공학박사학위논문

Optimized Control of Thermally Activated Building System in Office Buildings

사무소 건물에서의 구체축열 시스템 최적 제어

2017 년 8 월

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Abstract

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Building environments have been controlled by using heating and cooling systems to maintain comfortable interior temperatures. However, a recent popular trend in building heating and cooling system involves utilizing a radiant system to achieve energy savings and comfortable temperatures. One type of radiant system uses the concrete structure of a building as the heating and cooling system by embedding pipes inside it. This system has many advantages, such as reduced installation time, reduced building material requirements, and non-necessity of increasing the height of the building. Because the system uses the entire concrete structure of a building, individual control may be difficult to perform. Thus, the system was designed to remove the basic heating/cooling load in a building. Although many studies propose utilizing different parameters to determine the basic heating/cooling load of a building, the most common method used to remove the basic load involves keeping the radiant surface as the room setpoint temperature. When the surface temperature of the Thermally Activated Building System (TABS) is kept at the setpoint temperature of the room, the system will remove load based on how the air temperature of the room changes from the load. This concept is called the self-regulation effect, and

was useful for removing load without any feedback. Because only partial heating and cooling load can be removed by TABS via the self-regulation effect, the remainder of the load was removed by an air-based heating and cooling system. In a well-designed building with a small amount of heating and cooling load, the self-regulation effect can be very effective. However, the current method used for self-regulation was applied by supplying water at the room setpoint temperature. In addition, the load able to be removed by TABS is limited in a building with a significant amount of heating and cooling load. Thus, the objective of this study is to identify the thermal mechanism of TABS and increase its utilization by adjusting the supply water temperature depending on the load.

To increase the utilization of radiant systems, the current TABS control method should be carefully observed to determine how it can be improved. Because the self-regulation effect was applied by supplying water at the room setpoint temperature, the core layer where pipes are embedded will be close to the room setpoint temperature and the surface temperature of TABS cannot be kept at the room setpoint temperature from consistent effect from the load. Therefore, the heat exchange between the surface of TABS and room air temperature is lower than expected and utilization of TABS is decreased. Moreover, the air system removes the remainder of the load and keeps the room air temperature at the setpoint temperature. The amount of load removed by TABS when following the self-regulation concept decreases as the setpoint temperature is consistently met. Consequently, the active use of TABS should be executed by targeting the specific basic load.

For the active utilization of TABS, its thermal mechanism should be analyzed and the target load should be identified. The thermal mechanism of TABS demonstrates a significant amount of time delay due to the large heat capacity of concrete, which was one of the advantages of TABS. However, time-delay of TABS also means that the system needs a large amount of time to supply the heat into the room. With the various changes on supply water temperature and load, the TABS should use at least daily control instead of hourly control. Once the control timestep was chosen, the target basic load can be chosen by using the minimum load achieved over a 24-hour load period. Thus, a load prediction should be performed to determine the basic load. The minimum load over a 24-hour period was identified by studying load patterns based on historical data. In this study, two load prediction methods were utilized to select the supply water temperature for TABS. One popular method involved using the outdoor air temperature to calculate the temperature of the supply water. The heating and cooling curves are derived using a resistance-capacitance (RC) network. The second method is an intelligence-based method, and uses an artificial neural network (ANN) to recognize the load pattern. In the process of learning the load patterns, the input parameters of the ANN were selected by an analysis that divided the building load into external load, solar load, and internal load. The input parameters should be obtained prior to the prediction, and are defined as follows. The input parameters that consider the external load, solar load, and internal load were outdoor air temperature, cloud coverage based on weather forecasts, and type of day. Using these three input parameters, the accuracy of the load prediction became reliable after approximately one month of pattern learning. Because accuracy was poor

during the ANN learning period, this study proposes the use of load prediction based on outdoor air temperature during the ANN learning period, and then use the ANN prediction after it has been validated.

Based on our understanding of the thermal mechanism of TABS and load prediction methods, the goal of removing the minimum load of a building over a 24-hour period (using TABS) was executed using a co-simulation involving EnergyPlus and MATLAB. EnergyPlus was used to realize the actual building environment, and MATLAB calculated the supply water temperature and performed load predictions with the information obtained from EnergyPlus. The Building Controls Virtual Test Bed (BCVTB) was used as middleware connecting the two simulations to exchange information at each timestep. TThrough the co-simulation, the thermal output of TABS with different control strategies was compared to verify the utilization of TABS. Among control strategies, predictive control with ANN demonstrated the greatest thermal output of TABS. The validation of the method was executed by applying different weather conditions and showed equivalent results.

Keywords : Thermally Activated Building System, Predictive control, Thermal output characteristics, Co-simulation

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Symbols

Symbol	Meaning	Unit
A	Area	m^2
A_{Floor}	Floor Area	m^2
$A_{surface}$	Surface Area	m^2
b	Bias term	-
C	Heat capacity	J/K
C_p	Specific heat	J/kg K
h	Convection coefficient	W/㎡ K
k	Thermal conductivity	W/m K
$K_{wall.opaque.avg}$	Average thermal conductivity of wall	W/m K
K_{window}	Average thermal conductivity of window	W/m K
l	Length	W/m K
$\dot{m}$	Mass flow rate	kg/s
M_{avg}	Average of measured values	-
M_i	Measured value	-
n	Number of values	-
N	Infiltration rate	ACH
q''	Conduction heat flux on inside face	W/㎡
q''_0	Convective heat flux towards outside	W/㎡
q''_i	Convective heat flux towards inside	W/㎡
q''_{ko}	Conduction heat flux on outside face	W/㎡
$q_{downward}$	Downward heat transfer	W
$q_{outdoor}$	Heat transfer towards outside	W
$q_{overall}$	Heat transfer at the pipe layer	W
q_{total}	Heat transfer with outdoor air temperature	W
q_{upward}	Upward heat transfer	W
$q_{calculated}$	Calculated external heat transfer	W㎡
R	Resistance of wall	m K/W
R_1	Resistance on the left side	m K/W
R_2	Resistance on the right side	m K/W

Symbol	Meaning	Unit
S_i	Laplace complex term	radian/hr
$Schedule_{\min}$	Minimum schedule density	-
t	time	hour
T	Temperature	℃
T_1	Temperature of the left node	℃
T_2	Temperature of the right node	℃
$T_{average}$	Temperature of supply and return water temperature	℃
T_i	Inside face temperature	℃
T_{in}	Outside face temperature	℃
$T_{outdoor}$	Outdoor air temperature	℃
T_{return}	Return water temperature	℃
$T_{surface}$	Surface temperature of TABS	℃
T_{supply}	Supply water temperature of TABS	℃
$T_{surface}^{k}$	Surface Temperature of TABS in current time	℃
$T_{surface}^{k+1}$	Surface Temperature of TABS in next timestep	℃
w^T	Weight	-
WWR	Window to Wall Ratio	-
x	input parameter	-
X_j	Outside CTF coefficient, j = 0,1,...... nz.	-
Y_j	Cross CTF coefficient, j = 0,1,...... nz.	-
Z_j	Inside CTF coefficient, j = 0,1,...... nz.	-
ρ	Density	kg/㎥
θ_1	Setpoint temperature of upper floor for design	℃
θ_2	Setpoint temperature of the zone for design	℃
θ_v	Supply water temperature for design	℃
Φ_{Ψ}	Flux CTF coefficient, j = 0,1,...... nz.	-

Chapter 1 Introduction

1.1 Background and Purpose

The indoor environment of a building should be maintained within a temperature range that is comfortable for its occupants. The environment in office buildings is considered to be a particularly critical space, because discomfort may decrease the productivity of the occupants. One evaluation parameter that is commonly used to help maintain comfortable conditions in an office building is the indoor air temperature, which is controlled by supplying or removing heat via the heating and cooling system. Conventional air conditioning systems are all-air systems that maintain indoor air temperature by using convective heat transfer only. However, as concerns about energy conservation increase, the utilization of radiant heating and cooling systems has become popular. This is because radiant systems can improve thermal comfort by increasing the mean radiant temperature for heating, and decreasing the mean radiant temperature for cooling.[1)2)] Because these systems provide superior thermal comfort compared to all-air systems, the acceptable comfort range of the indoor air temperature may be increased. With higher setpoint temperatures for cooling and lower setpoint temperatures for heating, heat transfer between outdoor and indoor environments may reduce heat losses and gains.

Of the many types of radiant systems available, the Thermally Activated Building Systems (TABS) has become popular recently because its use of embedded piping within the concrete structure of buildings may decrease the installation, operation, and maintenance costs associated with air conditioning systems. Because TABS does not require additional installation provisions, the overall building height can be reduced, which dramatically reduces the amount of building materials needed for construction.[3)]

Within a building, many zones with different heating and cooling loads exist depending on the external and internal conditions of the building; these loads should be removed with different heating and cooling

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1) Rhee, K.N.; Kim, K.W. A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment. *Build. Eviron.* **2015**, *91*, 166-190.
2) National Renewable Energy Laboratory. *Department of Energy Commercial Reference Building Models of the National Building Stock*; Technical Report; National Renewable Energy Laboratory : Golden, CO, USA, 2011.
3) Olesen, B.W. *Operation and Control of Thermally Activated Slab Heating and Cooling Systems*; Proceedings of CIB World Congress 2004, Toronto, Canada, Jan 2004

systems that are designated for the proper zones. However, because TABS uses the concrete structure of a building as a heating and cooling system, difficulties arise when operating the system to remove specific load from a specific zone. Thus, the self-regulation control concept is applied to TABS control to handle low and constant basic loads that occur in all zones in a building. Self-regulation is implemented by setting the surface temperature of the system as the room setpoint temperature. Hence, when heating and cooling load occurs, the room temperature will change, and the difference between the room temperature and the system temperature will trigger heat exchange between the room and the surface of the system exposed to that roo m[4)5)]. Even a minor change in room temperature will trigger a significant amount of radiant and convective heat exchange between the room and the system; this is because TABS has large radiant surface area exposed in a given room. As the amount of heating and cooling load increases, the difference between the room temperature and the surface temperature of TABS will increase and more heat exchange will occur.

4) Babiak, J.; Olesen, B. W.; Petras, D. *Low Temperature Heating and High Temperature Cooling*; Federation of European Heating and Air-Conditioning Associations (REHVA): Brussels, Belgium, 2007.
5) Olesen, B.W.; Sommer, K.; Duchting, B. Control of Slab heating and Cooling Systems Studied by Dynamic Computer Simulations. *ASHRAE Trans.* **2002**, *108*, 698–707.

Previously, the self-regulation of TABS was executed by setting the supply water temperature as the setpoint temperature of the room to remove the low and constant loads as basic load. However, the current method used to perform self-regulation cannot keep the surface temperature of TABS as the setpoint temperature of the room, and may decrease the utilization of TABS. This is because the heat exchange from the current timestep will change the surface temperature of TABS in the next timestep, and therefore the self-regulation effect cannot be preserved. Moreover, the heat exchange between the zone air and surface temperature of TABS may be smaller than expected because the air system continuously maintains the room temperature as the setpoint temperature. Hence, the objective of this research is to increase the utilization of TABS by targeting a suitable basic load with an appropriate and optimized control time interval.

1.2. Scope and Method

A method to handle basic load with TABS is developed with appropriate system control aspect and decision on the amount of constant and low heating and cooling load. The research method and scope in each section is described as follows.

1) Preliminary studies on controls of TABS

Before proposing how TABS control strategy can be improved, preliminary studies are reviewed by examining previous research and assessing TABS operation in actual buildings. The composition of TABS is determined by investigating typical radiant systems and TABS by reviewing standards and guidebooks. In addition, because radiant systems deal with the time delay phenomenon, the dynamic thermal mechanism of TABS is explored. Moreover, the current TABS control strategy is categorized to seek potential improvements.

2) Observation of current control method and improvement direction of TABS

To discover potential improvements in TABS control, the principle of self-regulation is simulated with the dynamic simulator, EnergyPlus. Many Through an analysis of the results, the surface temperature of the system could not be kept as room setpoint temperature are discovered the changes of surface temperature depending on the amount load occurred. Furthermore, changing the supply water temperature depending on the return water temperature demonstrated the time-delay and concluded that the appropriate basic load of the building should be determined with load prediction.

3) TABS control method used to increase the load handled by TABS

With the improvement direction identified in the previous chapter, the system mechanism is analyzed to choose the control timestep of TABS. After deciding the basic control structure, the target load for TABS is calculated using outdoor air temperature because it is one of the most influential parameters, and because weather forecasts are relatively accurate. With the target load of TABS determined, the heating and cooling curve that changes the supply water temperature, depending on the outdoor air temperature, was derived. Because the outdoor air temperature calculates the minimum cooling load and the maximum heating load, the target load for TABS can be utilized only for cooling. Moreover, the calculated external load with outdoor air temperature does not correspond with the actual minimum load. Thus, a more promising solution for predicting the load, the artificial neural network (ANN), was used to predict the load. The thermal load was predicted and the supply water temperature was derived based on the target load.

4) Application of TABS control using system analysis and load prediction

Using the target load, the heating and cooling curve of the system, and the load prediction, a co-simulation was performed to realize the learning as the historical data was accumulated. The results demonstrated that the load prediction used to determine the target the load for TABS was accurate and effective. To validate the control method, different weather conditions were used to operate TABS. The load prediction maintained the accuracy and TABS performed better with the control method applied.

The research process, according to the proposed method and scope, is demonstrated by the research diagram in Fig. 1.1.

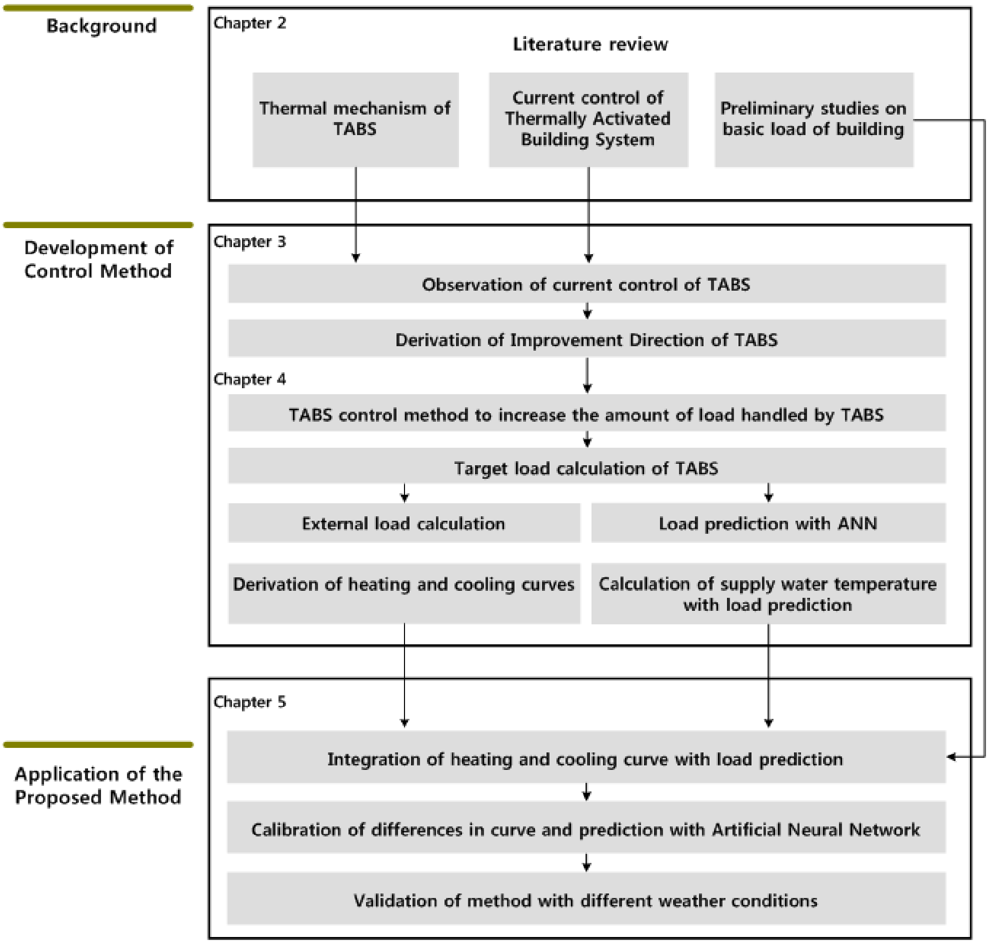

Figure 1.1 Research diagram

Chapter 2 Preliminary Studies on Control of TABS

Before proposing the improvement direction of the TABS control strategy, previous studies are reviewed. The composition of TABS is determined by investigating typical radiant systems and TABS by reviewing standards and guidebooks. In addition, because radiant systems deal with time delay phenomena, the heat transfer of the system by means of conduction, convection, and radiation is studied with the dynamic thermal mechanism of TABS. Moreover, the current TABS control strategy is categorized to investigate potential improvements. After reviewing the system and operation, the consideration of how much load TABS should handle is inspected by examining typical types of basic load.

2.1 Types of Radiant System and Thermal Mechanism of TABS

2.1.1 Types of Radiant System

TABS is one of many types of radiant systems that use a concrete structure as a storage system. A radiant system is a more energy-efficient terminal system than an air system for three reasons. A radiant system uses water pumps to deliver heat to a room, and an air system uses a fan to distribute heat throughout the room. A water pump requires a lower amount of energy than a fan to deliver heat to a room. With respect to heating and cooling coils, a typical air system requires a lower coil temperature than a radiant system because water has a higher specific heat capacity and carries more energy than air. As a result, more energy consumption is expected in an air system. From the perspective of thermal comfort, a radiant system has a lower mean radiant temperature than an air system and thus creates a more comfortable environment. Therefore, the setpoint temperature of a radiant system may be higher than that of an air system.

A radiant heating and cooling system can be classified into radiant heating and cooling panels, pipes isolated from the main building structure, and the TABS. The following figures and table describe the diverse types of radiant systems.

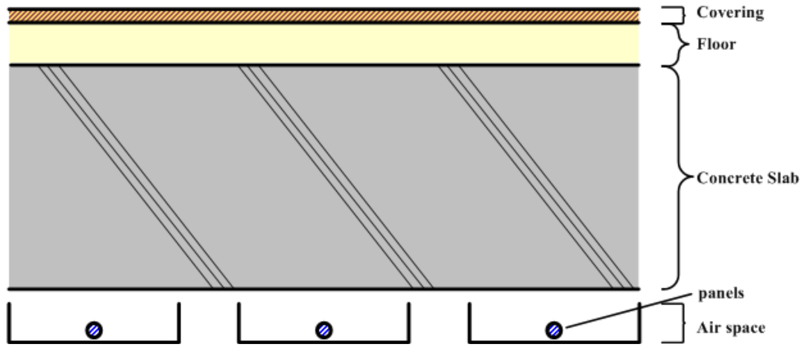

Figure 2.1 Ceiling panels structure

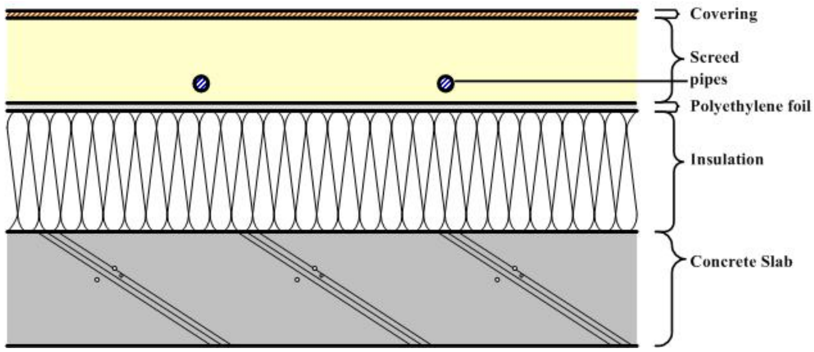

Figure 2.2 System with pipes embedded in the screed or concrete ("wet" system)

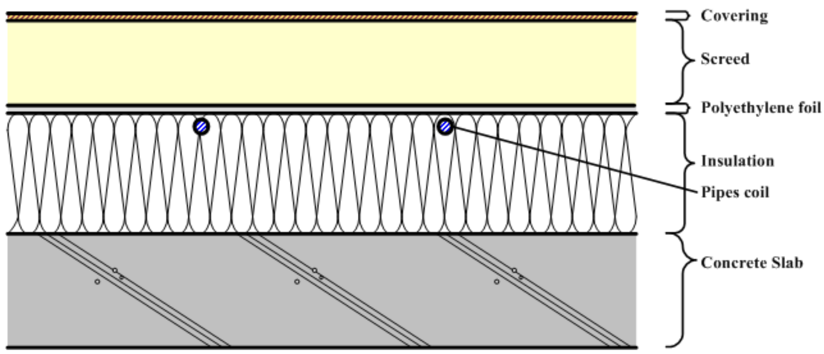

Figure 2.3 System with pipes embedded in the thermal insulation layer, "dry" system

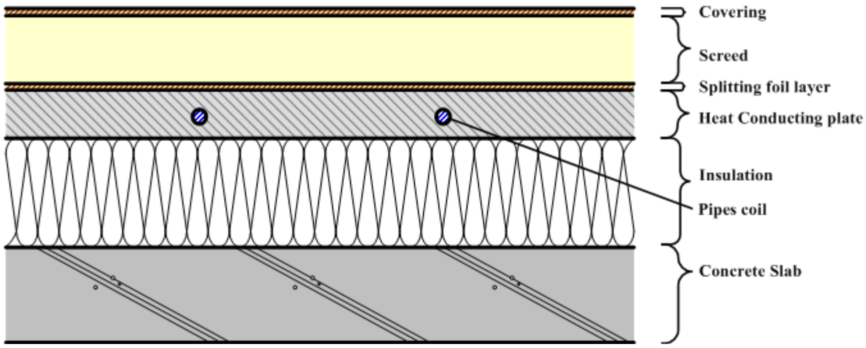

Figure 2.4 System with pipes embedded in the screed

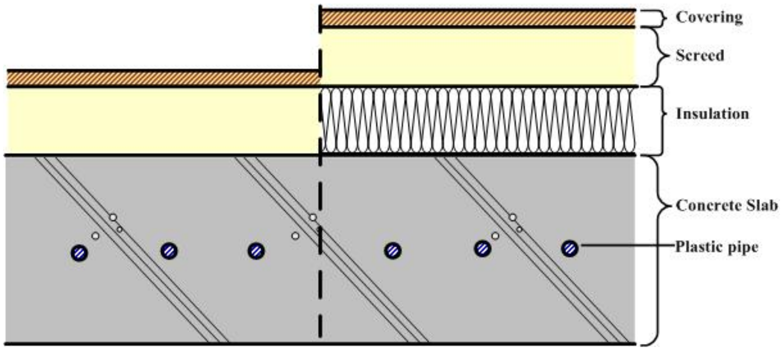

Figure 2.5 System with pipes embedded in the massive concrete slabs

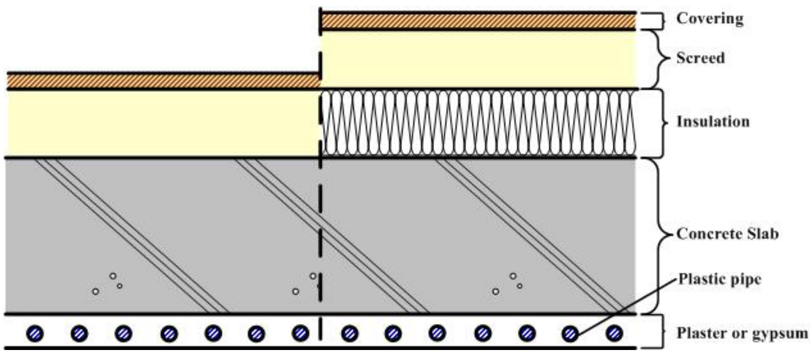

Figure 2.6 Capillary pipes embedded in a layer at the inner surface

Table 2.1 Types of radiant system

Radiant Systems	Types
Radiant heating and cooling panels	-
Pipe isolated from main building structure	▪ System with pipes embedded in the screed or concrete("wet" system) ▪ System with pipes embedded outside of the screed (e.g. in the thermal insulation layer, "dry" system) ▪ System with pipes embedded in the screed
Thermally Active Building Systems(TABS)	▪ System with pipes embedded in the massive concrete slabs ▪ Capillary pipes embedded in a layer at the inner surface

2.1.2 Thermal Mechanism of TABS

TABS transfers heat through the interactions among conduction, convection, and radiation as Figure 2.7. Conduction heat transfer occurs between the supplying layer of the TABS and the surface exposed to the room. Convection and radiation heat transfer occurs from the surface of the TABS to the zone. Convection heat transfer occurs from the surface of the TABS to the zone air. Radiation heat transfer occurs through longwave radiation exchange with internal sources, longwave radiation exchange with other surfaces in the zone, and shortwave radiation from transmitted solar lights. Convective heat exchange with zone air removes the same type of load as the air system; however, the TABS radiation heat transfer removes the heat that is supposed to be heating and cooling load in the future.

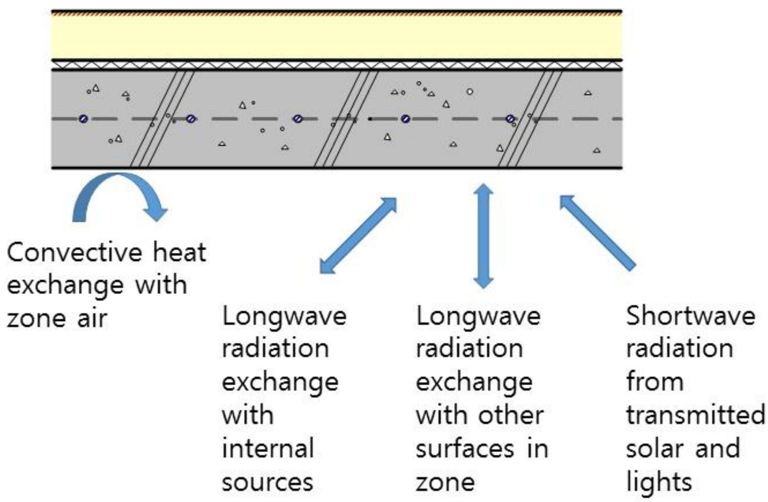

Figure 2.7 Mechanism of TABS

Thermal mechanism of TABS can be calculated using the thermal resistance method for steady-state conditions, and the finite element method (FEM) or finite difference method (FDM) for the dynamic mechanism of TABS. For the thermal resistance method, the following equations are the basic equations of conduction, convection, and radiation. Figure 2.8 presents a simple layout of TABS used for calculating the resistance.[6)]

The common application of the solution is a two-node state space. There are multiple types of conduction transfer functions, such as the staggered time history scheme, the sequential interpolation of new histories, and the master history with interpolation.

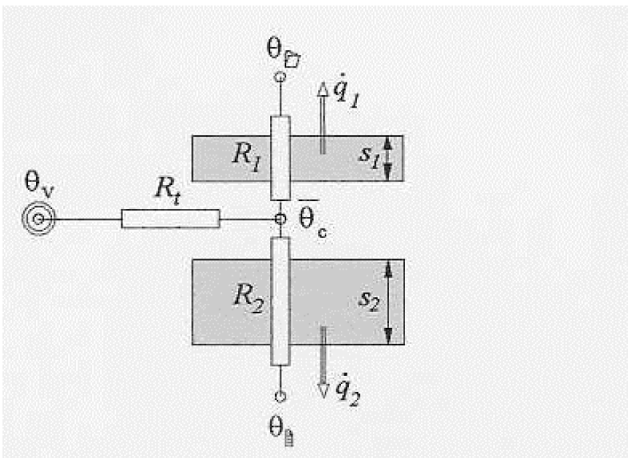

Figure 2.8 Resistance network

6) CEN. EN 15377 Heating Systems in buildings - Design of embedded water based surface heating and cooling systems - Part 1: Determination of the design heating and cooling capacity CEN 2005

Equations 2.1 and 2.2 are called conduction transfer functions, which replaced higher order terms with flux history terms. Equation 2.1 is a calculation of heat flux inside and Equation 2.2 is a calculation of heat flux outside.

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \quad (2.1)$$

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta} \quad (2.2)$$

Equations 2.3 and 2.4 are an example of the two-node state space. The left side of the equation represents the amount of energy stored according to time, and the right side of the equation represents the addition of conductive and convective heat transfer.

$$C\frac{dT_1}{dt} = hA(T_0 - T_1) + \frac{T_2 - T_1}{R} \quad (2.3)$$

$$C\frac{dT_2}{dt} = hA(T_i - T_2) + \frac{T_1 - T_2}{R} \quad (2.4)$$

Desired heat flux through the wall inward and outward is represented in Equation 2.5 and 2.6, respectively.

$$q''_i = h(T_i - T_2) \tag{2.5}$$

$$q''_0 = h(T_1 - T_0) \tag{2.6}$$

Resistance through conduction is represented in Equation 2.7.

$$R = \frac{l}{kA} \tag{2.7}$$

Stored heat is calculated with density, heat capacity, length, and area by Equation 2.8.

$$C = \frac{\rho C_p l A}{2} \tag{2.8}$$

The conduction transfer function considers the convection from the indoor space to the ceiling surface, and the conduction from the water pipes to the ceiling surface. The amount of convection and conduction to the surface is equal to the heat stored in the concrete structure. Equation 5 through Equation 8 describe the algorithm.

2.2 Previous Research on Design and Operation of TABS

2.2.1 Previous Method to Design TABS

Typical radiant system design is employed to ensure that all the load can be handled by the system. In EN15377, thermal output is proposed based on the material used in the flooring, as shown in Figure 2.9. Having obtained information on the maximum total heat gain in the space and the operating period of the system, an appropriate TABS inlet temperature is proposed in Figure 2.10. The expected thermal output of the system is proposed under certain conditions.

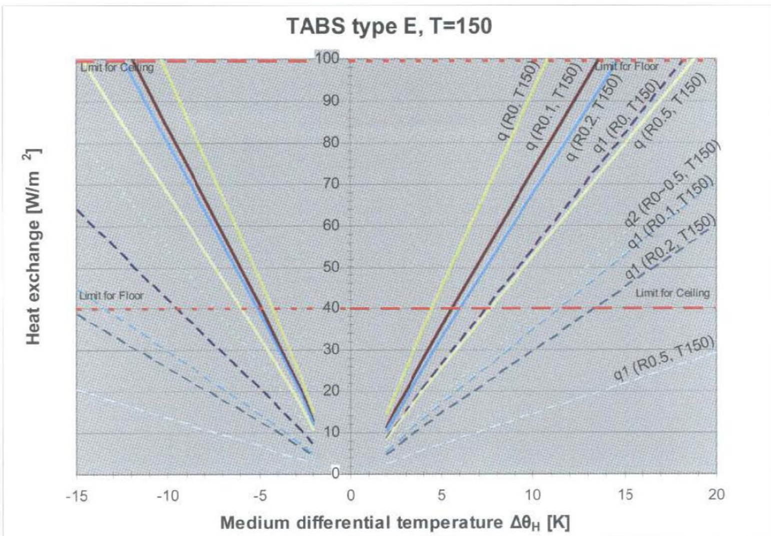

Figure 2.9 Heat exchanges as the function of water temperature and floor covering

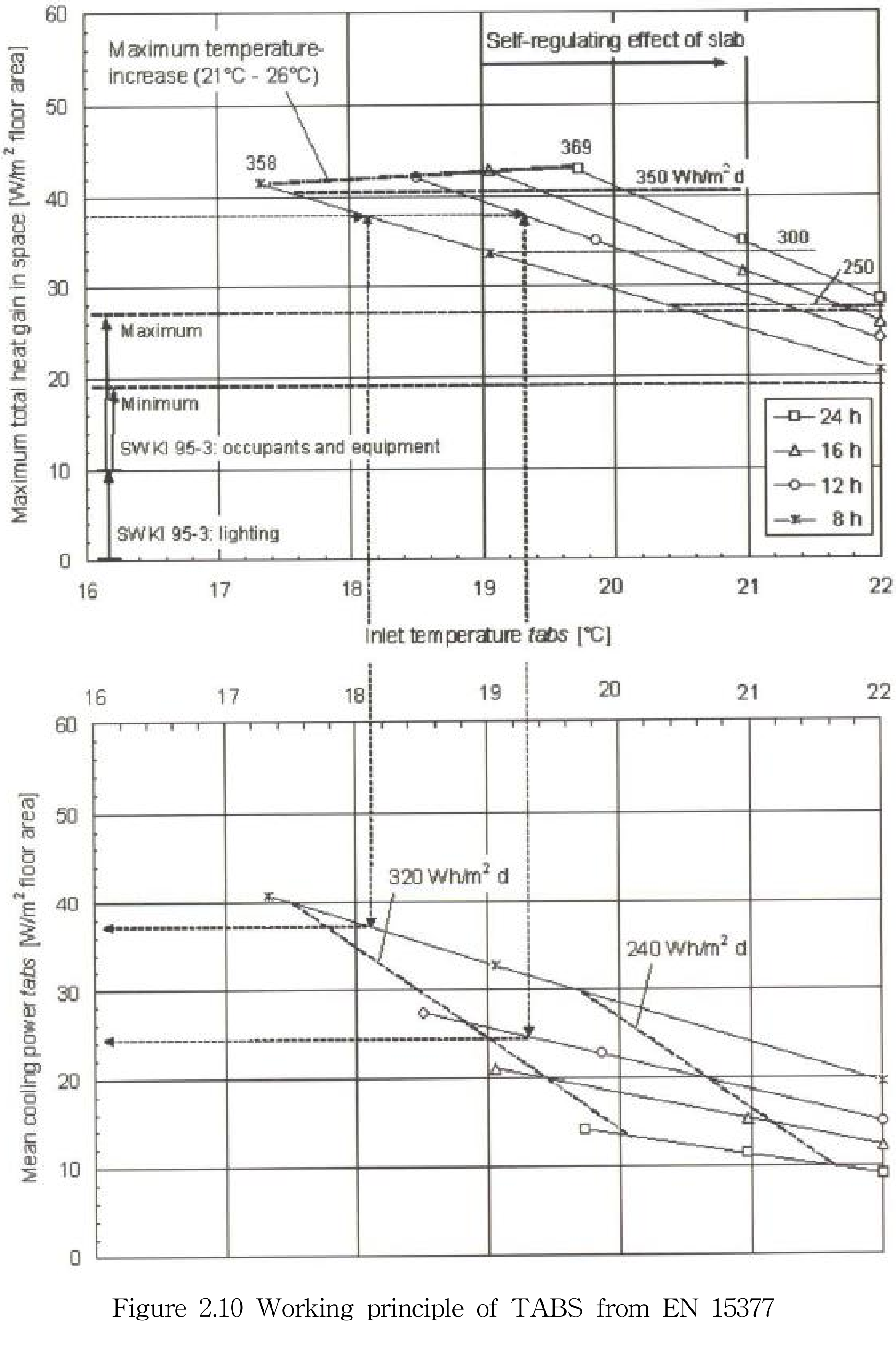

Figure 2.10 Working principle of TABS from EN 15377

2.2.2 Previous Method to Control TABS

The common radiant system control methods are water temperature control, flow rate control, and water temperature control and flow control. For Thermally Activated Building System, control methods are pump operation, water temperature, flow rate, and UBB method as Table 2.2.

Thermally activated building system control methods can be classified as supply water temperature control and flow rate control as Table 2.3. Constant water temperature control can be considered as operation instead of control because it uses consistent water temperature to work as opposite type of load.

Table 2.2 Control method of radiant system and TABS

Types	Contents
1) Radiant system control method	▪ Water temperature control ▪ Flow rate control ▪ Water temperature control +Flow rate control
2) Thermally Activated Building System control method	▪ Pump operation control ▪ Water temperature control ▪ Flow rate control ▪ UBB method and PWM method

Table 2.3 TABS control method

Control parameter			Supply water temperature	
			Constant temperature	Variable temperature
Flow rate	Conti-nuous flow	Constant flow	1) Pump operation control (24h)	3) Water temperature control 4) UBB method
		Variable flow		5) Flow rate control
	On/off Control	Bang-bang-control		
		Intermittent flow control	2) Pump operation control (12h, 8h)	6) PWM method (Pulse Width Modulation)

: Water temperature control　　: Water flow control　　: Water temperature control and water flow control

1) Pump operation control (24h)

The pump can be operated for 24 h with constant temperature to utilize the self-regulation effect, which exchanges heat between the ceiling surface and the room. This operation is a typical control scheme when TABS is used as a secondary system.

2) Pump operation control (12h, 8h)

When the pump is operated for 24 h, overcooling or overheating may occur because of unnecessary operation. To prevent unnecessary operation, pump operation may be reduced to 12 h or 8 h.[7)]

3) Water temperature control

Current radiant systems control the water flow and temperature for a certain thermal output and condensation can be avoided. Previous research offered the following control methods.[8)]

a) Operation at a dew-point temperature

b) Supply water temperature = 1.3 * 0.4 * (20 - Outdoor temperature) + 20

c) Average temperature of supply and return water = 1.3 * 0.4 * (20 - Outdoor temperature) + 20

d) Constant supply water temperature (18, 20, 22)

e) Constant average temperature of supply and return water (18, 20, 22)

According to previous studies, method b) was found to have achieved the greatest energy reduction.

7) Babiak, Olesen, Petras, Low Temperature Heating and High Temperature Cooling, REHVA, 2007.
8) Olesen, Control of Slab Heating and Cooling Systems Studied by Dynamic Computer Simulation

4) UBB method (Unknown But Bounded)

In TABS control, heat gain is considered on heating and cooling curves. Since the heat gain is difficult to predict, the maximum and minimum heat gain was used to set the range of upper bound and lower bound.[9)]

Adjustments to the supply water temperature based on the room temperature may not remove the cooling load because of the thermal inertia of TABS. Based on the graph of the upper and lower heat gain bounds, the supply water temperature may be controlled. The process of the UBB method is listed in the following order.

a) Based on the heating curve, adjustments to the supply water temperature are made as the outdoor temperature changes.

b) Minimum/maximum room temperature is calculated and lower/upper heat gain bounds are chosen.

c) Within the bound, on/off control is used.

5) Flow rate control

Similar to other radiant systems, the flow rate of supply water was adjusted.[10)]

9) Gwerder, Control of thermally-activated building systems
10) Babiak, Olesen, Petras, Low Temperature Heating and High Temperature Cooling, REHVA, 2007.

6) PWM method (Pulse Width Modulation)

Pulse width modulation operates the pump with intermittent on/off control. Preliminary research used 1 h on/off, 1/2 h on/off, and 1/4 h on 3/4 h off control patterns, and the pump energy consumption was reduced. Intermittent on/off control patterns should use a lower supply water temperature to reduce the same amount of cooling load. As a result, 1/4 h on 3/4 h off control conserves the most energy of all the flow control method s.[11)12)]

2.2.2 Operation Method in REHVA Guidebook

In the Representatives of the European Heating and Ventilating Association (REHVA) Guidebook, TABS operation was separated into three modes. The modes are pump operation control, water temperature control, and flow rate control.

TABS pump control methods include the continuous heat supply method and the intermittent heat supply method. In the continuous heat supply method, TABS operates for 24 h, 12 h, and 8 h. The intermittent heat supply method turns the system on and off on a consistent schedule. The following operating windows are offered: 15 min ON and 45 min OFF, 1 h ON and 1

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11) Gwerder_Control of thermally activated building systems(TABS) in intermittent operation with pulse width modulation

12) Lehmann_Thermally activated building systems(TABS) : Energy efficiency as a function of control strategy hydronic circuit topology and (cold) generation system

h OFF, and 30 min ON and 30 min OFF.

In water temperature control, TABS may be operated with changes in mean water temperature depending on the outdoor and indoor temperature. Equation 2.13 describes the supply water temperature equation.

$$T_{supply} = 0.52*(20 - T_{outdoor}) + 20 - (1.6*T_{in} - 22) \quad (2.13)$$

The second water temperature control method adjusts the average temperature of the supply water and the return water based on Equation 2.14.

$$T_{average} = 0.52*(20 - T_{outdoor}) + 20 - (1.6*T_{in} - 22) \quad (2.14)$$

In the third water temperature control method, the average temperature of the supply and return water is kept at 22 °C in the summer and 25 °C in the winter. In the fourth method, the supply water temperature is controlled with only external temperature during the summer, as shown by Equation 2.15.

$$T_{supply} = 0.35*(18 - T_{outdoor}) + 18 \quad (2.15)$$

The fifth water temperature control method is demonstrated in Equation 2.16 and the supply water temperature is controlled according to the equation in winter.

$$T_{supply} = 0.45*(18 - T_{outdoor}) + 18 \quad (2.16)$$

The last method involves controlling the water flow rate; however, the REHVA guidebook did not contain any information on that approach. Depending on the application, the REHVA guidebook indicates that the capacity of the cooling system may be reduced to 60% by storing the heat in TABS.

2.3 Estimation of Basic Load of Office Buildings

Among various control strategies, the safest and most effective TABS control method involves choosing supply water temperature based on the basic load of the building. Because the basic load of the building is constant and has a low value, operation based on basic load can remove the environmental load without considering other spontaneous loads.

The basic load of an office building can be estimated based on the minimum density of the internal load imposed by people, lighting, and equipment. A reasonably constant load based on the internal load can be considered as the basic load, because the occupants are expected to work at the office building. Although the basic load can be removed by TABS, in the winter season TABS may have heating load in the perimeter zones. Thus, targeting the internal load of the office building can be considered to be an adequate solution for TABS control. However, the utilization of TABS can be limited, so other loads should be considered to increase its effectiveness.

2.4 Summary

In preliminary studies, the basic construction of TABS was observed by reviewing different types of standard radiant systems. A typical TABS design was examined to determine the magnitude of the heat output. In addition, the method was applied under steady-state conditions, because the design was selected to ensure TABS can handle the appropriate amount of load under constant conditions.

Various control methods were reviewed from previous studies; however, 24 h operation with the concept of self-regulation was found to be the typical control method used in the field. The target load to remove was the constant and low basic load of an office building. Thus, the basic load of an office building was assessed and it was determined that the internal load within the interior zone could be considered as the basic load of the building.

Based on findings, the conditions of the TABS were set to observe potential improvements that could be made to its control method.

Chapter 3 Observation of Current Control Method and Improvement Direction of TABS

To discover potential improvements to the TABS control method, the principle of self-regulation is carefully observed and the problems associated with the current TABS control method are established. An office building with TABS and an air system is simulated with the dynamic simulator, EnergyPlus. TABS uses the supply water temperature that is equivalent to the room setpoint temperature in 24 h operation, and the remainder of the load is handled by the air system. To improve control by increasing the utilization of the TABS, new findings from the analysis of the simulation result are used to set the improvement direction.

3.1 Process of Improving the TABS Control

To verify potential improvements to the current control method, a detailed observation should be performed to determine if the goal is achieved. After defining the problem in actual situation, theoretical assumptions should be established to find the reason for the phenomenon. A theoretical approach can provide an opportunity to explore every option for improving TABS control. Theoretical assumptions can be confirmed by assessing TABS in different situations. If the results do not coincide with the theoretical assumptions, the theoretical assumptions should be restated based on the observations made in different situations. After the assumption is proven, the direction for theoretical improvements can be established to achieve the goal. The process of the deriving the improvement direction of TABS control is illustrated in the figure below.

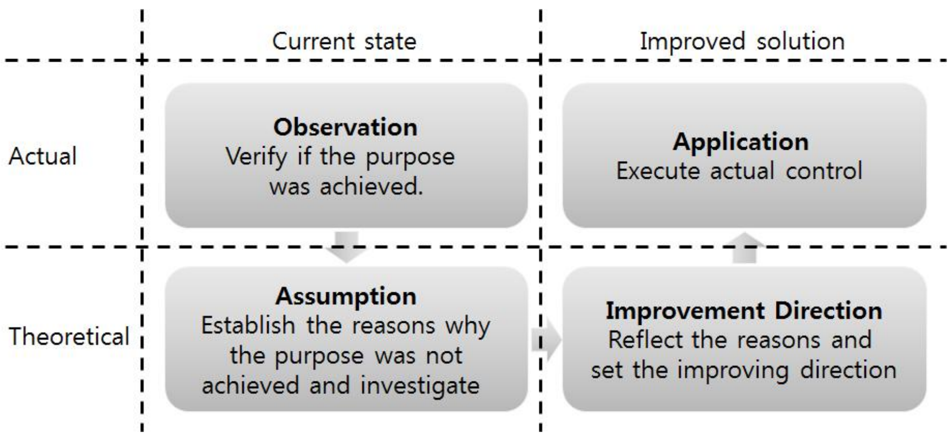


Figure 3.1 Process of deriving improvement direction

3.2 Observation of TABS Control with Simulation

3.2.1 Typical Control of TABS

The self-regulation control concept is applied to TABS control because of the difficulties associated with supplying heat into the system and a zone from long time delay effect. Self-regulation originates from the intention to remove rapidly varying heat gains, such as sunshine passing through a window. Self-regulation can be executed by keeping the surface temperature of the radiant system at the room setpoint temperature. In Figure 3.2, as heating or cooling loads occur, the room temperature will vary and the heat exchange between room and the system surface will remove the load without the changing the system control method. The heat exchange between the room and the system surface can decrease or increase depending on the amount of load.

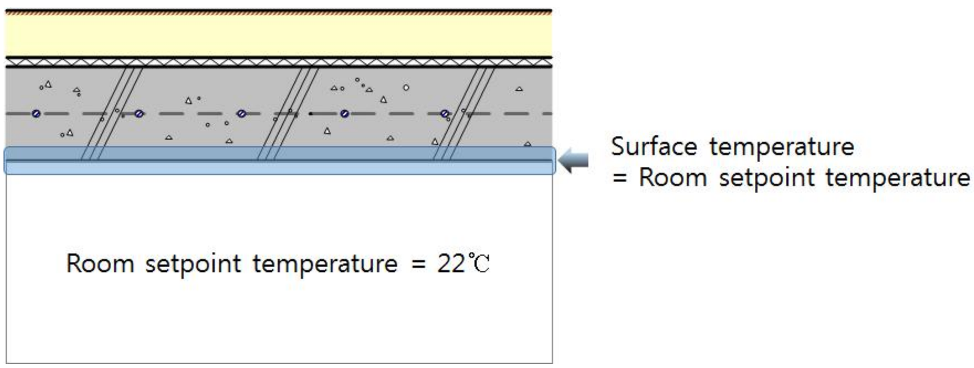


Figure 3.2 Concept of self-regulation

To properly apply the mechanism of self-regulation, the surface temperature of the radiant system should be kept at the room setpoint temperature, as shown in Figure 3.2. However, TABS use supply water temperature that is equivalent to the room setpoint temperature to apply the concept of self-regulation in the field. In steady-state conditions, supplying water temperature at the room setpoint temperature may have a self-regulation effect. However, in dynamic conditions, the surface temperature of the radiant system cannot be kept at the room setpoint temperature because of consistent changes in heating and cooling loads. Because the previous heating or cooling load affects the surface temperature of the radiant system, the utilization of TABS may be decreased. Therefore, the current TABS control method, which supplies water at the room setpoint temperature, should be applied in the dynamic simulation.

3.2.2 Simulation Conditions

The dynamic simulation is performed using EnergyPlus software v8.6, and the TABS and air system are modeled to remove heating and cooling loads. To choose a typical office building to observe common TABS mechanisms, the reference building proposed by the US Department of Energy is used to formulate the boundary conditions. An overview of the building is presented in Figure 3.3, and detailed conditions are described in Table 1. The typical internal heat gain schedule and density from the document provided by the National Renewable Energy Laboratory (NREL) of the US Department of Energy are used as illustrated in Figures 3.4, 3.5, and 3.6. In addition, the constant supply water temperature is 22 °C and the flow rate is 3,600 kg/h.

For modeling TABS, an internal source is applied on each ceiling using the system module, ZoneHVAC: Low Temperature; Radiant: ConstantFlow, to supply the water at a certain temperature. This system is connected to the plant loop module to produce heat. The air system module, ZoneHVAC: Ideal Loads Air System, is used for the air system. Peak heating and cooling days are chosen to examine the operation of TABS and the air system in extreme conditions.

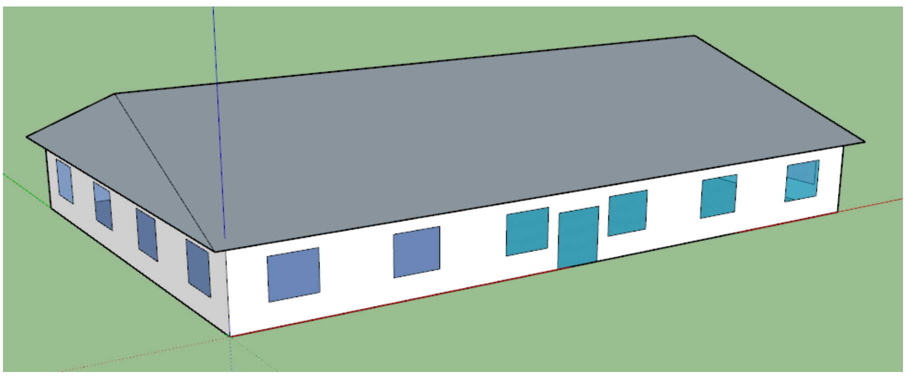


Figure 3.3 Small office building

Table 3.1 Detail information of small office building

Detail Conditions	Content
Building Orientation	South
District	Chicago, IL, USA
Area	28m x 18m (504㎡)
Building Height	3m (1 story)
Window Properties	Window to Wall Ratio 30%, Solar Heat Gain Coefficient of 0.39, No Blinds
Internal Heat Gain	People: 0.054 Person/㎡, Lighting: 10.76 W/㎡, Equipment: 10.76 W/㎡
Setpoint Temperature	22 °C
Supply Water Temperature of TABS	22 °C
TABS Operation	24 hrs of Operation
Air System Operation	24 hrs of Operation
TABS Placement	Ceiling (on the Slab)

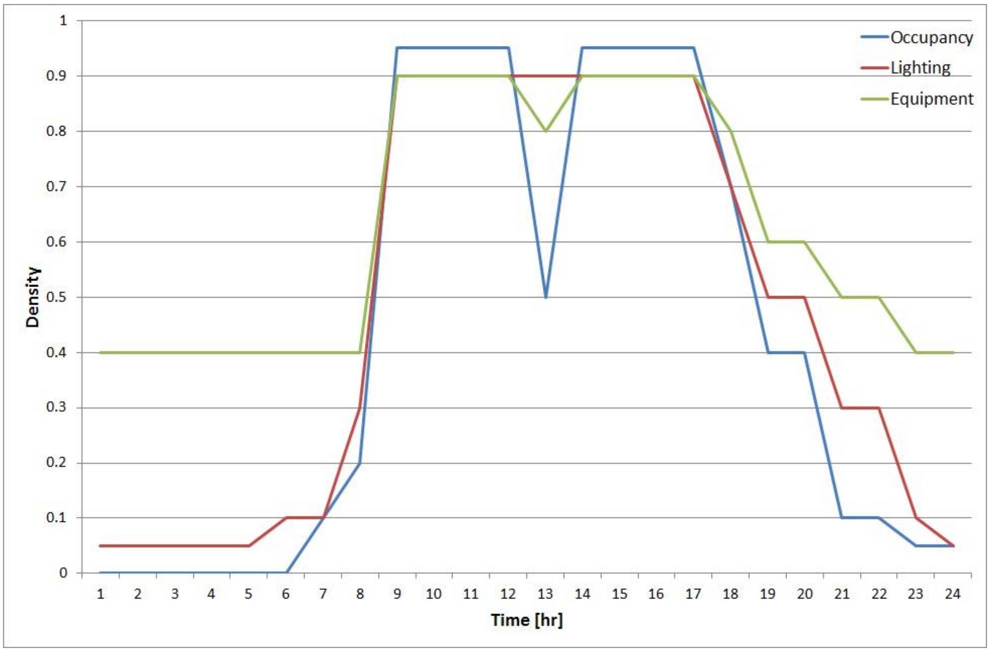


Figure 3.4 Internal load schedule on weekdays

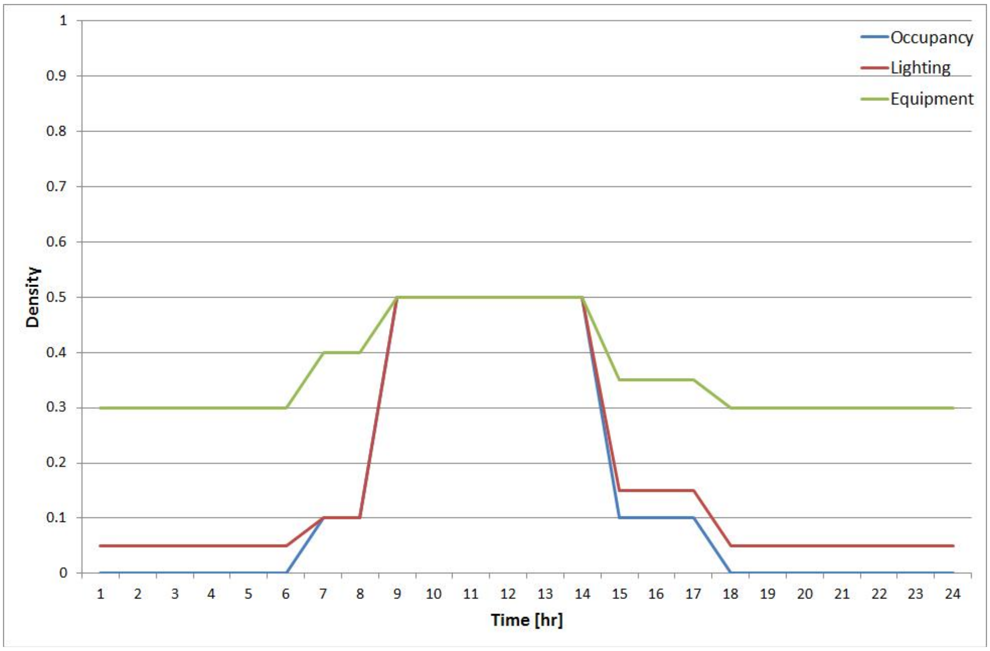


Figure 3.5 Internal load schedule on Saturday

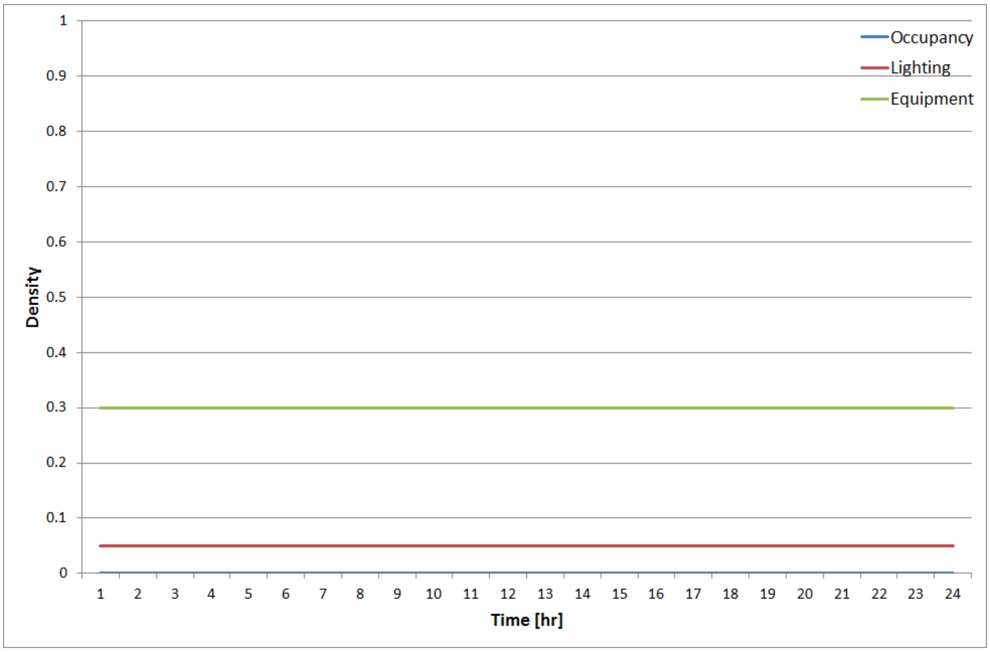


Figure 3.6 Internal load schedule on Sunday

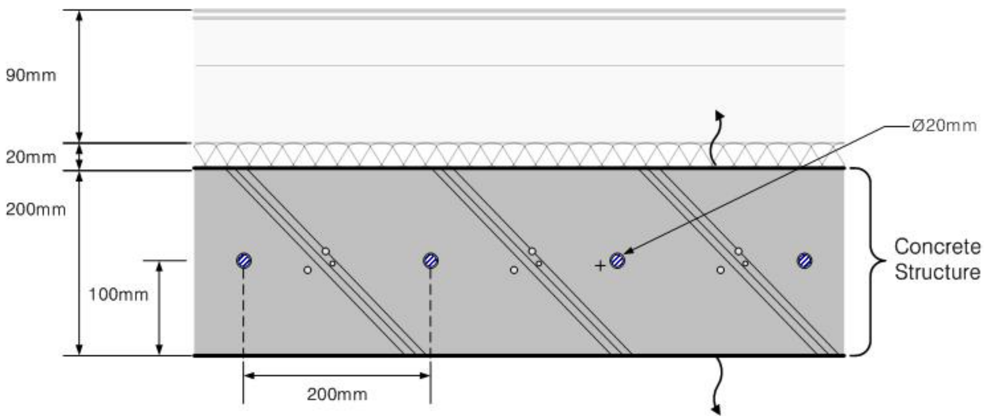


Figure 3.7 Section view of TABS

In the small office building, TABS is applied by embedding the pipes into the concrete structure, as illustrated in Figure 3.7. The typical slab thickness and insulation size is selected from ISO 11855. The building simulation developed in EnergyPlus v.8.6 is created using these conditions.

In order to determine the proper flow in the TABS pipes, the basic office building load, approximately 10 W/㎡, is set as the removal target. The thermal output of TABS is calculated using the equations from EN1264 and is demonstrated in Figure 3.8. In Equation 3.4, the temperature difference between the supply water and the return water is assumed to be 3 °C to avoid temperature asymmetry.

$$q_{overall} = q_{upward} + q_{downward} \tag{3.1}$$

$$q_{upward} = \frac{1}{(R_1R_2 + R_1R_t + R_2R_t)} * (R_t(\theta_2 - \theta_1) + R_2(\theta_{v\_}\theta_1)) \tag{3.2}$$

$$q_{downward} = \frac{1}{(R_1R_2 + R_1R_t + R_2R_t)} * (R_t(\theta_1 - \theta_2) + R_1(\theta_{v\_}\theta_2)) \tag{3.3}$$

$$q_{overall} = \dot{m}C_p\delta T \tag{3.4}$$

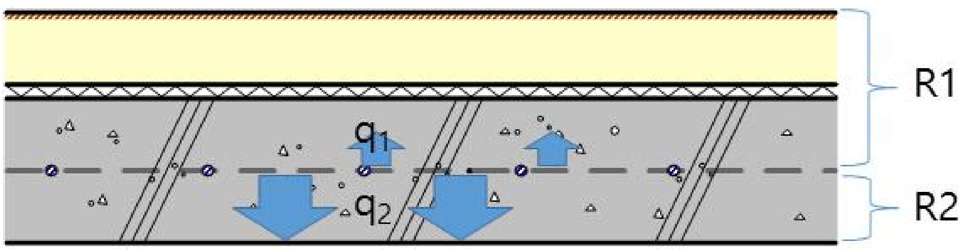


Figure 3.8 Heat transfer of TABS

3.3 Observation of Current Control of TABS and Establishment of Assumption for Improving Control

3.3.1 Supplying Room Setpoint Temperature into TABS

The effect of heating or cooling load on the surface of the radiant system is observed through the dynamic simulation. The typical control method that utilizes self-regulation is applied by supplying the water temperature at the room setpoint temperature. Hourly data from the simulation is observed and the surface temperature of TABS is not able to remain consistent with the room setpoint temperature, as illustrated in Figure 3.9. This means that the self-regulation effect was not able to remove the load as expected.

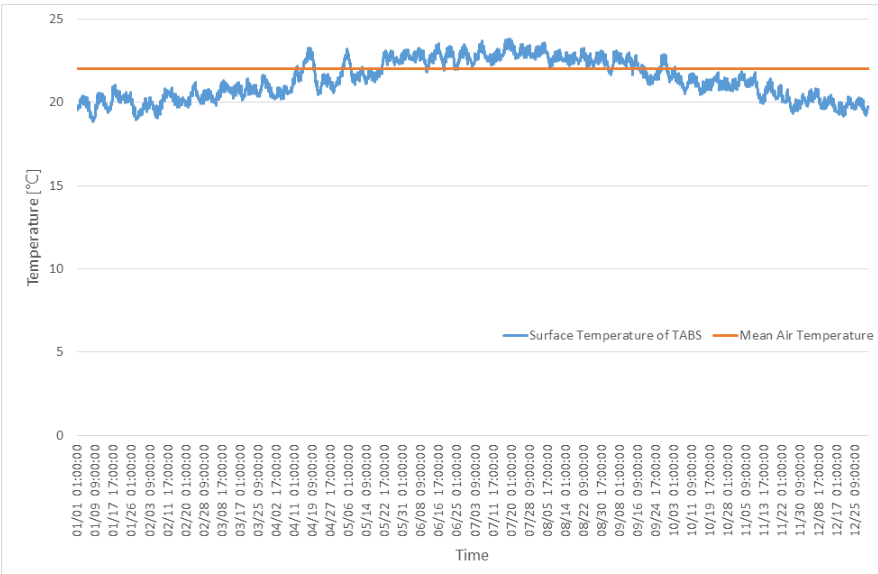


Figure 3.9 Surface temperature of the TABS with supplying 22℃

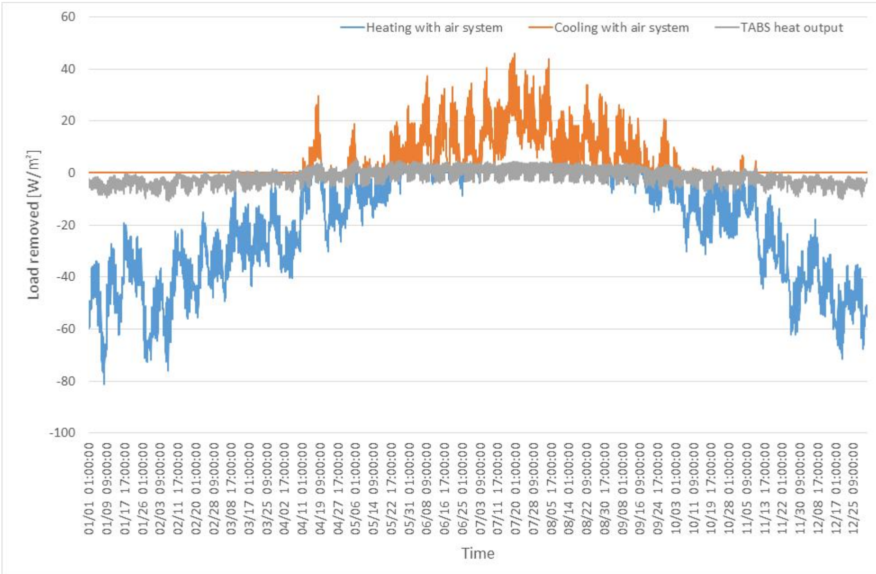


Figure 3.10 Load handled with TABS and ideal load

In Figure 3.9, the surface temperature shows a greater difference between the surface temperature of TABS and the room setpoint temperature during the winter and summer seasons. To confirm the theoretical assumption, room load and the load handled by TABS are compared. In Figure 3.10, the load handled with TABS correlates with the room load. Thus, the theoretical assumption is made that the TABS surface temperature proportionally changes with the amount of load. This theoretical assumption is demonstrated in Figure 3.11.

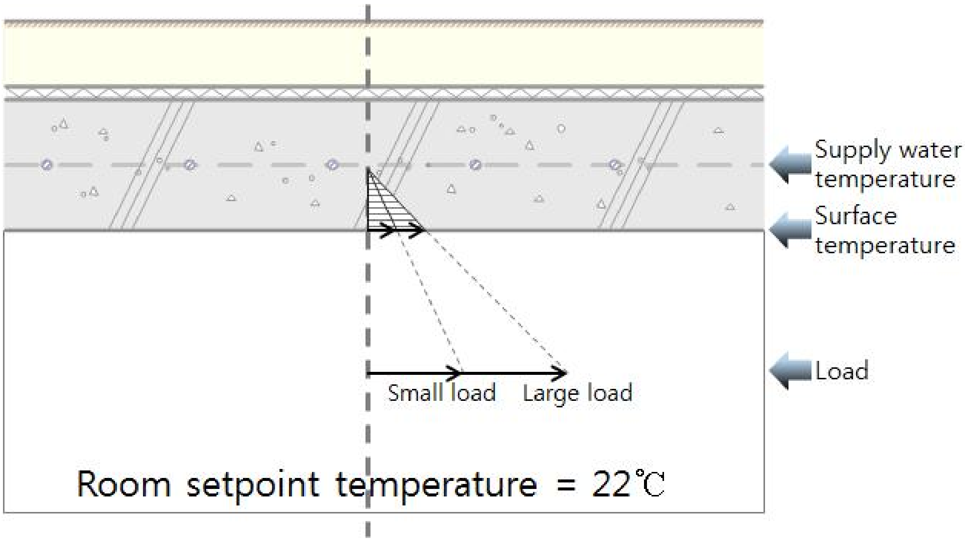


Figure 3.11 Surface temperature changes depending on the load

To verify the theoretical assumption, the surface temperature of TABS and the ideal load of the air system on peak heating and cooling days is compared in detail in Figures 3.12 and 3.13, respectively. The changes in TABS surface temperature demonstrate a similar trend with the amount of heating and cooling load.

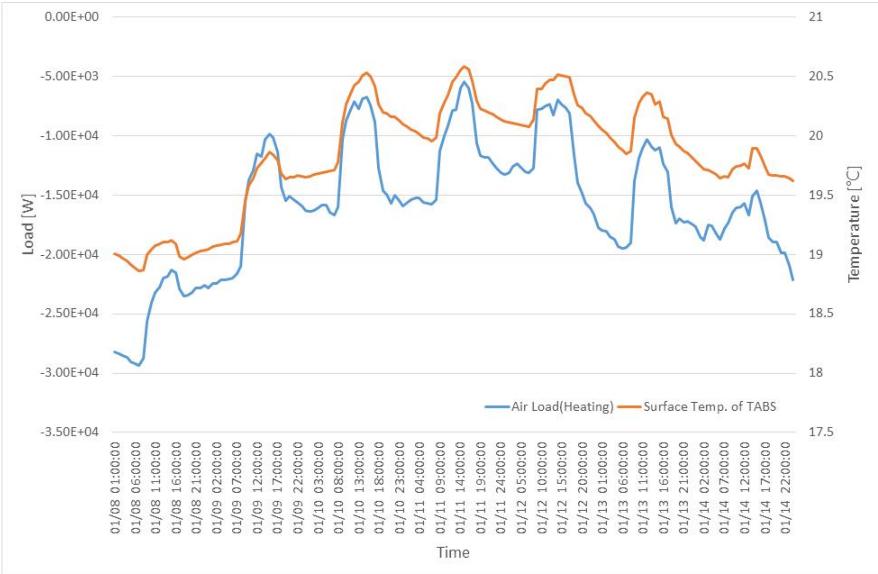


Figure 3.12 Surface temperature of TABS and load on winter season

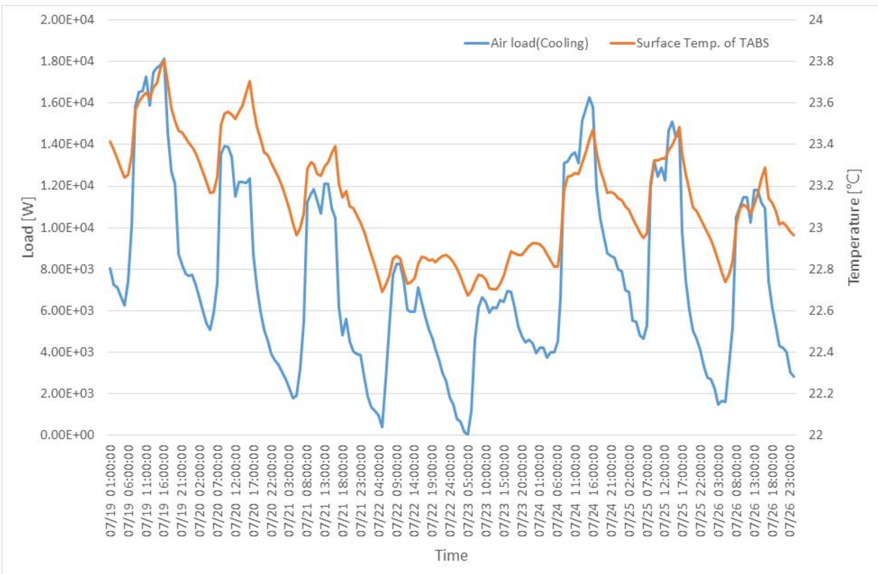


Figure 3.13 Surface temperature of TABS and load on summer season

Because the load changes will be affected by the previous loads, a possible situation in two time steps is considered. Changes in load can be categorized in the following cases.

Case 1. Type of load (summer and winter season)

1-1 Small load to large load

1-2 Large load to small load

Case 2. Simultaneous heating and cooling load (Intermediate season)

2-1 Cooling load to heating load

2-2 Heating load to cooling load

Two types of cases are described. First, when constant type of load occurs in the summer and winter seasons, most of the load will maintain the type of load and increase or decrease. Second, when simultaneous heating and cooling load occurs in the intermediate season, the changes on type of load will occur. Both cases are demonstrated in Figure 3.14 and detailed changes in the surface are illustrated in Figures 3.15, 3.16, 3.17, and 3.18

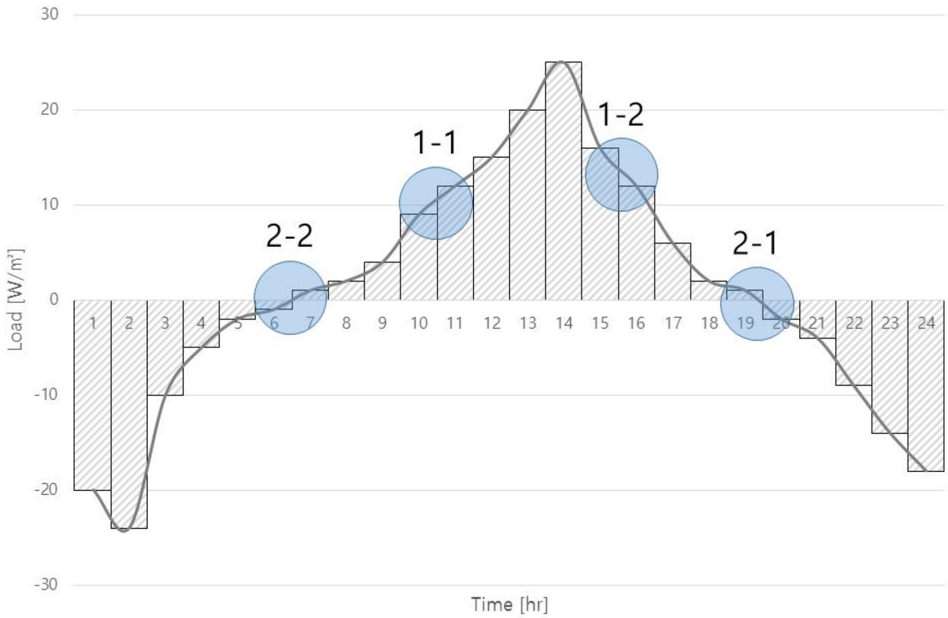


Figure 3.14 Type of load changes

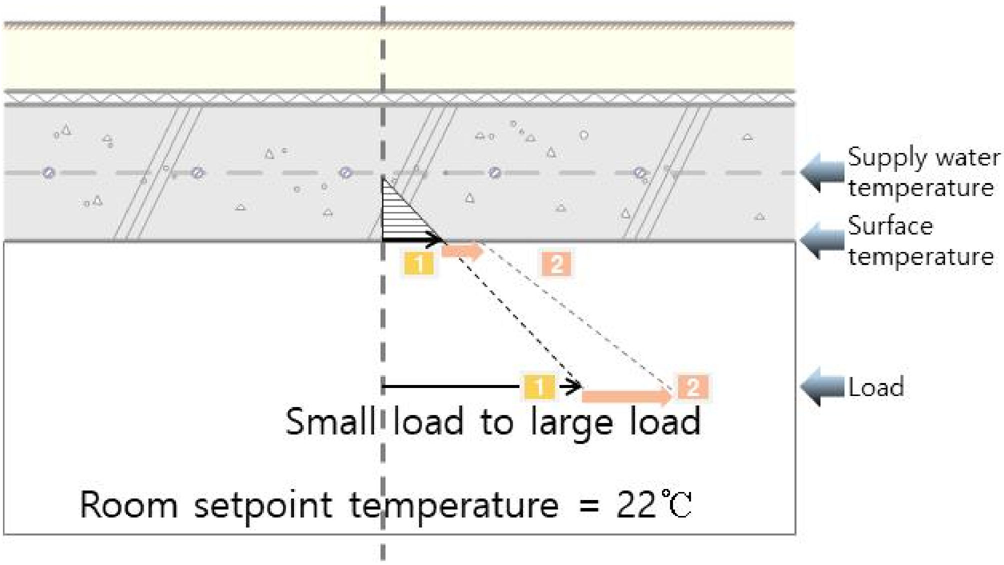


Figure 3.15 Small load to large load in summer and winter seasons (1-1)

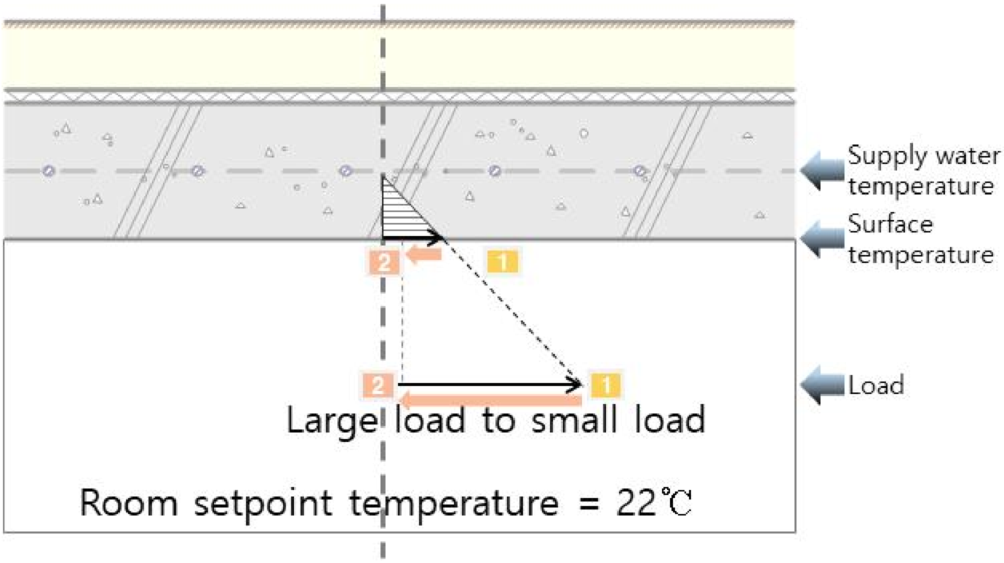


Figure 3.16 Large load to small load in summer and winter seasons (1-2)

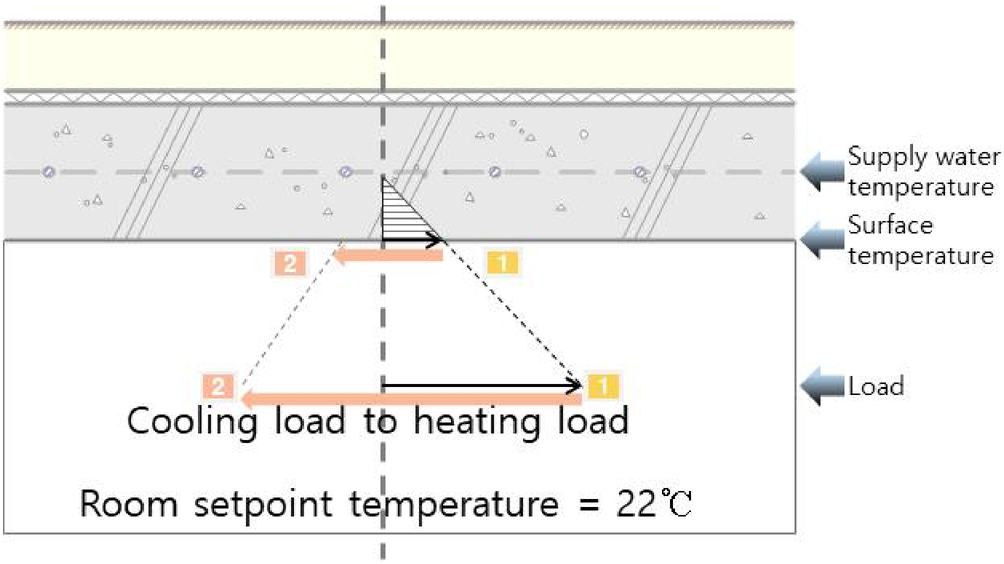


Figure 3.17 Cooling load to Heating load in intermediate season (2-1)

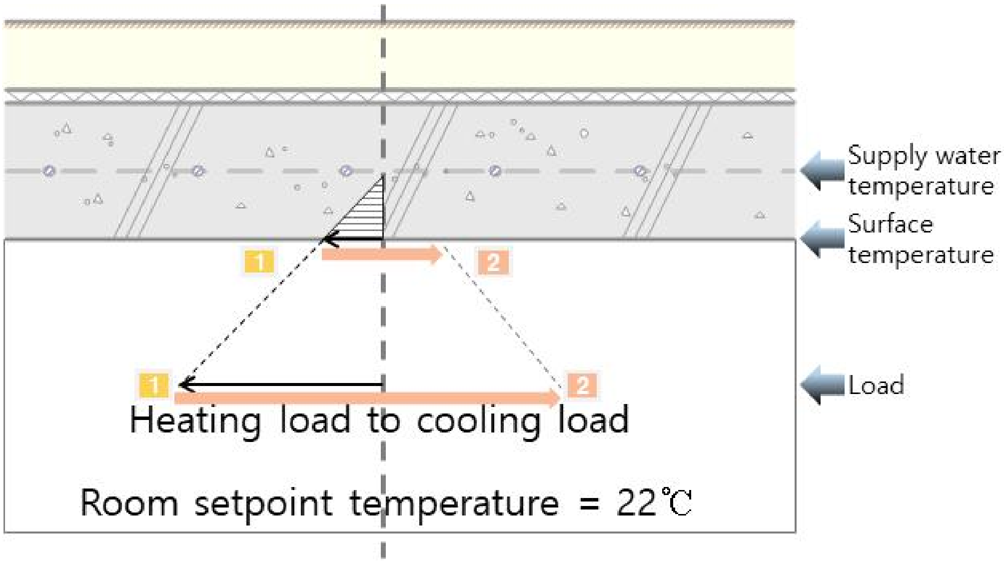


Figure 3.18 Heating load to cooling load in intermediate season (2-2)

When supply water temperature is maintained at the room setpoint temperature, the amount of building load can be assumed to be the dominant parameter. Thus, to keep the TABS surface temperature at the room setpoint temperature, the supply water temperature should be adjusted as shown in Figure 3.19. However, when the supply water temperature is changed, different scenarios can occur, as shown in Figures 3.20, 3.21, 3.22, and 3.23.

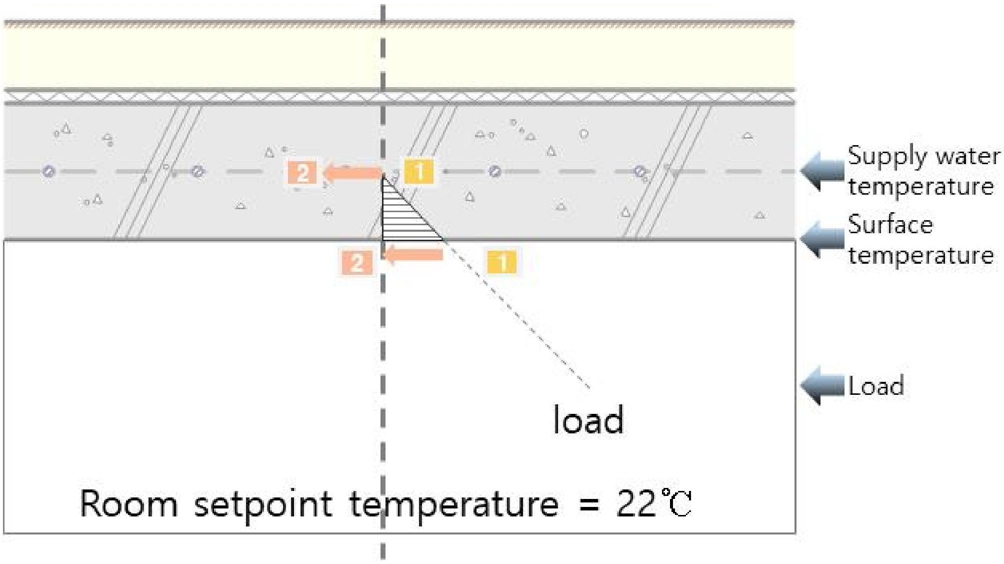


Figure 3.19 Supply water temperature according to the load

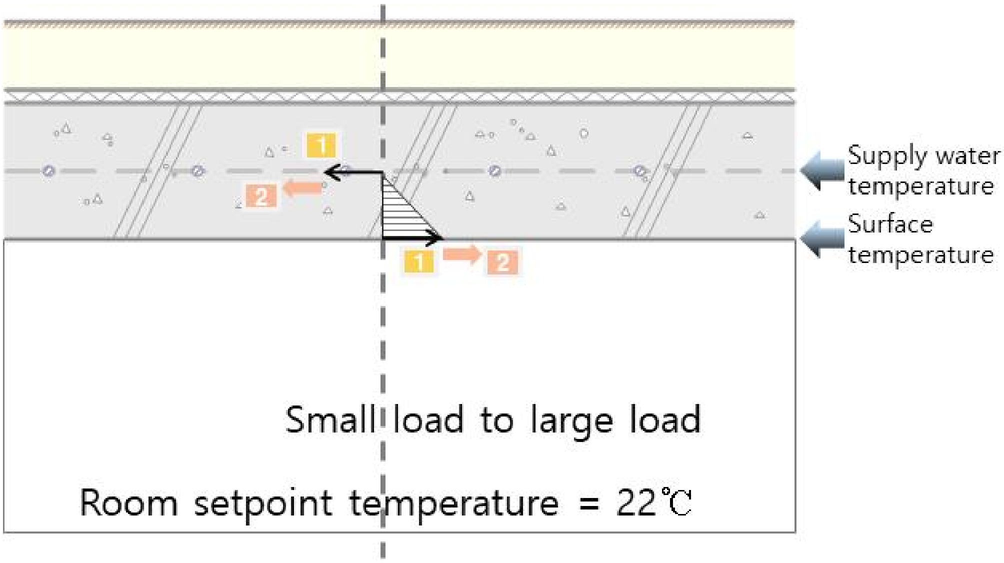


Figure 3.20 Supply water temperature strategy for small load to large load

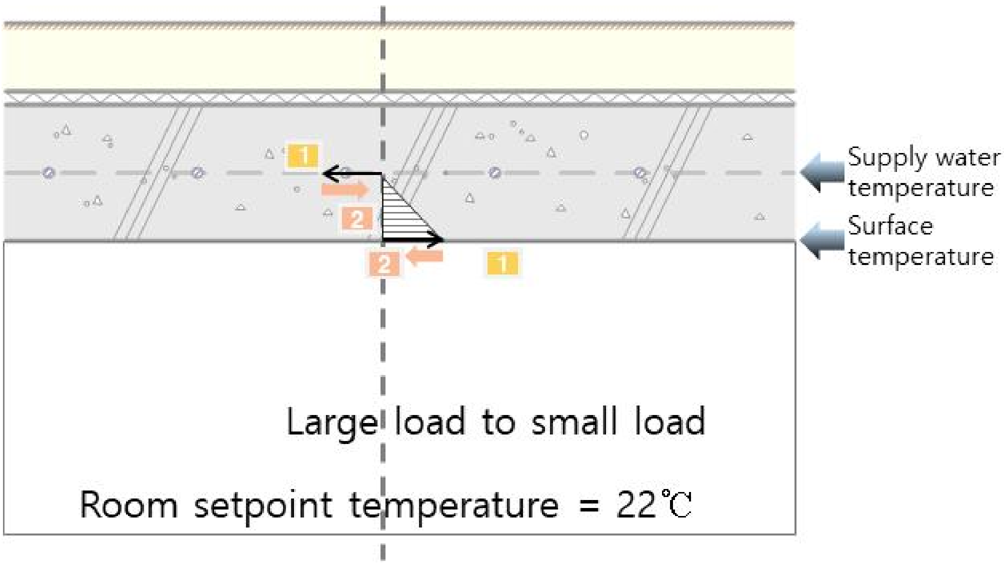


Figure 3.21 Supply water temperature strategy for large load to small load

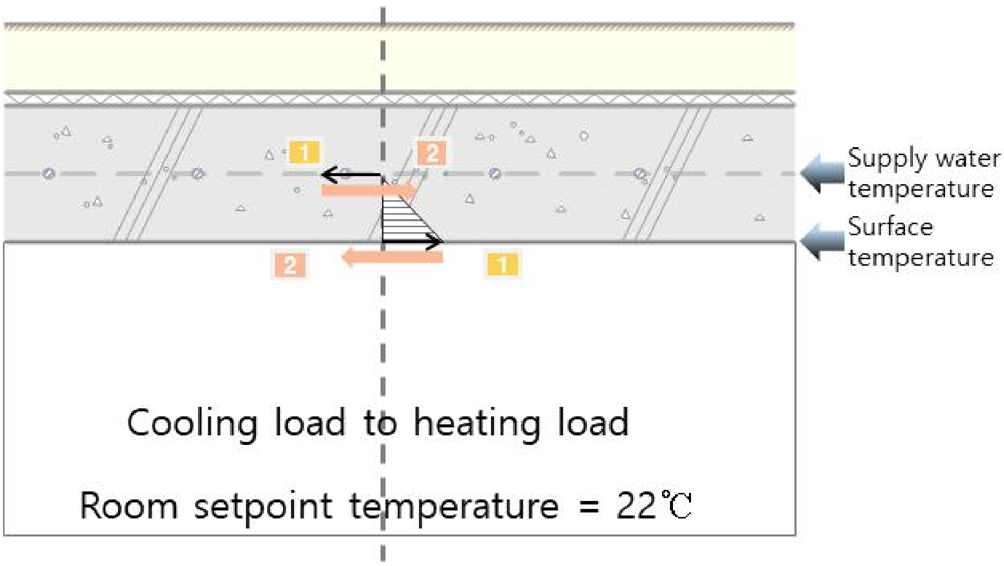


Figure 3.22 Supply water temperature strategy for cooling load to heating load

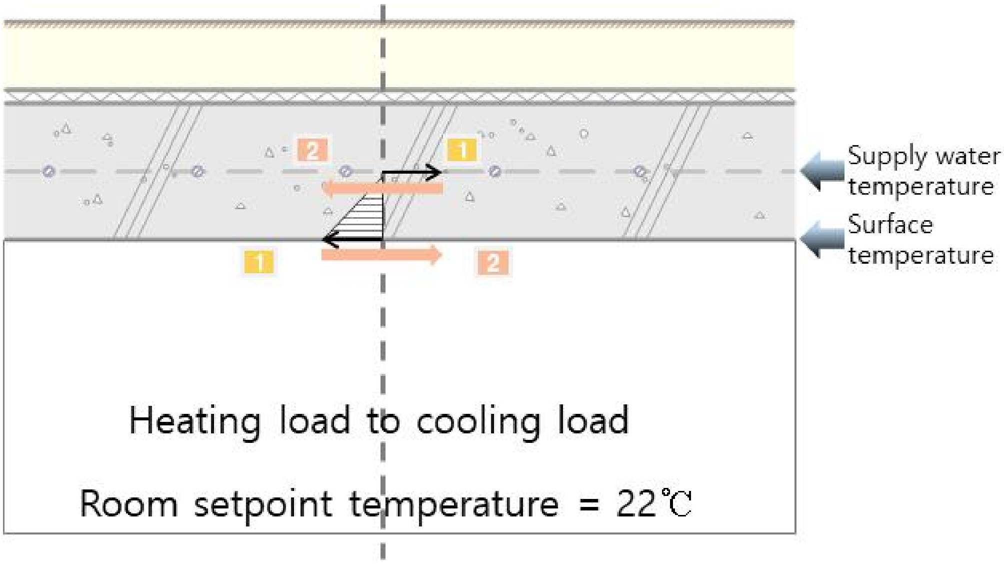


Figure 3.23 Supply water temperature strategy for heating load to cooling load

When the load changes from a small load to a large load within the same type of load, the supply water temperature can be increased and decreased for heating and cooling, respectively. In cases where the load changes from a large load to a small load within the same type of load, the supply water temperature should be decreased for heating and increased for cooling to maintain the TABS surface temperature. However, the high heat capacity of the system may maintain the temperature near the pipe and remove heat that the system provided previously. Thus, in the thermal analysis, the natural temperature changes should be considered to reflect the changes from a large load to a small load.

During the intermediate season, the type of load may change depending on the weather and internal conditions. Thus, the operation of the system should be determined depending how much mixing loss occurs.

As the amount of load changes, the load handled by TABS will proportionally change, and the return water temperature will also change accordingly. A control method was previously proposed to change the supply water temperature depending on the changes in return water temperature. Thus, the surface temperature of TABS is observed to determine if it was kept at the room setpoint temperature when the return water temperature control is applied.

3.3.2 Setting Average of Supply Water Temperature and Return Water Temperature as Room Setpoint Temperature

Because the surface temperature of TABS changes depending on the load, the average of the supply water and return water temperatures is set as the room setpoint temperature. Equation 3.5 is used in the simulation and Figure 3.24 demonstrates the supply water temperature and return water temperature of TABS.

$$\frac{Supply\,Water\,Temperature + Return\,Water\,Temperature}{2} = Room\,Setpoint\,Temperature \quad (3.5)$$

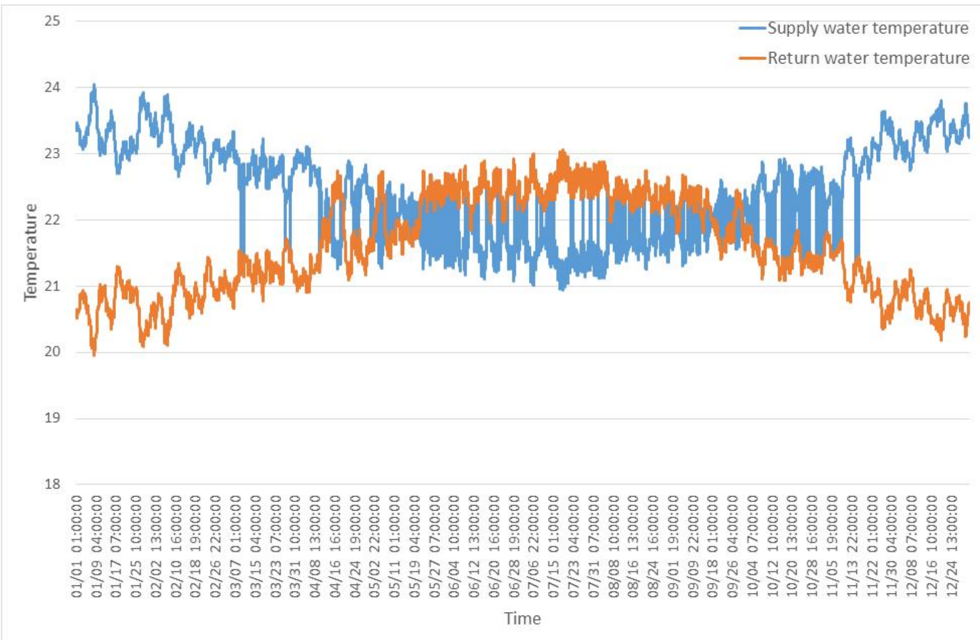


Figure 3.24 Setting the supply water temperature according to the return water temperature

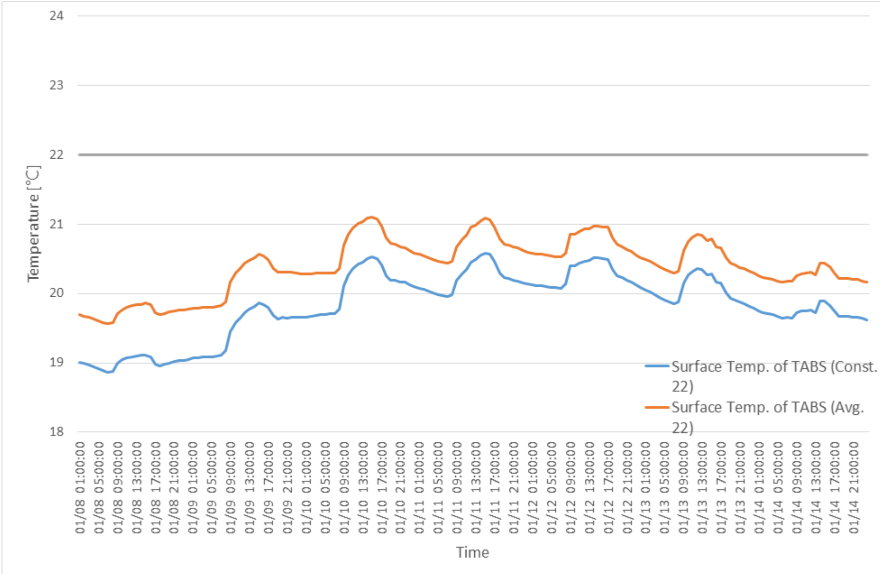


Figure 3.25 Surface temperature comparison between conventional control and average temperature on a peak heating week

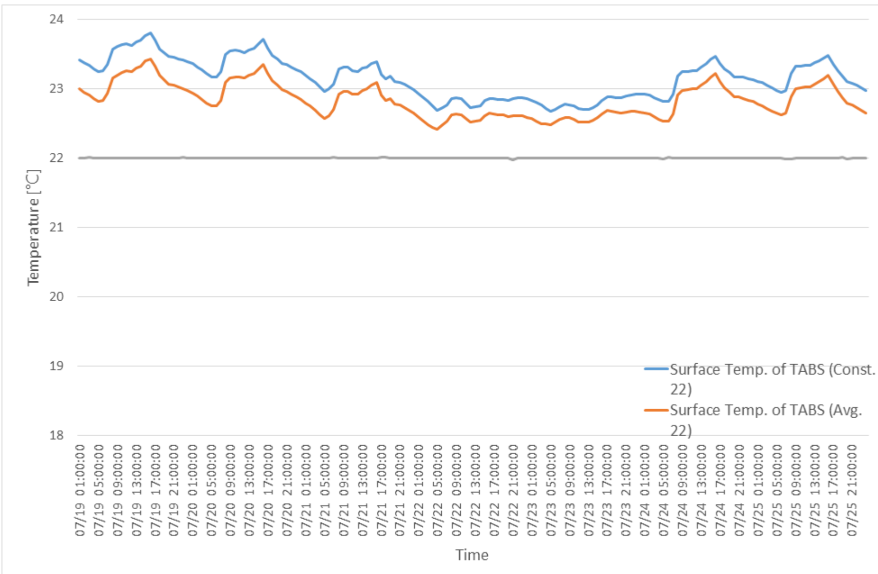


Figure 3.26 Surface temperature comparison between conventional control and average temperature on a peak cooling week

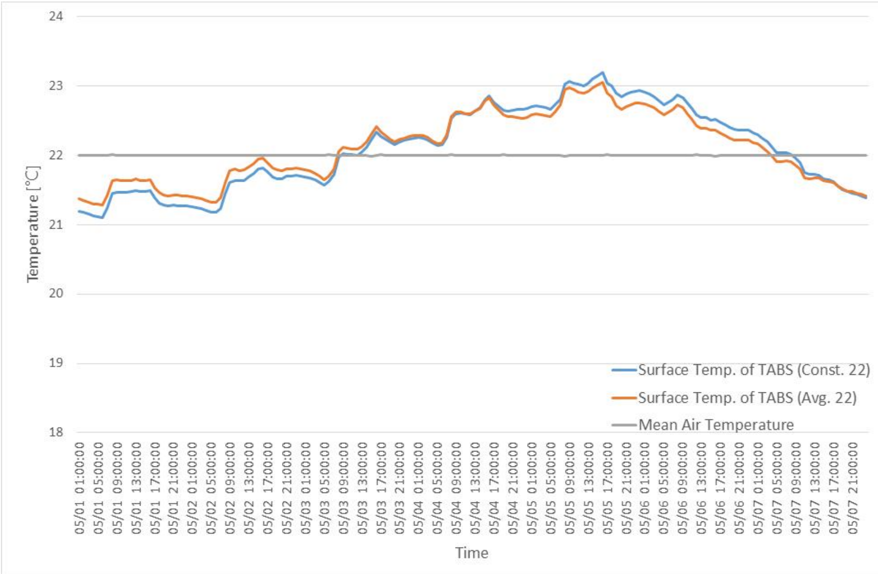


Figure 3.27 Surface temperature comparison between conventional control and average temperature on intermediate season

In the period near the peak heating and cooling days, setting the average temperature of the supply and return water as the room setpoint temperature does bring the surface temperature of TABS closer to the room setpoint temperature, as shown in Figures 3.25 and 3.26. However, in the intermediate season, when the type of load changes, changes of supply water temperature depending on the return water temperature takes time to appear the effect of the system, as shown in Figure 3.27. The thermal phenomenon is expressed in Figures 3.28 and 3.29.

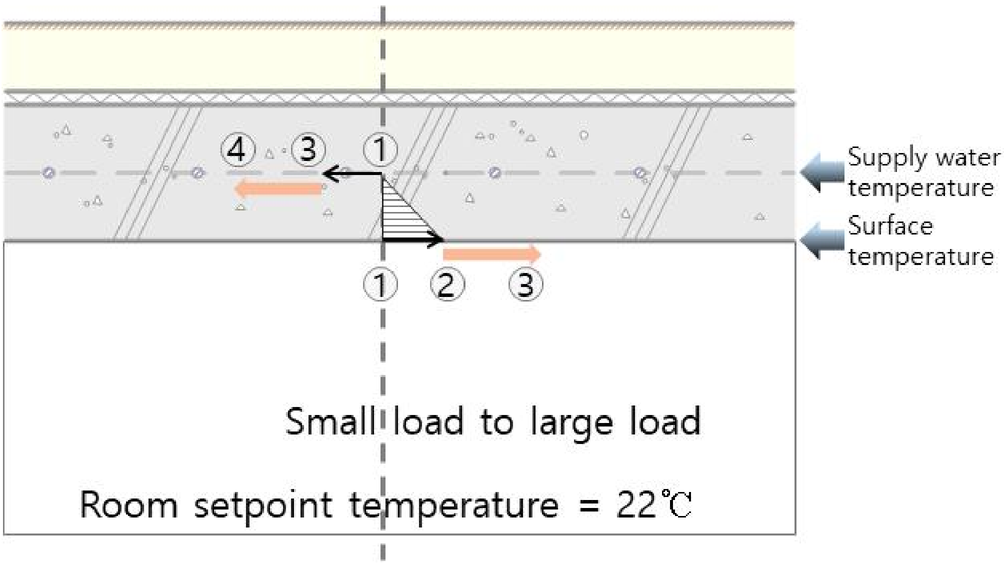


Figure 3.28 Supplying different water temperature depending on the return water temperature in case of small load to large load changes

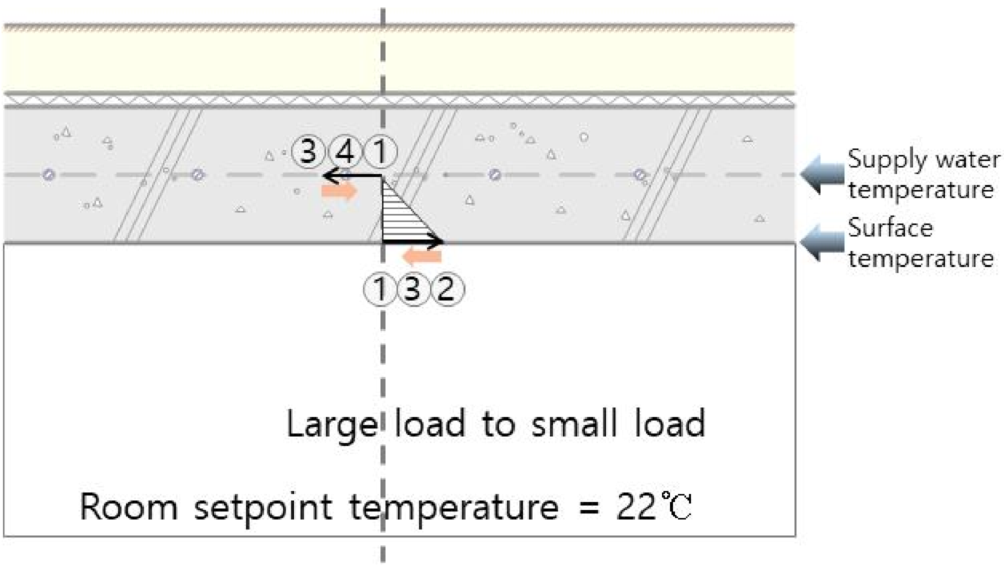


Figure 3.29 Supplying different water temperature depending on the return water temperature in case of large load to small load changes

Adjusting the supply water temperature based on the return water temperature will introduce more heat into the zone. However, changes in TABS supply water temperature will take time to provide the heat into a zone. Thus, supply water temperature should be adjusted ahead of time by considering the future load, to handle the target load. In addition, the time delay should be defined to supply the proper water temperature ahead of time. Although load effects are considered by changing TABS supply water temperature based on the return water temperature, the thermal output of TABS is still small because the air system is operated to keep the room air temperature at the setpoint temperature. Because of the energy efficiency of the radiant system, TABS should be actively utilized during heating and cooling seasons to handle more load.

3.4 Summary

To observe that the current method can be successfully used to control TABS, the specification of a small office building from the DOE reference building was used to simulate and consider the system characteristics of time delay. Current control methods utilize the self-regulation effect and continuously supply constant water temperature as the room setpoint temperature to handle the basic load of a building. The remaining load is handled by the air system to main the thermal comfort of the zone.

The observation of TABS with the current control method was conducted by inspecting the surface temperature of the system. The amount of load in the zone caused changes in the zone air temperature and triggered a heat exchange between the surface of the system and the zone air. Moreover, because TABS could not maintain the surface temperature at the room setpoint temperature, especially during the summer and winter seasons, the heat from the previous timestep was stored and carried to the next timestep period. With the continuous zone load, the concept of self-regulation could not be maintained, which decreases the amount of load handled by TABS below our expectations. Therefore, TABS should use higher supply water temperatures during the winter season, and lower supply water temperatures during the summer season. In intermediate season, the changes of supply water temperature depending on the return water temperature took time to provide the heat into the zone. Thus, the target load should be predicted ahead of time to apply proper supply water temperature on TABS.

Chapter 4 TABS Control Method to Increase the Amount of Load Handled by TABS

Based on the improvement direction specified in the previous chapter, the system mechanism is analyzed to determine the control timestep for TABS. After selecting the basic control structure, the target load for TABS is calculated using the outdoor air temperature, because it is one of the most influential parameters and weather forecasts are relatively accurate. Using the TABS target load, the heating and cooling curve that changes the supply water temperature depending on the outdoor air temperature is derived. Moreover, the calculated external load from the outdoor air temperature does not correspond with the actual minimum load. Thus, a more promising solution, the ANN, is used to predict the load. The thermal load is predicted and the supply water temperature is derived based on the target load.

4.1 Thermal Analysis of the TABS

Because the TABS has a large heat capacity, changes in supply water temperature will take a long time to introduce heat into the zone. Thus, the system mechanism should be analyzed to determine the time interval for TABS control. The types of parameters that affect the thermal mechanism of the system are classified as system parameters, control parameters, and zone parameters. System parameters include thermal conductivity, volume, specific heat, density, and area of the system. The control parameter is supply water temperature. Because the zone load influences the surface temperature of TABS, the zone load is set as a zone parameter.

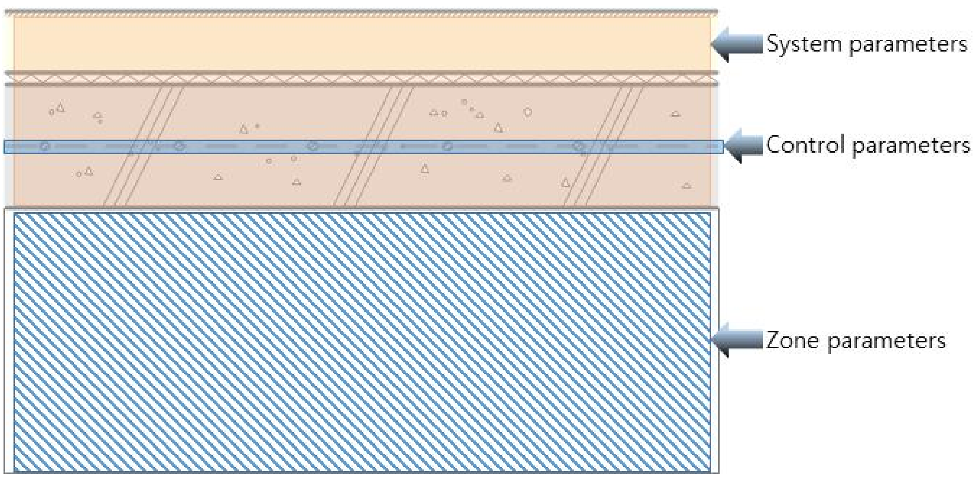


Figure 4.1 Parameters of TABS

To define the system characteristics, the correlation between system parameters and control parameters is analyzed without considering the zone parameter. Among the many methods available to explain the thermal dynamics of this scenario, the RC network is utilized to explain the relationship between supply water temperature and the surface temperature of the system. The basic equation used to explain the thermal mechanism is demonstrated in Equation 4.1. The Laplace transform presented in Equation 4.2 is used to derive the exact solution for the relationship between supply water temperature and surface temperature.

$$\rho C_p V \frac{dT}{dt} = kA(T_{supply} - T_{surface}) \tag{4.1}$$

$$T_{surface}^{k+1} = T_{supply} + (T_{surface}^{k} - T_{supply}) e^{\frac{-kA}{\rho C_p V} t} \tag{4.2}$$

The values of the system parameters are changed to observe the changes in TABS surface temperature in Figures 4.2 and 4.3. As the time constant and resistance of the system increase, the time needed for the heat to reach the TABS increases. In Figure 4.4, 22 °C, 25 °C, and 28 °C supply water temperatures are applied. As the supply water temperature increases, the time it takes for heat to transfer onto the surface of TABS increases.

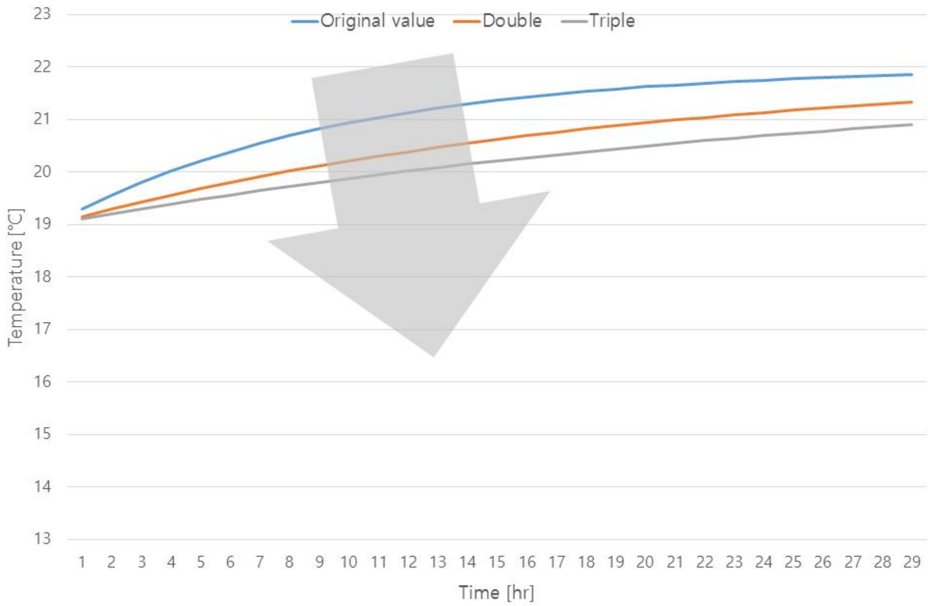


Figure 4.2 Changes of surface temperature with increase of time constant (specific heat, density, and volume)

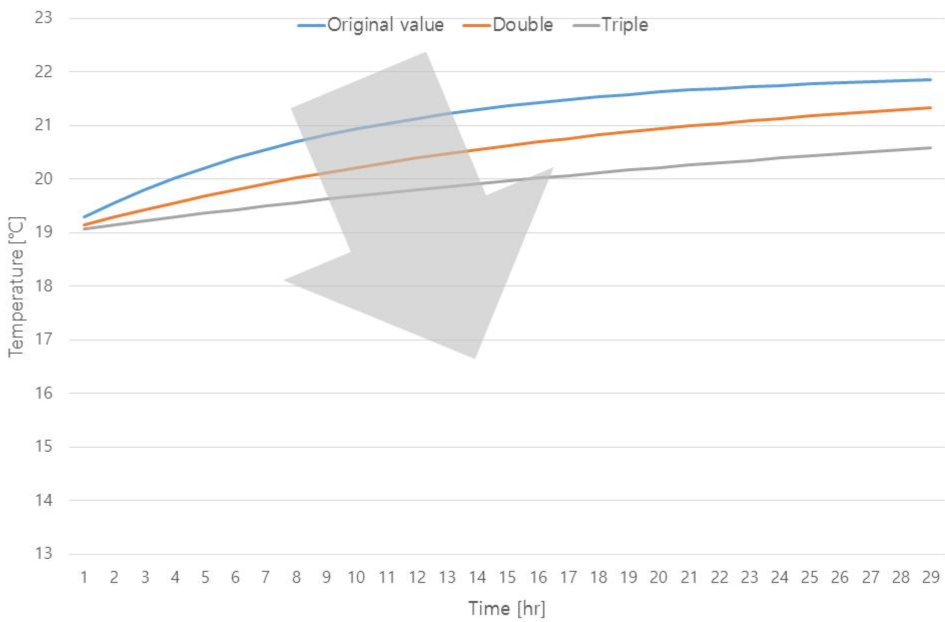


Figure 4.3 Changes of surface temperature with increase of resistance

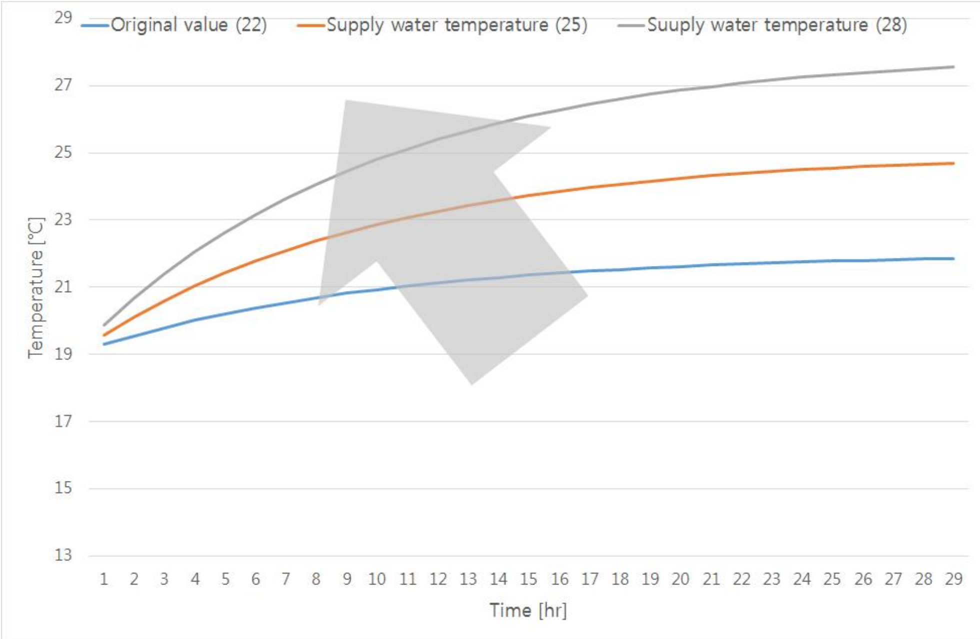


Figure 4.4 Changes of surface temperature with increase of supply water temperature

To verify the theoretical assumption, a room with constant load is modeled with EnergyPlus and changes are made to the supply water temperature. Constant heating load is assumed and the outdoor air temperature is set to −20 °C. With a constant heating load, the changes in supply water temperature are applied to examine how the characteristics of time delay change based on the difference in supply water temperature. In Figure 4.5, various supply water temperatures are used initially, and changed the supply water temperature to 22 °C. As initial supply water temperature becomes greater, the time it takes to transfer heat into the zone increases. Even changes as small as 1 °C take 24 h to reach a consistent surface temperature. In Figure 4.6, a 22 °C constant supply water temperature is used, and the supply water temperature was changed to various temperatures. In Figure 4.7 and 4.8, detailed information on when the supply water temperature is changed from 22 °C to 30 °C and from 30 °C to 22 °C are presented, respectively. As the supply water temperature increases, surface temperature and zone air is proportionately changed; however, the time it takes to transfer the heat is approximately 100 h. Thus, significant changes to supply water temperature should be executed long before the load occurs.

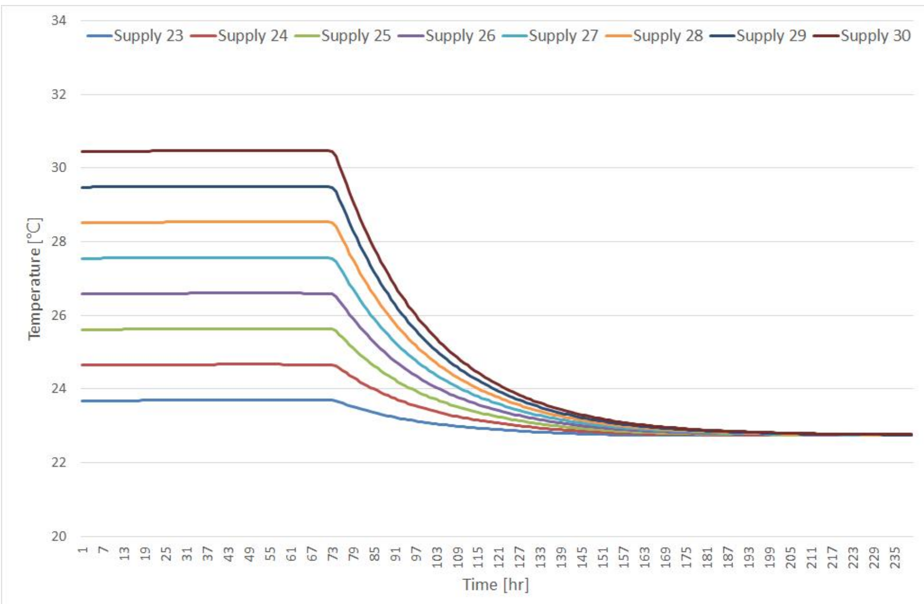


Figure 4.5 Changes from different supply water temperatures to 22℃ of supply water temperature

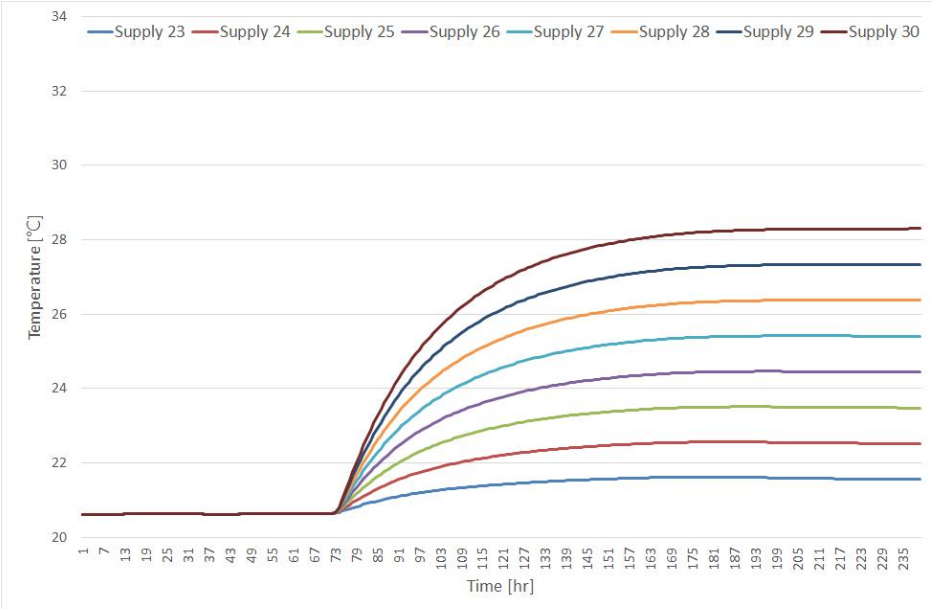


Figure 4.6 Changes from 22℃ of supply water temperature to different supply water temperatures

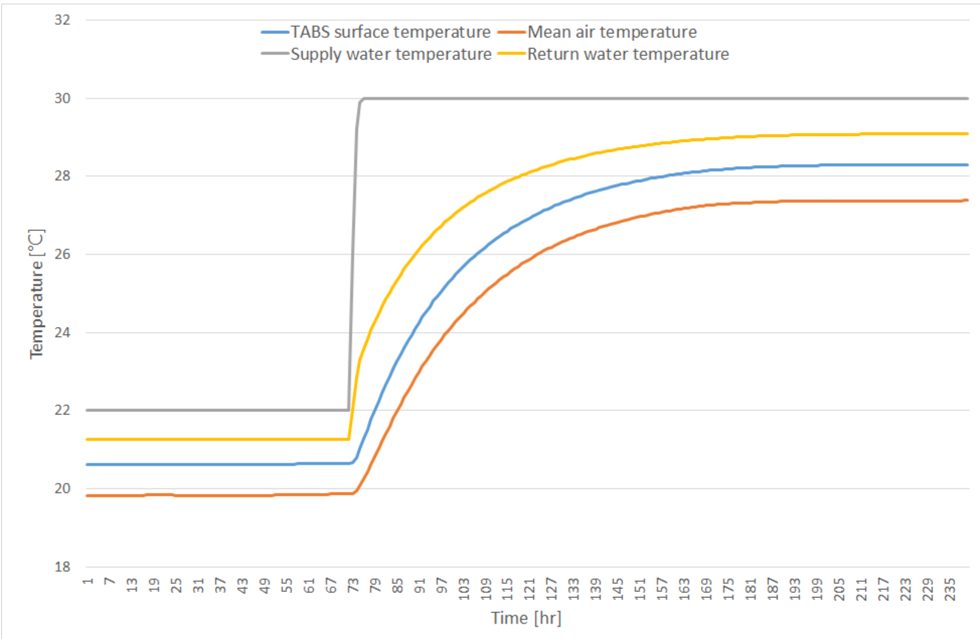


Figure 4.7 Supply water temperature change from 22℃ to 30℃

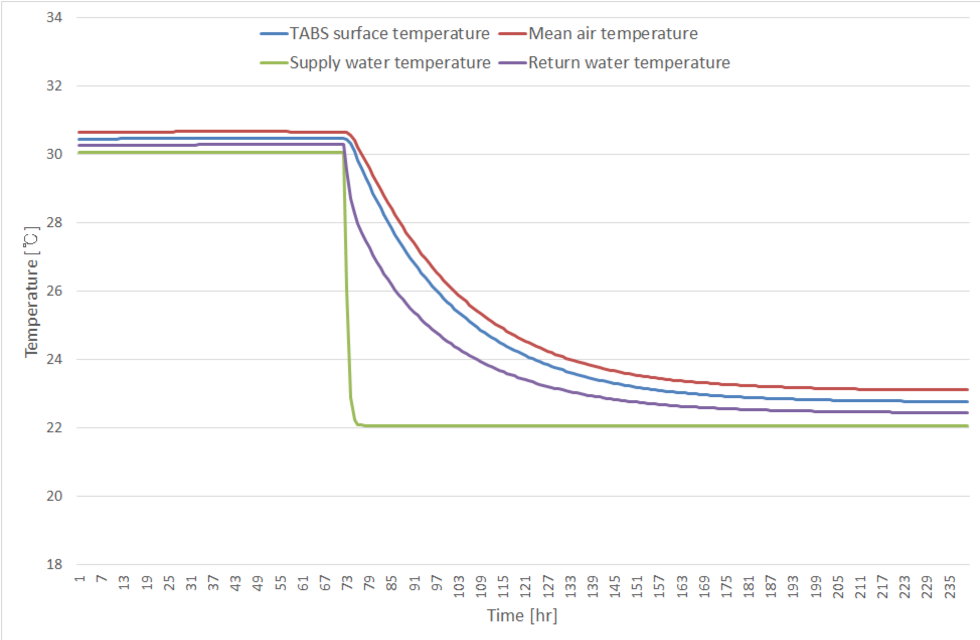


Figure 4.8 Supply water temperature change from 30℃ to 22℃

Changes from 22 degrees of supply water temperature to various supply water temperature is similar to the characteristics of surface temperature change from various supply water temperature to 22 degrees of supply water temperature. Thus, hourly control of supply water temperature will not be feasible, and the supply water temperature should be planned at least 24 hours before the load occurs.

4.2 Target load of TABS for Deciding the Supply Water Temperature

4.2.1 Target Load Based on Outdoor Air Temperature

Because the thermal output of the system changes depending on the amount of load, the load prediction should be applied to the supply water ahead of time. The most common basic load in an office building is the internal load in the interior zone. However, the internal load may differ from the design values and the load prediction may have high uncertainty. Therefore, the load prediction should be based on the steady load.

Many studies utilize weather forecast data from weather stations to predict simple loads, because the error between weather forecast data and actual weather conditions is relatively small. Among many values of weather forecast data, outdoor air temperature and solar radiation values are often used in research papers. Because solar radiation may have a high chance of changing due to cloud coverage, outdoor air temperature is selected to predict the basic load of the building.

In Figure 4.1, the correlation between outdoor air temperature and building load is observed, and it was discovered that the outdoor air temperature values were proportional to the building loads.

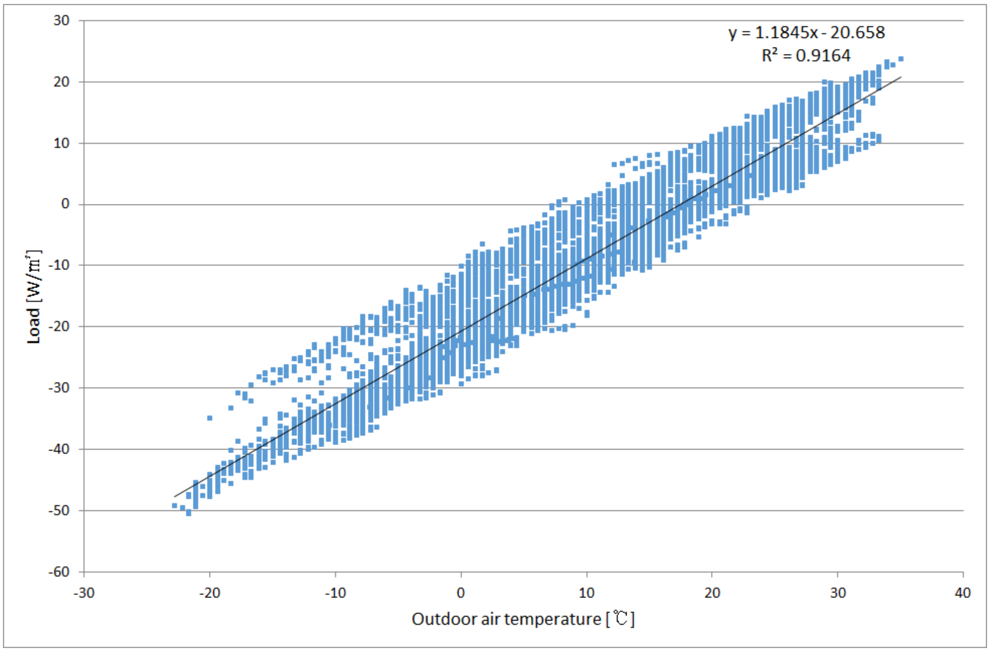


Figure 4.9 Correlation between outdoor air temperature and building load

An equation for simple steady-state conditions is used to express the linear relationship between outdoor air temperature and building load and expressed as 4.3 and it developed from Equation 4.4 to Equation 4.6.

$$q_{total} = aT_o + b \qquad (4.3)$$

$$a = [\frac{\Sigma K_{wall.opaque.avg} A_{surface}(1-WWR)}{A_{Floor}} + \frac{\Sigma K_{window} A_{surface}(WWR)}{A_{Floor}}$$

$$+ \frac{0.33 \times N \times V}{A_{Floor}} = 0.85 \qquad (4.4)$$

$$b = -[\frac{\Sigma K_{wall.opaque.avg} A_{surface}(1-WWR)}{A_{Floor}} + \frac{\Sigma K_{window} A_{surface}(WWR)}{A_{Floor}}$$

$$+\frac{0.33\times N\times V}{A_{Floor}}](T_{in})+\frac{Schedule_{min}\times Density}{A_{Floor}}=14.17 \qquad (4.5)$$

$$q_{outdoor}=0.85T_o-14.17 \qquad (4.6)$$

Table 4.1 Conditions to calculate the load from outdoor air

Building Conditions						
Width	27.69	m				
Length	18.46	m				
Height	3.05	m				
Floors	1	Floors				
Window area	27.8892	m^2				
Roof construction	Thickness		Thermal conductivity		Heat transfer coefficient	
1/2 in gypsum	0.0127	m	0.16	W/mK	0.19227769	W/m^2K
Attic floor nonres insulation	0.2368	m	0.049	W/mK		
1/2 in gypsum	0.0127	m	0.16	W/mK		
Roof membrane	0.0095	m	0.16	W/mK		
Metal decking	0.0015	m	45	W/mK		
Wall construction	Thickness		Thermal conductivity		Heat transfer coefficient	
1 in stucco	0.0253	m	0.6918	W/mK	0.698247997	W/m^2K
8 in concrete HW	0.2032	m	1.311	W/mK		
Mass non res wall insulation	0.04954946	m	0.049	W/mK		
1/2 in gypsum	0.0127	m	0.16	W/mK		
Floor construction	Thickness		Thermal conductivity		Heat transfer coefficient	
HW Concrete	0.1016	m	1.311	W/mK	2.252261926	W/m^2K
	Heat transfer coefficient					
CP02 Carpet PAD	0.2165	m2 K/W				
Window	Heat transfer coefficient					
NonRes Fixed Assembly Window	3.23646	W/m^2K				
Surface area	281.515	m^2				
Floor area	511.1574	m^2				
Roof area	511.1574	m^2				
Kwall.opaque.avg	0.698247997	W/m^2K				
Kroof	0.19227769	W/m^2K				
Kwindow	3.23646	W/m^2K				
Kfloor	2.252261926	W/m^2K				
Window to wall ratio	0.099068256					
Total floor area	511.1574	m^2				
Volume	1559.03007	m^3				
Internal (W/m^2)	10	W/m2	10			
Internal (W)	5111.574	W	5111.574			
Infiltration (ACH)	0	ACH				
Ground Temp	18	℃				
Setpoint Temp in winter	22	℃				
Setpoint Temp in Summer	22	℃				

The conditions associated with the effects of outdoor air temperature are listed in Table 4.1. Based on Equation 4.6, the load prediction values are plotted in Figure 4.10 with the actual building loads. Using outdoor air temperature, the minimum heating and cooling loads could be predicted. The hourly load prediction is presented in detail in Figure 4.11. To compare the actual load and the predicted load in detail, the hourly values of the actual load and predicted load during the winter and summer seasons are presented in Figures 4.12 and 4.13.

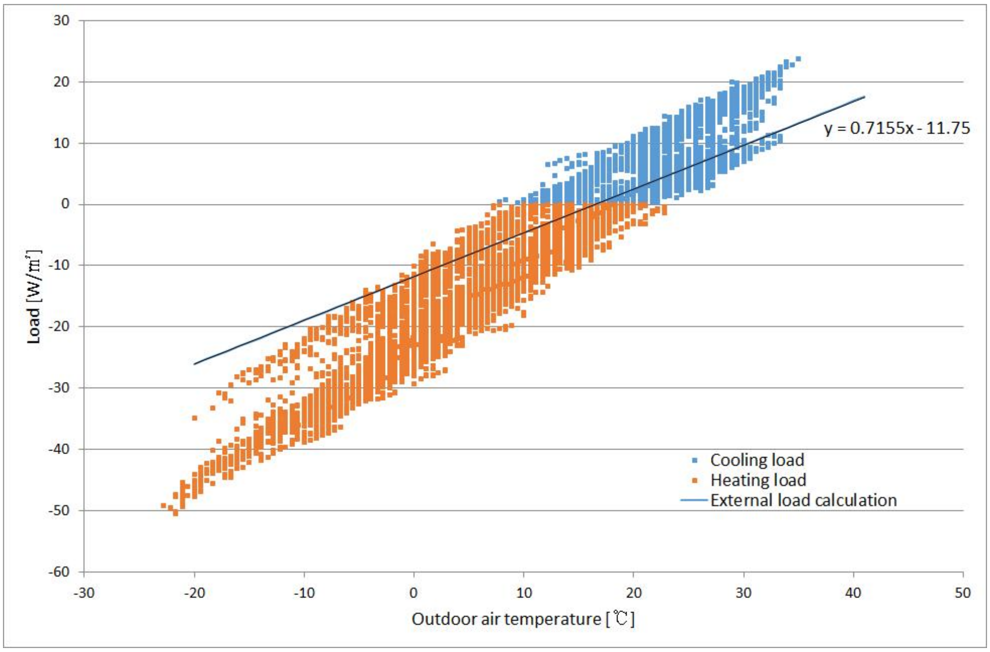
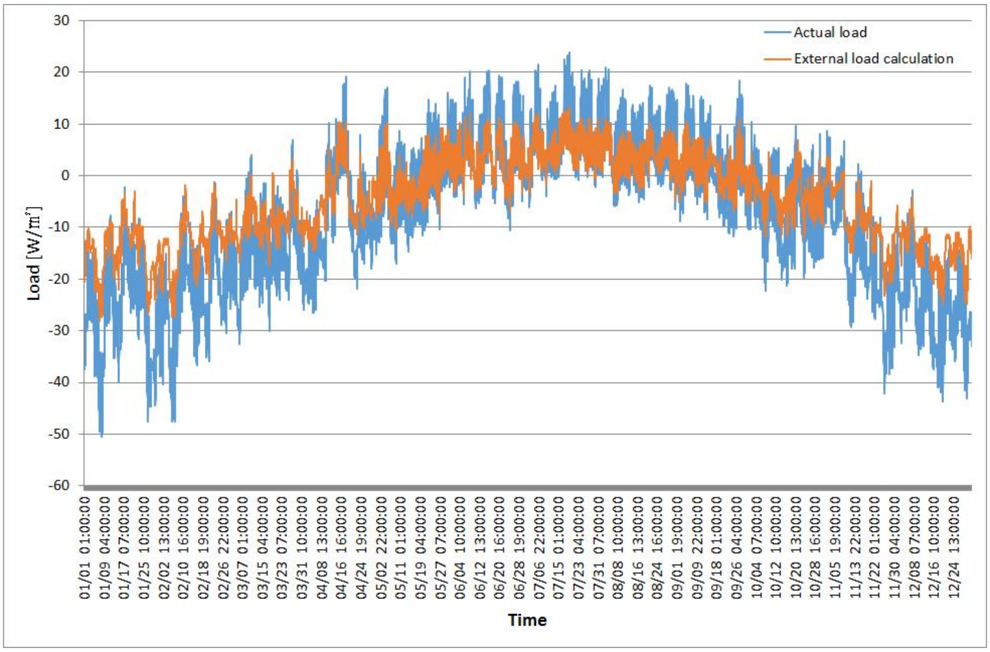
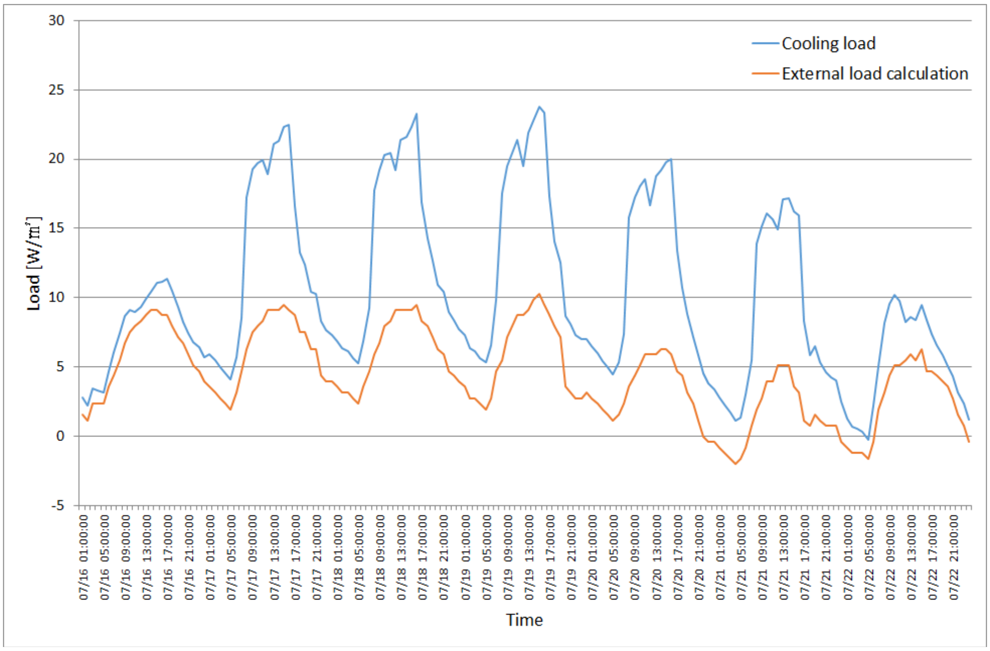


Figure 4.10 External load calculation curve



4.11 External load calculation in detail



4.12 Actual load and external load calculation on a peak cooling week

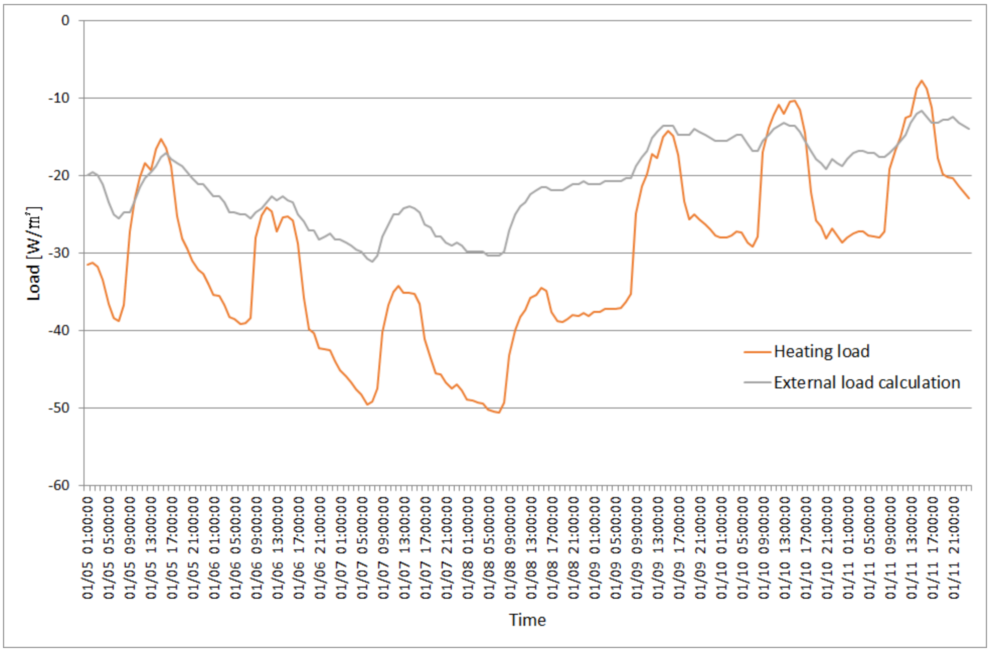


Figure 4.13 Actual load and external load calculation on a peak heating week

Using the external load calculation, the daily target load could be obtained, and with the target load, the relationship between the TABS supply water temperature and outdoor air temperature could be derived. The derivation is expressed by Equations (4.7), (4.8), and (4.9).

$$q_{calculated} = 0.85 \times T_o - 14.17 = kA(T_{average} - T_{surface}) \quad (4.7)$$

$$T_{average} = T_{supply} - T_{return} \quad (4.8)$$

$$T_{supply} = 2 \times (\frac{q_{calculated}}{kA} + T_{in}) - T_{return} \quad (4.9)$$

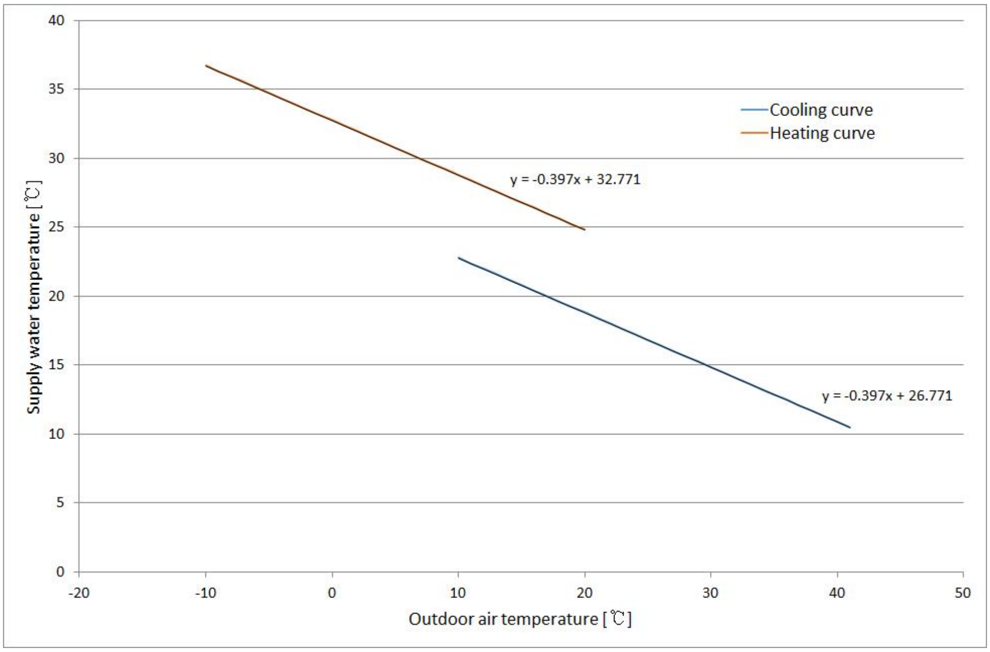


Figure 4.14 Heating and cooling curve of the TABS

Equation 4.9 is plotted in Figure 4.14. The heating and cooling curves are separately plotted because the expected return water temperature is different in the pipe layer.

4.2.2 Target Load Based on the Load Prediction with Artificial Neural Network

Only a limited amount of load can be removed when only using the outdoor air temperature; therefore, more parameters should be considered to handle more load with TABS. However, the parameters may have different patterns and may experience different basic loads each day. The appropriate amount of target load is determined by learning the patterns in previous data by using statistical methods.

Among the many statistical methods available, the ANN is selected to express the correlation between input parameters and building load. The ANN is one of the most commonly used statistical methods for data-driven building load predictions. The concept of the ANN comes from neurology. A function model family that uses the sigmoid function is selected because it may express the correlation better than a linear function. The function model family is demonstrated as follows.

$$f(x) = \sigma(w^T \times x + b) \tag{4.10}$$

$$\sigma(z) = \frac{1}{1 + e^{-z}} \tag{4.11}$$

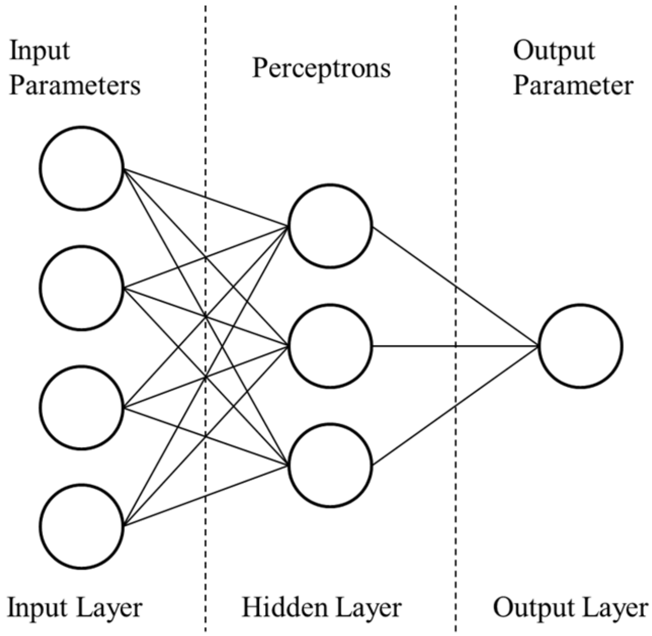


Figure 4.15 Concept of ANN

Back propagation is used to train the weights and the learning rate is set to 0.1. The learning rate is kept small because a larger learning rate may increase the calculation time and cause convergence problems. The default epoch is set to 500 times due to the possibility of overfitting.

As Figure 4.16 demonstrated, the input parameters for the ANN are chosen by considering the external loads, infiltration loads, solar loads, and internal loads. Because the information from a weather forecast station has relatively accurate prediction capability, the outdoor air temperature and cloud coverage are used to determine the external loads, infiltration loads, and solar radiation. Because the office building has a regular occupancy schedule depending on the type of day, Monday to Sunday was numbered as 1 - 7 and used as input parameters for the ANN.

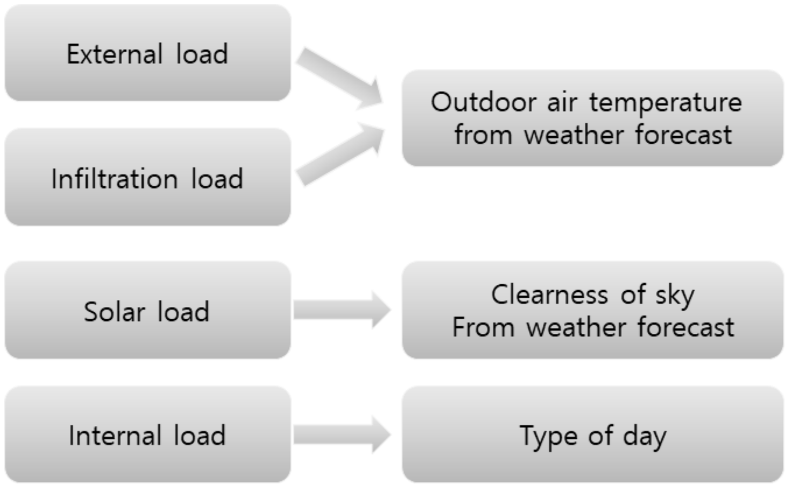


Figure 4.16 Input parameters for ANN

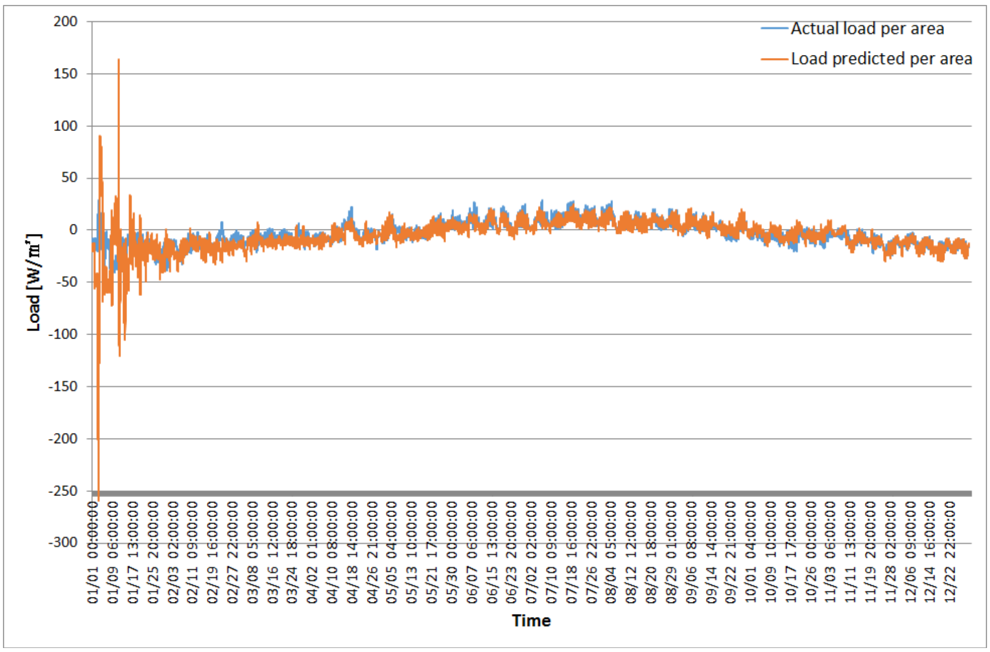


Figure 4.17 ANN load prediction

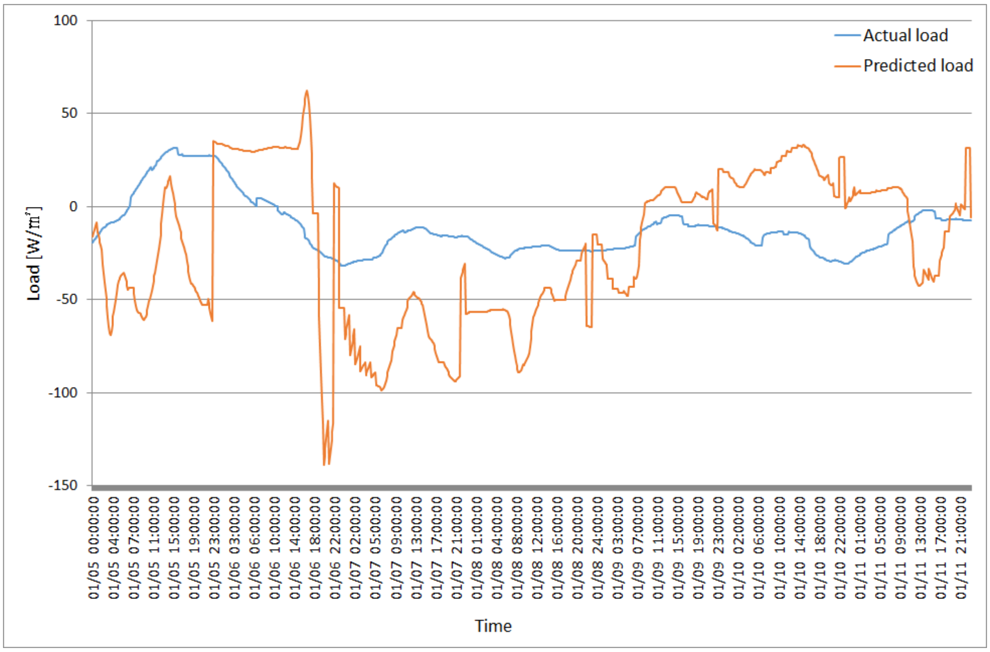


Figure 4.18 ANN load prediction on a peak heating week

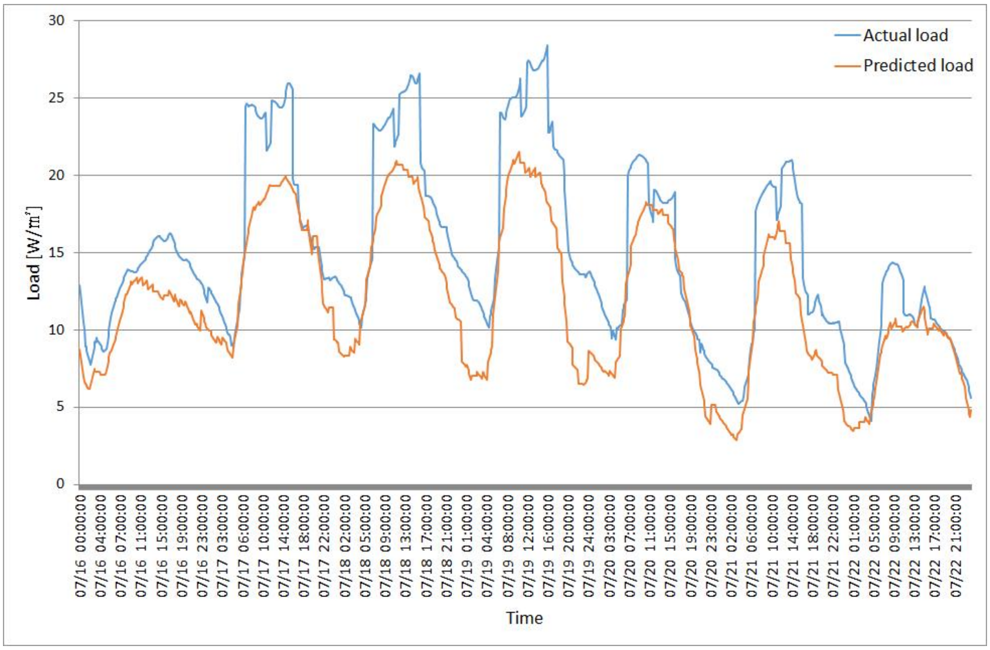


Figure 4.19 ANN load prediction on a peak cooling week

In Figure 4.17, the ANN load prediction is executed; however, the accuracy of the load prediction is very poor in the first month. A detailed ANN load prediction plot is presented in Figures 4.18 and 4.19. As Figure 4.18 demonstrated, load prediction cannot be used to target the load for TABS.

To decide when the load prediction is valid, the index to determine the feasibility is observed from standard. ASHRAE Guideline 14 proposes the mean bias error and the coefficient of variation of the root-mean-squared error (CVRMSE) to determine the accuracy of the predicted values. For hourly load prediction, the CVRMSE should be lower than 30% to be feasible. The equation used to calculate CVRMSE is demonstrated below.

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{n} (M_i - S_i)^2 / n}}{M_{avg}} \times 100 \qquad (4.13)$$

The hourly CVRMSE is calculated for each month to determine if the load prediction is applicable. Because the TABS targets the minimum value of the predicted cooling load and the maximum value of the predicted heating load, the CVRMSE of the minimum and maximum values were calculated and presented in Figure 4.20.

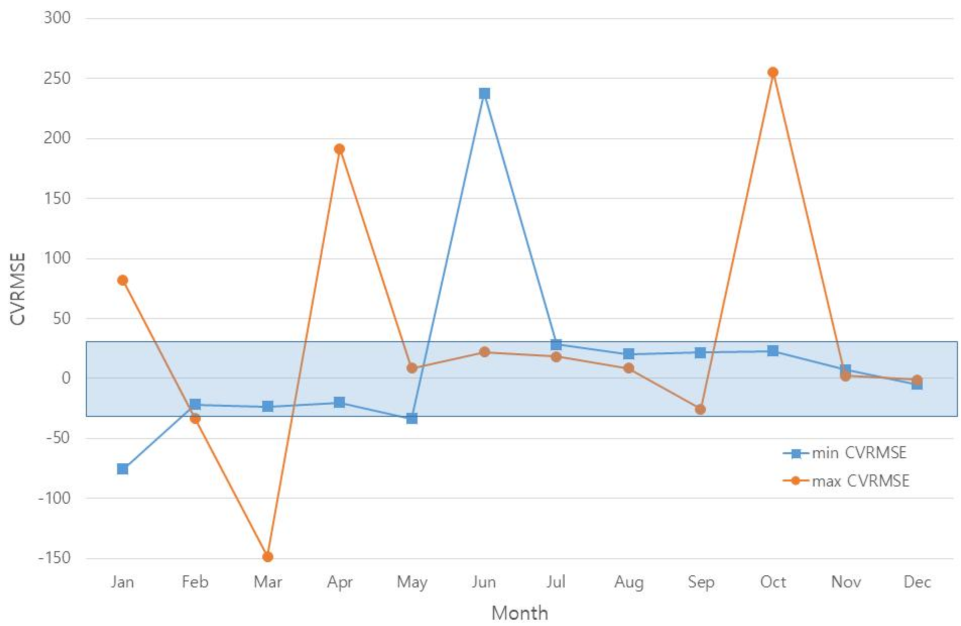


Figure 4.20 CVRMSE of minimum and maximum load prediction

After learning the load patterns for one month, the load prediction became feasible enough to incorporate into the TABS control method. However, the load prediction struggled in the intermediate season and became inaccurate. In the cooling season, the load prediction became accurate again and is ok to incorporate into the control method. The ANN load prediction demonstrated feasibility for load prediction during the heating and cooling seasons. Because the heating and cooling mechanisms differ from each other, the load prediction in the intermediate seasons struggled. However, after the extreme season is reached, the load prediction could be applied after one month of learning patterns.

4.4 Summary

To actively use the TABS, the system mechanism should be analyzed to identify the most appropriate control method. When using the RC network, a long time delay could be observed and it was decided that the control interval should be at least 24 h. Thus, daily TABS control with hourly load observation was proposed.

After analyzing the system mechanism to decide the control time interval, the magnitude of the load removed by TABS should be decided. Among the many parameters that affect the building load, the outdoor air temperature was selected to calculate the basic load of the building. This is because the outdoor air temperature is one of the most influential parameters, and the values obtained from weather forecasts are relatively accurate. Thus, the external load was calculated using the building characteristics, and the heating and cooling curve was used to determine supply water temperature based on the outdoor air temperature was derived.

Although the outdoor air temperature was one of the most influential factors and could predict the load relatively accurately, a difference between actual load and predicted load still existed. Thus, different parameters should be applied to increase the accuracy of the target load value. Because other parameters cannot be measured or simply predicted, the ANN statistical method was used to learn the pattern from the historical data. The ANN used outdoor air temperature, time, and type of day as input parameters. Initially, load prediction did not meet the tolerance level that proposed by the reference standards after one month. After one month, sufficient historical data has been obtained and increases the accuracy of the load prediction, resulting in the selection of an accurate target load.

Chapter 5 Application of Optimized TABS Control with System Analysis and Load Prediction

Using the target load, the heating and cooling curve of the system, and the load prediction obtained from the ANN in the previous chapter, the co-simulation is performed to realize the learning in each timestep with the accumulated historical data. In each case, the loads handled by TABS were compared to assess the utilization of TABS. The results demonstrate that TABS control with accurate load prediction is an effective solution. However, load prediction with ANN significantly struggles to learn the pattern at the beginning of the load prediction process. Thus, load prediction using outdoor air temperature obtained from a weather forecast should be used until the load prediction with ANN becomes stable. To validate the control method, different weather conditions were used to operate TABS.

5.1 Integration of Heating and Cooling Curve with Load Prediction

5.1.1 Co-simulation of Building to Apply Learning Algorithm

In order to apply the learning procedure to the control strategy, a co-simulation with EnergyPlus and MATLAB is used. EnergyPlus is used to realize the actual building, and MATLAB is used to predict the target load and select the supply water temperature. As middleware, the BCVTB is used to apply the control in each timestep while updating the values.

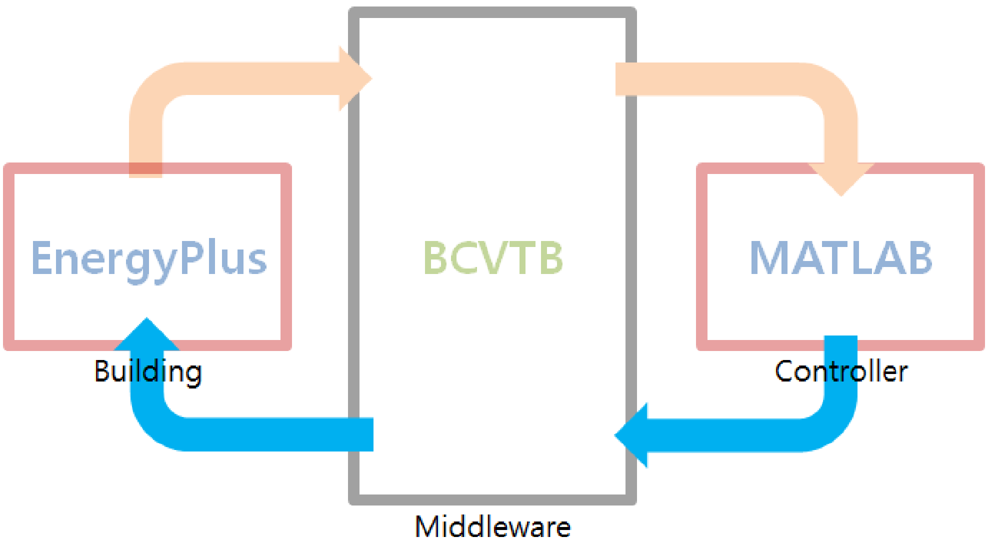


Figure 5.1 Concept of using middleware to optimize the control

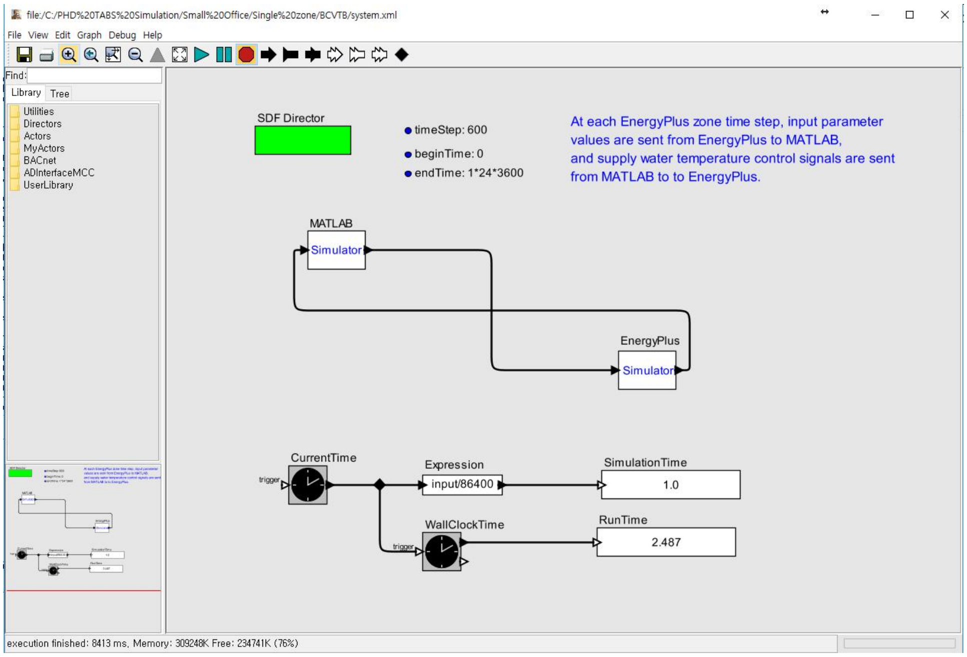


Figure 5.2 Overview of BCVTB

Due to a BCVTB software limitation, a 10 min timestep was used for EnergyPlus. The actual building load was calculated with the measurable values as the indoor air temperature, the TABS surface temperature, the supply air temperature of the air system, and the supply air velocity of the air system. According to the building load in each timestep, the ANN load prediction was adjusted, and TABS control was applied every 24 h to remove the basic load of the building.

5.1.2 TABS Control with Outdoor Air Temperature

Using outdoor air temperature information obtained from the weather forecast, the load is predicted using the building information. In Figure 5.3, the heating load can be predicted close to the actual value because it is the most influential value, especially during heating seasons, due to the significant difference between outdoor air and indoor air. During the cooling season, the load predictions was relatively inaccurate with outdoor air temperature, as shown in Figure 5.4. Significant difference occurred during the day and became accurate at night, which can conclude the great effect from solar radiation during the cooling season.

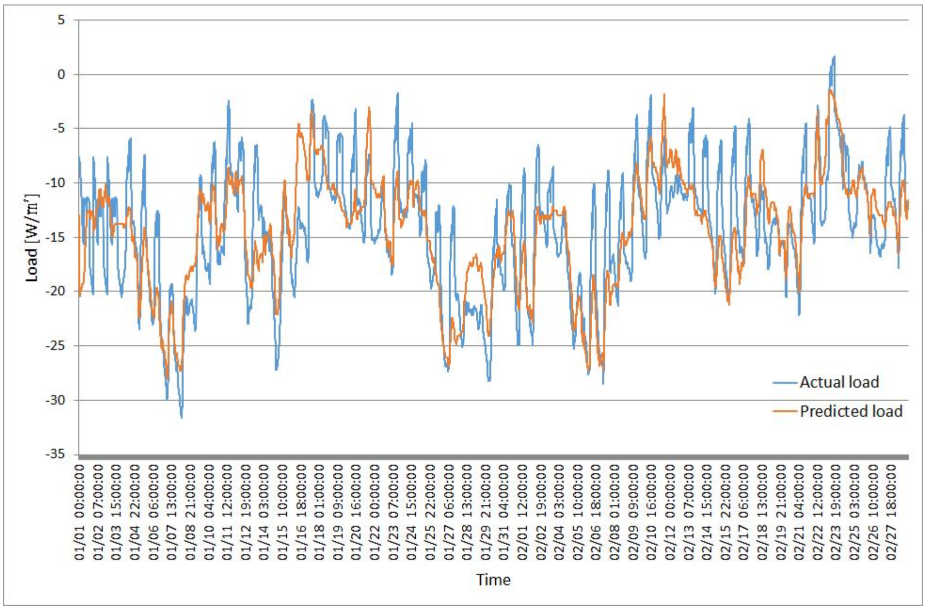


Figure 5.3 Load calculation with outdoor air temperature from weather forecast on the heating season

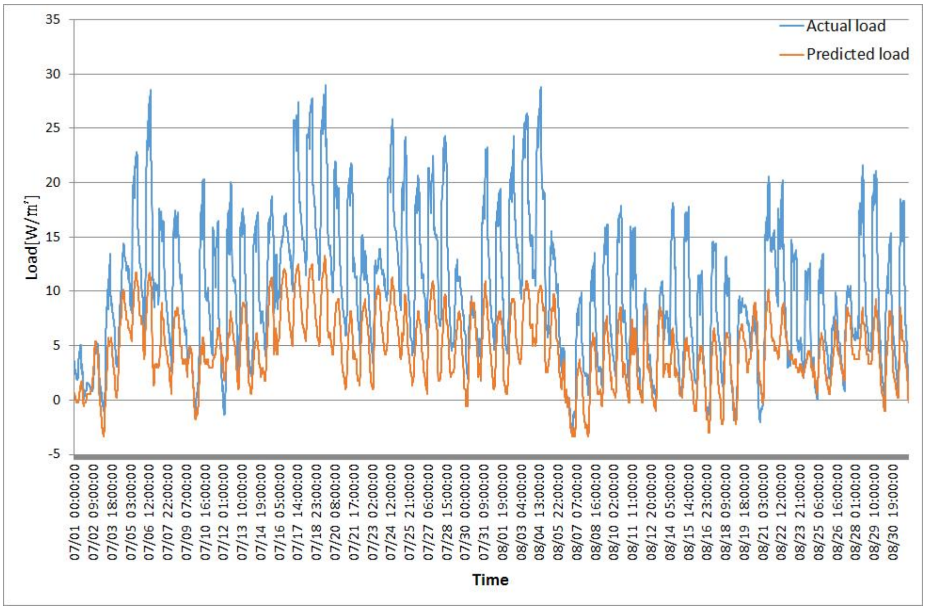


Figure 5.4 Load calculation with outdoor air temperature from weather forecast on the cooling season

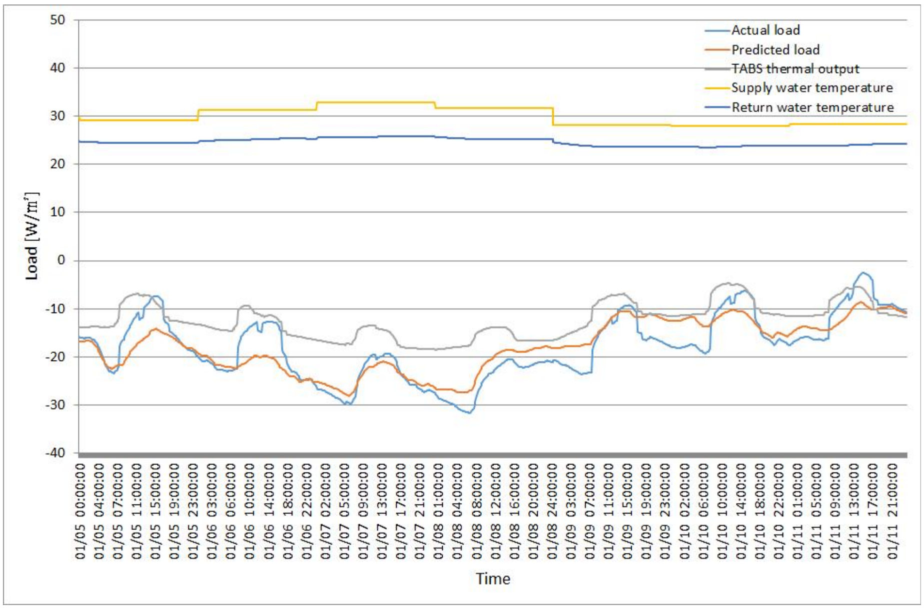


Figure 5.5 Performance of TABS with external load calculation on a peak heating week

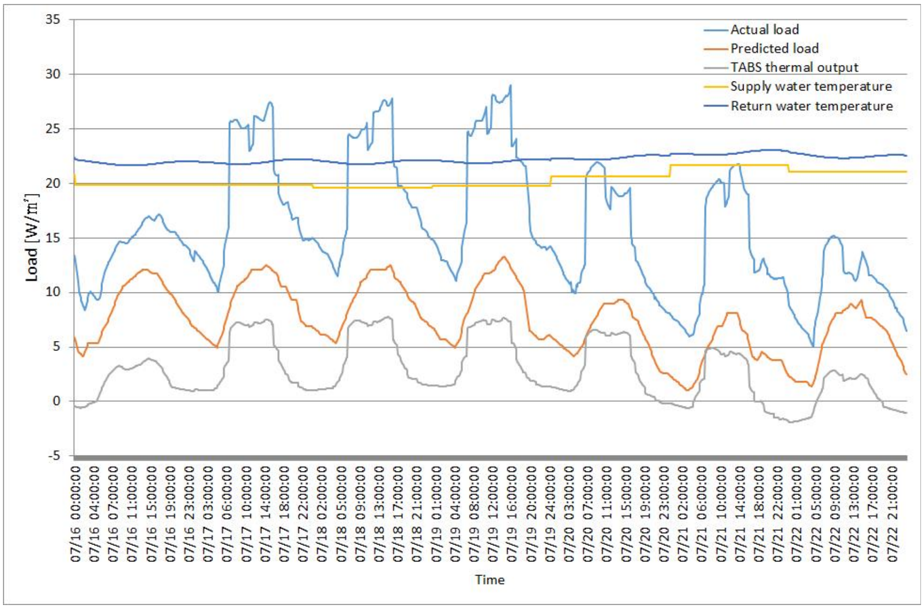


Figure 5.6 Performance of TABS with external load calculation on a peak cooling week

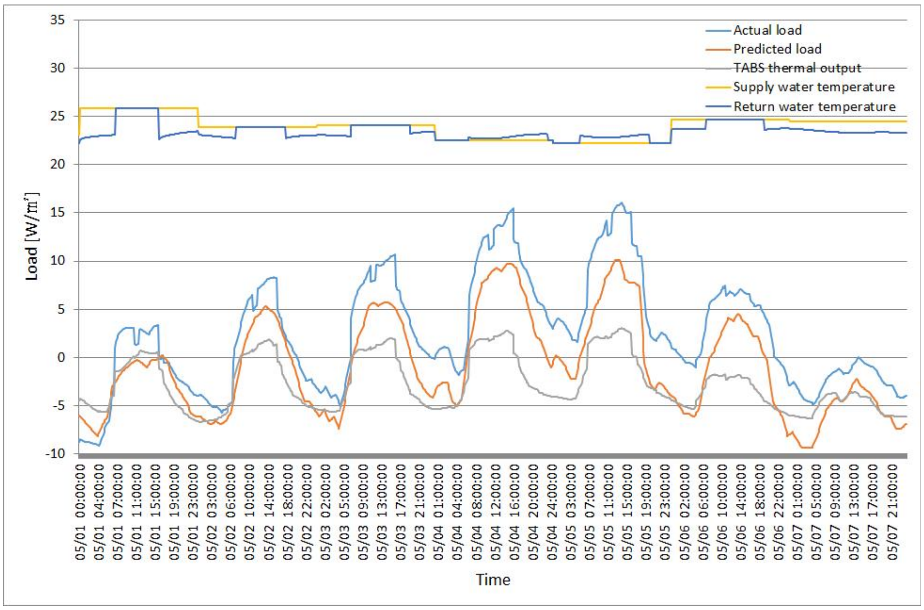


Figure 5.7 Performance of TABS with external load calculation on a week of intermediate season

TABS performance is observed during a week in the peak heating season, the peak cooling season, and the intermediate season, as shown in Figures 5.5, 5.6, and 5.7, respectively. TABS can remove the basic load of the building; however, it can only remove a small amount of load during the cooling season and intermediate season, because the load prediction is lower than the actual season. This results in a smaller TABS target load. Thus, load prediction that considers additional parameters should be utilized to increase the accuracy of the load prediction.

5.1.3 TABS Control with ANN Load Prediction

To increase the accuracy of the load prediction, a statistical method is used to consider solar and internal load by learning the patterns from historical data. In Figure 5.8, the load prediction using ANN is demonstrated and shows poor accuracy during the initiating period while learning the patterns of load. During the cooling season, a large amount of historical data increases the accuracy of the load prediction, as shown in Figure 5.9.

In figure 5.10, TABS is controlled by an inaccurate load prediction and overheats from January 6^{th} to January 7^{th}. Moreover, TABS cools while the air system heats from January 8^{th} to January 11^{th}.

During the cooling season, the ANN load prediction is accurate due to the learning pattern developed from a large amount of historical data. In Figure 5.11, the thermal output of TABS could be kept equivalent to the basic load of the building.

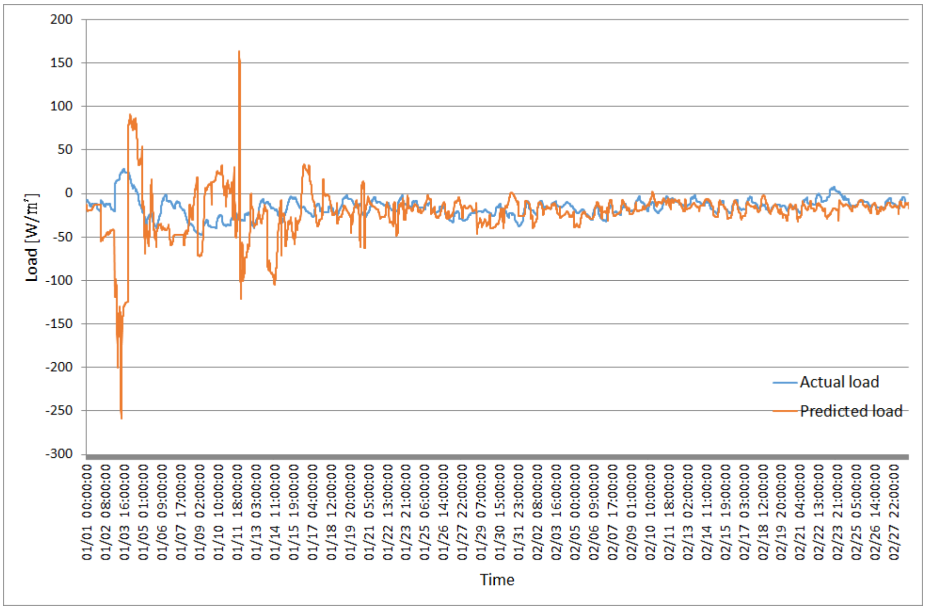


Figure 5.8 Load calculation with ANN on the heating season

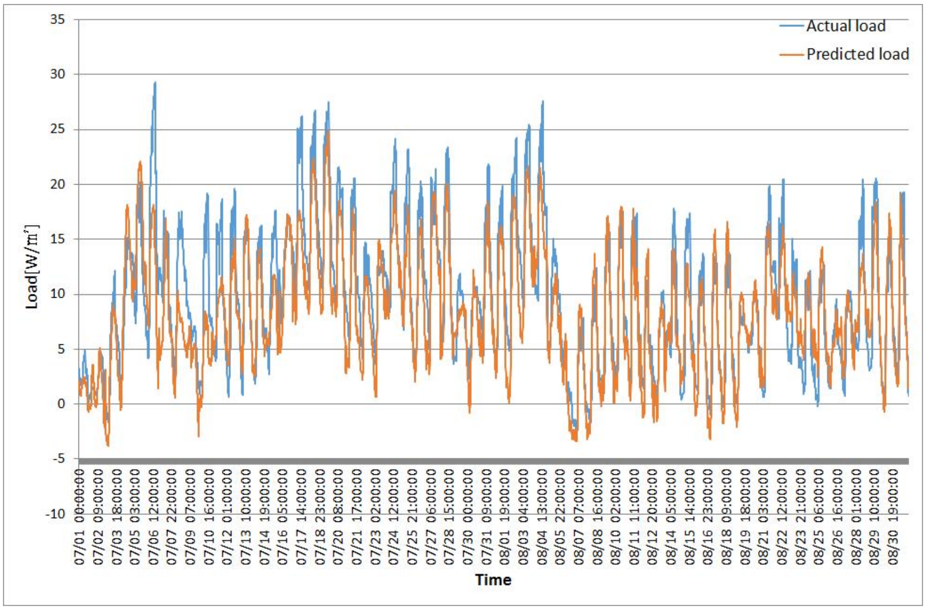


Figure 5.9 Load calculation with ANN on the cooling season

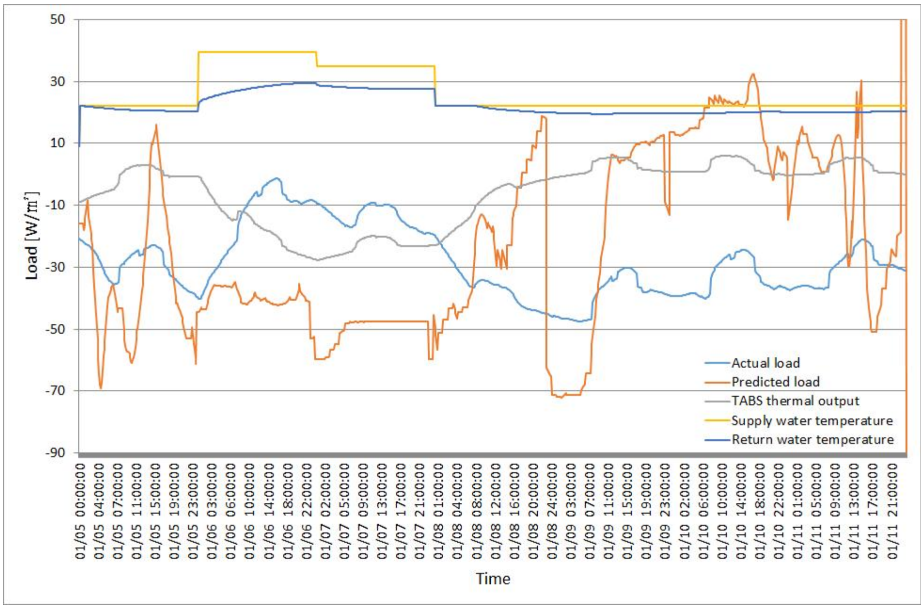


Figure 5.10 Performance of TABS with ANN load prediction on a peak heating week

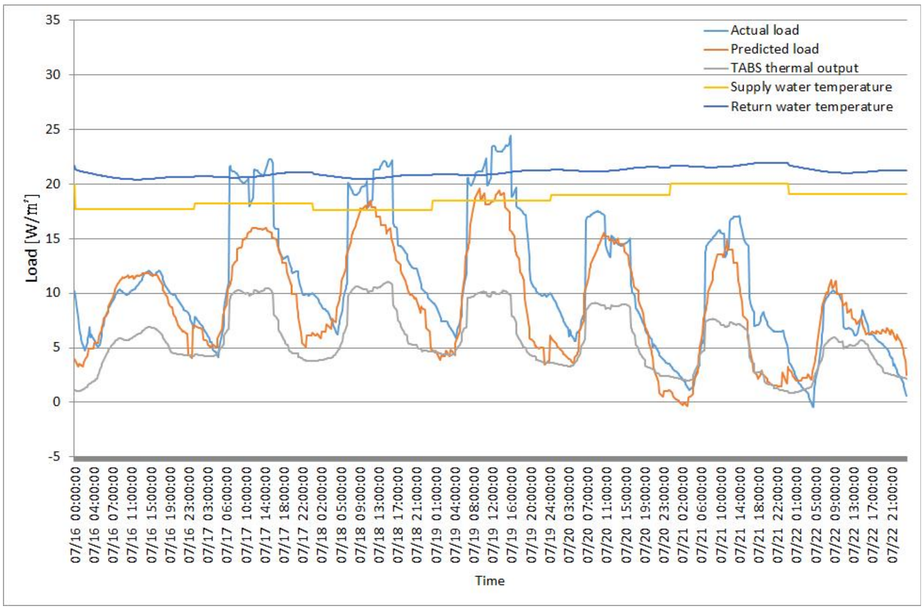


Figure 5.11 Performance of TABS with ANN load prediction on a peak cooling week

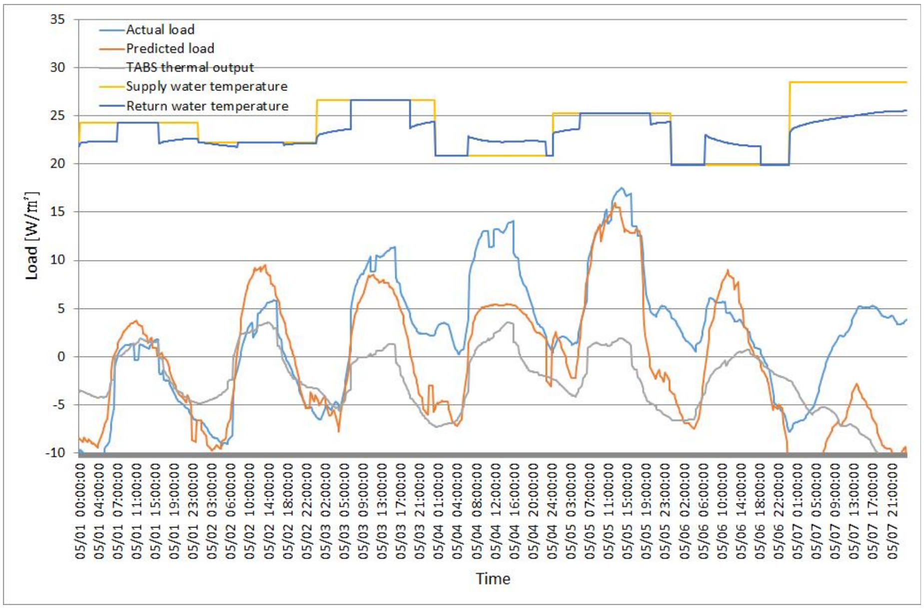


Figure 5.12 Performance of TABS with ANN load prediction on a week of intermediate season

During the intermediate season, because both cooling and heating load exist throughout the day, the type of target load is decided according to a comparison of the absolute value of the loads. Although the dominant load is targeted, the simultaneous heating and cooling loads can cause overheating and undercooling, depending on how the target load is determined. In addition, the accuracy of ANN during the intermediate season is very poor. Thus, a supply water temperature of 22 °C during the intermediate season is imposed to utilize the self-regulation effect instead of targeting the specific load. As Figure 5.13 demonstrates, overheating and undercooling can be avoided.

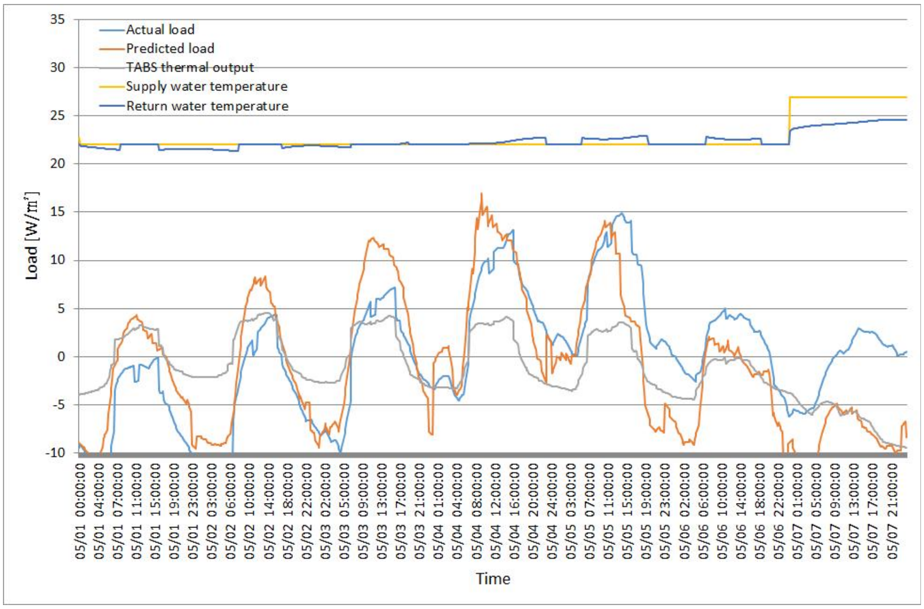


Figure 5.13 Performance of TABS with ANN load prediction on a week of intermediate season considering the overheating and undercooling

5.1.4 Integration of Outdoor Air Temperature Curve and load prediction

Because the performance of the ANN load prediction is very poor during the initiating period, the outdoor air temperature curve can be used until enough historical data is accumulated for the ANN. For a small office in the Chicago weather case, the ANN load prediction was inaccurate for a month and became accurate in February. Thus, the load prediction using outdoor air temperature is applied for a month and then the ANN load prediction is applied. In Figure 5.14, the integrated load prediction with outdoor air temperature and the ANN is demonstrated, and it can be seen that the overall accuracy of the prediction significantly increases.

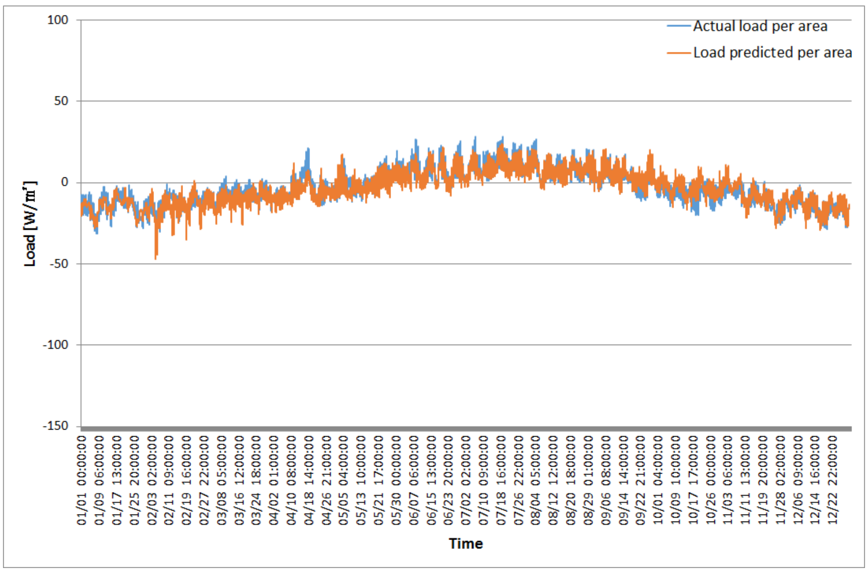


Figure 5.14 Outdoor air temperature curve and ANN load prediction

5.2 Validation of Control Method with Different Weather Conditions

5.2.1 Observation of Load Prediction and TABS Thermal Output

To perform a validation of the method, a co-simulation under Seoul weather conditions is performed. The integration of the outdoor air temperature curve and the load prediction is applied, and the daily TABS supply water temperature is decided based on the minimum predicted load over the next 24 h. In Figure 5.15, the load prediction is shown to have relatively high accuracy under Seoul weather conditions.

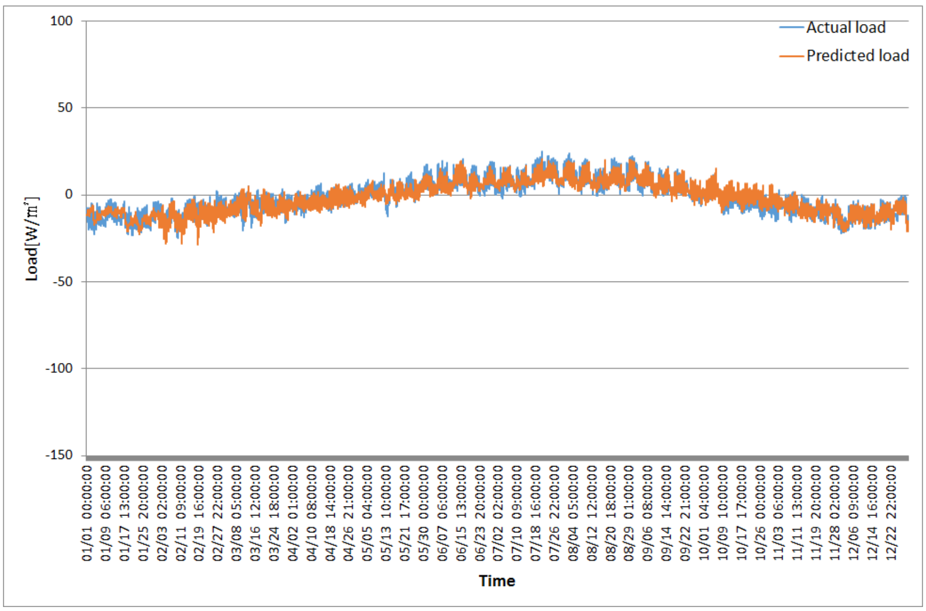


Figure 5.15 Outdoor air temperature curve and ANN load prediction with different weather conditions

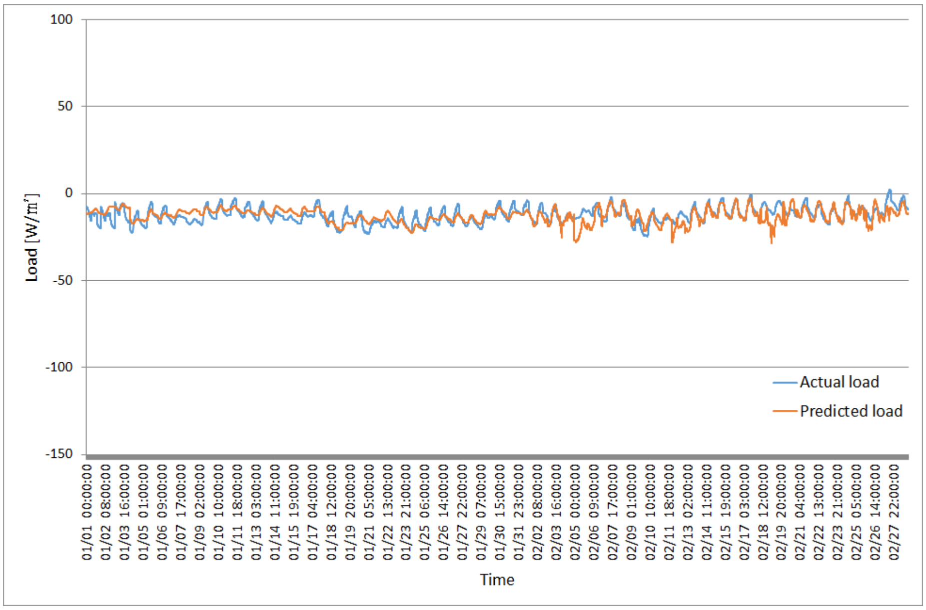


Figure 5.16 Outdoor air temperature curve and ANN load prediction with different weather conditions on a heating season

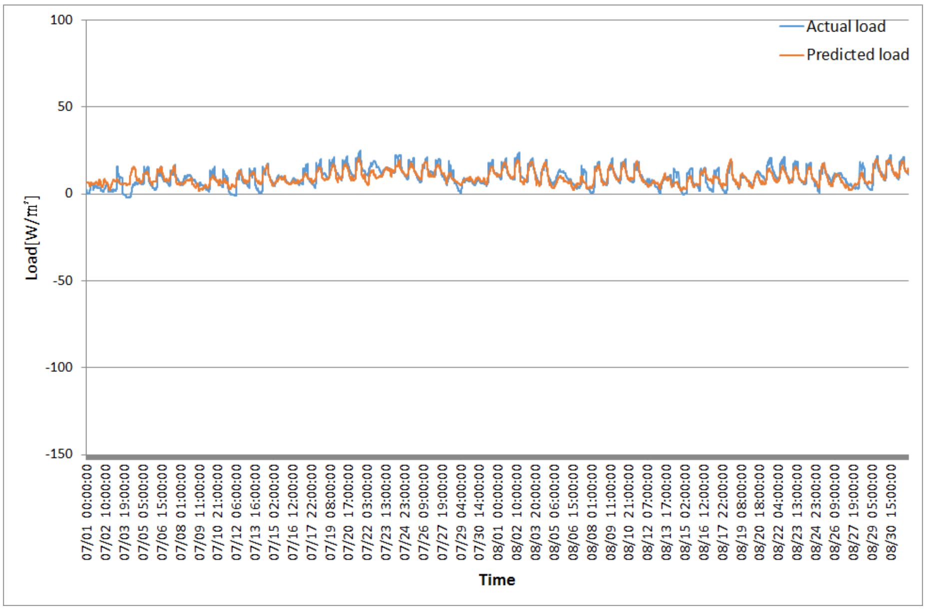


Figure 5.17 Outdoor air temperature curve and ANN load prediction with different weather conditions on a cooling season

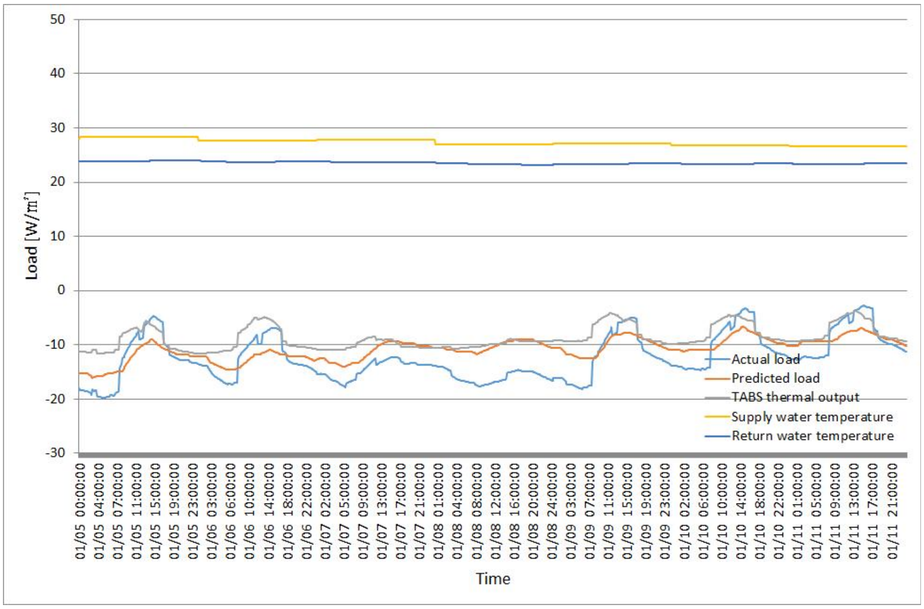


Figure 5.18 Performance of TABS with outdoor air temperature curve and ANN load prediction on a peak heating week

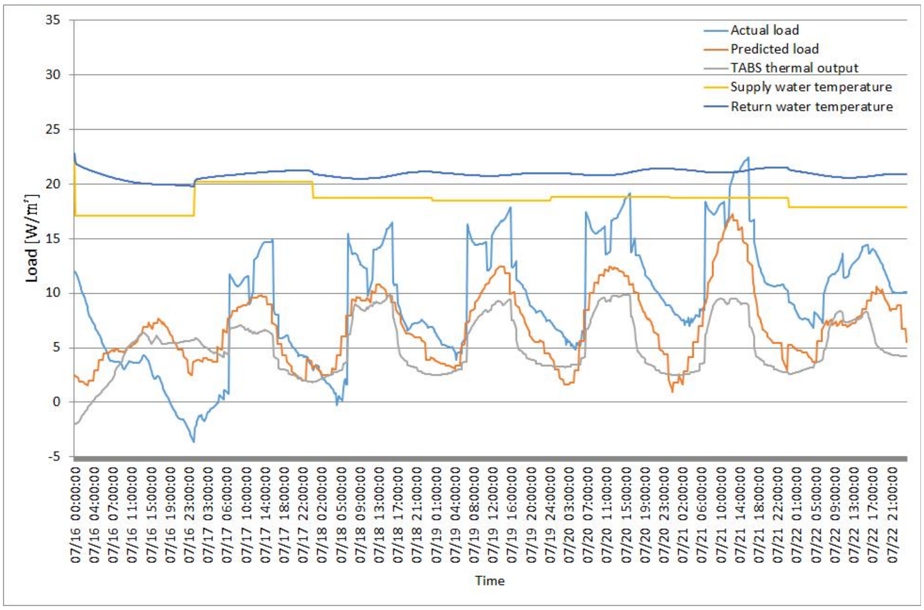


Figure 5.19 Performance of TABS with outdoor air temperature curve and ANN load prediction on a peak cooling week

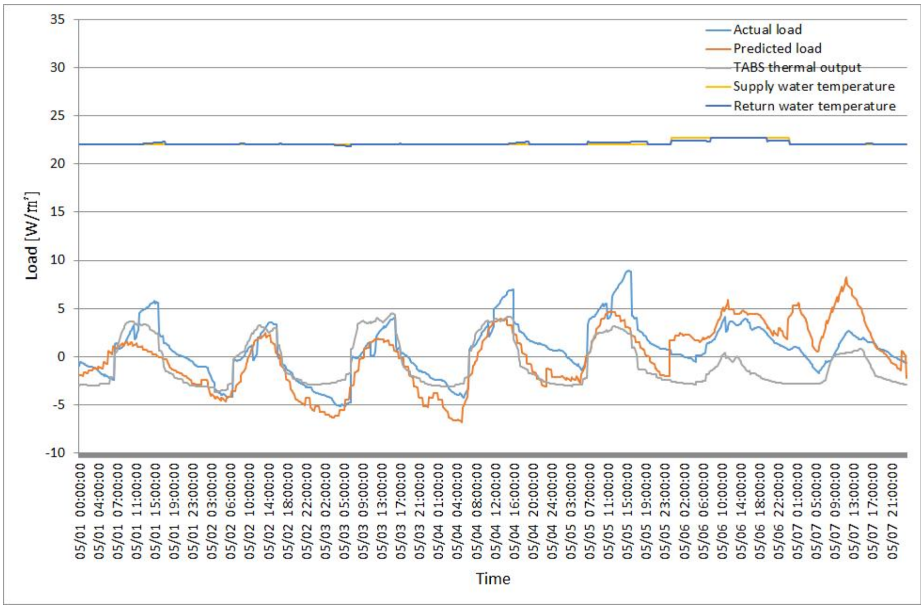


Figure 5.20 Performance of TABS with outdoor air temperature curve and ANN load prediction on a week of intermediate season

In Figures 5.18, 5.19, and 5.20, TABS can remove the target load as expected. However, condensation occurred on July 19th, 20th, and 21st because Seoul has more humid conditions than Chicago. Condensation on the surface should be avoided by limiting the minimum supply water temperature with the moisture calculation in each building.

5.3 Summary

To utilize the TABS with an accumulative learning pattern, the EnergyPlus and MATLAB co-simulation was performed with the middleware, BCVTB. During the heating season, the load prediction based on predicted outdoor air temperature demonstrated high accuracy due to the impact of outdoor air temperature on building load. However, the load prediction during the cooling season had lower accuracy because of the influences from solar radiation and internal load.

To increase the accuracy of the load prediction, other parameters, such as solar and internal load, should be considered. However, information on solar radiation and internal load were very difficult to obtain. Thus, the ANN statistical method was used to learn a pattern using historical data. The ANN load prediction was found to increase in accuracy after learning the pattern, and TABS could remove the basic load of the building. However, the initial period of the pattern learning process the pattern demonstrated poor accuracy. Therefore, the load prediction that used the outdoor air temperature curve and the ANN was integrated to improve the accuracy.

During the intermediate season, the target specific load for TABS may cause overheating and undercooling. Therefore, the conventional method to supply water at the room setpoint temperature may be applied to avoid the risk of overheating and undercooling.

Chapter 6 Conclusions

The most common methods used to control TABS utilize the self-regulation effect to keep the surface temperature the same as the room setpoint temperature. However, a problem arises from the lack of utilization of TABS, because the current control mechanism supplies the water temperature at the room setpoint temperature. Moreover, keeping the surface temperature at room setpoint temperature may have a lower effect than expected because the air system maintains the room within the setpoint temperature. The objective of the study is to identify the thermal mechanism and increase the utilization of TABS by adjusting the supply water temperature depending on the target load. To achieve this purpose, the following procedure was executed.

1) Observation of current method

A small office building from the DOE reference building was simulated and constant water temperature at the room setpoint temperature was supplied to TABS to handle the basic load of the building. However, the performance of TABS was not as high as expected because the amount of load triggers heat exchange and changes the surface temperature in next time period. Moreover, the air system removes the rest of the load and keeps the room air temperature at the setpoint temperature. The amount of load removed by TABS by the self-regulation concept decreases as the setpoint temperature was met at all times. Consequently, the active use of TABS should be executed by targeting the specific basic load.

2) Control method considering the characteristics of TABS

To actively use TABS, the system mechanism was analyzed with an RC network and it was discovered that the control interval should be at least 24 h. Thus, daily TABS control with an observation of hourly load was proposed.

After analyzing the system mechanism to determine the control time interval, the magnitude of load removed by TABS was decided. Among the many parameters that affect building load, the outdoor air temperature was selected to calculate the basic load of the building. This is because outdoor air temperature is one of the most influential parameter and the values from weather forecasts are relatively accurate. Thus, the external load was calculated using the building characteristics, and the heating and cooling curves used to select the supply water temperature based on the outdoor air temperature were derived.

Although the outdoor air temperature was one of the most influential factors and could predict the load relatively accurately, the difference between actual load and predicted load still exists. Thus, different parameters should be applied to increase the accuracy of the target load. Because other parameters cannot be measured or simply predicted, one of the statistical methods used to learn the pattern from the historical data, ANN, was used. ANN used outdoor air temperature, time, and type of day as input parameters. Initially, the load prediction did not meet the tolerance level proposed by industry standards for a one-month timeframe. After one month, a sufficient amount of historical data was gathered, the accuracy of the load prediction was increased, and the load could be properly targeted.

3) Application of control method and validation

To utilize TABS with an accumulative learning pattern application, a co-simulation of EnergyPlus and MATLAB was performed with the middleware, BCVTB. During the heating season, the load prediction using predicted outdoor air temperature demonstrated high accuracy due its impact on building load. However, the load prediction during the cooling season had lower accuracy due to the influences from solar radiation and internal load.

To increase the accuracy of load prediction, other parameters such as solar and internal loads should be considered. However, information on solar radiation and internal load are very difficult to obtain. Thus, the statistical method used to learn the pattern using historical data, such as ANN, was used. The ANN load prediction could increase the accuracy after learning the pattern, and TABS could remove the basic load of the building. However, the initiating period needed to learn the pattern demonstrated poor accuracy. Therefore, the load prediction that utilized the outdoor air temperature curve and the ANN was integrated to improve the accuracy.

During the intermediate season, the targeted specific load for TABS may cause overheating and undercooling. Therefore, the very conventional method of supplying water at the room setpoint temperature may be applied to avoid the risk of overheating and undercooling.

In this research, the utilization of TABS was increased by targeting the basic load with load prediction. The load prediction was specifically designed for TABS, and TABS was found to be able to remove the target load. In future, diverse types of buildings and schedules may be studied to increase the usability of TABS.

Appendix I Control algorithm in MATLAB

```
% Initialize model variables
delTim    = 600;  % time step
TIni      = 10;
tau       = 2*3600;
Q0Hea     = 100;
UA        = Q0Hea / 20;
TOut      = 5;
C         = [tau*UA 2*tau*UA];
MAT = [22]; % Values export to EnergyPlus
EP = zeros(1,8); % Value from EnergyPlus, 1) Heatoutput 2)
To 3)surface Temp 4) Zone air Temp 5)Air Cooling 6)Air
Heating 7)Supply water Temp 8)Return water Temp
% Initialize flags
retVal    = 0;
flaWri    = 0;
flaRea    = 0;
simTimWri = 0;
simTimRea = 0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Add path to BCVTB matlab libraries
addpath( strcat(getenv('BCVTB_HOME'), '/lib/matlab'));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
```

```
%%% Establish the socket connection
sockfd = establishClientSocket('socket.cfg');
if sockfd < 0
   fprintf('Error: Failed to obtain socket file descriptor.
sockfd=%d.\n', ...
      sockfd);
   exit;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Loop for simulation time steps.
simulate=true;
while (simulate)
   % Assign values to be exchanged.
   try
      [retVal, flaRea, simTimRea, EP] = ...
         exchangeDoublesWithSocket(sockfd,        flaWri,
length(EP), simTimWri, ...
         MAT);

   catch ME1
      % exchangeDoublesWithSocket had an error. Terminate
the connection
      processError(ME1, sockfd, -1);
      simulate=false;
   end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%    % Check return flags
    if (flaRea == 1) % End of simulation
        disp('Matlab received end of simulation flag from
BCVTB. Exit simulation.');
        closeIPC(sockfd);
        simulate=false;
    end

    if (retVal < 0) % Error during data exchange
        exception = MException('BCVTB:RuntimeError', ...
            'exchangeDoublesWithSocket returned value %d',
...
            retVal);
        processError(exception, sockfd, -1);
        simulate=false;
    end

    if (flaRea > 1) % BCVTB requests termination due to an
error.
        exception = MException('BCVTB:RuntimeError', ...
            ['BCVTB requested MATLAB to terminate by sending
%d\n', ...
            'Exit simulation.\n'], retVal);
        processError(exception, sockfd, -1);
        simulate=false;
    end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%    % No flags have been found that require termination
of the
   % simulation.
   % Having obtained u_k, we compute the new state x_k+1 =
f(u_k)
   % This is the actual simulation of the client.
   if (simulate)

      %save on matrix
      TABS ((simTimWri/600) +1,1) = EP(1);
      To ((simTimWri/600) +1,1) = EP(2);
      Ts ((simTimWri/600) +1,1) = EP(3);
      Ti ((simTimWri/600) +1,1) = EP(4);
      AirCoo ((simTimWri/600) +1,1) = EP(5);
      AirHea ((simTimWri/600) +1,1) = EP(6);
      Supply ((simTimWri/600) +1,1) = EP(7);
      Return ((simTimWri/600) +1,1) = EP(8);

      AirTotal = EP(5)+EP(6)*(-1);
      output ((simTimWri/600) +1,1) = AirTotal + EP(1);

      %hour matrix
      hour(1:52560,1)= 1:52560;
      hour = ceil(hour/6);
      hour = rem(hour,24);
```

```
        %day matrix
        day(1:52560,1)= 1:52560;
        day = fix((day-1)/144)+1;
        day = rem(day,7);

        %Define input parameters
        Para((simTimWri/600) +1,1) = EP(2);
        Para((simTimWri/600)  +1,2)  =  hour((simTimWri/600)
+1);
        Para((simTimWri/600)  +1,3)  =  day((simTimWri/600)
+1);

        %Reading variables
        if (rem((simTimWri/600)+1,52560) == 1)

            pPara  (1:52560,1)  =  xlsread('Outdoor.xls',
'sheet1', 'A2:A52561');
            pPara (1:52560,2) = hour;
            pPara (1:52560,3) = day;

            %for prediction
            pPara (52560:53704,3) = 0;


        end
```

```
        if (simTimWri/600) < 4464



        %runnung at the end of the day
        if (rem((simTimWri/600)+1,144) == 0)

            %Outdoor theoretical calculation
            pLoad  =  pPara((simTimWri/600)+2:(simTimWri/600)
+145, 1) * 365.64 - 6000;

            %Recording predicted Load
            pLoadRecord((simTimWri/600)    +1:(simTimWri/600)
+144, 1) = pLoad;

            %Min Max load record
            pLoadminRecord((simTimWri/600)+1,1) = min(pLoad);
            pLoadmaxRecord((simTimWri/600)+1,1) = max(pLoad);

            %Decide if Heating load or cooling load occurred
            TargetLoad = min(pLoad);

            if TargetLoad > 0
                TargetLoad = min(pLoad);
            else
                TargetLoad = max(pLoad);
            end
```

```
        %Intermediate Period
        if min(pLoad)<0 && max(pLoad)>0

            TargetLoad = (min(pLoad)+max(pLoad))/2;

        end

        %upper side heat loss
        TargetLoad    =    TargetLoad    +    (0.93    *    511
*(EP(2)-22));


        %Supply     water     temperature     =     2*(q/-kA
+Tin)-Treturn
        MAT =  2*(TargetLoad /(-8.29*511) + 22) - EP(8);

    end

    else

    %runnung at the end of the day
    if (rem((simTimWri/600)+1,144) == 0)

        %ANN Coding
        net=fitnet(10,'trainlm');
        net=train(net, Para', output');
```

```
%Applying next 24 hours and predict
nextPara = pPara((simTimWri/600)
+2:(simTimWri/600) +145, 1:3);
pLoad = net(nextPara')';

%Recording predicted Load
pLoadRecord((simTimWri/600) +1:(simTimWri/600)
+144, 1) = pLoad;

%Min Max load record
pLoadminRecord((simTimWri/600)+1,1) = min(pLoad);
pLoadmaxRecord((simTimWri/600)+1,1) = max(pLoad);

%Decide if Heating load or cooling load occurred
TargetLoad = min(pLoad);

if TargetLoad > 0
    TargetLoad = min(pLoad);
else
    TargetLoad = max(pLoad);
end

TargetLoad = TargetLoad + (0.93 * 511
*(EP(2)-22));
```

```
    %Supply water temperature = 2*(q/-kA +Tin)-Treturn
            MAT =  2*(TargetLoad /(-8.29*511) + 22) - EP(8);

            %Intermediate Period = supply water temp 22
            if min(pLoad)<0 && max(pLoad)>0
                MAT = 22;
            end
        end
        end

        % Advance simulation time
        simTimWri = simTimWri + delTim;
    end
end

%write matrix on file
xlswrite('write2.xls', TABS, 'sheet1', 'A2');
xlswrite('write2.xls', To, 'sheet1', 'B2');
xlswrite('write2.xls', Ts, 'sheet1', 'C2');
xlswrite('write2.xls', Ti, 'sheet1', 'D2');
xlswrite('write2.xls', AirCoo, 'sheet1', 'E2');
xlswrite('write2.xls', AirHea, 'sheet1', 'F2');
xlswrite('write2.xls', Supply, 'sheet1', 'G2');
xlswrite('write2.xls', Return, 'sheet1', 'H2');
xlswrite('write2.xls', output, 'sheet1', 'I2');
xlswrite('write2.xls', pLoadRecord, 'sheet1', 'J2');
xlswrite('write2.xls', pLoadminRecord, 'sheet1', 'K2');
```

```
xlswrite('write2.xls', pLoadmaxRecord, 'sheet1', 'L2');
exit
```

Appendix II Exact solution of RC network

$$\rho C_p V \frac{dT}{dt} = kA(T_{supply} - T_{surface})$$

(Laplace transform)

$$\rho C_p V(ST^{k+1}_{surface} - T^{k}_{surface}) = \frac{kAT_{supply}}{S} - kAT^{k+1}_{surface}$$

$$\rho C_p VST^{k+1}_{surface} - \rho C_p VT^{k}_{surface} + kAT^{k+1}_{surface} = \frac{kAT_{supply}}{S}$$

$$T^{K+1}_{surface}(\rho C_p VS + kA) = \frac{kAT_{supply}}{S} + \rho C_p VT^{k}_{surface}$$

$$T^{k+1}_{surface} = \frac{\dfrac{kAT_{supply} + \rho C_p VT^{k}_{surface}S}{S}}{\rho C_p VS + kA}$$

$$= \frac{kAT_{supply} + \rho C_p VT^{k}_{surface}S}{S^2\rho C_p V + SkA}$$

$$= \frac{\dfrac{kAT_{supply}}{\rho CpV} + ST^{k}_{surface}}{S(S + \dfrac{kA}{\rho C_p V})}$$

(Partial fraction)

$$\frac{A_o}{S} + \frac{B_o}{S + \dfrac{kA}{\rho C_p V}}$$

$$A_o(S+\frac{kA}{\rho C_p V})+SB_o=\frac{kA\,T_{supply}}{\rho C_p V}+ST^k_{surface}$$

$$A_oS+\frac{kA}{\rho C_p V}A_o+SB_o=ST^k_{surface}+\frac{kA\,T_{supply}}{\rho C_p V}$$

$$S(A_o+B_o)+\frac{kA}{\rho C_p V}A_o=ST^k_{surface}+\frac{kA\,T_{supply}}{\rho C_p V}$$

$$A_o+B_o=T^k_{surface}$$

$$A_o=T_{supply}$$

$$B_o=T^k_{surface}-T_{supply}$$

$$\frac{T_{supply}}{S}+\frac{T^k_{surface}-T_{supply}}{S+\frac{kA}{\rho C_p V}}$$

(Laplace inverse)

$$T^{k+1}_{surface}=T_{supply}+(T^k_{surface}-T_{supply})e^{\frac{-kA}{\rho C_p V}t}$$

k : Thermal conductivity [W/m K]

A : Area [㎡]

T_{supply} : Supply water temperature of TABS [℃]

$T^k_{surface}$: Surface Temperature of TABS in current time [℃]

$T^{k+1}_{surface}$: Surface Temperature of TABS in next timestep [℃]

ρ : Density [$\frac{kg}{m^3}$]

C_p : Specific heat [J/kg K]

V : Volume [㎥]

S : Laplace complex variable [radian/hour]

t : time [hour]

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국 문 초 록

건물실내 조건은 쾌적성을 유지시키기 위해 냉난방 시스템이 제어한다. 여러 가지 냉난방 시스템 중 에너지절약적이고 쾌적성을 증가시킬 수 있는 복사시스템이 대두되고 있다. 복사시스템 중 구조체를 냉난방 시스템으로 사용하는 구체축열 시스템은 파이프를 콘크리트에 매설하여 활용한다. 이러한 시스템은 별도의 냉난방 시스템을 설치하기 위한 공간이 감소하므로써 설치비용이 감소하고 건물 자재를 줄일 수 있으며 층고를 낮출수 있는 장점이 있다. 구조체 전체를 냉난방 시스템으로 활용하는 시스템은 세분화된 제어가 어렵기 때문에 시스템이 가장 기본적인 부하를 처리하게 설계된다. 많은 관련된 연구는 여러 가지의 요소를 바탕으로 기본적인 부하를 처리를 제안하지만 가장 기본적인 방법은 self-regulation을 이다. self-regulation 은 구체축열 시스템의 표면온도를 설정실온으로 유지하여 활용하여 부하발생 시 시스템 표면온도와 실온의 변화로인해 발생하는 열교환으로 처리하는 방법이다. 이러한 방법은 별도의 냉난방에 대한 고려 없이도 냉난방이 되는 것이 장점이지만 처리되는 냉난방 부하량이 제한되어 건물 실내의 쾌적성을 만족시키기 위해서는 별도의 공조시스템이 사용된다. 현재 self-regulation을 실행하기 위한 방법으로 공급수 온도를 실내설정온도로 사용하는데 이러한 방법은 구체축열 시스템의 냉난방 부하처리량을 감소시킨다. 따라서 본 연구에서는 구체축열 시스템의 열적 메카니즘 해석과 부하에 따른 구체축열 시스템 운전을 실행하여 구체축열 시스템의 활용성을 증가시키는 것을 목적으로 한다.

복사시스템의 활용성을 증가시키기 위해서는 과거 제어방안이 어떠한 열적 메카니즘으로 부하를 처리하는지 자세한 분석이 있어야한다. 구체축열 시스템의 상황별 열적 메카니즘을 바탕으로 제어의 방향성을 제시해야 한다. 과거 제어방안은 구체축열 시스템에 실내설정온도의 물을 공급하여 self-regulation을 구현한다. 하지만 이 방법은 표면온도를 실내설정온도로 유지할 수 없으므로 구체축열 시스템의 활용성을

감소시킨다. 또한 공조시스템이 지속적으로 쾌적성을 만족시키기 위해 실내설정온도로 실내 조건을 만들어주기 때문에 부하로 인해 발생하는 실내온도변화는 미비하여 구체축열 시스템의 활용성이 기대했던 것 보다 낮아진다. 그러므로 구체축열 시스템을 능동적으로 목표로 하는 부하에 대해 제어를 해야 활용성을 높일 수 있다.

능동적으로 구체축열 시스템을 활용하기 위해서는 구체축열 시스템의 열적 메카니즘이 분석되어야 하고 목표로 하는 부하가 설정되어야한다. 열적 메카니즘을 분석한 결과 구체축열 시스템이 가지고 있는 시간지연으로 인해 원하는 방열량에 도달하기까지 많은 시간이 소비되므로 시간별 제어가 아닌 일별제어를 제안한다. 목표로 하는 부하를 설정하기 위해서는 하루가 시작되는 시점에서 24시간 미래의 부하를 알아야 한다. 24시간의 부하 예측 중에서도 최소부하를 기준으로 구체축열 시스템을 운전해야 가장 기본적인 부하를 처리할 수 있다. 따라서 부하예측이 실행되어야 목표로 하는 부하를 설정될 수 있다. 본 연구에서는 외부온도를 RC network를 바탕으로 예측하는 보편적인 방법과 인공지능 방법인 인공신경망을 사용해 부하를 예측하였다. 인공신경망을 이용하는 부하예측은 부하 종류를 외부부하, 일사부하, 내부부하로 나누어 고려하였고 입력변수로써 외부온도와 청명지수와 요일을 사용하였다. 특히 외부온도와 청명지수는 일기예보를 활용하여 정확성을 높였다. 인공신경망을 활용하는 예측방법은 초반에 과거 데이터 부족으로 정확성이 떨어졌지만 한달동안의 학습으로 활용가능한 정확성을 나타냈다. 본 연구에서는 인공신경망이 부족한 정확성을 높이기 위해 외부온도를 활용하는 부하예측을 정확성이 확보될때까지 활용하는 방법을 제시하고자 한다.

제시된 부하예측 방법을 바탕으로 구체축열 시스템이 건물의 기본적인 부하를 처리하는 것을 구현하기 위해 EnergyPlus 와 MATLAB 의 co-simulation을 실행하였다. EnergyPlus 는 건물을 모사하기 위해 사용되었고 MATLAB 은 인공신경망을 계산하기 위해 사용되었다. 건물과 제어를 각 Timestep별로 사용하여 구체축열 시스템의 시간지연을 고려하기 위해 middleware인 BCVTB를 활용하였다. 본 연구

에서는 구체축열 시스템을 앞서 제시된 부하예측을 사용하여 기본부하를 처리하였고 각 다른 부하예측 방법을 적용시켜 비교분석을 실행하였다. 다른 날씨와 재실 스케줄을 사용하여 부하예측을 활용하는 구체축열 시스템의 활용성을 검증하였다.

주요어 : 구체축열 시스템, 예측제어, 방열특성, Co-simulation
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