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Research Article

Improved Thermally Activated Building System Design Method Considering Integration of Air Systems

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The purpose of the thermally activated building system design is to maintain the thermal comfort of the building indoor environment by securing enough thermal output of the system. For preventing the condensation on the thermally activated building system, the air system is mostly integrated with the thermally activated building system. However, the common design method in the standards only considers the thermal performance of the system itself and cannot reflect the effects of the air system. Thus, the design process of the thermally activated building system should include the consideration about the latent load and ventilation. In order to reflect the effect of the air system, the amount of sensible load removed by the thermally activated building system and air system should be included in the design process. The sensible load handled by the air system highly depends on the type of the air system and design consideration to prevent the condensation and maintain the indoor air quality. In this study, the air system choosing process was included by simulating and observing the sensible load removed by different types of the air system, and thermal performance adjustment in the design process was proposed.

1. Introduction

The climate is changing due to the greenhouse effect, and occupants in buildings require better thermal comfort. Thus, the heating and cooling loads of buildings have increased. The peak electricity load is also increasing every year, and reserved electricity is decreasing. An unexpected high peak in electricity may cause a major blackout, and it is best to maintain a similar level of electricity use to stabilize the system.

One of the solutions to mitigate the peak electricity use of a building is to reduce the peak heating and cooling load with a storage system. A storage system can be used to store heat at night, and use the stored heat when the building is occupied. Among the many types of storage systems, a thermally activated building system is an energy-efficient radiant system that uses a concrete structure to store heat. Because the operating temperature can be close to room temperature, it is possible to use renewable energy [1]. The system should be designed with proper thermal performance to maintain the thermal environment of the building. It should also have enough capacity to maintain a comfortable environment at all times. In the design stage of the building, it is common to calculate the appropriate maximum capacity of the system using standards. Several advanced research proposed different methods for designing thermally activated building system. Lim et al. and Rijksen et al. proposed designing guidelines of the thermally activated building system according to the outdoor air condition [1, 2]. Park et al. proposed the TABS load-handled ratio to be designed according to the occurrence percentage of the building load [3]. Chen et al. demonstrated the significance of operation in design of thermally activated building system [4].

During cooling periods in regions with a hot and humid climate, a thermally activated building system is commonly integrated with an air system because the system can only remove a sensible load by cooling down a large surface such as the floor or ceiling. If the latent load is not removed, the

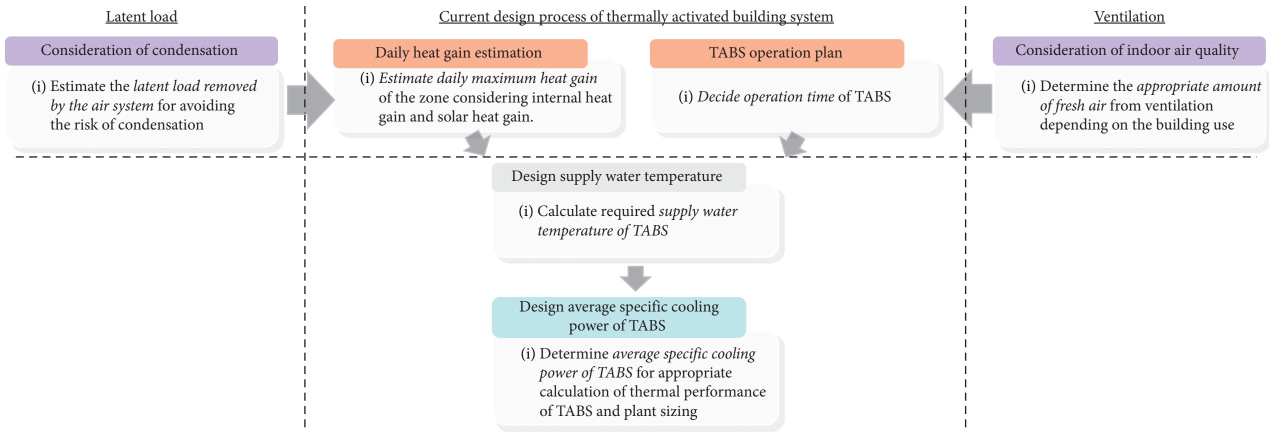

FIGURE 1: Current design method in ISO 11855 part 4 and additional consideration.

surface temperature may be below the dew point temperature, which can cause damage on the surface from condensation [1]. Moreover, the large specific heat of a thermally activated building system may not react to a large and sudden load. The system will only perform heat exchange as long as there is a difference between the zone temperature and surface temperature of the system, which is a form of self-regulation [5–9]. The sensible load that is not removed by the thermally activated building system is expected to be handled by the air system.

Although these systems are expected to be operated together, the standards discuss only the heat capacity of the thermally activated building system without considering the effect of the air system. Since the air system removes both the latent load and sensible load, the amount of sensible load removed should be considered in the process of designing the thermally activated building system because it can change the thermal performance. The objective of this study is to improve accuracy of thermal performance of thermally activated building system by including the air system design in the design process.

2. Current Design Methods

2.1. Design Considerations of Thermally Activated Building Systems and Air Systems. The design of thermally activated building systems is discussed in REHVA and ISO 11855 part 4 [10, 11]. The standards note that dynamic calculations should be carried out for the appropriate sizing of the heating capacity and cooling capacity of the thermally activated building system by using response factor series and the finite difference method because the system has a large specific heat. If the analysis of unsteady conditions is not appropriate, the standards are propose using a dynamic simulator for proper design.

The standards advise using a simplified diagram that is developed with the unsteady state analysis to determine the temperature of the supply water and the average cooling power of the thermally activated building system. A simplified diagram can be used with the daily estimation of the maximum heat gain for each specific zone and the operation hours of the thermally activated building system. Using (1) and (2), the supply water temperature can be calculated with the building orientation, number of active surfaces, thermal resistance of pipes, and thermal resistance of the concrete slab. Then, the average cooling power of the thermally activated building system is determined with the daily heat gain and operation hours with (3):

$$\theta_{\mathrm{Slab}}^{\mathrm{Av}} = \theta_{\mathrm{Comfort}}^{\mathrm{Max}} + \omega \times E_{\mathrm{Day}}, \tag{1}$$

$$\theta_{\mathrm{Water,In}}^{\mathrm{Setp}} = \theta_{\mathrm{Slab}}^{\mathrm{Av}} - \frac{E_{\mathrm{Day}} \times 1000}{n_{\mathrm{h}}} \times \left(R_{\mathrm{int}} + R_{\mathrm{t}}\right), \tag{2}$$

$$Q_{\mathrm{w}} = \frac{E_{\mathrm{Day}}}{n_{\mathrm{h}}}, \tag{3}$$

where $\theta_{\mathrm{Slab}}^{\mathrm{Av}}$ = daily average temperature of the conductive region of the slab (°C); $\theta_{\mathrm{Comfort}}^{\mathrm{Max}}$ = room maximum operative temperature allowed for comfort conditions (°C); ω = coefficient considering building orientation and number of active surfaces (–); E_{Day} = specific daily energy gains (kWh/m^2); $\theta_{\mathrm{Water,In}}^{\mathrm{Setp}}$ = water supply temperature required for ensuring comfort conditions (°C); n_{h} = number of operation hours of the circuit (h); R_{int} = internal thermal resistance of the slab conductive region (m^{2}K/W); R_{t} = circuit total thermal resistance, obtained via the resistance method (m^{2}K/W); and Q_{w} = average specific cooling power of TABS (W/m^2).

The daily maximum heat gain and operating hours of the thermally activated building system are the two main parameters that determine the temperature of the supply water and average specific cooling power. The rest of the load is expected to be handled by the air system to maintain the permissible air temperature. However, in reality, the air system is operated with the thermally activated building system simultaneously, and the thermal mechanism is different. Consequently, the air system should be considered in the beginning stages of the design process, as shown in Figure 1.

The main design parameters for the air system are the sensible load, latent load, and required minimum outdoor air for maintaining the indoor air quality, which are considered in ASHRAE 90.1 for energy efficiency and

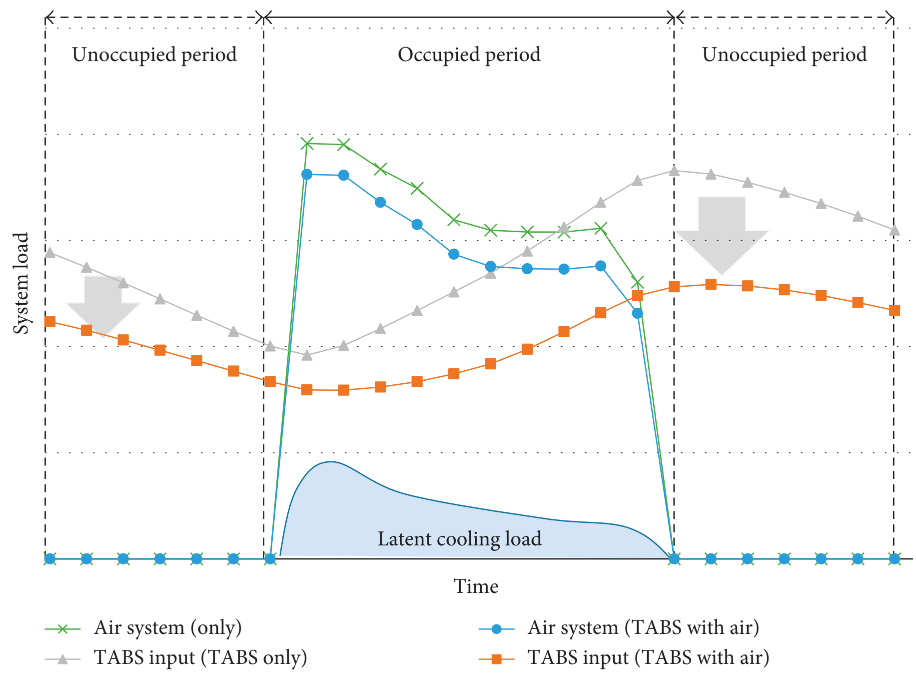

FIGURE 2: Changes in performance of the thermally activated building system integrated with the air system.

ASHRAE 62.1 for ventilation [12, 13]. For air system design, the first step to determine the capacity of the system is calculating the building's sensible load and latent load to maintain the appropriate temperature and humidity conditions based on the building characteristics. After the appropriate building load calculation, the amount of fresh air required from outside is decided based on the building use. The latent load and ventilation are the key elements for designing the air system. The risk of condensation from the thermally activated building system can be relieved by including the air system design process in that of the thermally activated building system.

2.2. Limitations of the Current Design Method. The system design mechanism with the simplified calculation method considers only the system itself and assumes that the air system removes the rest of the load after the design of the thermally activated building system. Since the air system is expected to operate when the building is occupied, the room temperature is expected to be within the permissible range of thermal comfort continuously. The performance of the radiant system highly depends on the heat exchange between the radiant surface and room temperature, which may affect the thermal performance of thermally activated building system. Hence, the supply water temperature and average specific cooling power in the standards may be lower than the actual amounts required in the thermally activated building system, as shown in Figure 2.

The design mechanism considers only how much the radiant system can remove in terms of the sensible load because the radiant system does not remove the latent load. However, the latent load should be analyzed in the system design process of because the condensation on the surfaces of the radiant system has to be considered to prevent damage

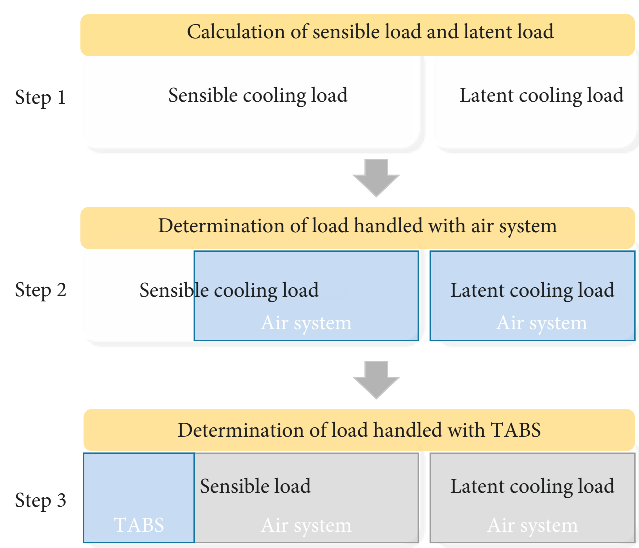

FIGURE 3: Design process of TABS in consideration of the latent load removed by the air system.

to the system. Since the air system may remove the latent load when the building is occupied, the latent load removed by the air system should be considered included in the design process for the radiant system.

Figure 3 illustrates the design process of the thermally activated building system in consideration of the latent load handled by the air system. In step 2 of the design process, the design target load is set with the latent load removed by the air system, and the correlation between the sensible load and latent load should be derived to simplify the design process. In step 3, the sensible load handled by the thermally activated building system is designed after designing the air system.

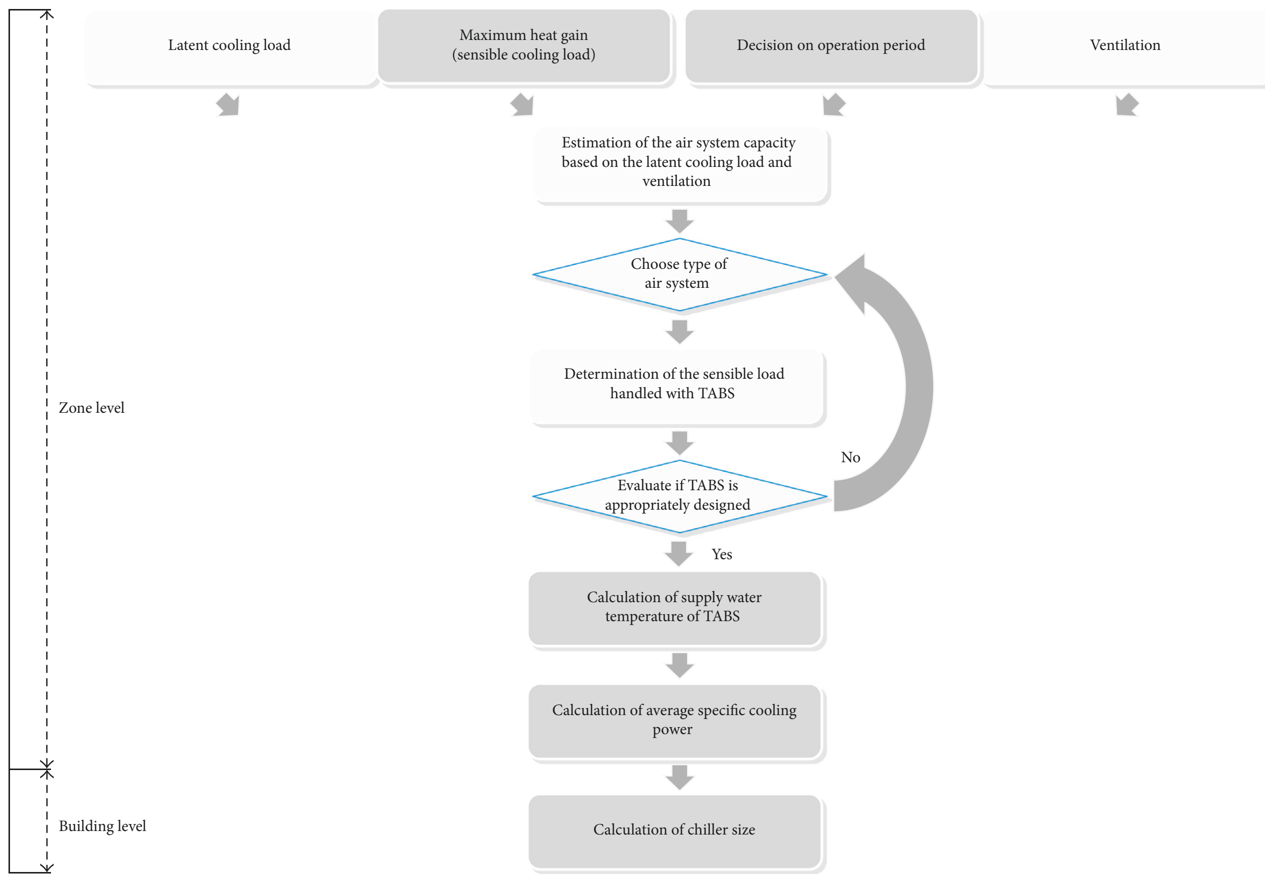

Figure 4: Schematics of the proposed design method.

2.3. Proposed Improved Design Schematics. To consider the latent load and ventilation load for the air system design, the latent load on a peak day and fresh outdoor air required for indoor air quality should be calculated. The greater capacity of the air system from calculations should be selected, and the rest of the sensible load should be designed to be handled with the thermally activated building system.

The risk of condensation and ventilation should be considered. The process of selecting the type of the air system is shown in Figure 4. Once the sensible and latent loads are calculated, the operation hours of the thermally activated building system and ventilation should be determined according to the building use. After the conditions are decided, an appropriate air system should be designed to supply enough fresh air for indoor air quality and remove the latent load to avoid condensation. The type of the air system should be selected to consider the ratio of latent and sensible load handled by the air system, which will change the performance of the thermally activated building system. The rest of the sensible load should then be the target load of the design of the thermally activated building system. If the design of the air system with latent load and ventilation can handle the total sensible load, the air system should be changed to a system with less sensible ratio.

After estimating the target sensible load value for thermally activated building system, the supply water temperature should be calculated. The supply water temperature calculation of the thermally activated building system in the standards only considers the system itself, the adjusted value with the effects of the air system operation should be applied. Based on the supply water temperature, the average cooling power of the thermally activated building system should be determined to estimate the thermal performance. The standards do not consider the plant consideration, and the building-level design procedure should be done as shown in Figure 4.

3. Analysis of Load and Evaluation on Thermal Performance of TABS Integrated with Air System

3.1. Analysis of Sensible and Latent Load of Air System. To observe the thermal performance changes in the thermally activated building system from integration with the air system, a dynamic simulation in EnergyPlus v8.8 was used to simulate the space in an educational building in Korea that has a thermally activated building system. The building is an energy-efficient building that is below the ground level, as shown in Figure 5. The building includes office spaces, lecture rooms, restaurants, and an auditorium. The thermally activated building system was installed in the office space and lecture rooms, which are on the second basement floor, as shown in Figure 6. The specifications of a concrete

Figure 5: Building overview.

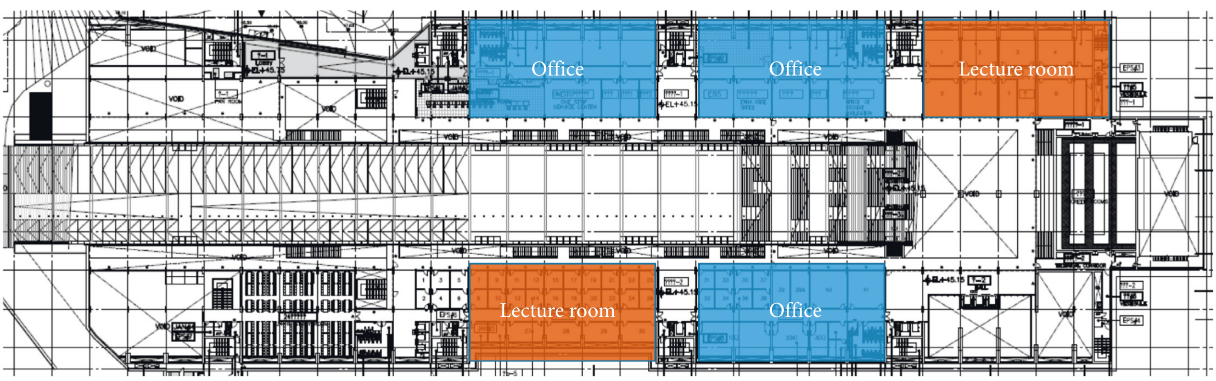

Figure 6: Plan view of the simulated space.

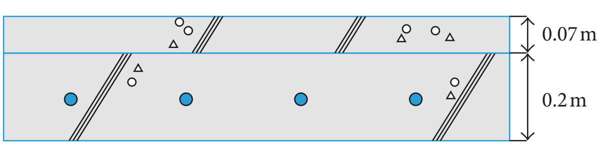

Figure 7: Section view of TABS.

Table 1: Simulation conditions.

Conditions	Content
Building orientation	South
District	Seoul, Korea
Area	$760\,m^2$ ($40\,m \times 19\,m$)
Internal heat gain	Equipment: $48\,W/m^2$
Permissible range of room temperature	22–26°C
TABS operation	8, 12, 24 hours of operation
Air system operation	9:00–18:00
TABS placement	Ceiling (slab)

structure from ISO 11855 were used to develop the model, as shown in Figure 7.

The cooling season was simulated using the simulation conditions in Table 1, and the peak cooling load occurred on July 21. The climate is hot and humid in this region, and the pattern of sensible and latent loads is demonstrated in Figure 8. The sensible cooling load was twice as much as the latent load, and the sensible ratio was approximately 0.72.

Based on the patterns of sensible and latent loads, typical air systems were modeled to observe the load removing mechanisms, such as a constant air volume (CAV) system, variable air volume (VAV) system, and dedicated outdoor air system (DOAS). Figures 9–11 demonstrate the sensible load and latent load removed by the CAV, VAV, and DOAS, on a peak day, respectively. Each system removed different amounts of sensible and latent loads, because of the different characteristics of the system. The CAV system removed more sensible and latent loads because the system continuously used the same amount of return air when the VAV system used smaller amount of return air. DOAS removed the least and had lower sensible load ratio because the system had a heat exchanger between supply and exhaust air. For calculating the amount of outdoor air in the air system, the ventilation rate for the latent load and indoor air quality was compared. The amount of outdoor air was chosen to be 0.5 ACH with the indoor air quality purpose. According to the Korean building code, new buildings are required to install the ventilation system that can intake at least 0.5 ACH of

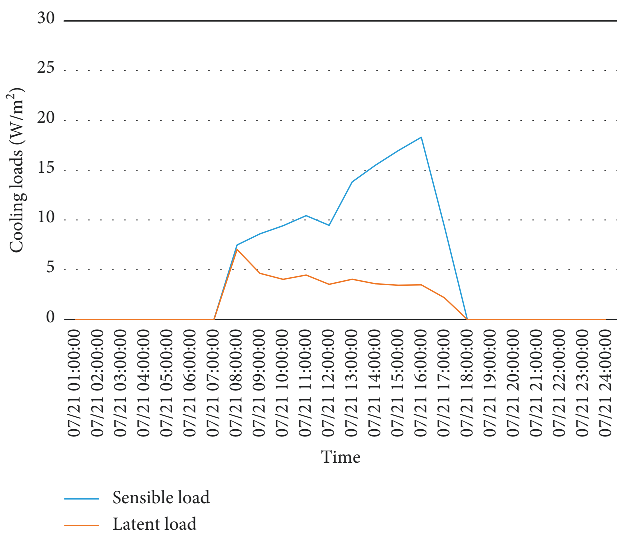

Figure 8: Sensible load and latent load on a peak day.

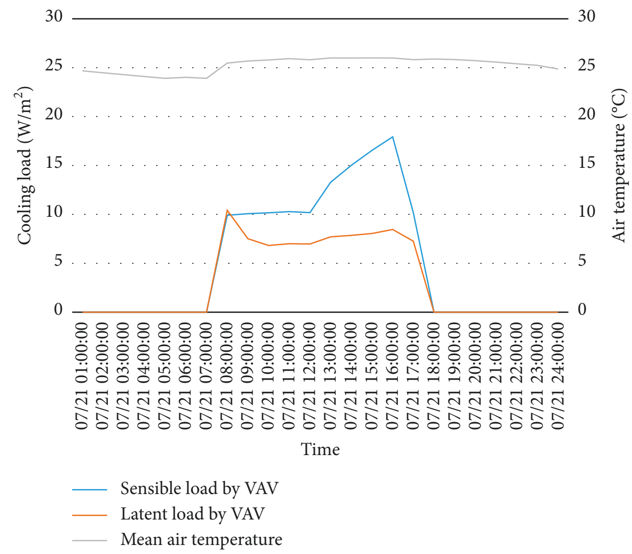

Figure 10: Sensible and latent load removed by VAV.

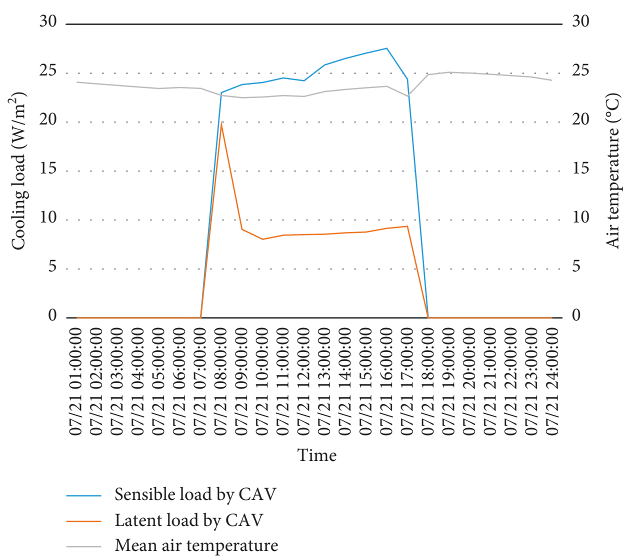

Figure 9: Sensible and latent load removed by CAV.

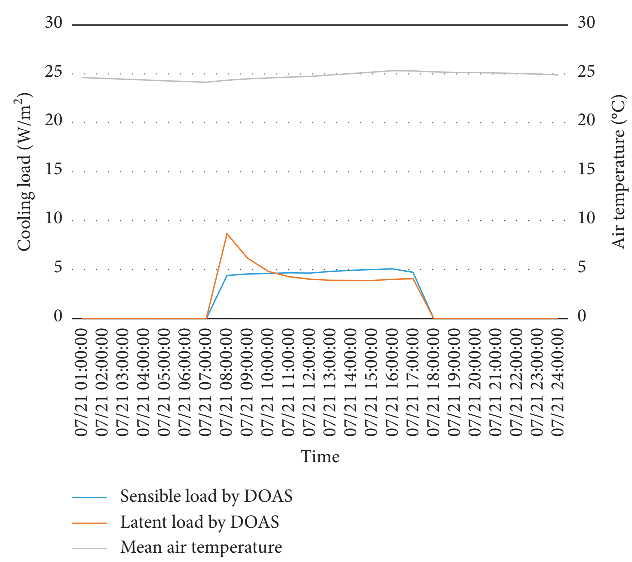

Figure 11: Sensible and latent load removed by DOAS.

outdoor air. According to the results of the simulation, the sensible load ratios of CAV, VAV, and DOAS are 0.72, 0.61, and 0.49, respectively. The sensible load ratios of each system should be considered to select the type of the air system. If the CAV system is selected, the sensible load handled by the air system will be dominant, and the thermally activated building system will have little or no target value to handle. To increase the utilization of the thermally activated building system, the VAV system or DOAS should be selected, especially for the climate of the region.

3.2. Changes on TABS Capacity with Integration of Air System. To assess the behavior of the system, simulations were done using a case with only the thermally activated building system, as well as a case with both the thermally activated building system and the CAV system, as demonstrated in Figure 12. For 24 hours of operation, the overall cooling power of the thermally activated building system decreased due to the sensible load handled by the air system. As the operation time decreased, a greater pick up load occurred.

The average cooling power from ISO 11855 was compared with the results from the simulations, as shown in Table 2. Since the CAV handles more of the sensible load than the VAV system, the average cooling power was greater with the VAV system. DOAS handles even less sensible load than the VAV system, so the average cooling power of the thermally activated building system increased with DOAS.

3.3. Adjustments on Supply Water Temperature and Capacity of TABS. The equations from ISO 11855 were adjusted to apply changes of the supply water temperature and achieve

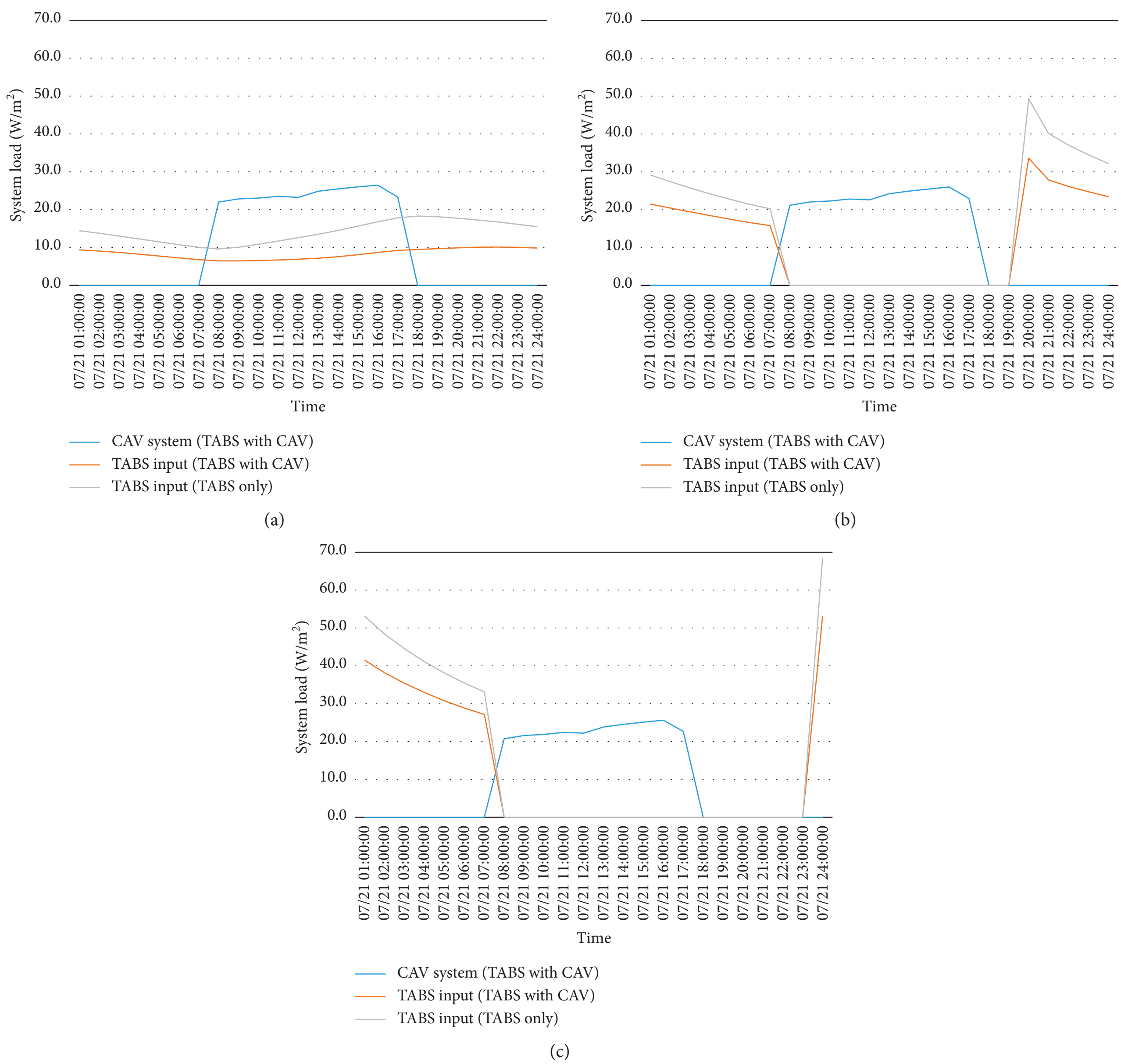

Figure 12: CAV system loads and TABS load with different operation times: (a) 24 hrs; (b) 12 hrs; (c) 8 hrs.

the appropriate average cooling power for the thermally activated building system. To calculate the daily average temperature of the conductive region of the slab and supply water temperature, the targeted daily energy gain was increased by multiplying the proposed adjustment coefficient, as demonstrated in (4) and (5). The proposed adjustment coefficients of the different air systems with different operation times were obtained from the dynamic simulation and are shown in Table 3.

$$\theta^{\mathrm{Av}}_{\mathrm{Slab.adj}} = \theta^{\mathrm{Max}}_{\mathrm{Comfort}} + \omega \times E_{\mathrm{Day}} \times \alpha, \qquad (4)$$

$$\theta^{\mathrm{Setp}}_{\mathrm{Water,In.adj}} = \theta^{\mathrm{Av}}_{\mathrm{Slab.adj}} - \frac{E_{\mathrm{Day}} \times \alpha \times 1000}{n_{\mathrm{h}}} \times \left(R_{\mathrm{int}} + R_{\mathrm{t}}\right), \qquad (5)$$

where $\theta^{\mathrm{Av}}_{\mathrm{Slab.adj}}$ = adjusted daily average temperature of the conductive region of the slab (°C); α = proposed adjustment coefficient considering the air system (–); and $\theta^{\mathrm{Setp}}_{\mathrm{Water,In.adj}}$ = adjusted water supply temperature required for ensuring comfort conditions (°C).

4. Results and Discussion

4.1. Application of Air System Selection with Latent Load Consideration. To validate the improved design methods, an office space and a lecture room were considered in a variety of cases. The typical internal heat gain was applied using standard information about the density of people, lighting, and equipment obtained from the National Renewable Energy Laboratory (NREL) of the US Department of Energy [13, 14]. The office space and lecture room were set to have 0.8 and 0.2 people per floor area, respectively. For selecting the air system, the total heat gain and latent load in the

Table 2: Average cooling power comparison of standard and simulation.

Simulation cases		TABS average cooling power from ISO 11855 (W/m^2)	TABS average cooling power from simulation (W/m^2)
TABS 24 hrs (21.3°C)	TABS only	20	18.3
	TABS with CAV		10.1
	TABS with VAV		14.4
	TABS with DOAS		16.3
TABS 12 hrs (19.4°C)	TABS only	38	49.3
	TABS with CAV		33.6
	TABS with VAV		42.4
	TABS with DOAS		45.8
TABS 8 hrs (17.8°C)	TABS only	58	68.4
	TABS with CAV		53.0
	TABS with VAV		61.7
	TABS with DOAS		65.0

Table 3: Proposed adjustment coefficient of different air systems with different operation times.

Simulation cases		Proposed adjustment coefficient (–)
TABS 24 hrs	TABS with CAV	1.98
	TABS with VAV	1.39
	TABS with DOAS	1.23
TABS 12 hrs	TABS with CAV	1.13
	TABS with VAV	0.90
	TABS with DOAS	0.83
TABS 8 hrs	TABS with CAV	1.09
	TABS with VAV	0.94
	TABS with DOAS	0.89

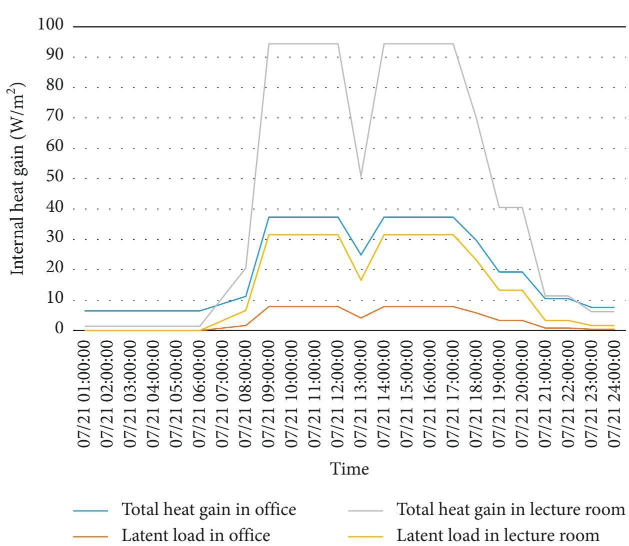

Figure 13: Internal heat gain of office and lecture rooms.

office space and lecture room were calculated, as shown in Figure 13. The majority of the building load was from the ventilation and internal load in the educational building because the office space and lecture room have a thermal buffer against the external environment.

Thus, the sensible ratios of the office space and lecture room were close to 0.6, and the DOAS should be selected to

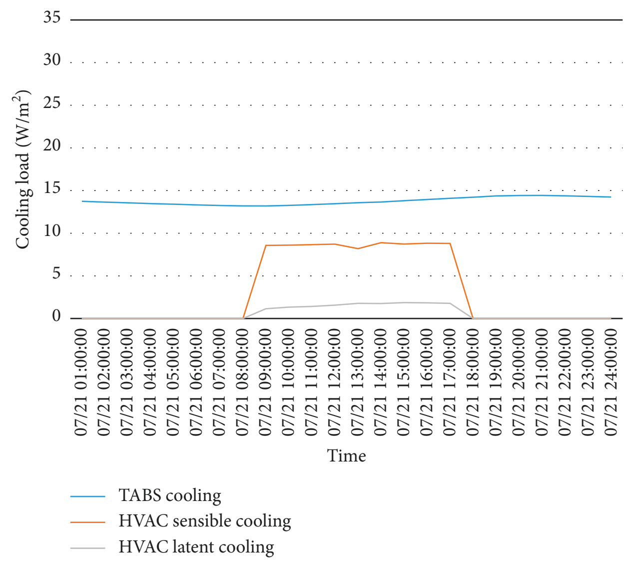

Figure 14: Amount of TABS and CAV systems' cooling in the office space.

decrease the risk of condensation and use the thermally activated building system. To prove that the DOAS is the appropriate selection, the amount of sensible cooling and latent cooling by the air system and the cooling by the thermally activated building system were compared with the CAV system. Figures 14 and 15 illustrate the amount of cooling performed with the thermally activated building system and CAV system in the office space and lecture room. The latent load removed by the CAV was much smaller than the amount removed by the DOAS, as shown in Figures 16 and 17. Due to the humidity removed from the heat exchanger, the DOAS could remove the significant amount of latent load, which could reduce the risk of condensation and helps it to avoid damage to the surface of the system.

4.2. Adjustments of Supply Water Temperature according to Improved Design Method. As shown in Table 4, the supply water temperatures of the office space and lecture room were 20.6°C and 16.7°C, respectively. The expected average

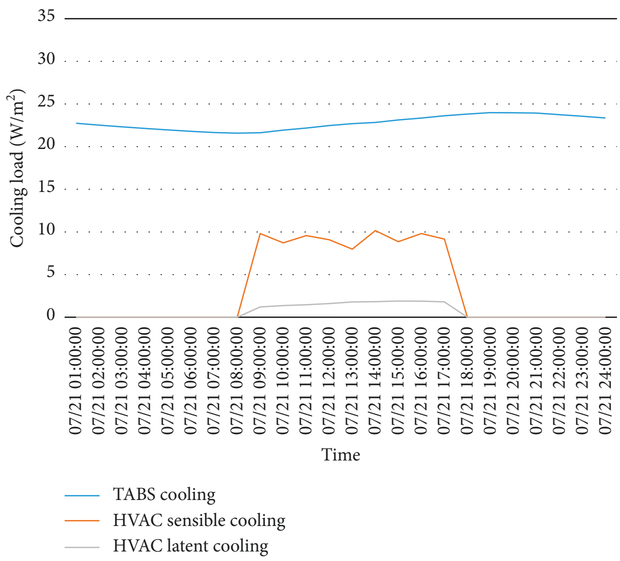

Figure 15: Amount of TABS and CAV systems' cooling in the lecture room.

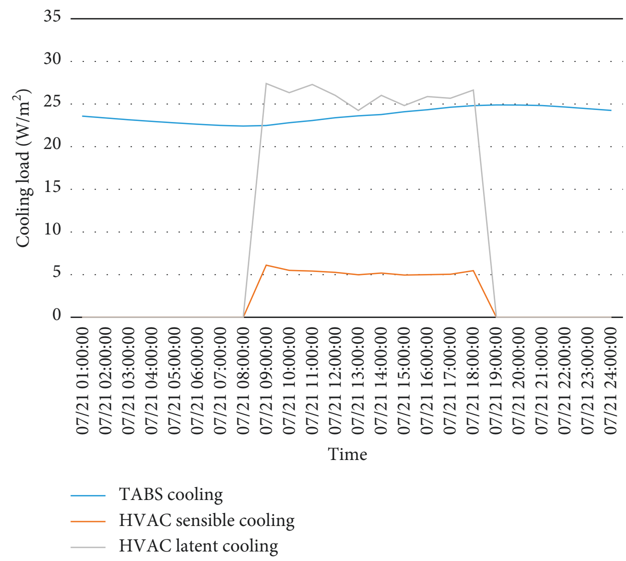

Figure 17: Amount of TABS and DOAS cooling in the lecture room.

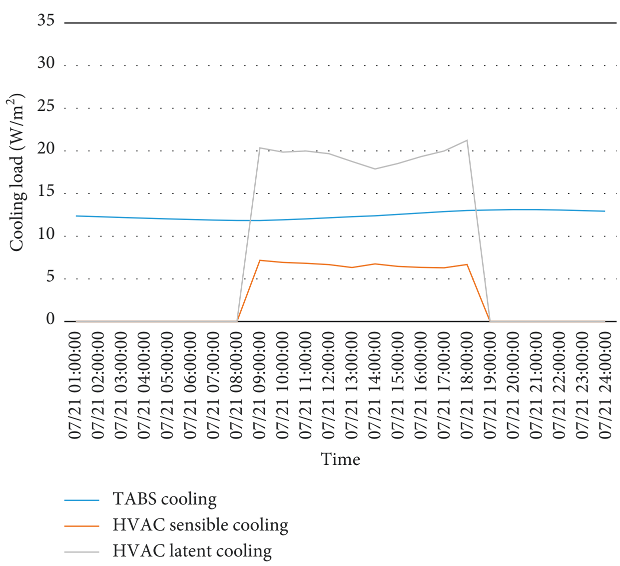

Figure 16: Amount of TABS and DOAS cooling in the office space.

cooling power of the thermally activated building system was 16.8 W/m^2 and 28.9 W/m^2. However, the simulated results of average cooling power of the thermally activated building system in the office space and lecture room were 13.1 W/m^2 and 24.9 W/m^2, which are smaller due to the sensible load removed by the DOAS.

The supply water temperature was recalculated by applying 1.23 as the proposed adjustment coefficient from Table 3 in (4) and (5). In the office space, the adjustment coefficient decreased the supply water temperature and the difference of expected average cooling power in the standards and average cooling power with the proposed adjustment coefficient is 6.5% as shown in Figure 18. Since the lecture room had the more occupants than the office space, the effects of adjusting the supply water temperature were significant, and the average cooling power with the proposed adjustment coefficient became greater than the expected average cooling power in the standards. The sensible and latent loads removed by the air system and thermally activated building system with the proposed adjustment coefficient in the lecture room are demonstrated in Figure 19, and the difference of expected average cooling power in the standards and average cooling power with the proposed adjustment coefficient in the lecture room is 4.5%. The average cooling power was very close to the expected average cooling power when using the coefficient.

The improved design method was validated by applying it to a simulated building. However, the validation was limited to hot and humid weather conditions and may need to be applicable to other weather conditions. The system was operated for 24 hours, but evaluation of the method with different operation times could expand its application range.

5. Conclusions

In this study, an improved thermally activated building system design method was proposed by applying the effects of an air system. Since the behavior of the air system is different, the process of selecting the air system was included, and the supply water temperature was adjusted to meet the targeted average cooling power of the thermally activated building system.

To decide the type of the air system, the sensible load and latent load removed by a CAV system, VAV system, and DOS were evaluated. The latent load was then targeted to be removed by the air system, and the rest of the sensible load was designed to be handled by the thermally activated building system.

The air system decreased the expected average cooling power of the thermally activated building system in standards, and the supply water temperature should be adjusted

Table 4: Comparison of supply water temperature and average cooling power with the proposed method.

Simulation cases		Supply water temperature in standards (°C)	Supply water temperature with proposed adjustment coefficient (°C)	Expected average cooling power (W/m^2)	Average cooling power with supply water temperature calculation in standards (W/m^2)	Average cooling power with proposed adjustment coefficient (W/m^2)
TABS 24 hrs	TABS with DOAS office space	20.6	19.4	16.8	13.1	15.7
	TABS with DOAS lecture room	16.7	14.6	28.9	24.9	30.2

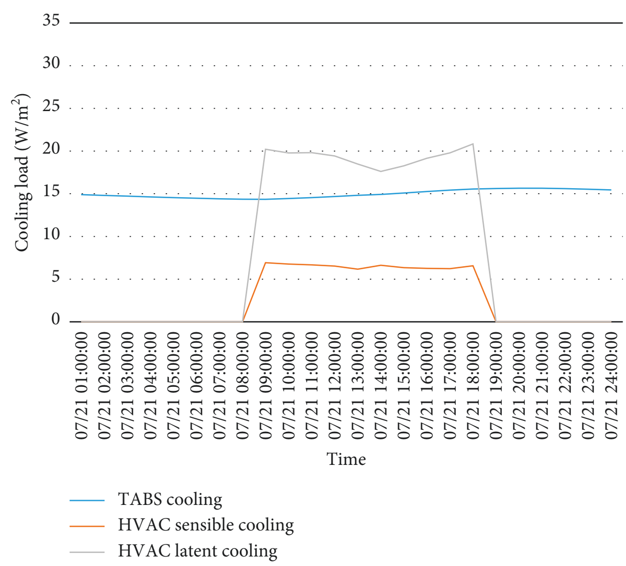

Figure 18: Amount of TABS and DOAS cooling in the office space with the proposed method.

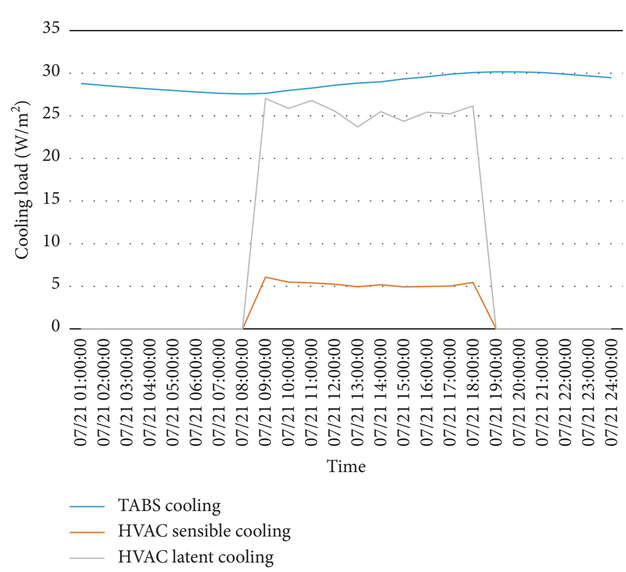

Figure 19: Amount of TABS and DOAS cooling in the lecture room with the proposed method.

to reach the target sensible load handled. An adjustment coefficient was proposed to change the target sensible load, and the supply water temperature was recalculated.

To validate the air system selection process and adjustment coefficient, the method was applied to different spaces with different loads. The appropriately selected air system removed a significant amount of the latent load, and the adjustment coefficient could increase the average cooling power to near the expected value. Therefore, the accuracy of the thermally activated building system was improved.

In future research, the practicality of the improved design method will be assessed with an experiment. Generalization of the proposed adjustment coefficient and validation studies will also be performed by applying different weather conditions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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