OPERATION MODE OF A THERMALLY ACTIVATED BUILDING SYSTEM ACCORDING TO THE STARTING TIME AND THE OPERATING HOURS IN RESIDENTIAL BUILDING

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1. Introduction

To maintain room the temperature comfortably, Packaged Terminal Air Conditioning (PTAC) Systems are applied in residential buildings. The areas of the application of PTAC are expanding very quickly. The wide use of PTAC systems, however, affects the total energy consumption and the peak electric energy consumption during cooling sessions. When the peak electric consumption occurs all at once, it causes problems with the power supply.

Compare to the PTAC system, the Radiant Cooling System has the advantages of energy savings and thermal comfort. To obtain these advantages, it is important to supply the proper temperature of cooling water from the heat source. Thermally Activated Building System (TABS), a type of radiant cooling systems uses the building structure as a type of thermal storage. This makes it possible to supply a higher water temperature for cooling due to the thermal storage effect reduces peak cooling load. Thus, TABS is a useful system which enables a heat source to supply a higher water temperature for cooling.

When designing TABS, it is important to consider the elements which affect the thermal performance of TABS. There are elements for design and operation. TABS could be used with PTAC to avoid condensation and to satisfy exact set temperature. Therefore, the operation time and pattern of PTAC should be considered.

Sensible cooling loads are compatible with TABS, in which pipes are embedded in concrete slabs. Because TABS uses the building mass for cooling, there might be thermal storage effect or time-lag. Therefore, control concept that should be used is predetermined. Especially in the case of a residential building, the internal heat gain is uncertain compared to an office building. Thus, the operation mode should be defined more carefully considering the PTAC operation mode and the cooling load pattern.

In this study, the correlations between various operation modes and thermal performance of TABS are estimated. Also, thermal performance according to the operation starting time and the operation duration time are presented by using dynamic computational simulation method. The objective of this study is to analyze the thermal performance of TABS according to various operation modes for residential buildings.

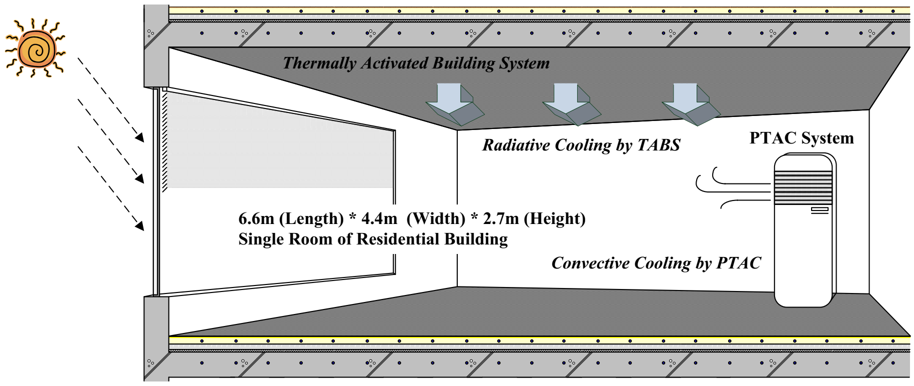
2. Method

To estimate the effect of the operation mode on thermal performance of TABS, the one zone model is simulated using a computational simulation program. The simulation cases consist of the operation starting time and the operation duration time of TABS.

2.1. Zone Model and Simulation Boundary Condition

The EnergyPlus (Ver.6.0.0) simulation program is used to analyze the thermal performance and to estimate the energy consumption of TABS under various operation modes. The Tab. 1 shows the boundary condition. The simulation assumes a standard one zone room 6.6m (Length) * 4.4m (Width) * 2.7m (Height) in size facing the southeast direction in Seoul, Korea. Because the purpose of this study is to estimate the thermal performance of the cooling period, the simulation is run for the period of July 1 to August 31. The room has a window ratio 75% and a typical blind. This represents the standard room in Korean residential building.

Tab. 1: Characteristics of the building component

Subject	Contents
Simulation program	EnergyPlus V.6.0.0
Orientation	East-South
Location	Seoul
Zone	Single room
Area	4.4m (Width) * 6.6m (Length) * 2.7m (Height)
Peak Cooling Load	45 W/m^2 (Sensible)
System	Packaged Terminal Air-Conditioning System Thermally Activated Building System Heat Exchanger
Room Model Used for the Computer Simulation of a TABS	

The peak sensible cooling load of this room is 45W/m^2 during simulation period. In this room, three different systems are applied. The heat exchanger is applied because the Korean Building Code forces the apartment buildings to install the heat exchanger since Jan 2006. Also, TABS and PTAC are applied. TABS once remove the cooling load as operation mode, and then PTAC is operated to remove rest of the cooling load to satisfy the room set point temperature.

2.2. System Design and Operation Mode Concept

The elements which affect on thermal performance of TABS could be classified into the two categories. The first is element for designing TABS associated with steady-state. This element is for designing TABS in a steady-state condition. The EN15377 introduces this element by defining the thermal resistance method equation to obtain heat output of TABS. This element includes Surface covering, Pipe, Concrete and Piping. The second element is for operating TABS associated with an unsteady-state. The thermal storage and thermal capacity term belong to this second element. Olesen (2007) performed previous study about this element. The previous study considers a thermal storage effect occurred by the pump operation. This element includes time of operation. In TABS, pipes embedded in the concrete slab would result in a system with a high thermal mass. In this case, the existing control method would not proper because of time delay effect. Previous study and Standards reveals that time related term is obviously affect on the thermal performance of thermal storage system.

This is the reason why the operation starting time and the operation duration time of TABS are estimated in this study. As TABS could only eliminate the sensible load, co-operation with PTAC should be considered to handle the latent load and to prevent condensation. The aim of the TABS operation mode control is lower the PTAC use and energy consumption.

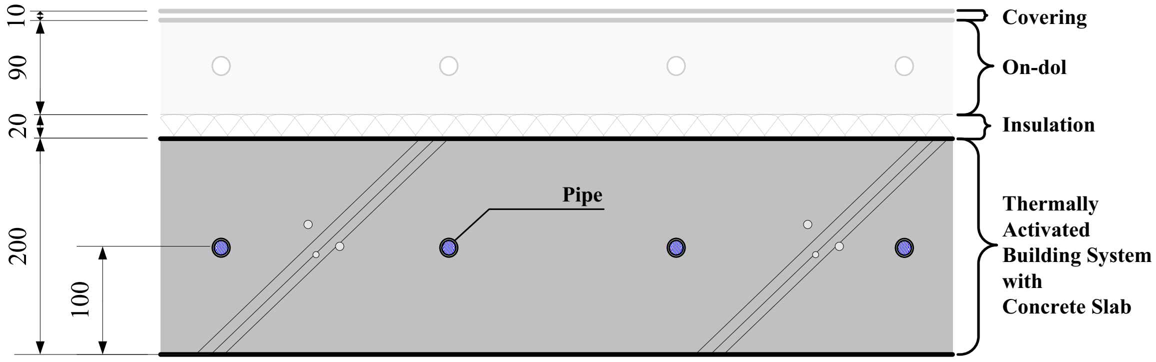


Fig. 1: Sectional design of thermally activated building system

2.3. TABS and PTAC System Configuration

TABS is a system which use a concrete slab as a heating and cooling surface and for thermal storage. Because it uses a structural slab for heating and cooling, it requires some critical design element. For example, the pipe spacing and piping depth according to the structural reinforcement should be considered. Kim (2010) and Park (2010) designed TABS considering these elements. In this study, a TABS section is designed considering the findings in previous research.

The TABS design is similar to the traditional radiant heating and cooling system, known as on-dol. However, it is designed by considering the critical design elements mentioned above. An influence analysis is done to determine the important elements that strongly influence the thermal output. The TABS is designed reflecting the priority of the design elements.

The elements outlined below were determined. These are listed in Tab. 2. The design elements were classified into the two categories of fixed or variable. The fixed design elements cannot change. Their values are determined through structural or constructional considerations that cannot change easily. These elements include the surface covering, pipe outside diameter, pipe thickness, pipe conductivity, concrete thickness and concrete conductivity.

On the other hand, the values of variable design elements are easy to change in the design of the thermal performance changes. These elements include the piping (the laying depth and spacing). In an earlier study, the laying depth was confirmed to be 100mm and the spacing was confirmed to be 200mm. A laying depth of 100mm would avoid interference with the upper and lower structural reinforcing rods. A spacing of 200mm offers a steady surface temperature distribution similar to that of a common radiant floor heating system.

In many cases, PTAC system is installed in Korean residential building. In cooling season, a resident use this system to control the set point room temperature satisfying ones thermal comfort. Regarding this situation, the regular capacity PTAC system is applied. PTAC system covers additional cooling load, when TABS dissatisfying the set point room temperature.

Tab. 2: Properties of thermally activated building system design element

Fixed						**Variable**	
Surface covering	**Pipe**			**Concrete**		**Piping**	
Thermal resistance [m^2°C/W]	Outside diameter [m]	Thickness [m]	Conductivity [W/m°C]	Thickness [m]	Conductivity [W/m°C]	Laying depth [m]	Spacing [m]
0.00	0.016	0.0015	0.35	0.20	1.90	0.10	0.20

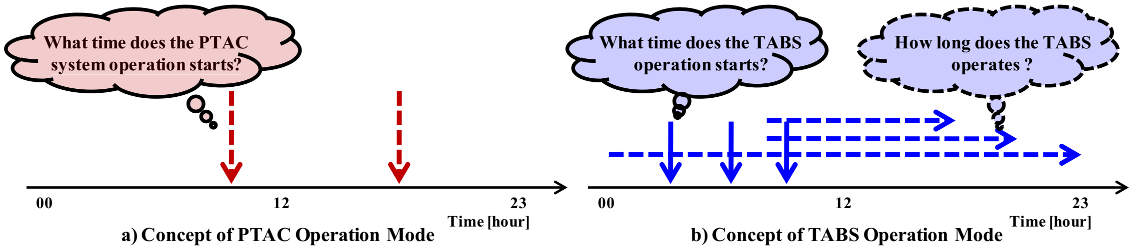


Fig. 2: Concept of PTAC and TABS operation mode

2.4. Description of System Operation Mode Concept

To applying TABS in a residential building, the correlation between the PTAC and TABS operation should be considered. In residential buildings, the cooling load profile is not constant. In the afternoon, the solar energy transmitted inside through windows and causes a change in the cooling load. In the evening the internal heat gain increases as the family members get back from work. To remove cooling load effectively, two factors are important in determining the operation mode of PTAC and TABS –the operation starting time and the operation duration time. Fig. 2 shows the control concept of PTAC and TABS. The red dotted line describes the PTAC operation mode. The operation mode of PTAC considers the PTAC use pattern in a residential building under cooling. The blue line describes the TABS operating mode. The solid blue line refers to the TABS operation duration time – a short operating time or long operating time. The blue dotted line refers to the TABS operation starting time – an early start or a late start.

2.5. Operation Mode

As mentioned above, the two main factors, the operation staring time and the operation duration time are closely considered when designing the TABS. Because the operation of TABS closely related to the operation of PTAC, the operation modes of PTAC and TABS should be determined. First, the operation mode of PTAC could be determined from the result of the PTAC Usage Time Study by the Korea Energy Management Corporation. Fig. 3 shows the pattern of the PTAC operating time in cooling session. From 10:00 to 15:00, PTAC operates as the solar heat gain increases. The peak cooling load occurs at 13:00. PTAC operation is also increased from 17:00 to 22:00 as the family members come from work increases.

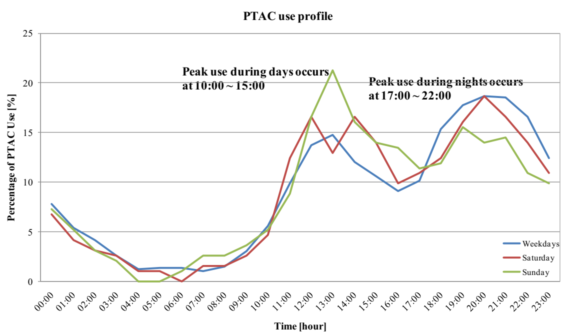


Fig. 3: PTAC use profile of residential building

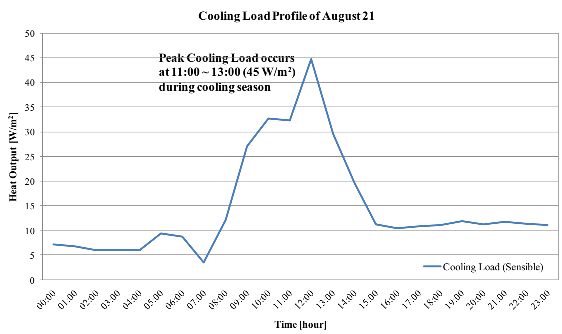


Fig. 4: Cooling load Profile and peak cooling load (Sensible)

Tab. 3: TABS operation mode according to operation starting time and operation duration time

Mode	System	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Mode1	TABS											■	■	■	■	■	■	■	■	■	■	■	■		
Mode2								■	■	■	■	■	■	■	■	■	■	■	■						
Mode3				■	■	■	■	■	■	■	■	■	■	■	■										
Mode4												■	■	■	■	■	■	■	■						
Mode5		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
-	PTAC											■	■	■	■	■					■	■	■	■	■

Second, the operation mode of TABS could be determined from the cooling load profile of the peak cooling load day (21st of August). Fig. 4 shows the pattern of the cooling load profile at 21st of August. The peak cooling load is 44.8 W/m^2. Due to the high solar heat gain through the windows, the peak load appears at 13:00. The operation mode of TABS is determined to estimate this cooling load efficiently as Tab. 3.

- *PTAC operation mode*

If PTAC is operated always, the set temperature would be easily satisfied. However, in this case, frequent PTAC operation may damage the PTAC compressor. It also requires a considerable amount of electricity for cooling for the long term use of PTAC. Therefore, the PTAC operation time should be set as close to the actual time as possible in keeping with the PTAC operating pattern. Considering this trend in PTAC use, the PTAC operation start time is set as 10:00 and 19:00. PTAC operation duration time is set as 5 hours from 10:00 and as 3 hours starting at 19:00.

- *TABS operation mode*

If TABS operates very briefly, this condition is not sufficient to remove the cooling load. In contrast, if TABS cools down the concrete structure for too long a time, the room would be under cooled and condensation will be occurred. Considering these conditions, the TABS operation duration time is to set 8 hours, 12 hours and 24 hours depending on the cooling load profile. The TABS operation starting time is also determined depending on when the peak cooling load occurs. The TABS operation start time is set as 10:00, 06:00 and 02:00 (earlier).

3. Result and Discussion

The simulation was done for both the operation starting time and the operation duration time. The results of the simulation are listed in Tab. 4. This table shows the simulation result according to the TABS operation starting time and the operation duration time. The results for the cooling period July 1 to August 31 are shown. The total number of hours in this period is 1,464. The simulation results are sorted according to the thermal comfort (room temperature, operative temperature, condensation on the surface) and the energy level (running hours, energy consumption of each system). The standard of comfortable room temperature is 24℃ to 26℃ based on the ASHRAE standard 55 and on the ISO 7730. The standards of the calculated operative temperatures are compared to the comfort range of 24℃ to 27℃ recommended for the cooling period in the ASHRAE standard 55 and in the ISO 7730.

Comparing operation starting time and operation duration time is estimated both total simulation period and detailed period. During detailed period of August 20 to August 22, the peak load is appeared as Fig. 5.

From simulation result, all modes are seen that the ceiling surface temperature never exceeds 26.0℃ and also below 17.0℃. It meets the acceptable surface temperature range for ceiling. The room temperature range is shown about 23.0 to 30.0℃. The maximum room temperature of 30.0℃ has some concerns because it could exceed thermal comfort range of the ASHRAE. Operative temperature also looks similar with room temperature. At all operation modes, TABS is operated first to eliminate the base load and next PTAC is operated to eliminate additional load.

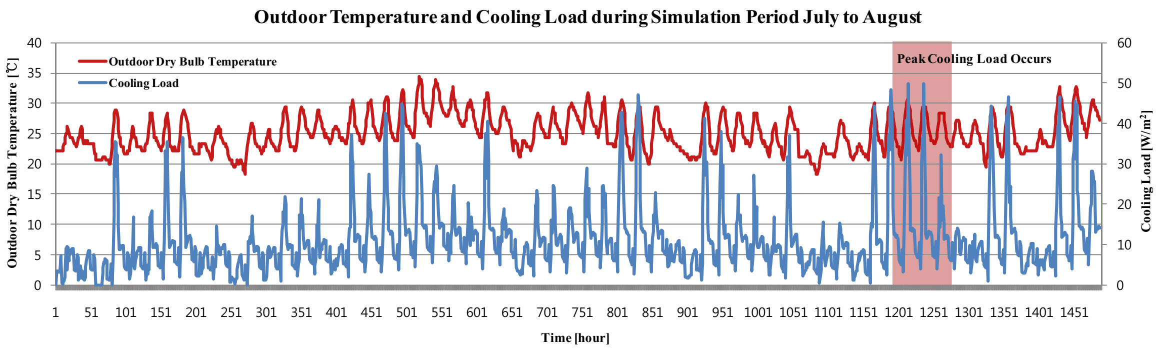


Fig. 5: Outdoor temperature and cooling load pattern during simulation period

Tab. 4: Room temperature, operative temperature, running hour of TABS and PTAC, energy consumption of TABS and PTAC, condensation occurring hour, and total energy consumption (Comparing Operation Starting Time)

Subject		**July 1 to August 31**		
		Mode1	**Mode2**	**Mode3**
		Start at 10:00	Start at 06:00	Start at 02:00
Room temperature [℃]	< 24	0	3	0
	24 - 26	1,123	1,087	1,091
	26 <	365	398	397
Operative temperature [℃]	< 24	0	0	0
	24 - 26	1,127	1,084	1,083
	26 <	361	404	405
TABS operating hour [hours]		744	744	741
TABS energy consumption [Wh]		339,358	340,287	339,995
PTAC operating hour [hours]		391	368	369
PTAC energy consumption [Wh]		140,369	142,810	142,014
Condensation occurring hour [hours]		0.0	0.0	6.0
Condensation ratio [% of time]		0.0	0.0	0.4
Total energy consumption [Wh]		479,727	483,097	482,008

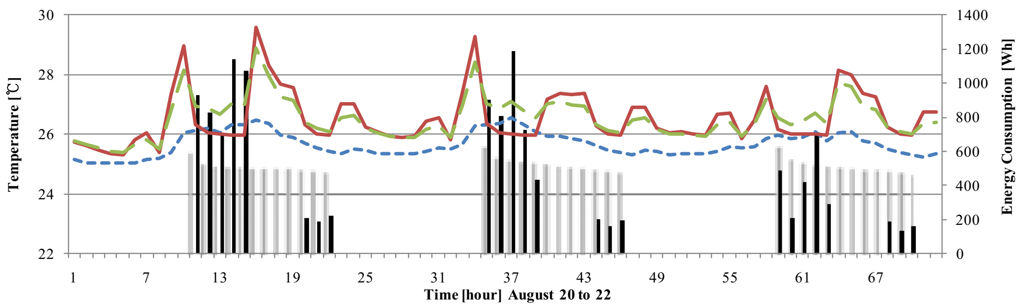
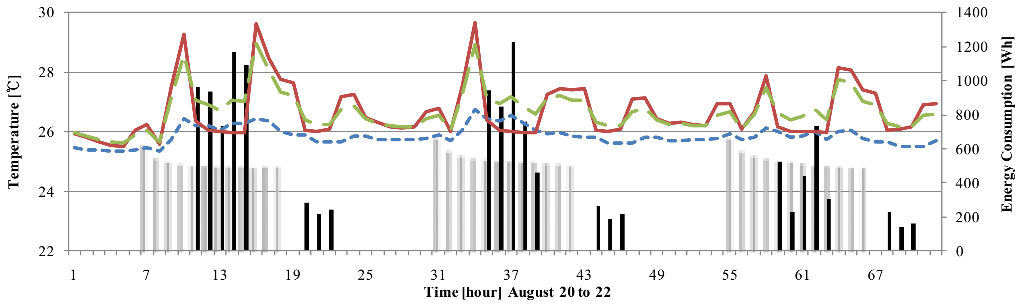
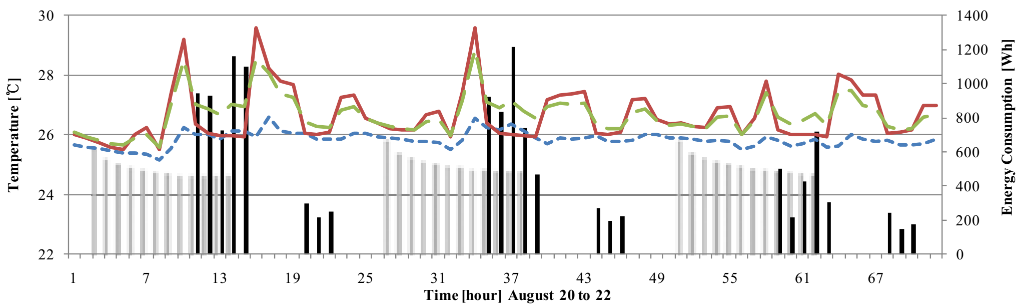
Tab. 5: Room temperature, operative temperature, running hour of TABS and PTAC, energy consumption of TABS and PTAC, condensation occurring hour, and total energy consumption (Comparing Operation Duration Time)

Subject		**July 1 to August 31**		
		Mode1	**Mode4**	**Mode5**
		Operated 12 hours	Operated 8 hours	Operated 24 hours
Room temperature [℃]	<24	0	0	31
	24-26	1,123	961	1,297
	26<	365	527	160
Operative temperature [℃]	<24	0	0	32
	24-26	1,127	832	1,339
	26<	361	656	117
TABS operating hour [hours]		744	496	1,448
TABS energy consumption [Wh]		339,358	274,115	441,069
PTAC operating hour [hours]		391	413	311
PTAC energy consumption [Wh]		140,369	171,847	96,459
Condensation occurring hour [hours]		0.0	0.0	67.0
Condensation ratio [% of time]		0.0	0.0	4.5
Total energy consumption [Wh]		479,727	445,962	537,528

3.1. Comparing Operation Starting Time

The mode1, mode2 and mode3 all have the same operation duration time of 8 hours. The difference is the operation start times of 10:00, 06:00 and 02:00, respectively. The reference case is mode1, where the operation start time is 10:00. Under the same operation duration time, mode2 and mode3 both move up the operation starting time by 4 hours. *(Mode1)* Mode1 operates 2 hours before the maximum cooling load appears. Because mode1 cools the room while the cooling load appears in the afternoon, it can very easily handle the cooling load. Only small percentage of overheating and no under-cooling occurs. TABS eliminate the cooling load of the day and the evening with the PTAC. Tab. 6 shows that operation mode1 is superior in cooling load pattern of the residential building. *(Mode2)* Generally, mode2 shows a temperature distribution and energy consumption pattern similar to mode3. The mode2 could decrease under-cooling early in the morning but has difficulty to handle the cooling load during the evening. The comfort temperature percentage is low compare to mode1. *(Mode3)* Mode3 runs TABS earlier at 02:00. Mode3 is superior when the peak cooling load occurs at night. However, when the cooling capacity is too high or the cooling load is too small, under-cooling can occur. The simulation result shows that TABS cools the room too much at night, implying that the occupants may feel thermal discomfort at this time. Because cooling starts very early, the cooling load which arises in the evening could not be eliminated. From Tab. 6, mode3 in this operation case is not appropriate to handle the cooling load at night, with a cooling load of 17:00 to 22:00. From Tab. 6 we can find the mode3 has the high surface and the high room temperature when TABS does not operate.

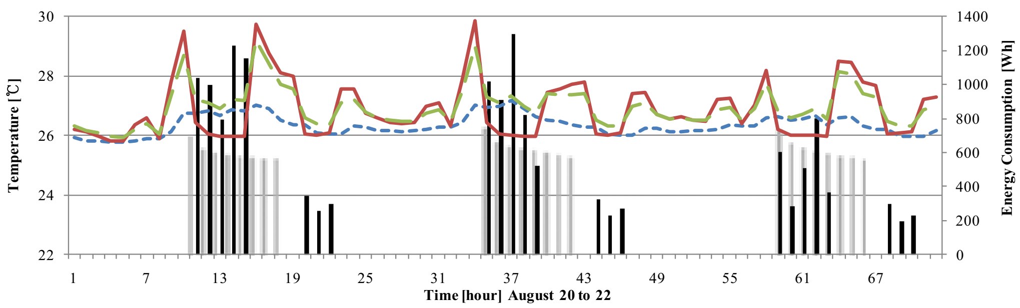
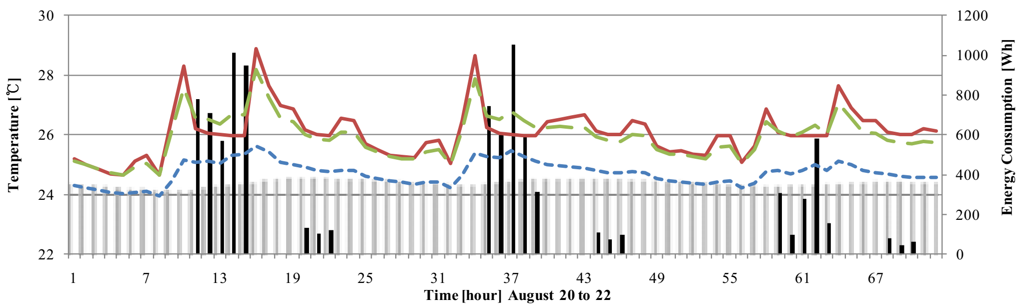
Tab. 6: Temperature and energy consumption according to the operation starting time

<table>
<tr><th>Operation Mode</th><th>Temperature and Energy Consumption
For Operation Starting Time (10:00, 06:00, 02:00)</th></tr>
<tr><td>Mode1
(Start at 10:00)</td><td>
</td></tr>
<tr><td>Mode2
(Star at 06:00)</td><td>
</td></tr>
<tr><td>Mode3
(Start at 02:00)</td><td>
</td></tr>
<tr><td>Legend</td><td>TABS energy consumption [Wh]   PTAC energy consumption [Wh]
Room Temperature [℃]   Operative Temperature [℃]   Ceiling Temperature [℃]</td></tr>
</table>

3.2. Comparing Operation Duration Time

The results of the simulation are shown in Tab. 7. Tab. 7 shows the outside temperature, room temperature and operative temperature distribution. *(Mode4)* TABS under operation mode4 (reduced operation time) is operated only 8 hours compared to mode5 at 24 hours for a reduced operation time. This cannot remove the cooling load as shown in Tab. 7. The operative temperature increases over the thermal comfort range during the day when the amount of the solar heat gain is great. Although the total running time of TABS is short and the amount of energy consumption is small, the occupants would feel thermal discomfort. In this case, more cooling energy is required. The energy consumption of PTAC is also high because TABS could not radiate sufficient heat output. As seen in Tab. 7 the temperature distribution is generally high. *(Mode5)* On the other hand, mode5 shows an operation mode of 24 hours of TABS running time. It shows a high percentage of time in the operative temperature comfort range due to the long time cooling operation. It is considerable that this result shows the TABS could handle a large percentage of cooling loads. However, the 24-hour operation incurs too much cooling output, as 31 hours of under-cooling occurs early in the morning. As seen in the Tab. 7 the ceiling surface temperature is low compared to other operation modes, although the graph is the result of the peak cooling load occurring day. The continuous operation leads to condensation due to the low ceiling surface temperature. Only during operation in mode5 was it noted that condensation occurs. 24 hours of operation results in significantly greater energy consumption of 441 kWh during the cooling period. In this simulation, the supply water temperature is set same in all operation modes. The all-time operation mode could be improved by adjusting supply water temperature. It means the percentage of cooling load for TABS could be lowered. *(Mode1)* The mode1 operates TABS neither short nor long, at about 744 hours while PTAC runs for 370 hours. In this operation mode, the total heat output and cooling load are balanced indicating that more than 75% of the occupants feel comfortable. The PTAC energy consumption and the total energy consumption in mode1 are low owing to the operation of TABS. Although some overheating occurs in the afternoon, this mode eliminates the cooling load effectively in conjunction with PTAC When cooling load pattern is not constant, it is proper that operating TABS before some hours before peak cooling load occurs.

Tab. 7: Temperature and energy consumption according to the operation duration time

<table>
<tr><th>Operation Mode</th><th>Temperature and Energy Consumption
For Operation Starting Time (10:00, 06:00, 02:00)</th></tr>
<tr><td>Mode4
(Operating 8 hours)</td><td>
</td></tr>
<tr><td>Mode5
(Operating 24 hours)</td><td>
</td></tr>
<tr><td>Legend</td><td>TABS energy consumption [Wh] PTAC energy consumption [Wh]
Room Temperature [℃] Operative Temperature [℃] Ceiling Temperature [℃]</td></tr>
</table>

4. Conclusion

In this study, the thermal performance of TABS for residential building is simulated. The PTAC system use pattern and the cooling load pattern could determine the operation mode of TABS. The various operation modes are estimated in this study. For the various operation modes, the operative temperature, run time of the TABS and the PTAC, energy consumption of the TABS and the PTAC, condensation occurring hour, and total energy consumption are estimated by computational simulation. The best thermal performance under similar thermal comfort temperature range could be achieved with the proper operation starting and the duration time.

If TABS is operated too early before the solar heat gain is not sufficient, the condensation would occur in mode3. When the operation starts early, it is important to prevent surface condensation and the under-cooling in the night or morning. Because TABS uses concrete slab as a thermal storage and a radiation surface, there only exist short hours of time delay. Therefore, setting the operation starting time properly before peak cooling load appears is very important. In well-insulated typical concrete structure residential building, the optimum operation starting time is about 2 hours before the peak cooling load appears.

The operation duration time is also considerable factor. If low temperature cooling water is supplied for a long duration time, the under-cooling and condensation could occur. In contrast, if the operation duration time is too short, the cooling load could not be handled. It is because the load profile of residential building is not constant. To maintain room temperature range comfortably, the operation duration time should be determined considering cooling load profile.

Although the operation mode is estimated by unsteady-state simulation, these results of the operation assume that the cooling load profile of peak day in cooling session. If cooling load pattern changed, there might be some other control strategies. The future study is about supply water temperature and pump operation control which could respond to various cooling load pattern.

5. Acknowledgement

This study was supported by Energy · Resources Technology R&D program (2008-E-BD11-P-13-0) under the Ministry of Knowledge Economy, Republic of Korea. The authors thank these institutions for their support. This would be beneficial for lower cooling energy consumption with similar levels of room temperature.

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