Energy Saving Potentials of Dedicated Outdoor Air System in High-rise Apartment Buildings

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Abstract

The main thrust of this paper is to investigate the optimized supply air condition and energy saving potentials of a dedicated outdoor air system (DOAS) applied to a high-rise apartment building. For a typical 132-m^2 apartment unit, it was assumed that two different systems, namely, a centralized DOAS integrated with ceiling radiant cooling panel (CRCP) and a decentralized energy recovery ventilator (ERV) operated with packaged air conditioner, were installed. The transient behavior and control characteristics of each system were modeled numerically using a commercial equation solver program and annual cooling coil load and heating load reduction potential of the two systems were compared. It was found in this research that a DOAS-CRCP system can reduce the cooling coil load by over 21% annually compared to the current energy recovery ventilator-packaged air conditioner pair. In addition, the use of DOAS can reduce the annual ventilation heating load by over 40% when the enthalpy wheel and the sensible wheel of the DOAS unit operate simultaneously. It was also found that the optimized dew point temperature of the DOAS supply air that accommodates the latent load of a space is 11–12℃.

Keywords: DOAS, high-rise apartment building, decentralized ventilation, centralized ventilation

Introduction

Over the last decade, the Korean market has witnessed the rapid planning and construction of high-rise apartment buildings as an alternative to reorganizing and expanding the urban residential environment. As a result of this trend, high-rise apartment building and a multipurpose building has become representative of Korean residential buildings and has become tighter and better insulated. With this development, the energy consumption owing to ventilation can become much greater than that caused by the heat transfer through the building shell. This increases the contradiction between improving the indoor air quality and reducing the energy used for ventilation. On the other hand, decentralized energy recovery ventilator and air-conditioning systems are increasingly being used in high-rise apartment buildings in Korea.

However, the operation of a typical decentralized air-conditioning system is not well understood. This is not because such systems are operated based on subjective decisions, but because building occupants are unknowingly worried about increasing their electric consumption charges and do not understand how to optimally operate a decentralized air-conditioning system to maintain a healthy indoor air environment [1, 2]. In addition, the maintenance of a decentralized air-conditioning system installed in a housing unit includes changing filters and washing a part of the energy recovery ventilator; this maintenance task is costly and time consuming. Therefore, to optimally control and maintain ventilation and air-conditioning system, there has recently been a gradual increase in interest to develop a ventilation system that can be controlled from a central station or a central plant. Compared with existing ventilation systems, a central ventilation system offers many advantages, as it supplies a sufficient rate of ventilation and can be systematically and economically maintained. In addition, if a central cooling system is used with a central ventilation system, we won't need any additional air-conditioning plant room in each household and we will able to use more additional area in residential building.

The use of a dedicated outdoor air system (DOAS) [3], which has aroused increasing interest in the EU and North America as a high efficiency central ventilation system, is one of the ideal solutions to this issue. With the aim to solve the problems posed by such a system, this research determines the optimized supply air conditions and estimates annual cooling and heating energy consumption when DOAS is applied to a high-rise apartment building. In addition, the resulting energy savings, as compared with the operation of existing air-conditioning systems, are analyzed quantitatively.

Overview of dedicated outdoor air system (DOAS)

When many researchers finally realized that systems were largely based up on the sensible heat transfer function of air in an air-handling system, they began to propose a "decoupled system"; that is, one that decouples the ventilation and the air-conditioning function, or decouples the sensible and latent load functions. After the 1990s, this new concept of a decoupled system prompted much research in North America and the EU. The latent cooling load is always handled by a DOAS. When the sensible cooling load exceeds the maximum capacity of the DOAS, the radiant panels are activated in order to handle the remaining space sensible cooling load. When the total space cooling load exceeds the DOAS cooling capacity, the radiant panel system accommodates the remaining cooling load (Figure 1).

(1) Components of DOAS

In a DOAS/radiant panel cooling system, the entire latent load, a portion of the sensible load, and the OA ventilation cooling load are handled by a combination of the enthalpy wheel and the DOAS cooling coil, which working in series. The radiant panel system accommodates the remaining sensible load. A properly designed DOAS with a parallel sensible system can save considerable energy compared to a conventional system while always supplying the correct amount of ventilation air, as required by the ventilation rate standards, to each space. The components of a DOAS include an enthalpy wheel, a cooling coil, a sensible wheel, and a supply/return fan.

Energy savings for the conditioning of fresh air can be achieved by the application of a DOAS, in which the sensible and latent heat recovered from the exhausted air is transferred to the supply air. At present, two kinds of approaches are available for heat recovery ventilators: sensible heat exchangers, and an enthalpy wheel and sensible wheel. An enthalpy wheel, which can save latent energy, is problematic due to its rotating moving parts. The OA enthalpy is reduced by the enthalpy wheel during the summer. An enthalpy wheel transfers the excess moisture and sensible heat contained in the OA stream to the relatively dry and cool exhaust airstream, reducing the energy consumed for heating and humidification. Silica gel and molecular sieves are the desiccants that are currently employed for enthalpy wheels. Enthalpy wheels with the familiar honeycomb matrix were made of aluminum, which has high heat transfer characteristics. In heat transfer, the excess moisture and sensible heat contained in the OA stream is transferred to the relatively dry and cool exhaust airstream, through the use of an aluminum wheel treated with a coating such as silica gel or molecular sieves (Figure 3).

A sensible wheel is simple and reliable, but it cannot recover latent energy and is not treated with a coating for the recovery of latent energy. Direct expansion coils or cold water coils are commonly used in cooling coils.

(2) Parallel system

A DOAS treats and supplies to the room only the required ventilation air at a constant volume. When a DOAS cannot handle the entire sensible load, an additional system is needed to handle the remaining cooling or heating load, to be operated along with a DOAS. In the case of Korea, existing residential buildings can use Ondol, which is used in current apartments as a parallel heating system in winter. There are also various parallel cooling systems that can be used in the summer: packaged air-conditioners, fan-coil units, etc. In this paper, it is assumed that ceiling radiant cooling panels are used, as their use with DOAS has received serious attention in investigations that focus on the improvement of their thermal and economic advantages [6, 7].

Estimation of supply air setpoint

The advantage of a DOAS when it is installed in a high-rise apartment building is that it maintains the indoor air quality (IAQ) and thermal comfort requirements by constantly providing the current required standard of ventilation air and removing the latent loads from the outside air (OA) intake and generating it in spaces using a 100% OA ventilation system. To remove the latent loads from the outdoor air intake, the dew point temperature (DPT) that is supplied to each household must be controlled. Consequently, this section addresses the selection of an appropriate DPT in the application of a central ventilation system to a high-rise apartment building.

(1) Determination of DOAS supply air rates

According to the standards of current Korean criteria for ventilation rates, a rate of 0.7 ACH is recommended for new or remodeled buildings that have more than 100 housing units. Therefore, ventilation rates are estimated using the current ventilation standard (Table 1). While the required ventilation for each space is estimated using the minimum ventilation rates recommended by ASHRAE Standard 62.1-2007, additional ventilation rate standards have recently been mandated for housing units that are higher than the 3rd floor. According to Standard 62.1, an apartment building requires 9 CMH of OA per person and 1.1 CMH of OA per unit floor area [4]. Figure 4 shows that the estimated design ventilation rates required for each space increase as the scale of an apartment grows larger; in addition, the difference between the required ventilation rates estimated by Korean standards and the ASHRAE standards increase.

(2) Determination of proper DPT of DOAS supply air during summer

During the cooling period, supply air must be removed from the latent load by the DOAS to supply the minimum required ventilation rates in each conditioned space, and the DPT of the supply air must be controlled in order to remove the latent load. Above all, the required supply air humidity ratio for each housing unit is calculated using Equation 1. This design is determined based on the indoor space latent load (Q_L), the required ventilation rates (V), and the indoor humidity ratio (W). The appropriate DPT can be obtained using a psychrometric chart to determine the humidity ratio of the supply air.

$$Q_L = 3.0 \times \dot{V} \times (W_r - W_\alpha) \qquad \text{(Eq. 1)}$$

Where, Q_L = Indoor latent load (W)

$\dot{V}$ = Supply ventilation rates (l/s)

W_r = Indoor humidity ratio (g/kg)

W_α = Supply humidity ratio (g/kg)

Generally, the latent load in an indoor housing unit is produced by the residents, infiltration, and use of the kitchen and bathroom. Among these factors, the latent load from the residents and infiltration is easily estimated using the existing method of load calculation, but the latent load produced by a variety of lifestyles is not as easy to estimate as the patterned lifestyle that is assumed in the existing method. In addition, some of the humidity that is present indoors is absorbed by the furniture, the building interior, and a number of possible unexpected factors.

Therefore, the dryness of the supply air required for each space must respond to different latent loads, which in turn calls for a different quantity of supply air.

On the other hand, a review of the available literature shows various case studies that attempt to predict the latent load in terms of moisture generation per hour or per day for each space, as determined through testing and experimentation. However, most of these studies involve experiments of short duration and a limited experimental area. Above all, the most important problem faced in the use of these data is the lack of consistency in among the previous literatures test results.

In this research, the latent load for each apartment space is estimated using Equation 2 for the maximum predicted latent load equation released by ASHRAE Fundamentals [5]. The proper DPT for a DOAS system is also calculated based on this result.

24˚C DBT, 50% RH was selected as the target space condition for setting the supply air DPT. This corresponds to 9.275 g/kg HR. Then, based on the above findings that predicted the maximum latent load using Equation 2 and estimated the supply air HR and DPT using Equation 1, the proper DPT of supply ventilation air for various apartment floor areas can be selected, as listed in Table 2.

$$Q_L = 20 + 0.22 \cdot A_f + 12 \cdot N_{oc} \qquad \text{(Eq. 2)}$$

Where, A_f =Indoor floor area (m^2)

N_{oc} =Number of occupants

As listed in Table 2, the proper DPT range of DOAS SA is 11.6‒12.2°C, with the application of a domestic ventilation standard and ASHRAE Standard 62.1 in various apartment floor areas during the summer. This means that if a DOAS system can provide a temperature of 11.6‒12.2°C to each space, most of the latent load is removed and is controlled only through the provision of the required quantity of ventilation air in a 24-h period.

During the dry season, such as winter or an intermediate season, indoor air conditioning can be controlled without the need for any additional control by using DOAS or by additional humidification if necessary [8]. Therefore, in this research, SA DPT is only estimated during the summer.

(3) Determination of proper supply air temperature of DOAS

In a DOAS system, the supply air DBT is determined in order to reduce the sensible cooling load from the quantity of ventilation rates. In the summer, when the ventilation DBT that is supplied to each room is lower than that of the room condition, it not only increases the indoor comfort level, but also increases the effectiveness of the sensible cooling load (Eq. 3).

$$Q_{S,vent} = 1.23 \times \dot{V} \times (T_r - T_\alpha) \qquad \text{(Eq. 3)}$$

Where, $Q_{S,vent}$ =Sensible cooling capacity of ventilation (W)

$\dot{V}$ =Ventilation rates (L/s)

T_r =Indoor DBT (℃)

T_α =DBT of ventilation air (℃)

In cool seasons, however, a DOAS can generally handle only a part of the space sensible load. If the space sensible load exceeds the DOAS sensible cooling capacity, this excess sensible load is handled by a parallel cooling system. The larger the sensible cooling capacity of a DOAS, the smaller the cooling capacity of a parallel system needs to be (Eq. 4).

$$Q_{S,parallel} = Q_s - Q_{S,vent} \qquad \text{(Eq. 4)}$$

Where, $Q_{S,parallel}$=Required sensible cooling capacity of parallel cooling system (W)

Q_s =Indoor sensible load (W)

The supply air that a DOAS supplies to each space can be controlled by the temperature of the air leaving the cooling coil (11–12°C) to become a neutral temperature that can better suit residents' comfort level (18–20°C), depending on their needs and preferences. When the supply air which passed through the enthalpy wheel to remove the humidity after that leaved the cooling coil is supplied to each space without any reheating and is cooled to a proper temperature of 11–12°C DPT, it can receive the maximum effect of the sensible cooling and the size of the parallel cooling system can be minimized. In this research, therefore, we selected a proper supply air temperature of 11–22°C, which provided a maximum sensible cooling effect.

On the other hand, when the space cooling load is low in an intermediate season and the space heating load is occurred, a supply air temperature of 18–20°C is selected, which does not affect the comfort level. In this case, the heat needed for supply air reheating is collected from the enthalpy wheel and sensible wheel of the DOAS and no additional energy consumption is required. However, an additional reheating system is needed, when the OA temperature is too low to provide the proper supply air condition from the sensible wheel and enthalpy wheel by the DOAS.

Energy performance of DOAS-parallel system

In order to further study the energy performance of the cooling coil load required in summer and to increase the quantity of the heating load obtained from ventilation, a typical floor (132 m^2) was modeled with a DOAS-parallel system in order to compare its energy performance with that of an existing decentralized air-conditioning system that is commonly used in high-rise apartment buildings.

(1) Summary of models

A virtual 132-m^2 (9 × 14.7 × 2.4 m) apartment building was selected as a test building for a comparison of a central DOAS cooling system with an existing decentralized air-conditioning system that is commonly used in high-rise apartment buildings (Fig 5). The configuration of each apartment unit that is occupied by 4 residents includes three bedrooms, a living room, a kitchen, and a bathroom. It has a 0.5 $W/m^2 \cdot h \cdot K$ curtain wall, which is commonly applied in apartment building exterior exposure, and 3.0 $W/m^2 \cdot h \cdot K$ double windows [11, 12]. The load calculations for two cases were performed based upon the assumption of the following conditions for the setting. The windows are located in the north and the east in each space, and the test building does not experience infiltration through the window frames or air gaps. The lighting load density is 20 W/m^2, and miscellaneous equipment generates sensible heat of 10 W/m^2. It was also assumed that the latent load in Equation 2 has always been the case in this residential building, as various lifestyles can create unpredictable latent loads.

(2) Summary of ventilation system

- *DOAS-parallel system*

In the central DOAS system, regardless of where the conditioned outdoor air is delivered, the dedicated outdoor air unit should be maintained at the proper DPT (12°C) to supply the appropriate amount of outdoor air required to achieve standard ventilation rates, so that the indoor latent load is eliminated. Among several candidates for a parallel sensible cooling system, a packaged air-conditioning system, which is usually used in high-rise apartment buildings, was selected for this research. A ceiling radiant cooling panel may be the best choice for the DOAS in terms of energy savings, thermal comfort, and indoor air quality.

- *Decentralized air-conditioning system*

It is assumed that a small decentralized air-conditioning system of the kind that is commonly used in high-rise apartment buildings is selected. In order for the indoor and outdoor air to meet the required ventilation rates, the sensible cooling load has to be handled by a packaged air-conditioning system, because a decentralized air-conditioning system does not have components to actively control the DPT and SA temperature as does a DOAS. Therefore, an additional component is essential to provide sufficient cooling and dehumidifying capacity. The target supply air temperature leaving a packaged air-conditioning system selects 16˚C commonly used, and DPT for dehumidification is selected as 12˚C, the same as that for DOAS.

Thermal performance of DOAS

(1) Comparison of cooling performance

In this study, HAP 4.20a was chosen for the estimation of the model building energy performance, with monthly and hourly peak load and cooling and latent load. The existing energy simulation program, however, cannot be modeled for DOAS. Therefore, a simulation model of DOAS and a decentralized air-conditioning system is presented based on the EES equation solver and the monthly and hourly cooling coil load is estimated using the energy performance of the model building. For the sake of simplicity, the following analysis assumes a 24-h-a-day ventilation mode. The ceiling radiant panel and packaged air conditioner were automatically controlled by meeting the target space conditions (i.e., DBT 24˚C and a relative humidity of 50%).

- Cooling Coil Load: DOAS-parallel ceiling radiant panel

The sensible cooling load of the cooling coil is the sum of the DOAS-cooling coil load and the sensible cooling load of the ceiling radiant panel. On the other hand, the latent load of the cooling coil is the outdoor air latent load that is reduced in the cooling coil in order to meet the target DPT (12˚C) (Eq. 6). The summation of these coil loads is the total cooling coil load for the DOAS-radiant cooling panel (Eq. 7).

$$Q_{s,cc} = Q_{s,DOAS,cc} - Q_{s,panel} \quad \text{(Eq. 5)}$$

$$Q_{l,cc} = Q_{l,DOAS,cc} \quad \text{(Eq. 6)}$$

$$Q_{t,cc} = Q_{s,cc} - Q_{l,cc} \quad \text{(Eq. 7)}$$

- Cooling Coil Load: decentralized air-conditioning system

In a decentralized air-conditioning system, the sensible cooling coil load is handled by the cooling coil in the air-conditioner units (Eq. 8). The OA latent load and the indoor latent load are handled by the decentralized air-conditioning system. The summation these coil loads is the total cooling coil load for a decentralized air-conditioning system (Eq. 7).

$$Q_{s,cc} = Q_{s,packaged,cc} \quad \text{(Eq. 8)}$$

$$Q_{l,cc} = Q_{l,packaged,cc} \quad \text{(Eq. 9)}$$

On the other hand, in a packaged air conditioner, when the indoor air is circulated by the cooling coil of the air conditioner, reheating of the load takes place by a process of cooling at the set point temperature and reheating before a supply is provided. Generally, the reheating of the supply air is handled by an electronic resistance heater installed in the packaged air conditioner.

(2) Determination of monthly cooling coil load

Figures 6 and 7 indicate that the thermal loads for these two cases were estimated based on alteration of the hourly cooling coil load for a July and August design day for the test building. There was no difference in the latent load of the coil load in each system. The sensible load of the cooling coil in a decentralized air-conditioning system, however, is higher than that of a DOAS-radiant cooling panel.

This signifies that the airflow rates of a packaged air conditioner are controlled by the sensible cooling load, but the large amount of airflow rates are always supplied by the packaged air-conditioner more than by DOAS-radiant cooling panel, which supplies the minimum required ventilation rates. In addition, reheating the load takes place by a process of cooling at the set point temperature and reheating before providing supply; the reheating energy is consumed by this process. The results for thermal performance are estimated as being the same as in July and August during the summer.

Figure 8 shows the monthly total cooling coil loads estimated for each system. One can see that in each month, the cooling coil load for the decentralized air-conditioning system is 19–24% higher than that for the DOAS-radiant cooling panel.

(3) Annual total cooling coil load

On the other hand, Figure 9 shows that the annual total cooling coil load for a decentralized air-conditioning system is 21% higher than that of a DOAS-radiant cooling panel, and additional reheating energy is needed for the decentralized air-conditioning system.

(4) Comparison of heating loads

When the indoor thermal condition is handled for a target temperature (e.g., 21°C) during the winter, using an enthalpy wheel system as in a decentralized air-conditioning system or DOAS-radiant cooling panel, cold OA for ventilation is preheated by the heat recovery process, and the increasing heating load and cold draft is mitigated for the directly supplied cold ventilation air. In addition, when dry air is used as the ventilation air supplied to a space during the winter, the space can become dry; however, the energy of the exhaust air is recovered by the DOAS or energy recovery ventilator, and a humidification effect can be expected from this process [10].

(5) Temperature change during winter

Figures 10 and 11 show and compare the hourly change in supplied air temperature for ventilation supplied by a decentralized air-conditioning system and a DOAS-radiant cooling panel during December and January design days. The results indicate that the supply air temperature of DOAS is always higher than that of a decentralized air-conditioning system. The source of this difference may be that decentralized air-conditioning systems have only one heat recovery component, while a DOAS-radiant cooling panel has an enthalpy wheel and a sensible wheel, which make a significant difference in the amount of heat recovery energy. Although they are not provided in this paper, data for the other months in the heating season showed a similar result for the supply air temperature. However, it is assumed that setting the target space condition at 21˚C and with a 0.7 enthalpy and sensible wheel effectiveness, leaving the decentralized air-conditioning system air at 15.2−20.5˚C during entire heating period, but leaving the DOAS-radiant cooling panel air at 17.1−20.7˚C. Relatively high SA temperature make affect of heating load reduction owing to required ventilation rates in winter.

(6) Comparison of heating loads for ventilation

It is essential that the heating load be increased for OA ventilation during the winter. Although OA ventilation air is preheated by energy recovery, it is always lower than the indoor air temperature. However, Figure 12 and Figure 13 show that the amount of increase in the heating load of the relatively high supply air temperature of DOAS is lower than that of a decentralized air-conditioning system.

On the contrary, in a comparison of the monthly increase in heating load shown in Figure 14, it can be seen that a DOAS may experience a 40% lower heating load than a decentralized air-conditioning system in every month. Consequently, this has a significant impact on the annual heating load; the additional annual heating loads for OA ventilation of a decentralized air-conditioning system and a DOAS are 923 kWh and 523 kWh, respectively. The additional load for a decentralized air-conditioning system is thus 59% higher than that of a DOAS-radiant cooling panel.

Conclusion

The aim of this research was to determine the proper supply air condition of a central ventilation system and to compare the energy simulation results of a DOAS radiant panel cooling system with a decentralized air-conditioning system. The main conclusions are as follows:

(1) The proper supply air DPT of a DOAS should be 11−20°C during a cooling period in order to handle the latent load. It is effective for reducing the energy consumption of a parallel cooling system that maintaining lowly the supply air temperature from leaving the cooling coil to neutral temperature.

(2) The annual cooling coil load of a DOAS radiant panel cooling system is 21% less than that of a decentralized air-conditioning system.

(3) Finally, a DOAS radiant panel cooling system can save 40% of the increased heating load compared with a decentralized air-conditioning system, and it can achieve a high supply air temperature because of the double heat recovery produced by the enthalpy wheel and sensible wheel during the winter.

Acknowledgement

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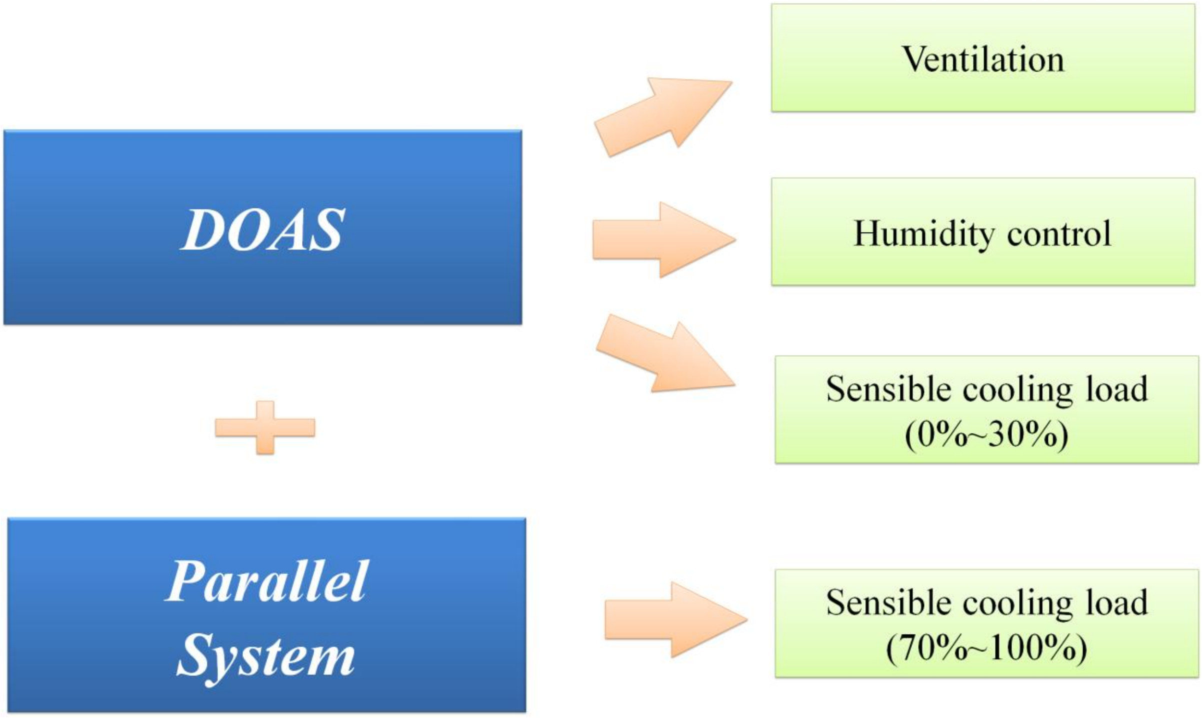

Fig. 1 Concept of DOAS-parallel system

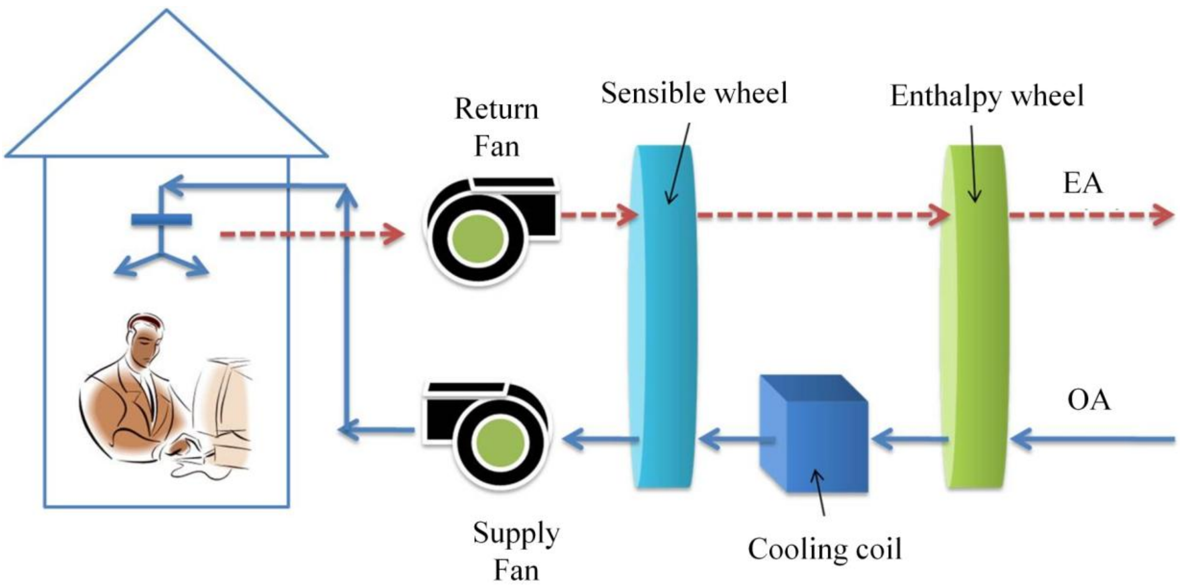

Fig. 2 Components of DOAS

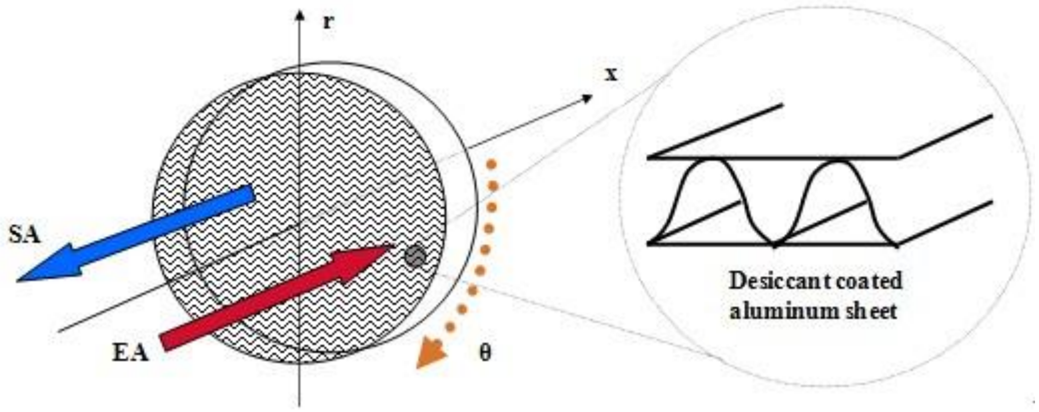

Fig. 3 Rotary-type enthalpy wheel

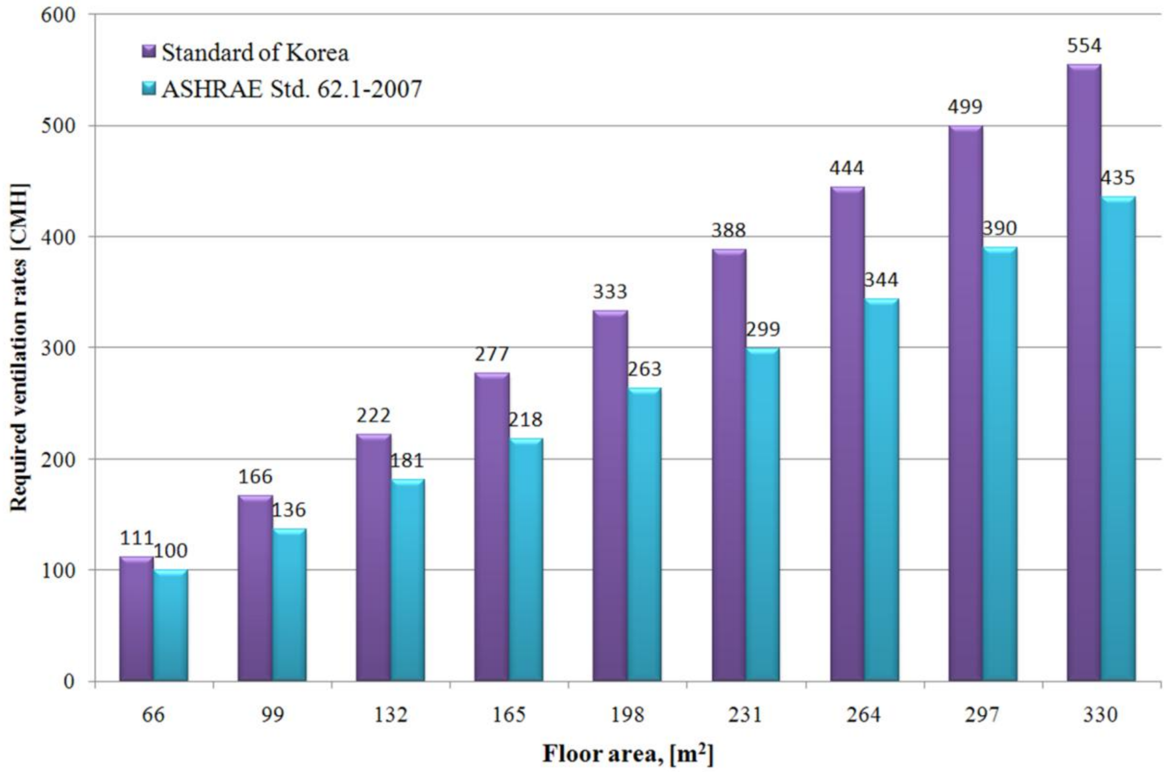

Fig. 4 Comparison of required ventilation rates

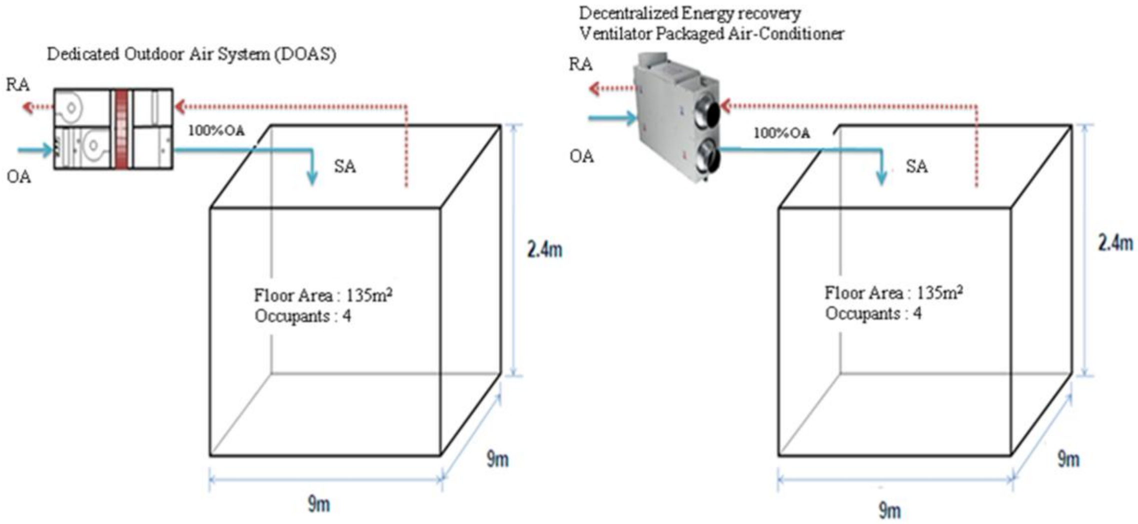

Fig. 5 Simulation model

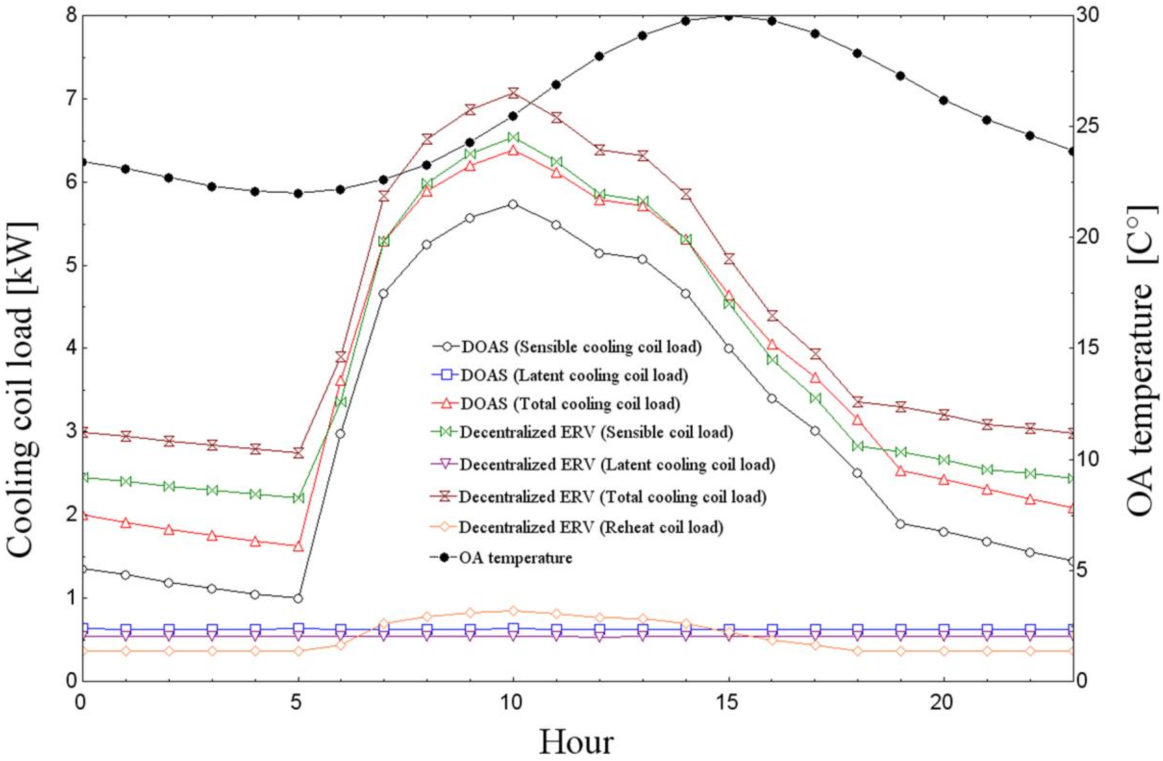

Fig. 6 Hourly design of daytime cooling coil for July

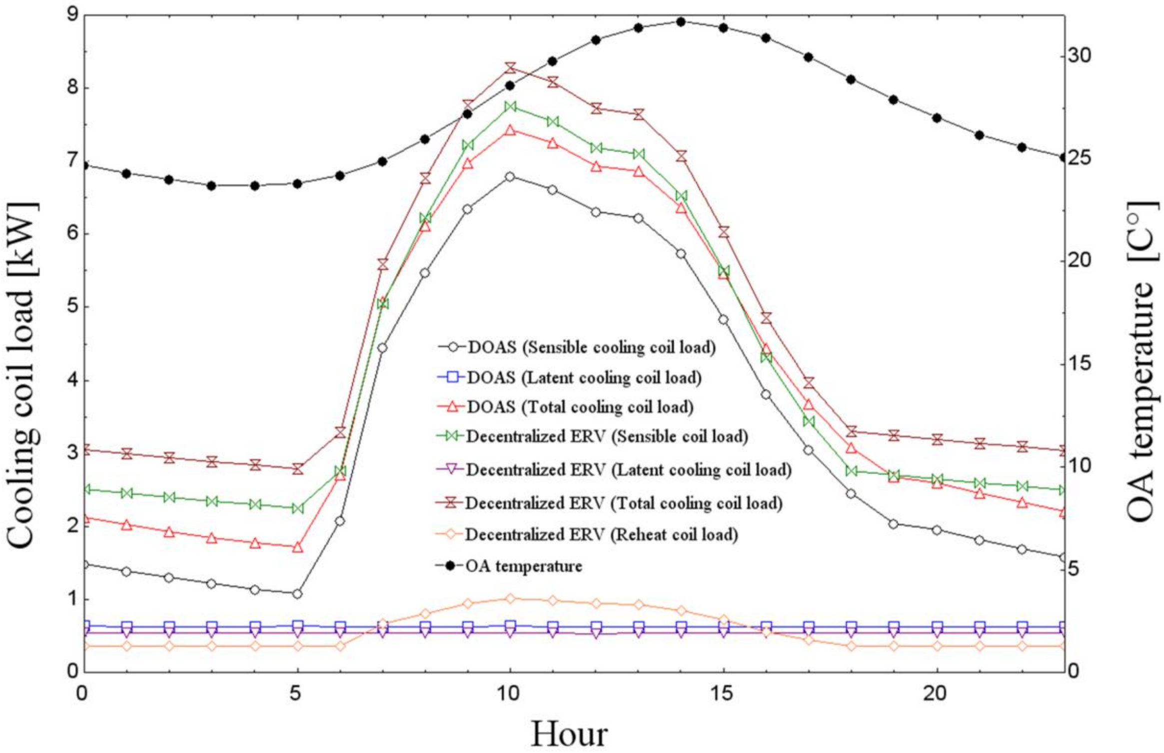

Fig. 7 Hourly design of daytime cooling coil for August

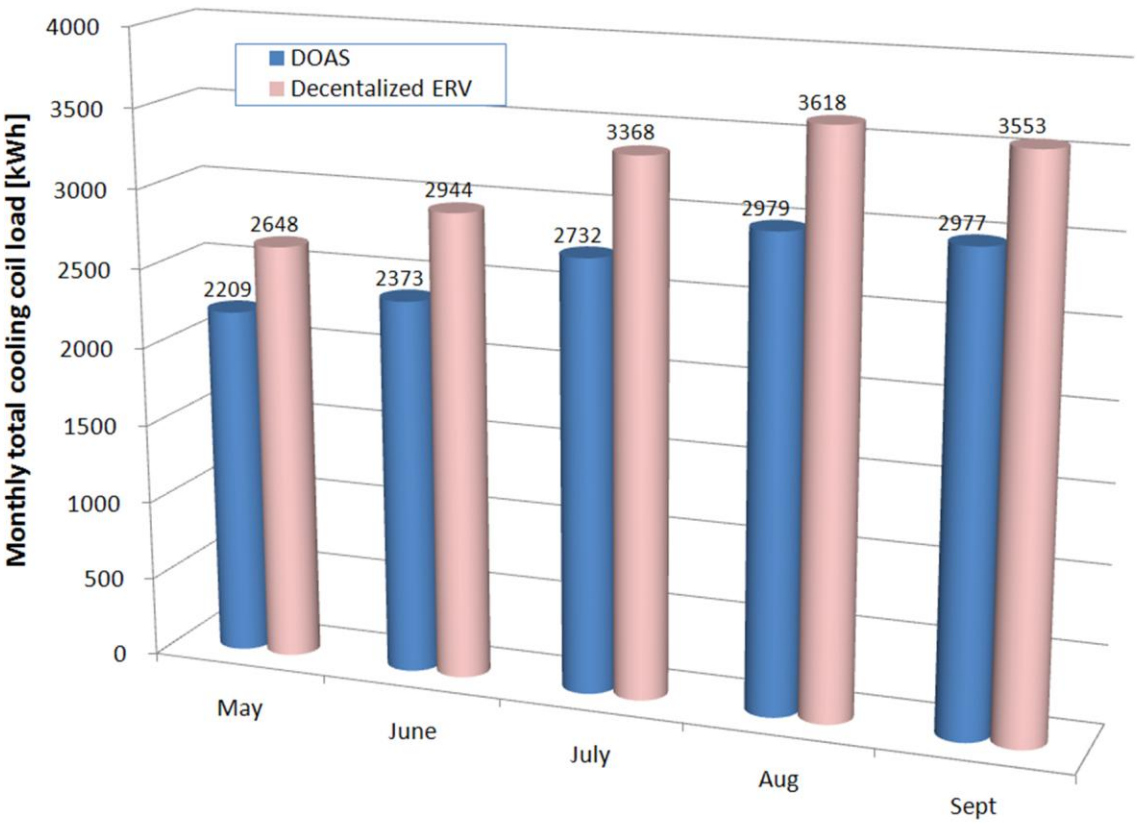

Fig. 8 Monthly total cooling coil load

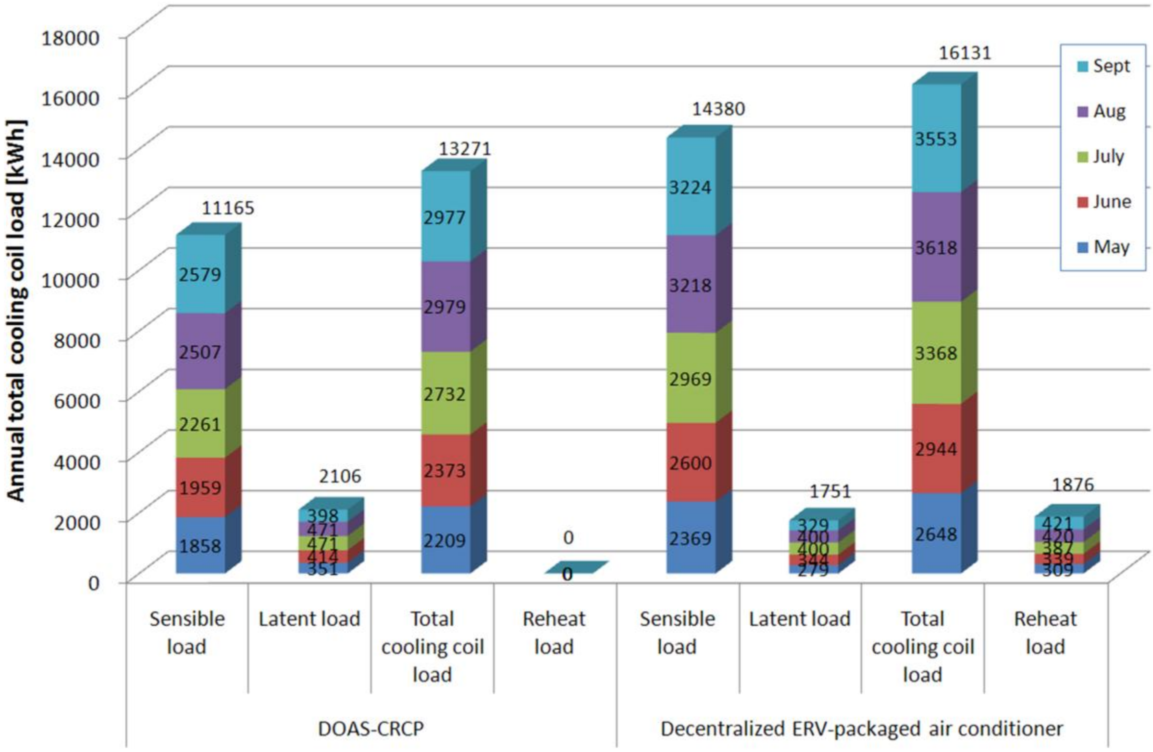

Fig. 9 Annual total cooling coil load

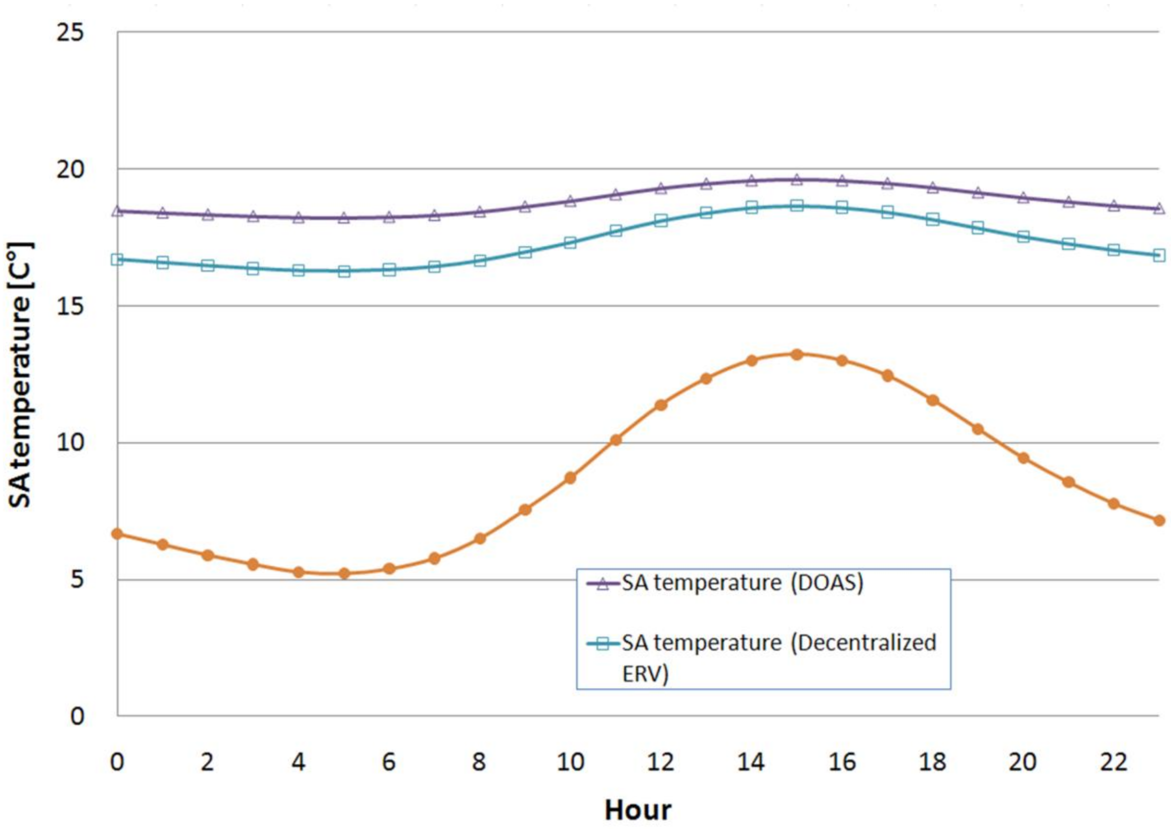

Fig. 10 Design of daytime change in supply air for December

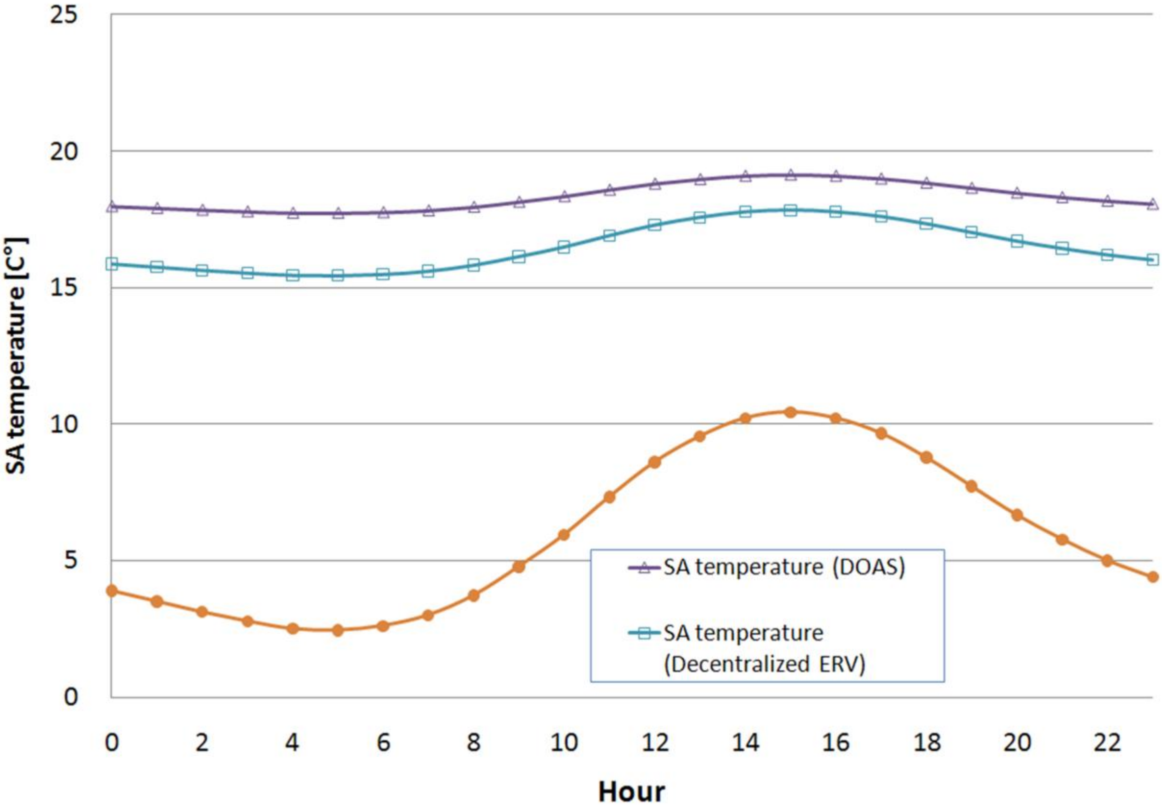

Fig. 11 Design of daytime change in supply air for January

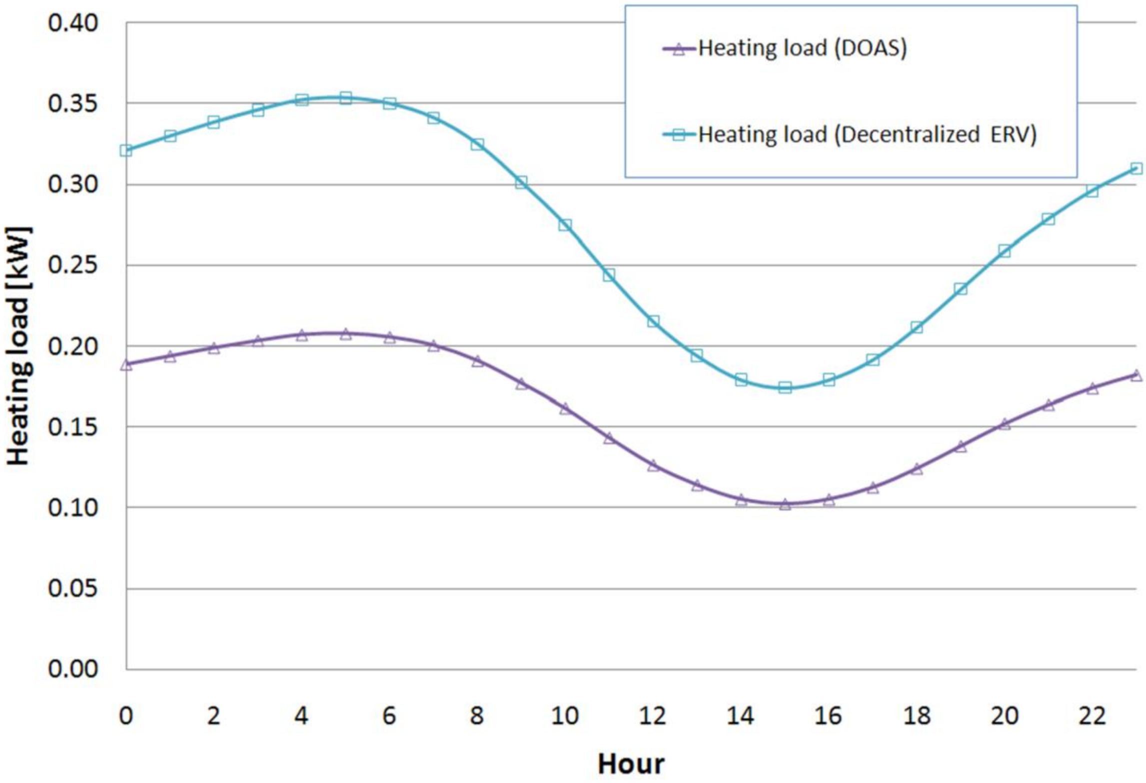

Fig. 12 Design of daytime heating load for December

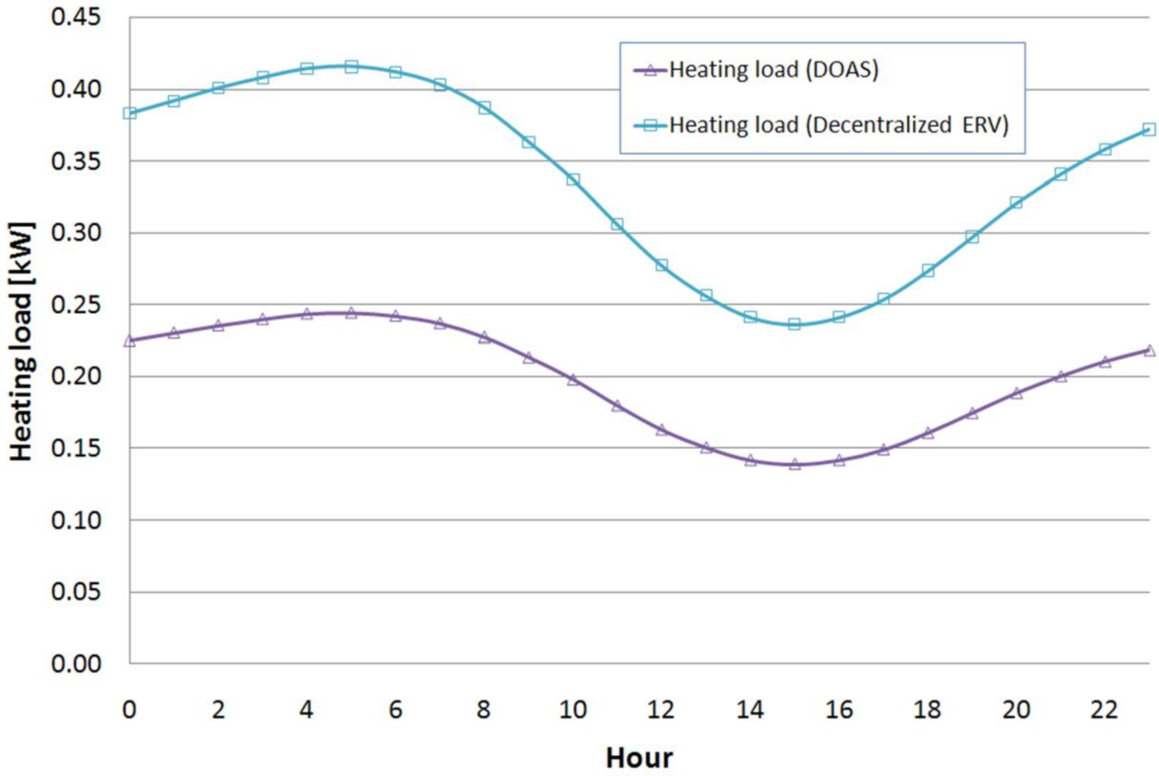

Fig. 13 Design of daytime heating load for January

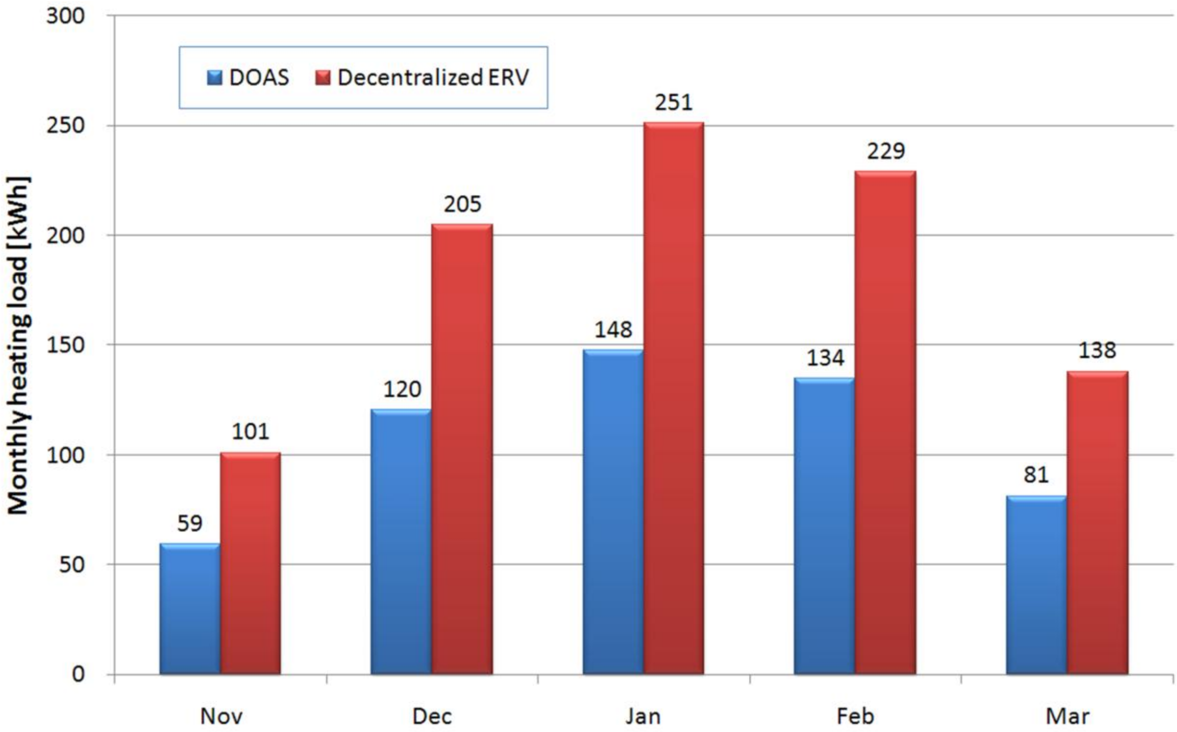

Fig. 14 Increasing rates of monthly heating load

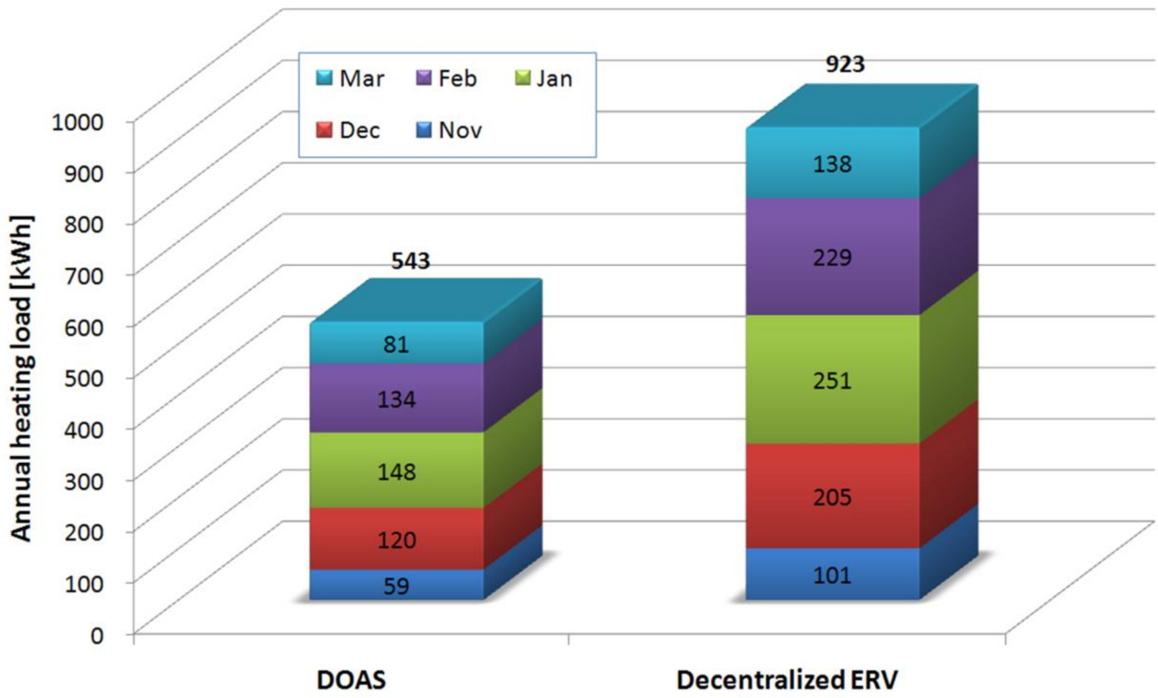

Fig. 15 Increasing rates of annual heating load

Table 1 Required ventilation rates per floor area

Floor area, [m^2]	Volume, [m^3]	Occupants	Required Ventilation rates, CMH	
			Standard of Korea	ASHRAE Std. 62.1-2007
66	158	3	111	100
99	238	3	166	136
132	317	4	222	181
165	396	4	277	218
198	475	5	333	263
231	554	5	388	299
264	634	6	444	344
297	713	7	499	390
330	792	8	554	435

Table 2 Proper DPT of DOAS supply air in a cooling period

Floor area, [m2]	Latent load, [W]	Required ventilation rates, [l/s]		Supply air humidity ratio, [g/kg]		Proper DPT of supply air, [℃]	
		Standard of Korea	Standard of ASHRAE	Standard of Korea	Standard of ASHRAE	Standard of Korea	Standard of ASHRAE
66	71	31	28	8.50	8.42	**11.6**	**11.4**
99	78	46	38	8.71	8.58	**11.9**	**11.7**
132	97	62	50	8.74	8.62	**11.9**	**11.7**
165	104	77	61	8.82	8.69	**12.1**	**11.8**
198	124	92	73	8.82	8.70	**12.1**	**11.9**
231	131	108	83	8.86	8.74	**12.2**	**11.9**
264	150	123	96	8.86	8.74	**12.2**	**11.9**
297	169	139	108	8.86	8.75	**12.2**	**11.9**
330	189	154	121	8.86	8.75	**12.2**	**11.9**