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Numerical performance investigation of decentralized ventilation compared to centralized ventilation system at a residential building: A case study in Norway

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Abstract. A main goal of the study is to investigate whether decentralized ventilation (DV) systems can outperform typically centralized ventilation (CV) system in terms of energy while keeping indoor air quality at acceptable levels. And additional research questions regarded heat recovery function and placement of DV units within the apartment space. The question about modeling the DV units themselves within a Software, IDA-ICE was investigated. The placement of DV unit has been proposed. The advantages and drawbacks of using such systems were outlined and compared to centralized ventilation. The question of modeling DV units in building simulation software was raised and discussed. Results show that, given the chosen set of boundary conditions and model of DV, it offers the best performance energy-wise in the mild season. The differences are most visible during colder months when the heat demand is highest. A DV came out with slightly worse energy performance with low heat recovery unit (HRU) performance. The differences weren't substantial and none of the analyzed systems met the TEK17 requirement for net delivered energy for residential buildings. No significant difference was shown regarding indoor climate indicators across systems. Seasonal energy analysis shows marginal differences between systems. HRU function showed significant energy-saving potential in cold seasons.

1 Introduction

Norway's highly developed economy [1] and rising demographics [2] pose a challenge to reducing electricity usage and accomplishing national and European climate targets. Norway's ambitious climate targets of reducing emissions by 55% by 2030 compared with the 1990 level, together with the ultimate reduction towards zero emissions by 2050 are under great dispute. According to reports [3] those goals will most likely not be met.

This study turns to focus on residential buildings and the potential of using decentralized instead of centralized ventilation to save energy. Ventilation represents a significant part of buildings' energy usage [4] and DV systems have been tested and proven to perform better than their CV counterparts in residential buildings. [5] Norwegian housing market is constantly in development [6] and the fact that people spend even more time at home now due to the post-pandemic job market situation [7] makes residential buildings an interesting field of study.

1.1 Types of mechanical ventilation systems

1.1.1 Centralized ventilation system

The centralized ventilation system is characterized by using a single piece of equipment, a central Air Handling Unit that is connected through a duct network to all rooms which will be supplied with fresh air, together with ducts for return and exhaust of used air. These can be visualized in Fig. 1. CV system is the most popular one in all types of buildings. Its principles are good understood by professionals and it is being designed most frequently due to versatility and known parameters [8]. Drawbacks of such a system are the amount of ducting that is necessary to distribute air, big volumes of AHU together with a need for extra equipment for zone-based control. Demand control ventilation is a solution to allow such control on the zone level thanks to the array of automation components [9].

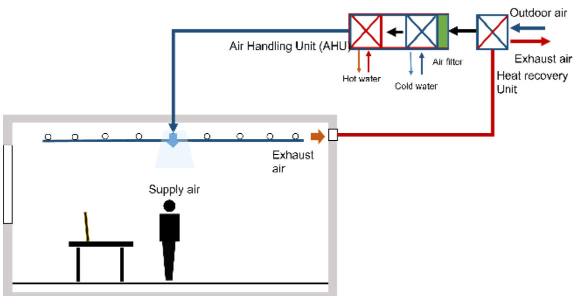

Fig. 1. Typical centralized ventilation system

1.1.2 Decentralized ventilation system

Decentralized ventilation systems work in a way that instead of one, centralized unit there are multiple ones, each supplying a different zone. This way, ideally, each person occupying a different zone can control its indoor environment, which is temperature and airflow locally, thanks to the DV unit placed right next to the user. Advantages of such a system are minimizing or even lack of ducting which gives more space for higher ceilings or other installations, more ways for adapting existing spaces due to smaller dimensions of units, and better control flexibility that lets the end user change supply airflow and temperature locally. DV units take less space within the apartment and allow more flexibility in placing them, in comparison to centralized AHUs [10-13].

As the name suggests, this type consists only of one unit placed by the façade or roof of a building, often sticking out into the room taking its space. Firstly, it's often equipped with bigger fans or a bigger number of them which enables it to deliver higher airflow rates. Another thing is its heating and cooling capabilities as it is often equipped with both heating and cooling coils. [11, 14-17] Therefore Single-Unit can regulate the temperature of incoming air to the room. Some models are also able to control and extract heat from moisture and phase change of cooling fluid such as water. [18]

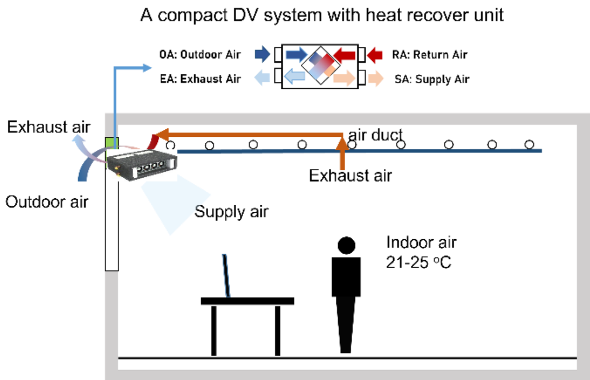

Fig. 2. Decentralized ventilation system

A heat exchanger in Single-Unit DV here described is of type recuperative cross heat exchanger, as shown in Fig.2. It has often better performance than small regenerative HRU. SFP of the fans installed in DV is also lower than in CV [5, 19-21].

2 Methodology

The first step in modelling the apartment was to gather knowledge about applicable building requirements according to Norwegian law. Forskrift om Tekniske Krav17 (TEK17) [22] which is regulations on technical requirements for construction works in Norway for residential building has been used to establish leading guidelines in terms of energy, building construction and indoor climate. U-values for the construction envelope has been chosen to be within the required values. Detailed list over requirements followed TEK17 regulations. Hourly weather data of Oslo city is shown in Fig.3. Oslo has cold weather in winter and mild summer weather. Therefore, it has high cooling energy demands, and relatively small cooling demands.

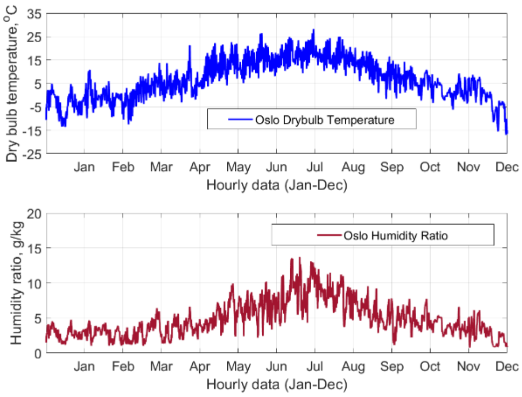

Fig. 3. Oslo Weather data.

2.1 Building boundary conditions

Orientation of the building has been based on an existing building located in Oslo at Fossveien. In Fig.4. building together with shading is shown as modelled in IDA-ICE and Fig.4. shows a satellite view of the existing building and apartment that the model has been based on. The floor plan of the modelled apartment took also starting point for the existing plan drawings found on the Norwegian building directorate database.

Fig. 4. Picture from a satellite view of Google Maps showing the existing building in question. North direction to the right. Yellow: building boundary. Blue: apartment boundary.

And Fig.4. and Table 1. present the building geometry and boundary conditions. And Table 2. illustrates the U-values of the building construction materials

Table 1. Building geometry and boundary conditions.

Para mete r	**Bathr oom**	**Kitc hen**	**Living Room**	**Bedr oom**	**Entr ance**	**To tal**
Width, m	2.2	2.8	3.6	3.7	1.1	
Length, m	1.8	2.1	3.7	2.2	2.1	
Height, m	3.2	3.2	3.2	3.2	3.2	
Area, m2	3.9	5.8	13.3	8.1	2.3	**33**
Volum e, m3	12.6	18.8	42.6	26.0	7.3	**10 7**

Table 2. Construction materials' U-value, W/m2K

Construction type	TEK 17 requirement
External walls	≤ 0,22
Internal walls	-
Internal floors	-
Roof	≤ 0,18
External floor	-
Basement wall towards ground	≤ 0,22
Slab towards ground	≤ 0,18
Glazing	≤ 1,2
Door construction	≤ 1,2
Integrated window shading	-
Normalised thermal bridges	≤ 0,03

2.2 Windows, shading and external surface

Modelled apartment was designed including openings: façade windows on the east and west, and internal doors. There are in total 5 windows in the apartment. 3 big windows, 1,7m high and 1.0m wide placed in the living room (2 pieces) and in the bedroom (1 piece). One tall window in the kitchen, 0.632m high and 2.28m wide and one, even smaller window in the bathroom 0.44m high and 1.2m wide. All glazing has a U-value of 1,2 W/m^{2}K and the same values for other related parameters such us g-value, transmittance, reflectance, and emissivity. An exemplary window set-up is seen in Fig.5.

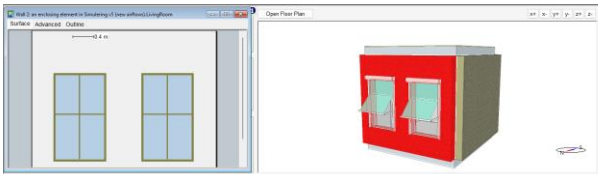

Fig. 5. Exemplary wall with facade windows. Here: Living Room. IDA-ICE.

All façade windows have been equipped with integrated, external shading of type, generic type of shading from the IDA-ICE database. For the purposes of the simulation, there has been using an automatic control based on the previously mentioned schedule of Apartment living. Shading control is in addition controlled by a Proportional Integral (PI) temperature controller.

2.3 Ventilation rates

To calculate how much airflow is needed in the modelled apartment, Method 1 from NS-EN 16798-1:2019 has been used. The apartment has been divided into rooms, from which corresponding functions have been figured out, as follows: "dry rooms": Living Room, Bedroom, and Entrance; "wet rooms": Bathroom and Kitchen. To perform a comparison between centralized and decentralized systems it was necessary to model these in IDA-ICE with their specifications. By taking the default "Standard Air Handling Unit" from IDA-ICE as a starting point, Single-Unit systems have been derived., together with varying values of parameters SFP, HRU, and heating and cooling coils.

2.4 Occupancy profile

The occupancy profile, shown in Table 3., was chosen from a list of defaults in IDA-ICE. It assumes a working week from Monday to Friday between 9:00 and 15:00. While at work occupancy is set to 0. From 15:00 to 17:00 it ramps up to 50% and is set to 100% at all other times. Simulations consider holidays based on the Swedish calendar that resembles the Norwegian one on an acceptable level. The profile is shown in Table 4.

Table 3. Occupancy profiles in the apartment

Day	Time	Occupancy	Occupancy
Mon-Fri	0-8	100%	100%
Mon-Fri	9-15	0%	0%
Mon-Fri	15-17	50%	50%
Mon-Fri	18-24	100%	100%
Sat, Sun	0-24	100%	100%

2.5 Numerical analysis

Heat recovery unit efficiency and fan power, Watt are defined by following equations.

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

where, T is temperature, °C

$$Fan\ power = V\Delta p / 3600\ \eta_{fan} \quad (5)$$

where Fan power is Watt, V is the volume flow rate of air (m3/h), η_{fan} is the fan efficiency, Δp is the total pressure rise (Pa) [23]

Ideal coefficient of performance (COP) value of a heat pump system is presented by following equation.

$$COP_{heating} = \frac{T_{condensor}}{T_{condensor} - T_{evaporate}} = \frac{Q_{heat\ output}}{W_{input}} \quad (6)$$

3 Results

The results are presented in two parts: Ventilation heating and cooling energy demands. In Fig. 6 and 7., we can see results from annual ventilation heating demand. A scenario with an HRU yields the lowest energy usage setup in the summer, but inversely it has the highest demand in the winter season. The lower heat recovery efficiency worsens energy performance significantly in cold climates. Fig.7 shows the results of ventilation heating demands with the heat pump system. Here a heat pump system with higher performance can reduce ventilation thermal demands. The results lead to a conclusion that turning HRU on has mainly contributed to improving energy performance in cold climates.

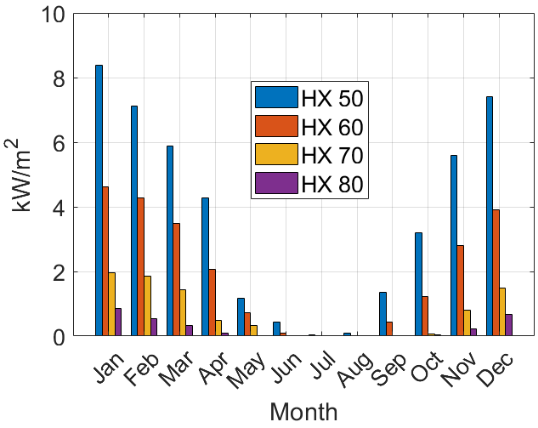

Fig. 6. Ventilation heating demand with the heat recovery efficiency, 50%, 60%, 70%, and 80% at Oslo, Norway.

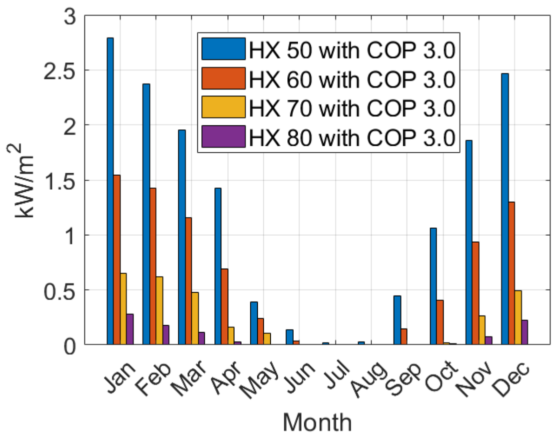

Fig. 7. Ventilation heating demand with the heat recovery efficiency, 50%, 60%, 70%, and 80% at Oslo, Norway.

Fig.8. presents ventilation cooling demands with a heat recovery unit in the summer season. The results illustrated that the higher HRU efficiency cannot significantly affect ventilation cooling demand in the summer season. It is because the local weather condition in summer season is quite mild, and the cooling demand is quite small. And even a fan-assisted hybrid ventilation system using a DV unit can be useful without HRU. Full- year energy simulation illustrates the performance of a ventilation system with HRU. A heat recovery unit is necessary and the better the efficiency, the nearer one can come to lowering the overall energy consumption in cold climates, however, mild weather season does not need a high-performance HRU unit because the impact is quite small. Therefore, DV system can be optimized in mild conditions due to short air passage length and the lower air pressure drop compared with CV system. One of the main benefits of using DV system is that it can use in the summer season as a hybrid natural ventilation system. It simply adjusts supply air volume flow rates depending on occupancy ratio and internal heat gains. So it could be optimized in the summer season in Norway to save thermal and fan energy consumption.

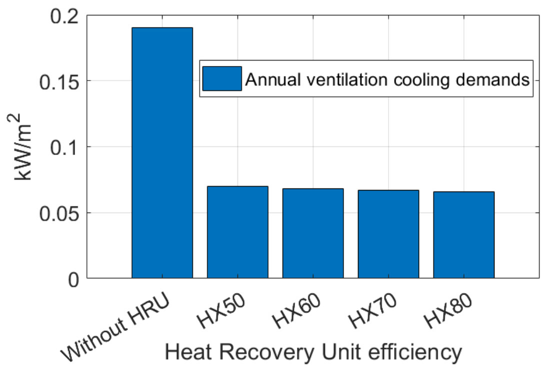

Fig. 8. Annual ventilation cooling demands with different heat recovery unit efficiencies, without, 50%, 60%, 70%, and 80% at Oslo, Norway.

Fig.9. presents comparisons of five different ventilation scenarios with DV, CV, HRU, heat pump and occupancy ratio. CV system has relatively higher fan energy demands, and the lower COP value of the heat pump system also significantly affects ventilation thermal energy demands.

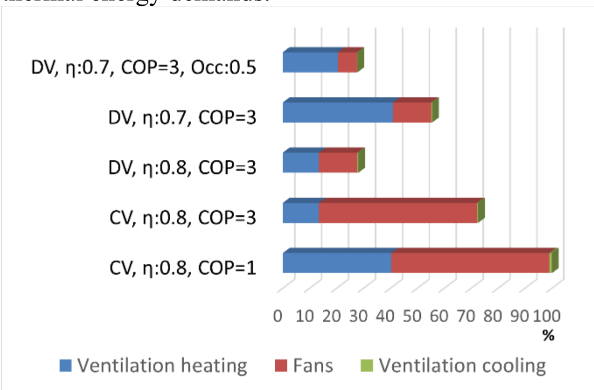

Fig. 9. Comparisons of different ventilation strategies at a residential building in Oslo: CV (centralized ventilation), DV (decentralized ventilation), η (heat recovery unit efficiency (0:zero-1:hundred percent)), Occ(occupancy ratio (0-1)).

DV system can reduce fan energy demand, lower HRU efficiency can dramatically impact thermal demands in cold climates. One of the main challenges of using DV system is that it is quite limited to improve HRU efficiency because DV unit volume has a compact size, and the larger volume can consume room volume as well. And a higher COP value can reduce thermal energy demand in a building; however, it cannot reduce fan energy demands. Therefore, using DV system and higher COP value of the heat pump system can effectively minimize thermal and fan energy demands. DV system with lower HRU efficiency can mainly increase ventilation heating demands in cold weather; however, the main strength of DV system is that it can simply adjust air volume flow rates depending on the occupancy ratio. The smart ventilation strategy with CO2 sensors using DV system has more potential for saving fan and thermal energy loads.

This study has some technical limitations to perform two ventilation strategies and should improve the deficiencies in future research. Even though some results came from actual measurement data, a numerical analysis could not reflect the real system's boundary conditions such as DV system's conduction and convection heat losses when it attaches near building façade areas. And when DV system needs additional heating and cooling outputs, DV should install heating and cooling coils, or a dehumidification process and it can consume more pump and thermal energy consumption. We would develop further research improvement via experimental analysis in the future.

4 Conclusions

This study analyzed the thermal and fan energy demand of DV system compared with CV system at a residential building in Oslo, Norway. We selected a local apartment in Oslo to evaluate the ventilation energy consumption strategies with different scenarios. DV system has lower pressure drop due to short passage to supply fresh air, and therefore, it can save much fan energy consumption. However, HRU efficiency strongly affects thermal energy demands in the cold season. Conversely, the HRU did not significantly impact the cooling energy demand in the summer season. A heat pump's higher COP values can gradually reduce thermal heating demands in the winter season; however, it cannot affect ventilation fan energy demands. A residential building using high performance heat pump system relatively has high fan energy consumption because the thermal demands can be reduced by high-performance heat pump system, but fan energy cannot be reduced. However, DV system can minimize fan energy demands due to short air passages to distribute air and simple adjustment of airflow by decentralized fans.

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