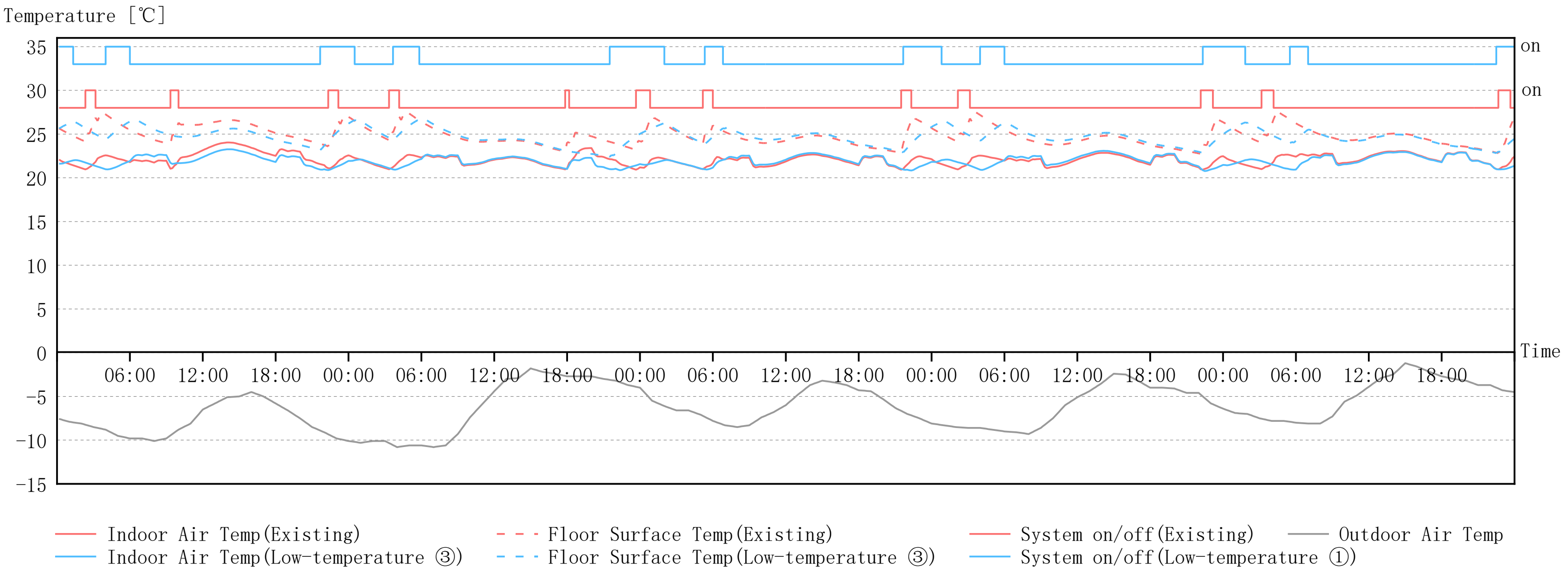
In this period, the maximum floor surface temperature of the existing heating system exceeds 26°C, while the maximum floor surface temperature of the low temperature district heating system is only just above 25°C.

As shown in [Figure 4.30], even when the heating load maintain high level, using a lower water temperature still allows the room temperature to reach the set-point and keeps the fluctuation of the room temperature within a reasonable range.

The two district heating systems with different water supply temperatures have slightly different operating period, but the variation in room temperature is very similar most of the time. The floor temperature and room air temperature of the existing district heating system are always slightly higher than the low temperature district heating system when the operating period of both district heating systems is nearly the same.



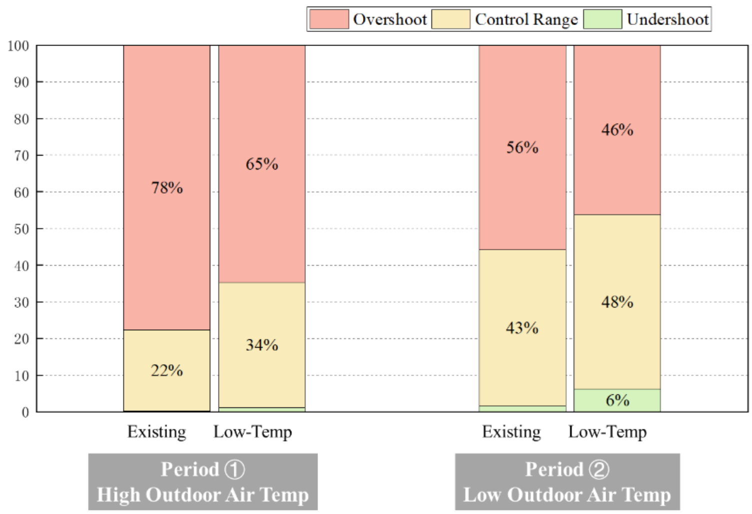
[Figure 4.29] Heating operation characteristics with relatively high outdoor temperature



[Figure 4.30] Heating operation characteristics with relatively low outdoor temperature

[Figure 4.31] statistically analyzes the ratio of time below the lower limit 21°C of the set range and the ratio of time above the upper limit 22°C for the existing district heating system and the low-temperature district heating system with outdoor reset control for each period, and the middle bar part indicates the ratio of time when the room temperature is within the set range.

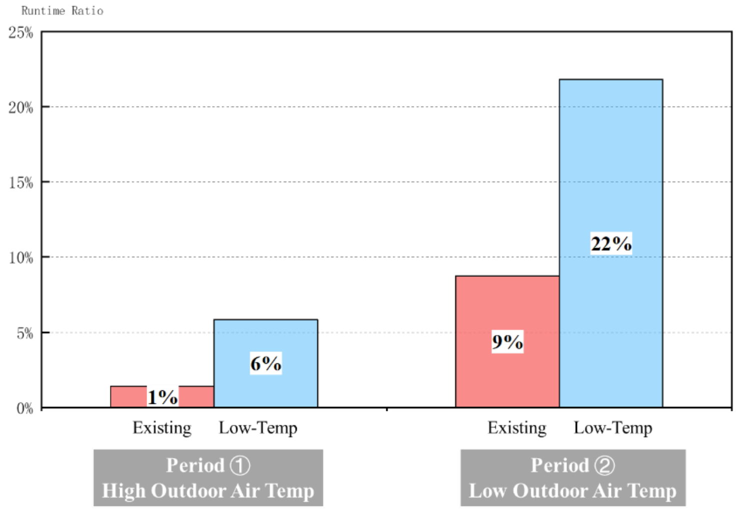
Lowering the water supply temperature can effectively improve the performance of the heating system with the different outdoor condition. Even though the time of undershoot has increased, it reduces a lot of the time that the room temperature produces Overshoot, thus increasing the time that the room temperature is in the control range.



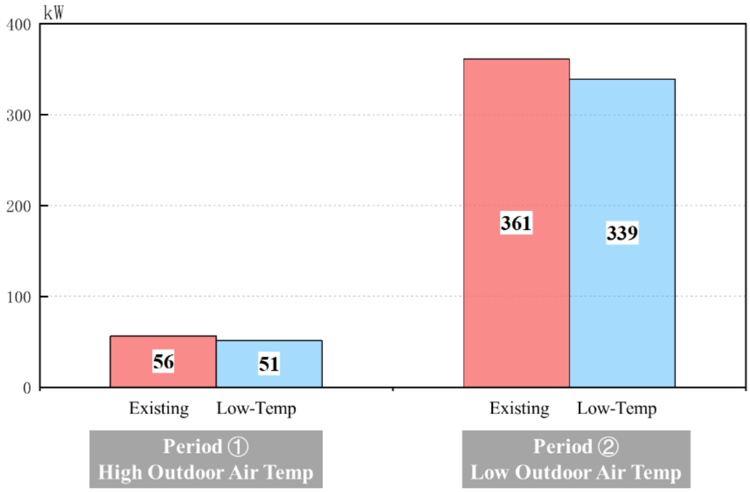
[Figure 4.31] Assessment of heating performance at different condition

The heating characteristics of each period show that the low temperature heating system runs for a longer time when start compared to the existing heating system. And the number of start-ups of the two heating systems in each simulation period selected for analysis periods is almost similar, so the ratio of heating operation time to the whole heating period is calculated in [Figure 4.32].

At the end, the energy consumption of the existing heating system and low-temperature heating system with the constant water temperature was evaluated by comparing their heating energy rate in different periods, as shown in [Figure 4.33]. Low temperature district heating systems with HIU equipment and suitable outdoor reset control reduce heating energy rate compared to existing heating systems, regardless of outdoor temperature conditions.



[Figure 4.32] Operation time ratio at different condition



[Figure 4.33] Heating energy rate of radiant heating panel at different condition

4.4 Summary

The heating load is consistently decreasing as the thermal insulation of the apartment envelope is continuously improved. In rooms with lower heating demands, the low-temperature heating system using lower temperature hot water as the heat medium offers a wide range of potential applications. As a result, by contrasting them with current heating systems, this chapter analyzes the applicability of low-temperature heating systems with various heat sources in well insulated, densely packed apartments.

The composition assessment results of each low-temperature heating system are organized as follows:

(1) This section focuses on the evaluation of the suitability of five different forms of low-temperature heating systems. There are two types of individual low-temperature heating systems using individual heat sources, one is a low-temperature individual heating system with a constant supply water temperature, and the other is a low-temperature individual heating system with a modified outdoor reset control. There are three forms of low-temperature district heating systems, one of which is a heating system that obtains a constant secondary-side water supply temperature through a heat exchanger installed in the mechanical room of the building. The second is a low-temperature heating system that regulates the secondary water supply temperature according to an outdoor reset control strategy determined by the maximum load in the building. The last type is a heating system with HIU equipment that can be individually controlled even with a centralized heat source such as district heating.

(2) They can meet the indoor heating demand in all three-analysis period, whether they are low-temperature heating systems with a constant water supply temperature or low-temperature heating systems that use outdoor reset control to instantly adjust the water supply temperature in accordance with the outdoor temperature. Both low temperature heating systems can improve the performance of the heating system by increasing the time that the room temperature is maintained in the set range, but the effect of using outdoor reset control on

heating performance is more significant.

(3) Because the outdoor temperature is typically higher than the design temperature of the heating system when using outdoor reset control, the water supply temperature of this low temperature heating system is always lower than that of a low temperature heating system with a constant water supply temperature. The outdoor reset control system's running time is the longest because it requires more time to operate to make indoor air temperature rise. However, under various outdoor situations, using outdoor reset control to reduce fuel consumption is quite effective.

(4) Different types of low-temperature district heating systems can maintain small fluctuations in indoor and floor surface temperatures under different outside air conditions. All low-temperature district heating systems improve the heating performance of the system when outdoor temperatures are high, resulting in shorter times for Overshoot to occur. However, only the third low temperature district heating system with HIU equipment and adjust the supply water temperature of radiant heating panels following the appropriate heating curve can still enhance the heating performance when the outdoor temperature is low and the heating load is high.

(5) The hot water temperature of the three low-temperature district heating systems is gradually reduced, so the time required for the system to reach the upper limit of the control range, i.e., the turn-on time, increases in each ON/OFF control cycle. Lowering the water supply temperature is possible in most period to reduce the heating energy rate of radiant floor heating panels, where the use of HIU equipment can minimize the heating energy consumption.

Chapter 5. Conclusion

The energy consumption of heating systems, such as urban gas consumption and district heating systems energy consumption, accounts for more than 40% of the total energy consumption of the entire residential building sector. After examining the literature on existing heating systems with different heat sources, it was found that even though the heating load of current residential buildings has changed dramatically from when radiant floor heating systems were introduced, the supply water temperature of the heating system remains high.

Because of the high energy efficiency of low-temperature heating systems, as well as the ability to use low-temperature heat sources and other points, international tend to use low-temperature heating systems in eco-friendly t buildings. Once the geometry parameters of the radiant floor heating panels, which are widely used in Korea, are determined, the water supply temperature and flow rate determine the heat output of the heating system. Higher water temperatures are required to meet indoor heating needs in older residential buildings with less-than-excellent insulation and high heating loads. With the continuous improvement of building envelope insulation and tightness, it allows for the use of low-temperature heating systems in such highly insulated and airtight apartments.

Referring to the design standards of energy-saving building envelope, this thesis establishes a model of a high-insulation and high tightness apartment building with a maximum design heating load of 32.5 W/m^2. And five different forms of low-temperature heating systems were constructed by investigating and referring to the structure and control methods of current heating systems. Then the corresponding HVAC models were built using the dynamic simulation software EnergyPlus, and the operation of each low-temperature heating system was simulated for the whole heating season. Its applicability was also evaluated by comparing it with existing heating systems.

The results of this study are organized as follows:

(1) All low-temperature heating systems are available to meet the heating needs in the study period.

(2) None of the low temperature heating systems operate with a floor surface temperature above the ASHARE HANDBOOK specified upper limit of 29°C. A drop in water supply temperature in terms of heating operating characteristics will result in a drop in floor surface temperature. Owing to the Korean habit of entering rooms without shoes, low-temperature heating systems may cause some discomfort.

(3) The operation time of both low temperature individual heating systems has increased due to the lower water temperature. The individual low temperature heating system using outdoor air temperature control has the longest run time, but it is also the most energy efficient. The use of outdoor reset control to regulate the supply temperature during boiler operation can reduce the natural gas consumption of the heating system. The performance of the heating system can be further improved using outdoor reset control to better maintain the indoor temperature within the set range.

(4) For households in a middle location with low heating demand, low temperature district heating systems with constant water temperature on the secondary side and low temperature district heating systems with water temperature on the secondary side regulated according to an outdoor reset control strategy determined by the room with the highest heating load in the building can improve the performance of the heating system to some extent. However, the heating performance of low-temperature heating systems where HIU equipment is installed to enable individual regulation of water temperature have the most significant improvement in heating performance.

(5) Compared to the existing heating system, the low temperature district heating system has a longer operating time. During most of the operation periods, since the number of operation cycles of the existing heating system and the low-temperature district heating system are comparable, although the operation time of the low-temperature district heating system is longer, the instantaneous heating energy rate of the low-temperature heating system is lower, so that the low-temperature heating system uses less heat in turn during the whole operation interval. When using HIU equipment, which has the longest operating time within all low temperature district heating system during the same study period, it can reduce the amount of heat released by 9% when the outdoor temperature is higher and by 6% when the outdoor temperature is lower. It is worth noting, however, that an increase in the number of runs may lead to an increase in heat release.

(6) Although low-temperature heating systems have many advantages, due to the lower water supply temperature, if the same radiant floor heating panels are used, the ground temperature and room temperature rise more slowly compared to existing heating systems. In addition, in the low temperature heating system installed with HIU, how to solve the peak load generated by family members who turn off the heating system at work and then turn on the heating system when they arrive home after work has become a potential problem.

Bibliography

1. Yo, Ing -Yu. "Building energy use has been on the decline over the past three years". *KHARN* 6 June 2021.Web. Accessed 10 Apr 2022.
2. Lee, gon et al. "Design of Radiant Heating System for Housing". *The Magazine of the Society of Air-Conditioning and Refrigerating Engineers of Korea.* Vol.6, No.2, (1977): 110-124.
3. Park, Seok-bong. " To accept the space of balcony as non-heating space of indoors = Study on Heating Load of Multiple Dwelling Units". *Industrial technology research.* Vol.6, (1996): 39-42.
4. Lee, Youn-Jung et al. "Design of the Radiant Floor Heating Panel Considering Heating Load of Residential Building". *Journal of Architectural Institute of Korea.* Vol.27, No.9, (2011): 349-357.
5. Korea District Heating Corp. 2020, Standard of Heating Facility Standard.
6. Ministry of Construction, Building Regulation, 1979/1980/1984/1987.
7. Ministry of Construction, Regulations on Building Facility Standards, 1992.
8. Ministry of Construction and Transportation, Regulations on Building Facility Standards, 2001.
9. Ministry of Land, Transport and Maritime Affairs, Regulations on Building Facility Standards, 2008/2010.
10. Ministry of Land, Infrastructure and Transport, Energy Saving Design Standards of Buildings, 2013/2016/2018.
11. KOSIS National Statistical Portal, kosis.kr
12. Jung, Hae-Kwon et al. "Comparative Analysis on the Heat Transfer Characteristics between Dry and Wet Ondol Systems." *JOURNAL OF THE ARCHITECTURAL INSTITUTE OF KOREA Planning & Design*. Vol.25, No.11, (2009): 315-322.
13. DIN EN 1264-2, "*Water based surface embedded heating and cooling systems - Part 2: Floor heating: Methods for the determination of the thermal output using calculations and*

experimental tests", 2021.
14. Yeo, Myoung Souk and Lyong Ryoo Seong. "Control Method of Hot Water Ondol Heating System in Residential Buildings". *Magazine of the SAREK*. Vol.34, No.8, (2005): 33-42.
15. Mun, Seung hyun. Design and Control Method of Radiant Floor Heating System by Reducing Heating Load of Apartment House Using District Heating Source. 2019. Seoul National University, Master.
16. Jeong, Chang Ho. Handling Strategies of Hydronic Thermal Energy System for Heating Demand on Low Energy Residential House. 2017. The Seoul National University, Doctorate.
17. Yoo, Mi Hye. Analysis of Effectiveness with Improved Alternative for Individual Heating Systems Using Flow Bypass. 2013. The Seoul National University, Master.
18. John Siegenthaler, P.E. MODERN HYDRONIC HEATING for residential and light commercial buildings. 3rd edition, DELMAR, 2012. p.381.
19. The Boiler (Efficiency) Regulations 1993, SI (1993) No 3083, as amended by the Boiler (Efficiency) (Amendment) Regulations 1994, SI (1994) No 3083.
20. Cho, Heung-won, "Energy Conservation and Environmental Improvement Effects of Condensing Boiler", *Boiler Equipment*, No.92, (2001):112-114.
21. Satyavada, Harish, and Simone Baldi. "A novel modelling approach for condensing boilers based on hybrid dynamical systems." *Machines* 4.2 (2016): 10.
22. Lee, Seung-ro, Sung-Min Kum, and Chang-Eon Lee. "Performances of a heat exchanger and pilot boiler for the development of a condensing gas boiler." *Energy* 36.7 (2011): 3945-3951.
23. American Society of Heating, Refrigerating and Air Conditioning Engineers ASHRAE. ASHRAE handbook HVAC systems and equipment; 2020.
24. Han, Do-Young, and Sung-Hak Kim. "Effective dynamic models for the development of control algorithms of a condensing gas

boiler system." *Korean Journal of Air-Conditioning and Refrigeration Engineering* 20.6 (2008): 365-371.
25. Kyungdong Navien Product Comprehensive Catalog, http://en.kdnavien.com/index. Accessed 20 Apr 2022.
26. Ioan Sarbu, Calin Sebarchievici, "Chapter 5 - Solar Water and Space-Heating Systems," *Solar Heating and Cooling Systems*, Academic Press, 2017. 139-206.
27. Kwag, Hyun Ju et al. "Transition to the 4th Low Temperature District Heating Systems in SEOUL District Heating System." *Transactions of the Korean Society of Mechanical Engineers*. B45.12 (2021): 691-699.
28. Jin, Hua Guo. Characteristics and Improvement of Hot Water Supply in Apartment Housing using District Heating Source. 2013, The Seoul National University, Master.
29. Choi, Chang-Sik et al. "Analysis on the heat source and the distribution system operation of apartment house complex using a district heating source." *Proceedings of the SAREK Conference* (2015): 545-546.
30. Lee, Tae-Won, and Kim. Yong-Ki. " A Study on the Operating Conditions for the Demand Side Facilities of the District Heating System." *Proceedings of the SAREK Summer Conference* (2011): 533-538.
31. Seoul Housing & Communities Corporation, Facilities Manager Technical Textbook.
32. BOERSTRA, Atze et al. "The health, safety and comfort advantages of low temperature heating systems: a literature review". *In: Proceedings of the 6th international Conference on Healthy Buildings*. 2000, p.629-634.
33. Eijdems, H. H. E. W., A. C. Boerstra, and P. J. M. Op't Veld. "Low temperature heating systems: Impact on iaq, thermal comfort and energy consumption." vol. Annex 37 (2000).
34. Hesaraki, Arefeh, and Sture Holmberg. "Energy performance of low temperature heating systems in five new-built Swedish dwellings: A case study using simulations and on-site measurements." *Building and Environment* 64 (2013): 85-93.

35. Buker, Mahmut Sami, and Saffa B. Riffat. "Solar assisted heat pump systems for low temperature water heating applications: A systematic review." *Renewable and Sustainable Energy Reviews* 55 (2016): 399-413.
36. Cooper, Samuel JG, et.al. "Potential for use of heat rejected from industry in district heating networks, GB perspective." *Journal of the Energy Institute* 89.1 (2016): 57-69.
37. Maivel, Mikk, and Jarek Kurnitski. "Low temperature radiator heating distribution and emission efficiency in residential buildings." *Energy and Buildings* 69 (2014): 224-236.
38. Lund, Henrik, et al. "The status of 4th generation district heating: Research and results." Energy 164 (2018): 147-159.
39. Teskeredzic, Armin, and Rejhana Blazevic. "PLATE HEAT EXCHANGER MODEL AS PART OF INDIRECT HEATING SUBSTATION." *Annals of DAAAM & Proceedings* (2019): 709-717.
40. Olsen, Peter Kaarup, et al. "Guidelines for low-temperature district heating." *EUDP–DEA. Denmark* (2014).
41. Emmeti UK, Heat Interface Units Communal Heating Schemes.
42. Mun, Jung-Hyon, Lee, Jong-Ik, and Kim, Min-Sung. "Study on Estimation of Infiltration Rate (ACH natural) using Blower Door Test Results." *Proceedings of Korean Institute of Architectural Sustainable Environment and Building* 14.6 (2020): 687-698.
43. Satyavada, Harish, and Simone Baldi. "Monitoring energy efficiency of condensing boilers via hybrid first-principal modelling and estimation." *Energy* 142 (2018): 121-129.
44. Ministry of Land, Infrastructure, and Transport, Structural Standards for Blocking Floor Impact Noise between Floors for Noise Prevention, 2018
45. Olesen, Bjarne W. "Radiant floor heating in theory and practice." *ASHRAE journal* 44.7 (2002): 19-26.

국문 초록

관련 통계에 따르면 건물 내 아파트 등 주거용 건축물이 전체 건축부문 에너지 소비량의 43.4%를 차지하고 있다. 전기 시스템의 에너지 소비 외에 다음으로 주목할 만한 것은 난방 시스템의 에너지 소비이다.

본 논문은 관련 연구문헌을 살펴보고 분석함으로써 최근 아파트 건물 외피의 단열성능과 기밀성은 개선되는데 난방 부하가 상대적으로 낮은 수준으로 감소하였음을 발견했다. 하지만 개별 난방이든 지역 난방이든 상관없이 기준 난방시스템에서 높은 온도의 온수를 이용하고 복사 바닥 난방 패널을 통해 실내의 열을 전달하는 데가 유지하고 20세대 초반과 큰 변화는 없다.

외피 단열성능의 강화로 아파트의 난방 부하가 지속적으로 감소하면서 주거용 건물에 저온 난방 시스템을 적용할 수 있는 이론적 가능성을 제공하고 있다. 이에 본 논문에서는 개별 가스보일러를 열원으로 사용하는 저온 난방시스템과 기존 지역난방시스템을 참고하여 저온 지역 난방시스템을 구축하였다.

단열성과 기말성이 좋은 아파트 내 저온난방시스템의 적용가능성을 분석하기 위해 동적 시뮬레이션 소프트웨어 EnergyPlus 9.5를 연구 도구로 사용하여 해당 건물 및 난방시스템의 모델을 만들었다. 그리고 저온 난방 시스템의 적용 가능성을 평가하기 위해 난방 성능, 열적 쾌적성, 에너지 소비의 세 가지 관점에서 평가방범을 구축하였다. 마지막으로 평가 시스템에 따라 기존 난방 시스템과 비교하였다.

본 연구의 주요 결과는 다음과 같다:

(1) 모든 저온 난방 시스템이 실내 난방 수요를 만족시킬 수 있음을 확인하였다. 바닥 표면 온도와 실내온도은 기존 난방 시스템보다 낮은 경향이 있다. 그리고 바닥면 온도는 ASHARE HANBDBOOK에서 요구하는 상한 29℃를 초과하지 않다.

(2) 저온 개별 난방 시스템의 경우에서 난방 성능을 향상시킬 수 있으며, 실외 리셋 컨트롤을 사용하여 수온을 조절하는 저온 개별 난방 시스템은 난방 성능을 더욱 향상시킬 수 있다. 저온지역난방시스템에 대한 평가에서 HIU 장비를 갖춘 저온지역난방시스템이 난방성능을 가장 크게 향상시킨 것으로 나타났다.

(3) 공급 온수온도가 낮아짐에 따라 저온 난방 시스템은 실내 난방요구를 만족하기 위해 더 긴 작동 시간을 필요로 하는 경우가 많다. 그렇기 때문에 실외 리셋 제어 기능이 있는 개별 저온 난방 시스템 및 HIU 기능이 있는 지역 저난방 시스템의 작동 시간이 가장 길다. 그러나 런타임 시나리오와 달리, 서로 다른 열원을 사용하는 가장 오래 지속되는 두 저온 난방 시스템의 연구 기간 중 에너지 많이 절약이 된다.

주요어: 난방시스템; 바닥 복사난방시스템;저온 난방;
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