Comparative Numerical Energy Analysis of Decentralized Ventilation Adapting to Local Norway Climates

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Abstract

The present work evaluates the performance of different decentralized ventilation control strategies in the local Norway climate. Evaluation is performed using a monthly time-step energy analysis and the IDA-ICE simulation tool for a comparative primary energy analysis on the strategy combinations. Primary energy comparison is conducted with respect to a centralized constant air volume system for comparative analysis. The evaluation results show that the representative decentralized ventilation (DV) system has the most significant energy performance. The lower heat recovery efficiency significantly impacts on the ventilation energy of DV system in the cold climate, and the low specific fan power can efficiently be used for zone cooling in summer.

Introduction

In Norway, buildings have accounted for 45 % of the total energy usage (Grini et al., 2009). And heating, cooling, and mechanical ventilation for residential and service buildings represent more than 20% of this energy consumption, where infiltration and ventilation is one of the main contributors to that 20%, although that percentage varies with climatic, building, and HVAC context (Santos & Leal, 2012). With decentralized ventilation, the mechanically allocated air flows are directly transported through the façade rather than by a single centralized large air handling unit (AHU) by transportation through a net of ductwork, so that concerning for the stricter energy demands, decentralized ventilation units offer lower SFP values than a centralized ventilation (CV) system (Altendorf et al., 2022; Baldini et al., 2014; Cui et al., 2017; Kim, 2022; Kim et al., 2014; Speer et al., 2014). Baldini and Meggers (Baldini, 2008) presented that the DV system, which has fan power of 55 Pa, and fan efficiency of 20% could reduce around 76 % fan energy demand compared with the CV system, which has 800 Pa of pressure drop and 70% of fan efficiency. And the CV system has 14.5 times higher total pressure loss than the DV system because of relatively longer air passages and many duct branches. Bigger power fans come with greater fan efficiency, the missing ductwork leads to lower pressure losses and thus lower power consumption (Merzkirch et al., 2016). Figure 1 shows the schematic visualization of CV system. Typical CV system has been used in most commonly in buildings; however, it has a relatively long fresh air supply and exhausted air distributions with air duct systems (Bonato et al., 2020; Kim & Baldini, 2016; Kim et al., 2014; Merzkirch et al., 2016; Novoselac & Srebric, 2002; Ren et al., 2022; Tantasavasdi et al., 2001). Figure 2 presents DV system with a heat recovery unit. And Figure 3 illustrates schematic visualization of DV system through the façade of a building. DV system can directly supply fresh outdoor air with the shortest air passages through a compact DV system. Therefore, it can save air pressure and heat transmission loss in long distribution passage ducts (Heidt et al., 1998; Manz et al., 2001). Baldini and Meggers described that the DV system offers a possibility for significant fan energy saving (Baldini, 2008). The estimated DV system's reduction factor was 4.16 for a flow rate of 8000 m3/h compared to a CV system (Baldini, 2008). Norway's weather conditions have quite small cooling and high heating loads. DV system can easily adjust supply air volume flow rate with compact fans depending on surrounding weather conditions and occupant ratio. For example, in the mild summer season, occupants can adjust air volume flow rate such as fan assistant natural ventilation system. Using DV system could be enough for air ventilation and cooling demands in the summer season in buildings in Norway as a fan-assisted natural ventilation system. Kim and Baldini presented (Kim & Baldini, 2016) that the total availability of fan-assisted natural ventilation is about 22-32% per year in the west and central European countries. In order to minimize ventilation energy demand, DV system recommends combining with radiant heating and cooling system to provide sensible heating (Baldini et al., 2014; Kim & Baldini, 2016; Meggers et al., 2013). DV system can simply make individual zoning control in a room (B. Mahler, 2008). Outdoor air passes through a compact ventilator with fans and supplies into space.

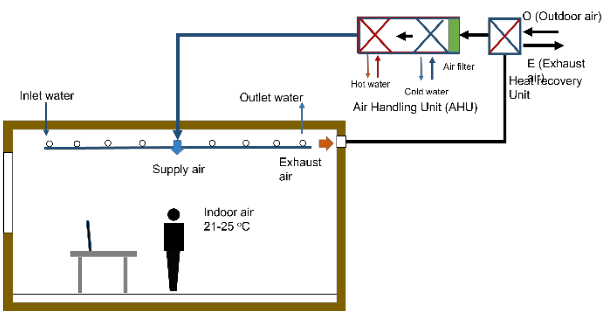

Figure 1 Schematic of a typical CV system

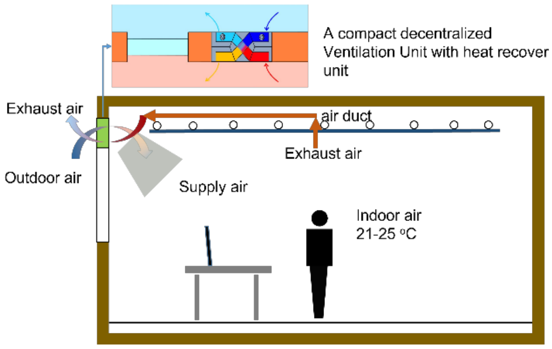

Figure 2 Schematic of DV system with a heat recovery unit

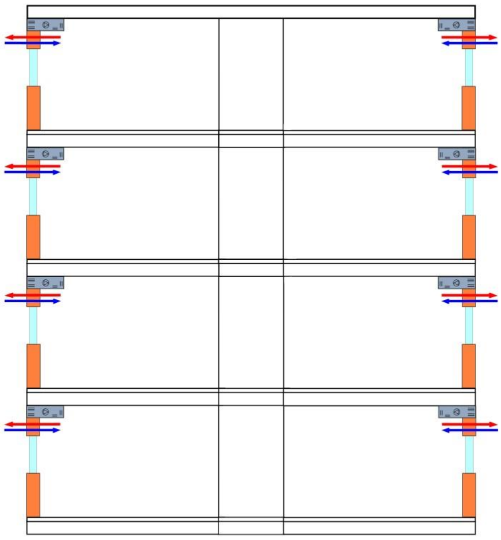

Figure 3: Schematic visualization of DV system though façade in a building

The main aims of this study are to present the performance of DV system adapting to the local Norway climate with respect to primary energy consumption compared to a conventional centralized ventilation system. And this study also shows the numerical performance using different ventilation control strategies and the heat recovery unit.

Methods

We selected one office room, which adopted a heat pump system for the heating and cooling process. The building is located in Oslo, and an office unit is designed for simulation. Oslo weather conditions are described as cold winter and mild summer season. Therefore, this study considers that the DV system can adapt well to high heating demand and relatively low cooling demand conditions in Oslo.

The recommended ventilation rate and energy demands followed the Norwegian building code TEK 17 (Authority, 2017) and NS 3701:2012 (Standard, 2012) guidelines, while NS-EN ISO 7730:2005 (ISO, 2005) and TEK 17 guidelines for comfort. And this study also applied for the verification of occupancy behavior in the office rooms of NS-EN 15193-1:2017 (Standard, 2017).

The building simulation is done through IDA ICE version 4.8 and is conducted for a more accurate representation of the primary energy consumption of each control strategy, and for a more substantial conclusive power when comparing the control strategies to each other. The accuracy of the produced results is limited to the accuracy of the building simulation program itself and the boundary conditions, assumptions, and input combinations used when running the simulations, which is further explained in detail for a full overview. Firstly, the zone model is described, with the general specifications that are equal for all the ventilation control strategies and cases. The constructed office zone model can be seen in Figure 4, and the full set of input parameters can be seen in Table 1. The weather data used is Oslo/Fornebu, 01.04.19 – 31.03.20. Table 1 shows the zone model's boundary conditions and the system conditions.

This study simulated four different types of ventilation strategies: centralized Constant Air Volume (CAV) system, Decentralized CAV system, Decentralized Ventilation with a Passive InfraRed control sensor (DV PIR), and Decentralized Ventilation with a CO_2 sensor (DV CO2).

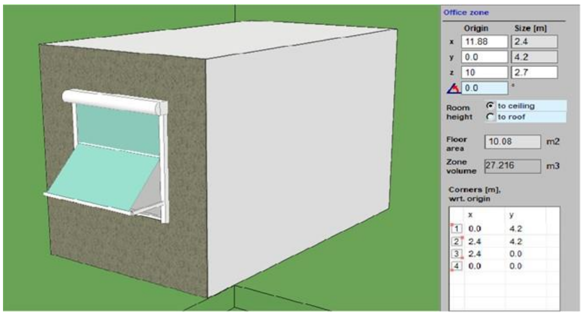

Figure 4 The geometric office values in IDA-ICE.

Table 1: System description of the reference room

Parameter	Value
Height to ceiling	2.7 m
Net room volume	27.0 m3
Occupancy	1 person
Internal heat gain	120 Watt per person, 85 Watt, electric device, and 34 Watt of lighting
Infiltration	0.1 ACH
Ventilation rate	Min: 8.0 m^3/h, Max: 58 m^3/h
Operation temperature	24.5 ± 1.0 °C (summer) 22.0 ± 1.0 °C (winter)

The three ventilation strategies, CAV, DVPIR, and $DVCO_2$ are illustrated in Figure 5,6 and 7. Figure 5 presents the scheduled CAV control strategy with the typical operation time. Figure 6 illustrates DV schedule by a PIR sensor. And Figure 7 shows the ventilation strategy with a CO_2 sensor. And Figure 8 illustrates the pre-defined CO_2 and temperature custom control strategy in IDA-ICE. Once the indoor CO_2 concentration reaches around 1000 ppm, the air ventilation rate is set to a maximum, which is in accordance with the IDA-ICE simulation input.

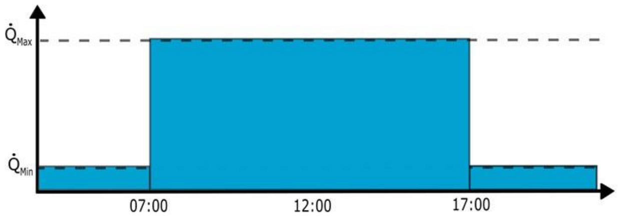

Figure 5: CAV control strategy schedule

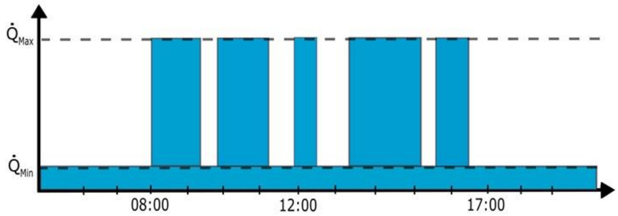

Figure 6: DVPIR control strategy schedule

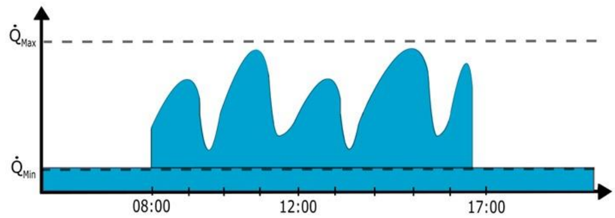

Figure 7: DV CO2 control strategy

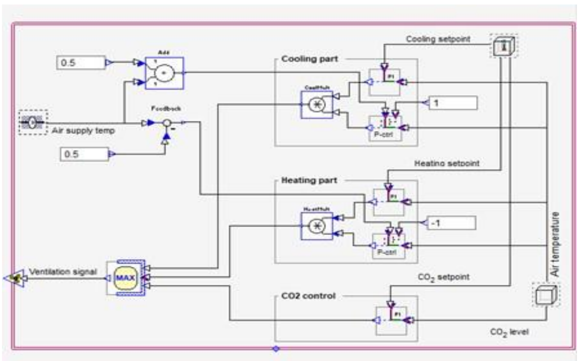

Figure 8 Pre-defined CO2 and temperature custom control in IDA-ICE

In addition, this study presents the performance of a ventilation system's heat recovery unit (HRU). Usually, an HRU shows the most prominent effect during higher temperature differences between indoor and outdoor air temperature, so colder climates rely more on HRU for saving energy. Figure 9 illustrates the schematic of a DV heat recovery unit.

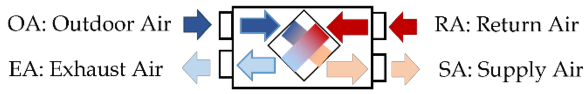

Figure 9: Schematic of a DV heat recovery unit

The specific fan power (SFP) is defined as the ratio between an electrical input and an airflow. And HRU efficiency can calculate with considerations to leakage by $R_{int,}$ which activates the possibility of difference between mass flow rates, $m_{extract}$ and $m_{exhaust}$ and only considers the sensible heat and is calculated with the following equations.

$$SFP = \frac{P}{qv} \qquad (1)$$

where, p is the electrical power input of the unit, qv is airflow through the unit

$$\eta_{fan} = \frac{\text{Aerodynamic power output}}{\text{Electrical power input}} = \frac{qv \times p_{fan}}{P} \qquad (2)$$

where, p_{fan}: total fan pressure difference between inlet and outlet

$$SFP = \frac{p_{fan}}{\eta_{fan}} \qquad (3)$$

$$\eta_{HRU} = \frac{T_{supply} \times m_{supply} - T_{ambient} \times m_{ambient}}{T_{extract} \times m_{extract} - T_{ambient} \times m_{ambient}} \qquad (4)$$

where, T is temperature, ^{o}C, m is mass flow rate, kg/h

Fan power is calculated by the following equation (Niu et al., 2002):

$$Fan\ power = V\Delta p / 3600\ \eta_{fan}$$

where V is the volumetric flow rate of air (m3/h), Δp is the total pressure rise (Pa)

Based on the simulation analysis, this study combined experimental data (Åse Lekang Sørensen, 2017), which were tested at an office building near Oslo, Norway. The technical report described that the building used CV system, and the heating and cooling energy of AHU accounted for 24% of the actual total HVAC energy demand. Using the experimental data, this study presents a comparative analysis of energy consumption demands between CV and DV systems.

Results

This study analysed the weather condition of Oslo city in Norway. Oslo weather condition shows relatively cold winter and mild summer. In the season, between June and September, a DV system can supply outdoor air into a room without additional thermal demands. In the summer season, outdoor air temperature is generally lower than 25^{o}C, so the DV system can directly supply outdoor air as a fan assist-hybrid ventilation strategy. Therefore, DV system can save ventilation cooling energy in a building (Kim & Baldini, 2016; Kim & Choi, 2019; Kim et al., 2014; Ren et al., 2022).

Based on the boundary conditions in Figure 5- 8 and Table 1, this study simulated the energy demands of the CV and DV systems with control strategies. Figure 10 presents that the centralized CAV system had around 34-68 % higher fan energy consumption than the DV systems. DV systems consumed relatively lower fan and cooling energy than the CV system because DV system simply adjusts air volume flow rate depending on outdoor weather conditions and the short air passage can minimize air pressure drop and the thermal energy transmission loss in air distribution systems. The DV system with a CO2 sensor has the lowest energy consumption. It is because the CO_2 sensor can sensitively adjust thermal energy and airflow rates with occupancy patterns in a room. However, this study did not include water pump energy demands due to pressure drop in the hydronic water supply for DV system. Kim and Baldini (Kim & Baldini, 2016) described that the DV system had around 1 % higher pump energy consumption than the CV system.

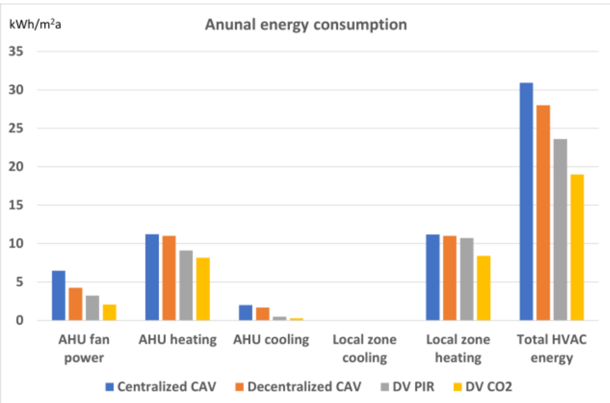

Figure 10: Comparison of the HVAC energy consumption for centralized CAV, decentralized CAV, DV with a PIR sensor, and DV with a CO2 sensor

DV systems can save fan and cooling energy demands. Usually, CV systems designed supply air temperatures about 15-17°C in the summer season (Kim & Baldini, 2016). However, DV systems has more flexible the designed supply air conditions. For example, in the outdoor air temperature of around 17-20°C, the DV system can directly supply the outdoor air-condition without additional cooling loads (Baldini et al., 2014). The individual fans can increase the supply air volume flow rate for air ventilation and cooling in a room as a hybrid natural ventilation strategy. Therefore, DV systems can dramatically reduce air ventilation and cooling energy consumption compared with the CV system.

Figure 11 and 12 illustrate a comparison of AHU heating and cooling energy demand using a heat recovery unit. Generally, high-temperature differences between outdoor and indoor conditions dominate heat recovery units' performance. Specially in the winter season, AHU heating demands are strongly affected by the HRU effectiveness. However, in the summer season, the lower temperature differences influence small energy demands for cooling in buildings. Figure 11 shows the performance of AHU heating system. Conventional CV systems consumed more AHU energy for heating compared to DV system; however, the higher HRU efficiency of CV system can compensate for the heating demand loss because the HRU can save so much energy in the cold winter season. To increase HRU efficiency of DV system, we can design a bigger DV system. But it also challenges maximizing the DV system's volume because it consumes much room volume. In contrast, in the summer season, the HRU efficiency could not significantly affect cooling demand because the lower temperature differences rarely impact the cooling energy savings. Hence, in the summer season, the fan control strategies and air volume adjustment can mainly reduce the cooling demands of the AHU and improve indoor thermal comforts as a fan assist-hybrid natural ventilation system. As the comparisons of two figures in Figures 11 and 12, the DV system with a PIR and CO_2 sensor mainly dominates energy saving during the cooling season. In contrast, the HRU efficiency highly impact on the heating demand in the winter season. Hence, once we consider the DV system with sensors to install in buildings, we consider the higher HRU efficiency of a DV system for heating in cold climates.

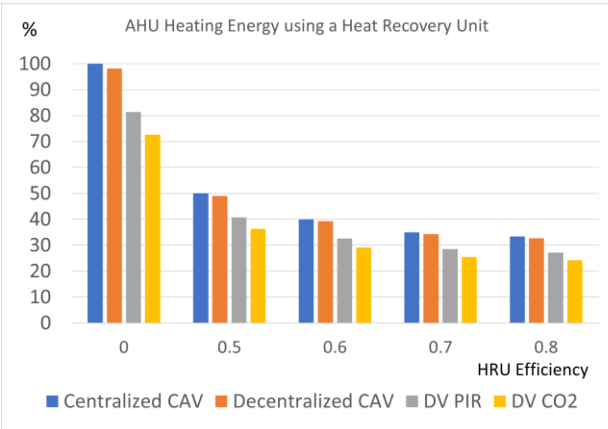

Figure 11: Comparison of AHU heating energy demands using a heat recovery unit

The DV system can optimize utilizing ventilation and cooling in mild condition. It is because the DV system can simply combine the hybrid-natural ventilation systems using a fan assist fan control system. An independent DV control system can adjust a room's air volume for cooling and ventilation based on occupant behaviour. The DV system needs to combine a heat recovery unit for heating in cold climates. It can save so much thermal energy in winter.

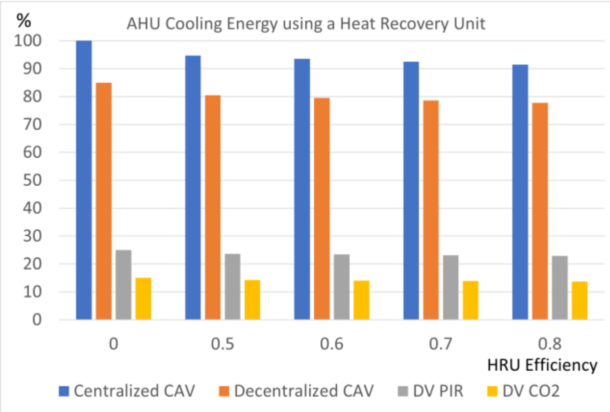

Figure 12: Comparison of AHU cooling energy demands using a heat recovery unit

In summer, we can also carefully check the performance of HRU system due to unnecessary cooling demand required additionally. For example, with outdoor temperature around 15-20°C, the HRU can increase cooling demands because indoor air temperatures around 25°C can raise the supply air temperature. Therefore, in the ambient condition of 15-20°C, we do not need the HRU to supply fresh outdoor air and can directly supply outdoor air into a room without additional cooling output. We can consider a bypass control system for DV systems due to unnecessary cooling demands of HRU system in the intermediate and summer season. And the control strategy will be more complicated to add a bypass design in the DV system. The HRU performance of DV system highly affects the thermal energy demand in winter, however, it does not significantly affect cooling demand in the summer season. A fan control and free cooling as a hybrid natural ventilation can more highly affect cooling demand in summer season.

Figure 13 and 14 present a comparison of energy demands AHU heating and cooling, and fans based on the experimental data of a case study (Åse Lekang Sørensen, 2017). With high heat recovery efficiency, fan energy dominated actual ventilation system energy demand. However, with low heat recovery efficiency, η: 0.5, ventilation heating mainly dominated the ventilation energy consumption. And there is no significant energy saving benefits using the DV and DV PIR system strategy compared to CV system. Regarding the energy saving strategy of DV system, the heat recovery unit efficiency is crucial to install in cold climates. And if the occupancy ratio highly fluctuates in a building, DV system has more benefits to reducing ventilation energy demands because it simply adjusts supplying outdoor air flow rate. In contrast, if the indoor occupant ratio is constant, DV system's heat recovery efficiency is crucial factor to install the system for energy saving.

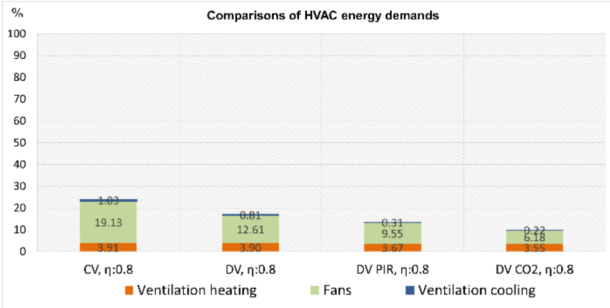

Figure 13 Comparison of energy demands of CV and DV systems using a heat recovery unit (η: HRU efficiency)

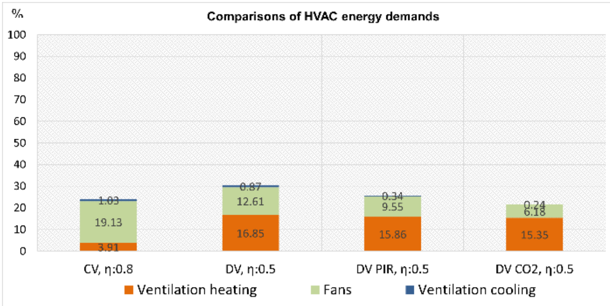

Figure 14 Comparison of energy demands of CV and DV systems using a heat recovery unit efficiency (η: HRU efficiency)

Additionally, this study has some technical limitations remained to explore via further research. a DV system needs to connect heating and cooling sources to supply comfortable air into a room because adding a heat recovery unit does not have enough thermal energy demand to supply chilled and heated air in extreme cold or hot season. So, to add a heating source, it needs to connect a hydronic system for heating and cooling in a DV system, and it additionally consumes electric pump energy. And the DV system is attached external facades, therefore, it can consume additional conductive and convective heat loss between a facade and the DV system. In a further study, we can present the additional heat and cooling losses of DV systems. And the location of the DV system is also quite important to present air ventilation performance and thermal comfort in a room. Next studies should consider the DV system's location of supply and exhaust air for improving indoor air quality and thermal comfort. And CO_2 based demanded control system can save energy by minimizing air ventilation demand (Meggers et al., 2013). Therefore, we can show the experimental results using the CO_2 based demanded control strategy in the next studies.

Conclusion

Using a numerical simulation tool, IDA-ICE, we conducted ventilation performance to evaluate three decentralized ventilation strategies compared with a typical centralized ventilation system in an office room in Norway. The DV system was more energy efficient than the CV system. Specially, the DV system with CO_2 sensor showed good performance for saving thermal and fan energy due to shorter supply and exhaust air passages. This study found that the DV system can significantly reduce fan energy and it can be well adapted to individual space because it can simply adjust input air volume depending on indoor occupancy ratio. In addition, it can efficiently control cooling output by compact air fans in the DV system in the summer season. A heat recovery unit is also quite important to save thermal energy in a cold season. The CV system has relatively more consumed thermal energy compared to the DV system; however, the higher HRU efficiency of the CV system significantly impacts on the energy performance compared to the lower HRU efficiency of the DV system in the winter season. However, the HRU efficiency could not strongly impact the energy performance in the summer season due to the smaller temperature difference between indoor and outdoor condition. In the summer season, the DV system's fan control can be utilized to reduce energy consumption.

Acknowledgement

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