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Component Analysis of Thermally Activated Building System in Residential Buildings

Woong June Chung[1], Yu ji Lee[1], Mi hye Yoo[1], Sang Hoon Park[1], Myoung Souk Yeo[2] and Kwang Woo Kim[2]

[1] Department of Architecture and Architectural Eng., Graduate School of Seoul National University, Seoul, Korea
[2] Department of Architecture and Architectural Eng., College of Eng., Seoul National University, Seoul Korea

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Abstract The packaged terminal air conditioner, the typical cooling system for the residential buildings, consumes a large amount of electricity in a short period time during peak hours. In order to reduce the peak load and conserve the electricity, the thermally activated building system can be used as a secondary system to handle the partial cooling load. However, the thermally activated building system may cause condensation and under-cooling. Thus, design of both systems should be performed with careful investigation in characteristics of both systems to amplify the advantages.

Since the thermally activated building system has the time-delay effect which may cause under-cooling, the system is designed to handle the base load of the building. Hence, simple simulation with EnergyPlus was performed to observe the characteristics of cooling load in residential buildings. Once the possible range of the load handling ratio of the thermally activated building system was decided, characteristics of system was analyzed in terms of hardware component and operation parameters. The hardware components were analyzed in plant and system aspects and the operation parameter was evaluated in the thermal comfort aspect. As the load handling ratio increased, the thermal comfort increased due to the lower radiant mean temperatures. Within the range of thermal comfort, the several adjustments were made in setpoint temperature and electricity consumptions of difference cases were observed to decide which components and parameters were important for designing the systems.

Keywords: Thermally Activated Building System, Component Analysis, Energy Simulation, EnergyPlus

1. INTRODUCTION

1.1 Research Background and Purpose

The packaged terminal air conditioner is one of the most commonly used cooling systems in Korean residential buildings, which can be easily installed and quickly remove the cooling load. However, the packaged terminal air conditioner may consume a large amount of electricity in a short period of time during peak hours. In order to reduce the energy consumption, the radiant system can be a great alternative because it has decrement effect and time-delay effect, which can reduce the amount of peak load. However, the latent load cannot be removed with radiant system which may cause the condensation on surfaces. Thus, load handling ratio of the packaged terminal air conditioner and radiant system should be determined through careful investigations on characteristics of both systems.

In the preliminary studies[1], three advantages of the radiant system were discovered. The first advantage of the radiant system is that the radiant system pump consumes less amount of energy to operate than the fan in the packaged terminal air conditioner. Second advantage is that the radiant system requires higher water temperature for cooling than the supply air for the packaged terminal air system due to the difference of air and water thermal capacity, which will reduce the electricity consumption. Third advantage is that the radiant system can decrease the mean radiant temperature to provide better thermal comfort.

In residential buildings, the thermally activated building system may be easily applied as a secondary system to handle the partial cooling load, because the typical residential buildings are constructed with the concrete mass structure. The construction cost for the application of the thermally activated building system may be reduced.

In order to investigate the feasibility of the thermally activated

Corresponding Author: Myoung Souk Yeo, Professor
Department of Architecture and Architectural Eng., College of Eng., Seoul National University, Seoul, Korea
Tel: +82-2-880-7353 e-mail: msyeo@snu.ac.kr

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1 Babiak J., Olesen, Bjaren W., Petras D., (2007) Low Temperature Heating and High Temperature Cooling, rehva.

building system in residential buildings, load handling ratio of both systems and the electricity consumption of the packaged terminal air conditioner and the thermally activated building system should be analyzed to avoid condensation on surface and maximize the advantages of both cooling systems in terms of components.

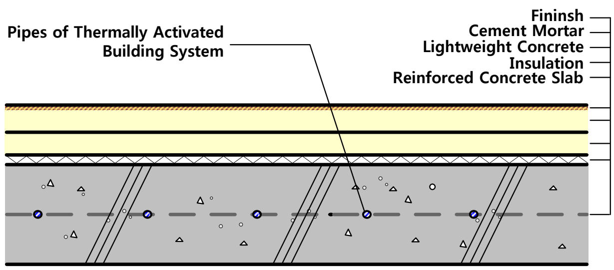

Figure 1. Section view of thermally activated building system

1.2 Research method and Scope

Components of the air system and the thermally activated building system are categorized as hardware components and operation parameters for through analysis. Hardware components are related to the mechanism of the tangible components which are plant and terminal system and the operation parameters are related to the zone thermal comfort. Careful analysis of hardware components and operation parameters with electricity consumption of the cooling systems is performed to amplify the advantages of each system.

2. COOLING SYSTEM OF RESIDENTIAL BUILDINGS

2.1 Types of Cooling System

2.1.1 Usage of Packaged Terminal Air Conditioner

The packaged terminal air conditioner system uses a refrigeration cycle to extract the heat from the zone. Among fan, compressor, expansion valve, and condenser coil in the system, the most of the electricity consumption occurs in the fan and the compressor. Since the system is based on convection, the cooling load can be removed instantly. However, the large electricity consumption in a short period of time may require the system to have high maximum capacity and it may reduce the efficiency while partial load occurs.

2.1.2 Application of Thermally Activated Building System

The thermally activated building system is a system that inputs pipes in the concrete mass structure to supply water through the pipe as shown in Figure 1. The coolness can be stored ahead of time by supplying the low temperature and release it when the residential building has the cooling load, which can avoid the large amount of electricity consumption in a short period of time. However, the thermally activated building system has difficulties in controlling the supply water temperature because of the high heat capacity of the concrete structure of the system. Since the coolness in the thermally activated building system is released over certain period of time, the coolness may be released when the cooling load does not occur and may cause under-cooling. Moreover, the surface of the system may be lower than the dew point temperature and may cause the condensation. Therefore, the air system should be integrated with the thermally activated building system to minimize the problems in control. The integration concept of thermally activated building system and air system is demonstrated in Figure 2.

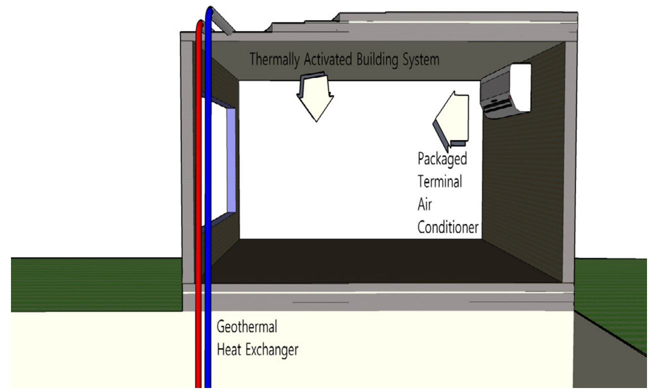

Figure 2. Concept of packaged terminal air conditioner integrated with thermally activated building system

2.2 Separation of the Components

Components of the packaged terminal air conditioner and the thermally activated building system are separated for investigating the amount of electricity consumption and the characteristics of system mechanisms in each part.

The schematic diagram of cooling systems demonstrates the cooling system mechanism in Figure 3. The part that consumes the most of the electricity is described in terms of the hardware components and the operation parameter. The analysis and comparison of the cooling system was performed through the system separation and demonstrated in Figure 4.

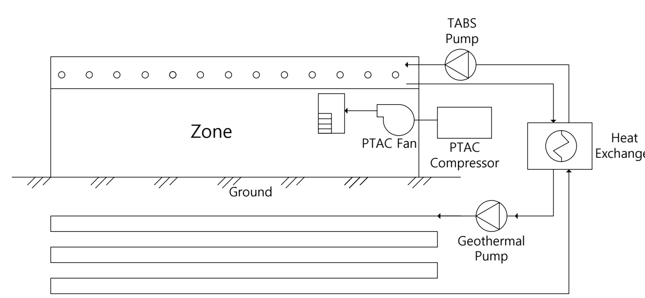

Figure 3. Schematic diagram of cooling system

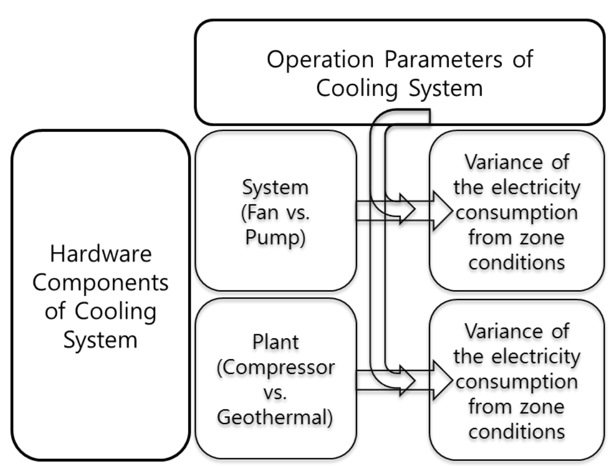

Figure 4. Analysis and comparison through system components

2.3 Hardware Components of Systems

As the packaged terminal air conditioner is utilized in typical residential buildings, the main resource to operate the packaged terminal air conditioner is electricity used in compressor and fan. Compressor in the packaged terminal air conditioner decreases the coil temperature that cools the supply air and the fan in the packaged terminal air conditioner delivers the cool supply air throughout the room by convection. For applying the thermally activated building system, the main resource is also the electricity utilized in TABS pump for supplying the water throughout the pipes embedded in concrete structure and geothermal pump for heat exchange between ground and water to decrease the supply water temperature.

For the evaluation of the hardware components, the system aspect and plant aspect should be investigated separately. The system is defined as components that supply the coolness into the zone and the plant is defined as components that create the coolness.

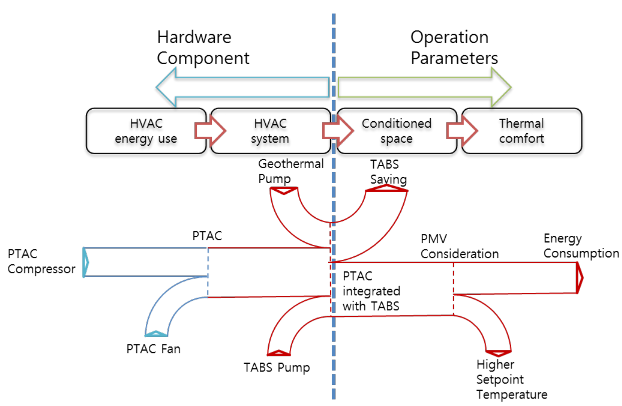

Figure 5. Map of the energy flow for the integrated system

The thermally activated building system has an advantage on required supply water temperature because radiant system requires higher supply water temperature than air system for using high heat capacity substance for refrigerant. Thus, the thermally activated building system may use geothermal heat exchanger for the plant system instead of heat pump system. With the geothermal heat exchanger system, the supply water temperature can be approximately 18℃ and higher, because the ground temperature is approximately 16℃ throughout the year. The process of heat exchange and two pumps will raise the temperature about 2℃.

2.4 Operation parameter of Systems

Operation parameter is related to the conditions in the zone and the thermal comfort of the occupants can be one of the critical parameters in the zone. Figure 4 explains how the operation parameter of the cooling system can affect the electricity consumption of hardware components. In Figure 5, the map of the energy flow for the integrated system explains how the components are separated. HVAC energy use and HVAC system can be categorized as the hardware component and conditioned space and thermal comfort can be categorized as the operation parameter. The operation parameter section describes how thermal comfort may play an important role in saving electricity consumption.

Analysis of the thermal comfort can be evaluated with predicted mean vote in ASHRAE standards 55, which is one of the most common factors to determine the thermal comfort of the zone.

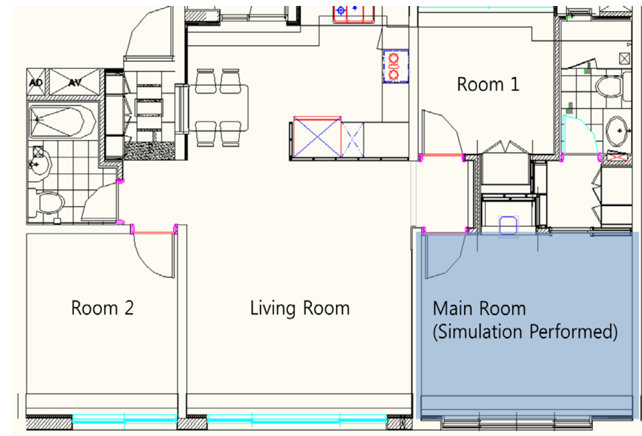

Figure 6. Plan view of the typical residential building

In ASHRAE standard 55, PMV is scaled from -3 to +3 which are defined from cold to hot, respectively. The equation from ASHRAE standard 55 describes that the most influential factors of PMV are room temperature and mean radiant temperature. The rest of the parameters are metabolic rate, effective mechanical power, clothing insulation, clothing surface area factor, relative air velocity, water vapor partial pressure, convective heat transfer coefficient, and clothing surface temperature. ASHRAE standard 55 recommended thermal comfort range from +0.7 to -0.7 for occupants' comfortable conditions.

The thermally activated building system can improve the thermal comfort of the room because the radiant system can lower the mean radiant temperature with radiant heat exchange between surfaces of wall, ceiling, and floor in the room. Thus, the setpoint temperature of packaged terminal air conditioner integrated with thermally activated building system can be higher than the setpoint of the packaged terminal air conditioner and conserve the electricity.

3. UTILIZATION OF COOLING SYSTEM IN RESIDENTIAL BUILDINGS

3.1 Utilization of Thermally Activated Building System

The capacity design of the thermally activated building system and packaged terminal air conditioner was usually conducted with consideration of base load of the building. The base load is the amount cooling load that consistently occurs. For instance, the office building has a base load that is a constant load from appliances and people which can be handled by the thermally activated building system. The rest of the cooling load is unpredictable and it is handled with other systems. For the residential buildings, more analysis on the cooling load should be analyzed.

A simple simulation was conducted with EnergyPlus for observing the cooling load of the residential buildings. Conditions of a typical residential building in Korea were used as inputs and the characteristics of cooling load were observed. The plan view of the typical residential building is demonstrated in Figure 6, which is obtained from the current residential building. The main room of

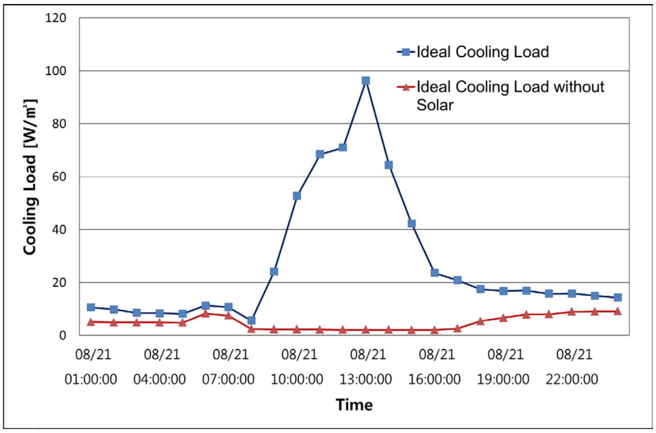

Figure 7. Comparison of cooling load with and without solar radiation on peak day

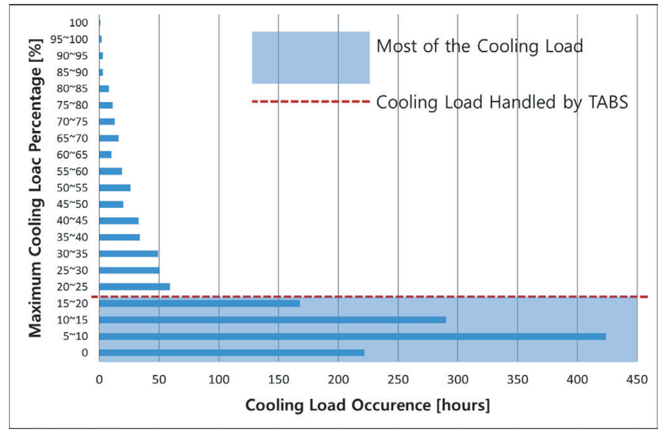

Figure 8. Frequency of the cooling load of July and August

the apartment was monitored, because the most used space in the residential building is the main room.

Simulation of ideal cooling load with and without the solar load of the residential building was performed for a year. Figure 7 demonstrates that the amount of peak cooling load was 96W/m^2 and it occurred on August 21st. The solar load is the majority of the cooling load, because balcony was extended by residents' preferences for larger usage of space. Also, the residential buildings have large windows, which significantly increase the solar load. However, the solar load is not predictable and cannot be considered as a base load of the building. Thus, the observation of an hourly cooling load for a year was performed by considering the condensation and under-cooling.

3.2 Load Handled by Thermally Activated Building System

The partial cooling load that can be handled by the thermally activated building system is decided by the supply water temperature. As the cooling water temperature becomes lower, more loads may be handled by the thermally activated building system. However, supply water temperature of radiant system should be determined with consideration on the condensation.

Previous research[2] on thermally activated building system considered only condensation because it is the most critical factor of radiant cooling system, which may cause the fungus on the wall and damage the finish and building systems. It is one of the main considerations for every radiant system for cooling in design stage. Condensation on the surface of the structure may form the mold on the surface, which can damage the surface. The condensation may be prevented by designing the supply water temperature higher than dew point temperature.

In recent, consideration on conservation of energy is becoming an issue and under-cooling should be also considered because it may consume more energy than designed by cooling the zone when it does not demand cooling. Often, under-cooling occurs when the thermally activated building system is operated with sensors in the zone, and the coolness from the system output after certain period of time, when it does not have the cooling load.

Table 1. Conditions for the simulation

Conditions	Content
Building Orientation	Southeast
District	Seoul, Korea
Area	29m² (6.6m x 4.4m)
Window	South 75%
Internal Heat Gain	2 people, 100W lighting, 150W equipment
Setpoint Temperature	26℃
Blind	0.2 Reflectivity, Horizontal
TABS Operation Period	12 Hours of operation
TABS Operation	10:00~22:00
PTAC Operation	24 Hours of operation
TABS Placement	Ceiling (Slab)
Ventilation System	Heat Exchanger

Since there is a delay on output of the coolness by the thermally activated building system, the supply water temperature of the system can be decided with base load. However, the base load in residential buildings is significantly low. Thus, observation of the cooling load occurrence may be performed to decide the amount of base load. Figure 8 illustrates the occurrence of the cooling load and shows that the most of the cooling load occurs less than 20 percent of the maximum load. Thus, 20 percent of maximum cooling load may be considered as a base load that can be used for designing the load handling ratio of the thermally activated building system. However, feasibility of 20 percent of maximum cooling load should be verified considering the condensation and under-cooling statement.

For the simulation to prove the feasibility of the thermally activated building system, the conditions based on the typical residential buildings in Korea from previous research[3] are shown in Table 1. The operation period of the thermally activated building system is based on the thermal restoration of the geothermal energy and the occupancy of residents. If the water in the ground loop was circulated for 12 hours, the ground needs 12 hours to recover.[4]

In order to utilize the system when the people are occupied, the thermally activated building system needs to operate from 10pm to 10am, because most of the internal load occurs at night and the coolness can be used after

2 Chung W.J. (2011) "Applicability of Thermally Activated Building System Considering Heat Storage Characteristics" Spring Conference of Korean Institute of Architectural Sus-tainable Environment and Building System 2011.

3 Chung W.J. (2011) "Applicability of Thermally Activated Building System Considering Heat Storage Characteristics" Spring Conference of Korean Institute of Architectural Sus-tainable Environment and Building System 2011.

4 Babiak J., Olesen, Bjaren W., Petras D., (2007) Low Temperature Heating and High Temperature Cooling, rehva.

supplying the water for the thermally activated building system.

Table 2. Definition of cooling systems variant

Case	Content
Case 1	PTAC Operation Only
Case 2	PTAC with TABS Handling 10% of Maximum Load
Case 3	PTAC with TABS Handling 10% of Maximum Load (Higher Setpoint Temperature)
Case 4	PTAC with TABS Handling 20% of Maximum Load
Case 5	PTAC with TABS Handling 20% of Maximum Load (Higher Setpoint Temperature)

According to the design with occurrence of the load system, different load handling ratio of the thermally activated system and packaged terminal air conditioner was simulated. Different setpoint temperature was used for the observation of the thermal comfort in the zone. Simulation cases for verification are listed in Table 2.

The results of the condensation and under-cooling statement are demonstrated in Table 3. Increment of 10 percent of load handling ratio and the load handling ratio of the thermally activated building system was aimed at 20 percent. For the correct heat output of the thermally activated building system, the supply water temperature was calculated with the EN1264. As the load handling ratio and supply water temperature of the thermally activated building system changed, the volume flow rate, packaged air conditioner energy consumption, percentage of the time in which condensation occurred, percentage of time in which under-cooling occurred, heat output of the thermally activated building system, and handled load percentage of the thermally activated building system. The supply water temperature, volume flow rate, and heat output of the thermally activated building system was calculated before the simulation.

The rest of the results on the Table 3 were calculated with the simulation. The results of the simulation shows that the most effective load handling ratio was 20 percent with the heat output of the 19 W/m^2 avoiding the condensation and the under-cooling statement of the zone. In order to output $19W/m^2$, the supply water temperature of the thermally activated building system should be 20℃. With the thermally activated building system handling 20 percent of maximum load, the system handled 44 percent of the total cooling load in July and August. The energy consumption of the packaged terminal air conditioner was reduced by 35 percent.

4. APPLICATION OF THERMALLY ACTIVATED BUILDING SYSTEM

4.1 Plant Electricity

Comparison of electricity consumption of air conditioner and the thermally activated building system was achieved by evaluating the electricity usage of the compressor to cool the coil and geothermal pump to cool the water in Table 4. Compressor of the packaged terminal air conditioner consumes most of the electricity and typical COP of the compressor is 3. In order to provide low temperature air for cooling, the coil of the packaged terminal air conditioner should be approximately 6℃. The temperature of the coil in the packaged terminal air conditioner is relatively low compared to the supply water temperature. This factor will result in the large amount of the energy consumption.

In plant aspect, the electricity consumption of compressor in the packaged terminal air conditioner significantly decreased as the thermally activated building system handles more loads. The electricity consumption of the geothermal pump remains the same because cooling process of the supply water temperature will not be affected by the operation of the cooling system.

4.2 System Electricity

For the system components, the circulation pump of the thermally activated system to supply cooling on the concrete mass structure and the fan in packaged terminal air conditioner to distribute the air throughout the room were compared. These two components are related to the system to provide the cooling demand. The characteristics of these two components were analyzed.

Table 3. Energy Consumption for different load handled by TABS in July and August

Load Handling Ratio	Heat Output	Supply Water Temperature	Volume Flow rate	Condensation	Under-cooling	Total Load Handling Percentage
[%]	[W/m^2]	[℃]	[LPM]	[%]	[%]	[%]
0	-	-	-	-	-	-
10	10	23	1.3	-	-	22
20	19	20	2.7	-	-	44
30	29	17	4.0	1	10	62
40	39	14	5.3	5	32	76
50	48	12	6.7	16	61	85
60	58	9	8.0	30	77	91
70	67	7	9.3	44	6	96

Table 4. Comparison of components for different systems in July and August

Type	Components			Thermal Comfort		Thermal Comfort
		Case 1	Case 2	Case 3	Case 4	Case 5
		PTAC ONLY	10%	10% 26.5℃	20%	20% 26.5℃
		[kWh]	[kWh]	[kWh]	[kWh]	[kWh]
System	TABS Pump Electricity Consumption	0	30	30	60	60
	PTAC Fan Electricity Consumption	47	39	34	29	25
Plant	Geothermal Pump Electricity Consumption	0	30	30	60	60
	PTAC Compressor Electricity Consumption	1,947	1,618	1,475	1,216	1,087
Total Electricity Consumption		1,994	1,716	1,569	1,365	1,232

As illustrated in Table 4, the electricity consumption of pump in the thermally activated building system doubled as the load handling ratio doubled. As demonstrated in Table 3, the supply water temperature and volume flow rate were designed to have a fixed value because the temperature difference of supply water temperature and return water temperature from the room should be about 3℃ for equal distribution of supply water temperature.

4.3 Comparison of Thermal Comfort of the Zone

As the amount of load handled by thermally activated building system increased, the mean radiant temperature of the room decreased. Lower mean radiant temperature on summer will cause the improvement of the thermal comfort, because the PMV will decrease. As Figure 9, PMV becomes closer to neutral as the mean radiant temperature is decreasing.

The mean average of PMV for July and August is demonstrated in Table 5. Two months mean average of the PMV for the room with the packaged terminal air conditioner was 0.5, which was within the range of the comfort standards. The average PMV of the room using the packaged terminal air conditioner integrated with the thermally activated building system were 0.46 and 0.39 for 10 percent and 20 percent of partial load handled, respectively.

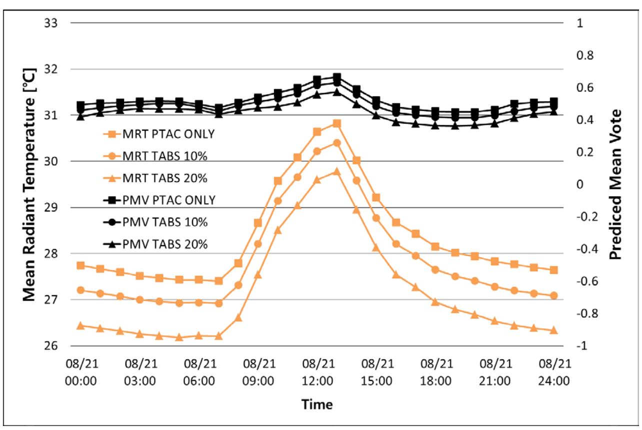

Figure 9. Mean radiant temperature and PMV comparison of peak day

Since the thermal comfort is increased with the thermally activated building system, the setpoint temperature of the room may be adjusted to 26.5℃. PMV in Table 5 indicates that the PMV declined as the thermally activated building system handles 10 percent of the maximum cooling load. However, when the thermally activated building system handles 20 percent of the maximum cooling load, PMV average of two months was 0.47, which was better than the thermal comfort with operation of the packaged terminal air conditioner.

5. RESULTS AND DISCUSSIONS

The packaged terminal air conditioner integrated with the thermally activated building system can be improved in many aspects compared to the system with only packaged terminal air conditioner. The validation for feasibility of the thermally activated building system in residential buildings should be analyzed by comparing the electricity consumption of the hardware component and thermal comfort of the operation parameter.

The comparison of the cooling systems is demonstrated in Table 4. The thermal comfort is directly related to the electricity consumption from the hardware component because the setpoint temperature could be adjusted and the electricity consumption of systems will change. The simulation with higher setpoint temperature was performed because the thermally activated building system lowered the mean radiant temperature and maintained within the same level of thermal comfort. The setpoint temperature of the packaged terminal air conditioner was increased by 0.5℃ and the thermally activated building system handled 10 percent and 20 percent of the maximum cooling load.

As the thermally activated building system handled 10 percent and 20 percent of the maximum cooling load, approximately 8 percent and 22 percent of PMV decreased, respectively. The thermally activated building system affected predicted mean vote exponentially as the thermally activated building system handled more loads. Thus, much higher setpoint temperature may be used as the radiant system utilized more.

Table 5. Average PMV comparison of different systems and settings in July and August

	Case 1	Case 2	Case 3	Case 4	Case 5
System	PTAC Only	10%	10% 26.5℃	20%	20% 26.5℃
PMV	0.5	0.46	0.57	0.39	0.47

Considering the thermal comfort of the zone, the electricity consumption of the hardware component was evaluated. For the plant component, the thermally activated building system utilized the geothermal pump. For the plant aspect of the packaged terminal air conditioner, the compressor electricity consumption was compared with the geothermal pump of the thermally activated building system.

The compressor of the packaged terminal air conditioner consumed less amount of electricity as the thermally activated building system handled more load. The electricity consumption of the compressor of the packaged terminal air conditioner occurs when the temperature of the cooling coil is reduced in the packaged terminal air conditioner. The coil temperature is determined by the amount of the cooling load in the room. Since the amount of operation time and cooling load reduced, the compressor used less amount of electricity to cool the room. The geothermal pump with the heat exchanger spent relatively small amount of the electricity and the same amount of the electricity according to the load handling ratio.

For the system component, the pump of the thermally activated building system that circulates the water in the pipes embedded in the concrete mass structure was compared with the fan in the packaged terminal air conditioner that provides the air in the zone. The water volume flow rate of circulation pump of the thermally activated building system varied according to the design of the thermally activated system. When load handling ratio of the thermally activated building system increases, the volume flow rate increases because the distribution of the heat output throughout the surface of the system can be equally provided.

Although the pump of the thermally activated building system consumed less amount of electricity than the fan of the packaged terminal air conditioner, the conservation of electricity in plant components is far less than the savings in system components. Thus, the strategy to reduce plant component electricity is more effective than considering electricity conservation of the system components. The difference of the electricity consumption of each component is demonstrated in the Figure 10.

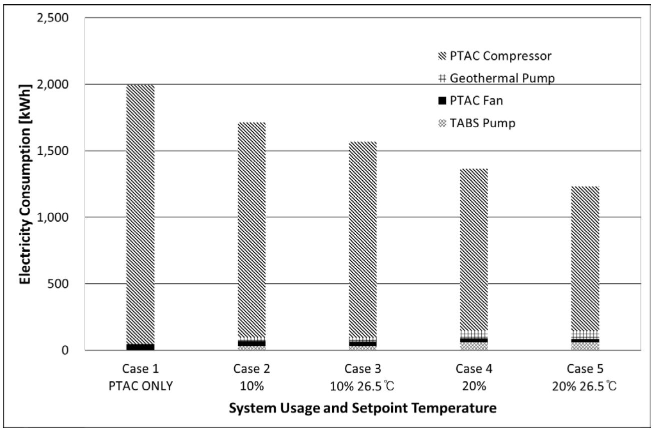

Figure 10. Electricity consumption in different components

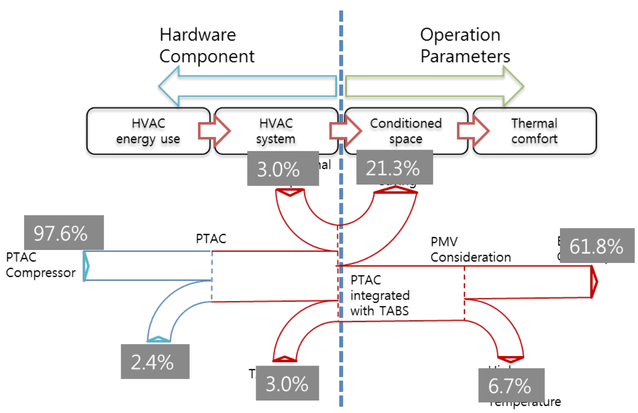

Figure 11. Percentage of the electricity consumption of system in the map of energy flow

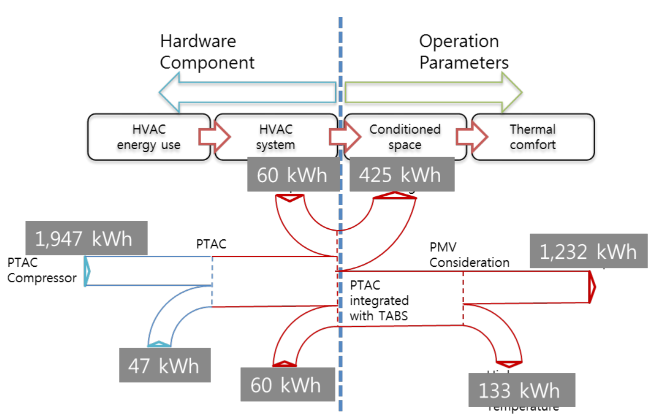

Figure 12. Electricity consumption of the system in the map of energy flow

In Figure 11 and 12, the electricity consumption of the system in the map flow is demonstrated. The map of energy flow starts with the energy consumption of the packaged terminal air conditioner operated only system. And as the thermally activated building system handles 20 percent of the maximum cooling load, the electricity consumption percentage becomes 84.7 percent. As the thermal comfort of the room becomes one of the factors of operation, the setpoint temperature was set to 26.5℃ and 6.7 percent of the total cooling load could be conserved. Compared to the packaged terminal air conditioner, integrated system could use 61.8 percent of the total electricity consumed by the packaged terminal air conditioner only system.

The main concerns of this research were obtaining the proper way to select load handling ratio of both systems by analyzing the hardware components and operation parameters. As the load handling ratio of the thermally activated building system and setpoint temperature of the room increased, the electricity consumption reduced. The main focus on the results is that 0.5℃ increase on setpoint temperature has almost equivalent effect as increment on 10 percent of load handling ratio of the thermally activated building system. Therefore, the setpoint temperature changes according to the thermal comfort should be one of the main parameters in design and operation of the thermally activated building system.

6. CONCLUSIONS

In this research, the feasibility of the thermally activated building system was analyzed through the comparative evaluation of hardware components and operation parameters. The objective was to discover the proper load handling ratio of the thermally activated building system and the packaged terminal air conditioner.

In hardware component, the plant component was a significant factor compared to the system component. The amount of electricity consumption in plant was far greater than the system component, and it should be the main consideration for designing the system.

In operation parameters, thermal comfort increased exponentially with the increase of load handling ratio of the thermally activated building system, which indicates the importance of load handling ratio of the thermally activated building system.

Considering the thermal comfort, small increase on setpoint temperature reduced a lot of electricity consumptions and it is equivalent to significant increase on load handling ratio. Hence, the thermal comfort should be considered as one of the main parameters in design and operation stage.

For the further studies, the control strategy of the thermally activated building system according to the load prediction can be studied for considering the time delay of the system to increase the load handling ratio.

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