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Heat recovery ventilation design limitations due to LHC for different ventilation strategies in ZEB

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ABSTRACT

Today's buildings are becoming more insulated and airtight to reduce transmission heat losses. Energy use for ventilation can represent up to half of these buildings' total energy use. Heat recovery in ventilation and demand-controlled ventilation (DCV) are energy-efficient measures to reduce ventilation energy use, especially when combined. However, this study revealed that the often-overlooked longitudinal heat conduction (LHC) in aluminium rotary heat exchangers might yield less efficient heat exchangers, particularly for intended high-efficiency heat recovery at low ventilation rates in DCV. This study presents a theoretical method to assess the effect of LHC on the amount of energy used to heat ventilation air for several ventilation strategies. The method is demonstrated in a case study for a virtual office building in a cold climate (Oslo, Norway). When neglecting the LHC effect, the energy used to heat the supplied air using DCV with a rotary heat exchanger is about three times smaller than when considering LHC. Unlike earlier studies, we find that DCV may consume more ventilation heating energy than constant air volume (CAV) ventilation when the selected wheel is deep and oversized due to LHC. This study highlights the need to design rotary heat exchangers carefully in order to account for the LHC effect, particularly when targeting zero emission buildings (ZEB).

1. Introduction

Adequate ventilation is vital to sustaining satisfactory indoor thermal comfort, ensuring healthy indoor air quality and avoiding building damage, particularly for highly insulated and airtight buildings. Nevertheless, ventilation energy use ranges from 10 to 50% of buildings' electricity consumption [1]. Moreover, buildings' energy use accounts for approximately 40% of global energy consumption and over 30% of total greenhouse gas emissions [2,3]. DCV and heat recovery ventilation are widely accepted energy-efficiency measures, and they have been extensively studied and applied after improving building envelopes [4–7].

HVAC systems in buildings usually operate at part loads depending on the weather conditions, internal loads and occupancy profiles [8–10]. Typically, offices operate at a rate of 10–40% below total capacity, restaurants operate at 30–60% below total capacity and schools operate at 10–70% below the total capacity [11]. Due to new home office work habits that arose during COVID-19 and continue today, the rate of HVAC operation in offices can be even lower [12] and is expected to remain this way. DCV systems that modulate ventilation rates in response to the concentration of selected markers can use less energy while maintaining acceptable indoor air quality (IAQ) [13]. Wachenfeldt et al. [6] measured energy savings of 21% on heating demands and 87% on fan consumption in two Norwegian schools. Furthermore, Ahmed et al. [5] used a verified dynamic simulation to calculate a decrease of 33–41% in energy use for heating, cooling and fans in a Finnish office building compared to a CAV system.

Ventilation heat recovery systems are often recommended or required to save heat energy in high-performing buildings. For instance, the parameter-based requirements of the latest Norwegian building regulation, TEK 17 [14], require a temperature efficiency over 80%. With the development and optimisation of heat recovery systems, over 90% of ventilation heat can be recovered [15–20]. Rotary heat exchangers perform efficiently in counterflow with simple ductwork connections [17,18]. Their recovery efficiency depends on multiple factors including exchanger design, operating ventilation rates, efficient area for heat transfer and rotary speeds.

When airflow rates are reduced in DCV, heat recovery efficiency is expected to increase. However, the presence of longitudinal heat conduction (LHC) in the flow direction in rotary heat exchangers jeopardises the efficiency of heat recovery. The driving force of LHC is

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Nomenclature

Parameters

A	Heat transfer area [m^2]
A_k	Cross-sectional area of the matrix wall [m^2]
C^*	Ratio of minimum to maximum heat capacity rates [−]
C_{min}	Minimum heat capacity rate, m^*c_p [W/K]
C_r^*	Ratio of total matrix heat capacity rate
G	Fluid mass velocity based on the minimum free area [kg/m^2]
g_c	Proportionality constant [−]
h	Convective heat transfer coefficient [W/m^2 K]
k	Thermal conductivity [W/(mK)]
L	Depth of the wheel [m]
m	Mass flow rate [kg/s]
N	Rotation speed [RPM]
Re	Reynolds number [m^2]
U	Overall heat transfer coefficient [W/m^2 K] or uncertainty

Subscript

m	Matrix
min	Minimum

Abbreviations

CAV	Constant air volume
DCV	Demand-controlled ventilation
LHC	Longitudinal heat conduction
NTU	Number of heat transfer units
SV	Scheduled ventilation

Greek letters

α	Aspect ratio of the channel
λ	Dimensionless parameter for longitudinal heat conduction
δ	Thickness of the wall [m]
ε	Temperature efficiency
Δp	Pressure drop [Pa]
φ	Dimensionless parameter

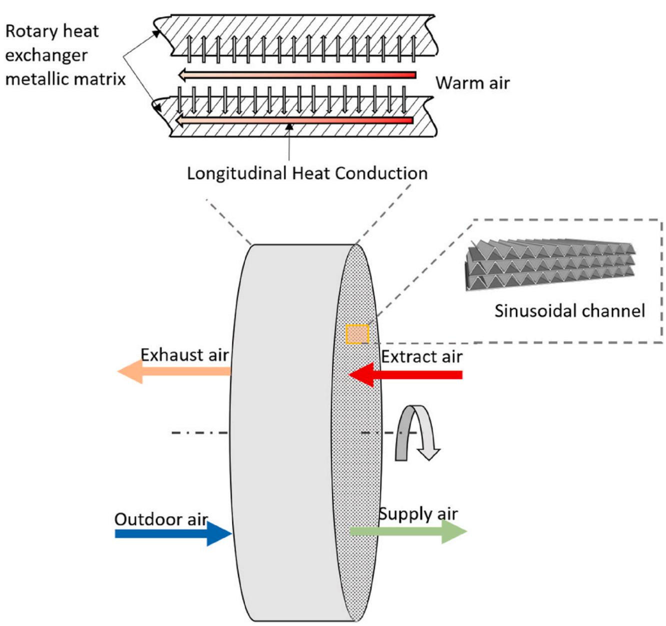

Fig. 1. Rotary heat exchanger and longitudinal heat conduction (adapted from [18]).

temperature differences in the metallic heat storage matrix (Fig. 1). LHC in the metallic matrix flattens the temperature distributions, thus reducing the mean outlet temperature of the supply air [21]. The significant effect of LHC on highly efficient heat exchangers was revealed and studied several decades ago [14–16,23,24]. Nevertheless, methods of improving recovery efficiency, including through the development of highly efficient rotary heat wheels with a reduced LHC effect, have not been developed until recently. For example, Liu et al. [18] theoretically developed highly efficient wheels by reducing LHC and enhancing heat transfer characteristics for residential ventilation. When constructed with plastic and stainless steel, the temperature efficiency of these heat wheels can reach 90%, which was verified against experimental measurements. However, to the authors' knowledge, the LHC effect for large heat wheels in non-residential buildings has not been studied.

In a existingzero-carbon neighbourhood in Belgium [25], demand-controlled exhaust ventilation systems and mechanical ventilation systems with heat recovery were compared. Using automatic monitoring data, in situ measurements and occupant surveys, the DCV system has been shown to use less electricity, have comparable heating demands and provide a comparable indoor air quality relative to heat recovery ventilation in this case study [25]. Mercer and Braun [26] found that DCV combined with heat recovery is the recommended solution to save energy and reduce costs compared with CAV for small commercial buildings. Using ANSI/ASHRAE/IES Standard 90.1–2010 as a base case, Jiru [27] used the energy performance simulation software EnergyPlus [28] to demonstrate how HVAC energy conservation measures can save energy. In Jiru's study, primary schools and standalone retail stores were able to reduce energy consumption by combining total energy recovery systems and DCV energy conservation measures compared to the base case for the selected climates and locations [27]. When DCV is combined with economizer control in buildings, indoor air quality can be improved and cooling/heating energy consumption can be reduced [29]. The combination of DCV and heat recovery is a viable solution to reduce energy demand in ventilation systems for non-residential, nearly-zero-energy buildings [30]. However, none of the above studies considered the inefficiency due to the LHC effect for the combination of heat recovery and DCV.

Lower flow rates and a high thermal conduction matrix (e.g. the commonly used aluminium) aggravate the negative effect of LHC. In contrast to the improved recovery efficiency for lower airflow rates in DCV, the measured temperature efficiency – and thus energy savings – turn out to be much lower than calculated or simulated when LHC is taken into account. Indeed, various studies have observed and modelled the reduction in temperature efficiency due to the LHC effect at low airflow rates [21,22,31]. Shah and Sekulic [21] calculated an efficiency reduction for a rotary heat exchanger from 91% to 73% due to LHC. Similarly, Liu et al. [31] observed a 20% efficiency reduction (from a designed efficiency of 90% to a measured efficiency of 70%) in a highly efficient heat wheel used in a renovated Norwegian office building. Significant thermal efficiency deterioration in heat exchanges as a result of LHC has also been detected in numerous studies, including [18, 31–35].

In summary, the efficiency reduction due to LHC degrades energy efficiency, making it more challenging for buildings to achieve the target of zero emissions. To the authors' knowledge, the LHC effect in rotary heat exchangers that incorporate DCV or CAV has not been investigated from the perspective of annual performance for office buildings. Fig. 2 illustrates the LHC effect on temperature efficiency and heat energy use in DCV and CAV ventilation. Under certain conditions, DCV with heat recovery can require more energy to heat ventilation air than CAV with heat recovery due to the LHC effect (Fig. 2). These conditions, however,

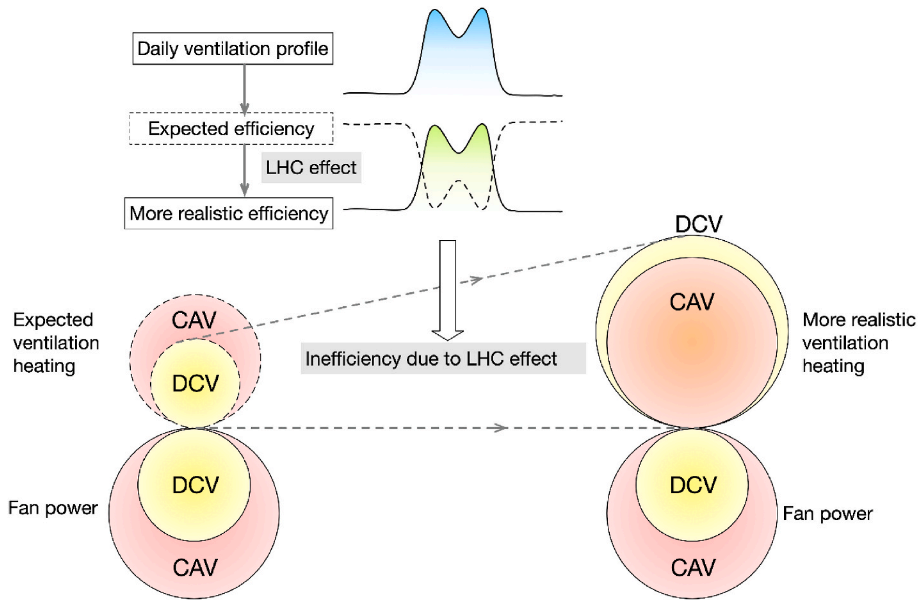

Fig. 2. Illustration of LHC effect on energy use for DCV and CAV (not to scale).

have not yet been identified.

This study was carried out to explore the potential limitations of using heat recovery with different ventilation control strategies and to investigate more realistic ventilation energy uses for DCV and CAV when LHC effects are considered. The novelty and key contributions of this work are as follows:

- This study investigates the role of the LHC effect for different ventilation schemes that incorporate rotary heat exchangers, thus revealing potential design limitations.
- We detect non-optimal rotary heat exchanger designs that lead to energy-inefficient ventilation for the first time. This finding can be used to improve the design of energy-efficient ventilation heat recovery.
- We provide the theoretical basis for the energy-efficient combination of DCV with heat wheels. This can be further considered using building performance simulation software, such as IDA-ICE [36] or EnergyPlus [28]. Highly efficient ventilation systems contribute to closing the energy performance gap and facilitating zero-emission buildings.

This article is organised as follows. Section 2 details and validates the method of calculating temperature efficiency and ventilation energy use for the rotary heat exchanger considering the LHC effect. It also presents the specifications of the studied building and ventilation system. Section 3 demonstrates and discusses the simulated temperature efficiency of the rotary heat exchanger and ventilation energy use in a virtual office building in Oslo, Norway, employing the proposed methods for different ventilation control strategies and occupancy profiles. Finally, the conclusions are presented and discussed at the end of this paper.

2. Methodology

2.1. Temperature efficiency of rotary heat exchanger

In this paper, the temperature efficiency for rotary heat exchangers with and without the LHC effect has been numerically solved and empirically correlated [21]. We developed the correlation based on the commonly used $\varepsilon - NTU$ method. The essential equations we employed to calculate the temperature efficiency and ventilation energy use are provided below.

Temperature efficiency for rotary heat exchangers neglecting LHC can be obtained with Eq. (1) [21]. The first term on the right-hand side of the equation reflects the influence of the number of transfer units (NTU) in counterflow arrangement and accounts for the efficiency of pure counterflow heat exchangers. The term in parentheses denotes the influence of effective heat transfer capacity from wheel to air (i.e. the influence of effective heat storage into the matrix of the heat wheel).

$$\varepsilon_{exclude\_LHC} = \frac{NTU_o}{1+NTU_o}\left(1-\frac{1}{9C_r^{*1.93}}\right) \tag{1}$$

To consider the LHC, an additional term is introduced to Eq. (1), and the correlation becomes the following:

$$\varepsilon_{include\_LHC} = \frac{NTU_o}{1+NTU_o}\left[1-\frac{1}{9\left(C_r^*\right)^{1.93}}\right]\left(1-\frac{C_\lambda}{2-C^*}\right) \tag{2}$$

where C_λ is a function of NTU and λ is the LHC indicator of the wheel material. C_λ is calculated from Eqs. (3) and (4):

$$C_\lambda = \frac{1}{1+NTU_o(1+\lambda\Phi)/(1+\lambda NTU_o)} - \frac{1}{1+NTU_o} \tag{3}$$

$$\Phi \approx \left(\frac{\lambda NTU_o}{1+\lambda NTU_o}\right)^{1/2} tanh\left\{\frac{NTU_O}{[\lambda NTU_o/(1+\lambda NTU_o)]^{1/2}}\right\} \tag{4}$$

where Φ (Eq. (4)) is a process parameter and

$$\lambda = \frac{k_m A_k}{LC_{min}} \tag{5}$$

λ ranges from 0 to 1. The higher the λ value, the greater heat conduction and efficiency loss in the rotary heat exchanger. A good thermal conductor (with a high k_m, like aluminium) and low airflow rates (e.g. the reduced airflow rates in DCV) lead to lower heat capacity (C_{min}) and thus yield higher LHC and higher efficiency loss.

NTU_o is the number of transfer units, defined by Eq. (6):

$$NTU_o = \frac{U_o A}{(\dot{m}Cp)_{min}} \tag{6}$$

A is the effective heat transfer area. Compact heat wheels have large heat transfer areas resulting from their corrugated surfaces. $(\dot{m}Cp)_{min}$ is the minimum heat capacity of the air in the supply and exhaust sides.

The overall heat transfer coefficient, U_o, is obtained as follows:

$$U_o = \left(\frac{2}{h} + \frac{\delta}{3k_m}\right)^{-1} \quad (7)$$

where $\frac{2}{h}$ represents the convective resistance for the balanced supply and extract air and $\frac{\delta}{3k_m}$ represents the transverse heat conduction in a rotary heat exchanger [15]. The convective heat transfer coefficient, h, is calculated from Eq. (8):

$$h = \frac{Nuk_{air}}{D_h} \quad (8)$$

The Nusselt number, Nu, is determined under the thermal boundary of a constant heat transfer rate. It is calculated for sinusoidal channels with the laminar flow as follows [21]:

$$Nu_{H1} = 1.9030\left(1 + 0.4556\alpha + 1.2111\alpha^2 - 1.6805\alpha^3 + 0.7724\alpha^4 - 0.1228\alpha^5\right) \quad (9)$$

where α, the aspect ratio, is the ratio of the channel height to the period.

Given hourly ventilation rates, hourly temperature efficiency with and without the influence of LHC can be calculated with Eq. (1) through (6).

Ventilation energy use consists of two parts: 1) energy used for heating the ventilation air (we assume that there is no need for cooling in Norway) and 2) fan power used for delivering ventilation air. In this study, we use the specific fan power of 1.5 kW/(m^3/s) for the supply and extraction of air in energy-efficient buildings [14].

Heat recovery can partially or fully heat the air to the set point of the supply air temperature. A heating coil is needed to heat the air further if the supply air temperature setpoint is not reached after heat recovery. As a result, the rotary heat exchanger's temperature efficiency impacts the ventilation heating energy. The total annual energy use for heating ventilation air in a reference year is described by Eq. (10):

$$Q = \sum_{i=1}^{8760} \dot{m}_i c_p \left(t_{supply} - \left(Eff_i\left(t_{indoor} - t_{outdoor,i}\right) + t_{outdoor,i}\right)\right) t_i \quad (10)$$

In Eq. (10), the term $(Eff_i(t_{indoor} - t_{outdoor,i}) + t_{outdoor,i})$ represents the air temperature at the outlet of the supply side of the heat recovery system. Thus, the difference between the set point of supply air temperature (t_{supply}) and the air temperature at the outlet of the supply side of the heat exchanger must be heated by the heating coil (post-heater) in air handling unit (AHU). The hourly temperature efficiency of heat recovery (Eff_i) considering controls for frosts and overheating prevention can be obtained with Eq. (11).

$$\mathrm{Eff}_i = \begin{cases} \dfrac{t_{supply} - t_{outdoor,i}}{t_{indoor,i} - t_{outdoor,i}}, \text{if } \left(t_{outdoor,i} + \varepsilon\left(t_{indoor,i} - t_{outdoor,i}\right) > t_{supply} > t_{outdoor,i}\right) \\ 0, \text{if } \left(t_{outdoor,i} > t_{supply}\right) \\ \dfrac{t_{indoor,i} - t_{frost\ protection}}{t_{indoor,i} - t_{outdoor,i}}, \text{if } \left(t_{indoor,i} - \varepsilon\left(t_{indoor,i} - t_{outdoor,i}\right) < t_{frost\ protection}\right) \\ \varepsilon, (\text{for the rest of the conditions}) \end{cases} \quad (11)$$

In Eq. (11), the temperature efficiency is adjusted to prevent overheating when the outdoor air temperature is relatively high and to protect the heat exchanger from freezing by reducing the recovery efficiency. When the outdoor air temperature exceeds the set point of the supply air temperature, the rotary heat exchanger is stopped (the temperature efficiency becomes zero) and the ventilation air is bypassed from the heat recovery unit.

2.2. Studied building and ventilation

We developed a simulation case for a virtual office building in Oslo, Norway. The building performance complies with Norwegian Building Regulation TEK17 [14]. The design occupancy density is 15 m^2/person, and the maximum number of occupants is 60. The building is equipped with a DCV with balanced supply and exhaust. The building's ventilation rates are assumed to respond ideally to occupancy. The ventilation rates are specified to 26 m^3/h/person, consistently with the Norwegian building codes [14]. They also reflect building materials: 2.5 $m^3/h/m^2$ when the room is in use and 0.7 $m^3/h/m^2$ when it is vacant. The set point of the supply air temperature is 18 °C, and the frost protection temperature of the exhaust air is −5 °C.

Table 1
Specifications of the verified rotary heat exchanger.

Parameter	Value	Parameter	Value
Wheel depth	150 mm	Air density	1.2 kg/m^3
Wheel diameter	400 mm	Rotary speed	10 RPM
Wall thickness	0.055 mm	Channel shape	Sinusoidal
Wall material	Aluminium $k = 205$ W/(m•K) $c_p = 900$ J/(kg•K)	Channel height and channel period	Channel height: 1.4 mm Channel period: 3.0 mm

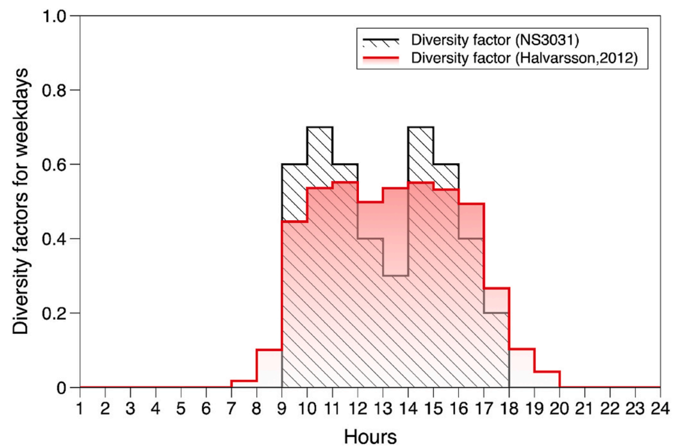

Fig. 3. Occupancy diversity factors in a landscaped office building during weekdays from NS3031 [38] and Halvarsson [37].

Fig. 3 shows the occupancy diversity factors on weekdays for office buildings from the standard NS3031 [20] as well as Halvarsson's [37] measurements for office buildings in Nordic countries. Halvarsson constructed the hourly diversity factors by averaging ten offices' yearly occupancy [37]. As shown in Fig. 3, the measured occupancy in office buildings in Nordic countries is lower than the occupancy defined by Norwegian Standard NS3031 [38]. A similar trend was detected for an American office building when the standardised values in ASHRAE 90.1 were compared to measured occupancy diversity factors [39]. The occupancy diversity factor is zero outside working hours and during weekends. In this study, we compare the ventilation energy use for these two schemes of occupancy diversity factors and the corresponding ventilation rates.

2.3. Validation of temperature efficiency and LHC effect

We validated the temperature efficiency and the effect of the LHC for the rotary heat exchanger using the measured temperature efficiency of a rotary heat exchanger in the laboratory. The specifications of the tested rotary heat exchanger are given in Table 1. The experiment was conducted according to EN 308 [40]. Fig. 4 shows the rotary heat exchanger's test box and airflows.

Eq. (12) calculates the total uncertainty of the parameters of interest, which is composed of bias and precision errors [41]:

Fig. 4. Test box of the rotary heat exchanger in the laboratory (adapted from [19]).

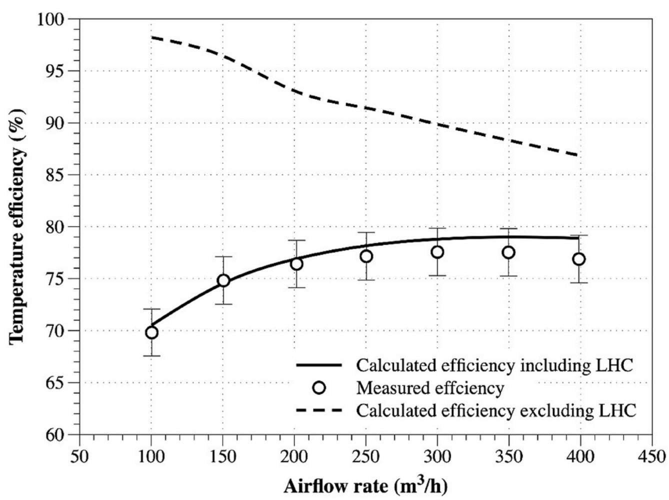

Fig. 5. Verification of temperature efficiency: calculated efficiency vs. measured efficiency including and excluding the LHC effect. The lines around the measured efficiency are the error bars with a 95% confidence interval.

$$U_r = \sqrt{\left[\left(\frac{\partial r}{\partial X_1} U_{X_1}\right)^2 + \left(\frac{\partial r}{\partial X_2} U_{X_2}\right)^2 + \ldots + \left(\frac{\partial r}{\partial X_i} U_{X_i}\right)^2\right]} \quad (12)$$

where U_{X_i} represents the total uncertainty of the measured variables. This value can be determined with Eq. (13):

$$U_{x_i} = \sqrt{B^2 + P^2} \quad (13)$$

The Pt100 temperature sensor used for the measurements in this study has a measurement accuracy of ±0.1 °C. The airflow measurements using orifice plates and manometers have a total uncertainty of ± 1.5%. Finally, the measurement of static pressure is subject to an uncertainty of ±1.0%. Taken together, the total measurement uncertainty of the temperature efficiency is estimated to be ±3.0%.

The temperature efficiency with and without LHC is calculated with Eqs. (1)–(9). The measured and calculated temperature efficiencies are shown in Fig. 5. The calculated temperature efficiency including the LHC effect agrees well with the measured values. In contrast, the correlation neglecting LHC overestimates the temperature efficiency, especially for low airflow rates (Fig. 5). Fig. 5 shows that the maximum loss of efficiency due to LHC is approximately 30% at a low airflow rate; this loss of efficiency is smaller for higher flow rates. It is challenging to achieve a temperature efficiency higher than 80% with the tested wheel. The reason is that at low airflow rates, the LHC effect is dominant and acts as a heat dissipator, while efficiency begins to fall with decreasing *NTU* values at higher airflow rates.

Based on the $\varepsilon - NTU$ method and the heat transfer characteristics addressed in Section 2.1, scaling up the rotary heat exchanger while increasing airflow rates should be equivalent to a small heat exchanger with low airflow rates. Therefore, the validation should hold for large rotary heat exchangers and higher airflow rates in office buildings. The flow rates in DCV are usually reduced due to partial loads. Hence, the estimated energy savings are significantly overestimated if the efficiency loss resulting from LHC in the aluminium rotary heat exchanger is ignored.

3. Results and discussion

3.1. Temperature efficiency of rotary heat exchanger in DCV

The method described in the Methodology section determines the ventilation rates for DCV in the virtual office building with a maximum occupancy of 60 occupants. Fig. 6 shows the results of week 3, representing winter, and week 14, representing the shoulder seasons. The occupancy and ventilation rate profiles are otherwise repeated each week. Table 2 specifies the properties of the selected aluminium rotary heat exchanger.

Fig. 6 shows the temperature efficiency for weeks 3 and 14. The largest difference between considering and neglecting the LHC effect is about 20%; this difference occurs when the building is unoccupied, as low ventilation is supplied at such times. The efficiency loss due to the LHC effect is relatively small when the building is occupied and ventilation rates rise. The influence of the efficiency loss due to LHC on ventilation energy use will be illustrated in Section 3.3.

The annual average temperature efficiencies with standardised and empirical occupancy profiles are presented in Table 3. For both occupancy profiles, if the rotary heat exchanger is not controlled to prevent overheating and frost, the annual average difference in temperature efficiency when including or excluding LHC is about 15%. When controls for frost and overheating are included, the average annual difference in temperature efficiency is 10%. The effect of the two occupancy profiles on the annual average temperature efficiency is negligible if no controls on overheating and frost are applied.

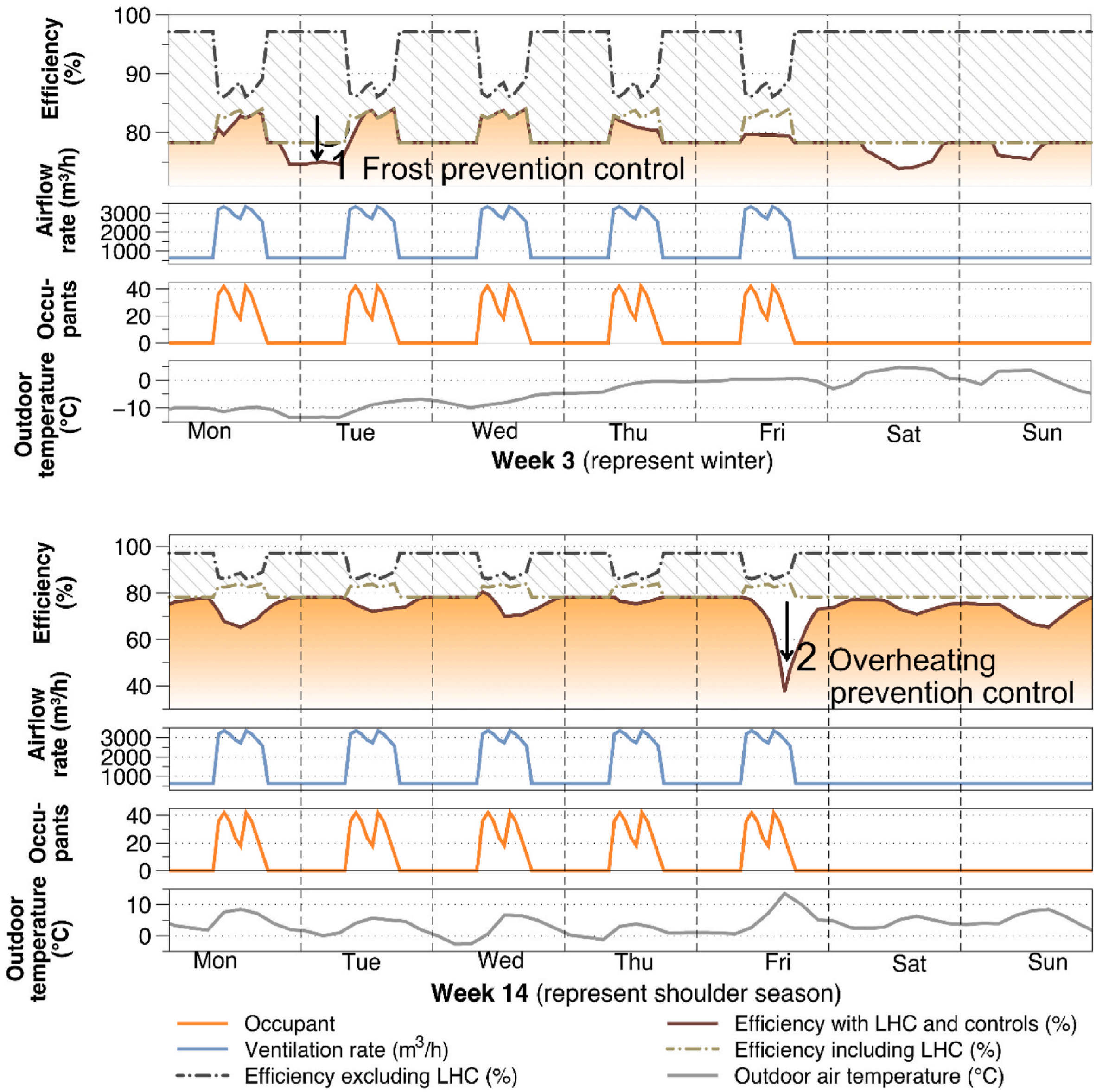

Fig. 6. Occupancy profile for NS 3031 (maximum of 60 occupants), including ventilation rates and temperature efficiency of the rotary heat exchanger with and without the LHC effect for week 3 (representing winter) and week 14 (representing shoulder seasons). The upper part marked with diagonal lines represents the efficiency loss due to the LHC effect.

Table 2
Specifications of the aluminium rotary heat exchanger analysed in this study.

Parameter	Value	Parameter	Value
Wheel depth	200 mm	Rotary speed	10 RPM
Wheel diameter	1200 mm	Channel shape	Sinusoidal
Wall thickness	0.05 mm	Channel height and channel period	Channel height: 2.0 mm Channel period: 3.0 mm

Table 3
Annual average temperature efficiency for an office building with a nominal occupant number of 60.

Occupancy profiles	No controls on overheating and frost excluding LHC	No controls on overheating and frost, including LHC	With controls on overheating and frost excluding LHC	With controls on overheating and frost, including LHC
NS 3031 [38]	94.5%	79.6%	83.7%	73.4%
Halvarsson [37]	93.6%	80.3%	90.4%	78.8%

The annual average temperature efficiency indicates that achieving the high expected recovery efficiency of rotary heat exchangers is difficult due to the LHC effect. Therefore, it is necessary to develop and adopt highly efficient heat recovery methods to contribute to energy-efficient HVAC systems and decarbonised buildings.

The occupant and ventilation rate profiles are identical for each week, as the diversity factors and ventilation demand are identical for the occupancy profiles of NS 3031 [38]. In addition to the effect of varying airflow rates, heat recovery efficiency is also affected by controls to prevent freezing inside heat exchangers during winter (Fig. 6, week 3, arrow 1) or overheating during shoulder seasons (Fig. 6, week

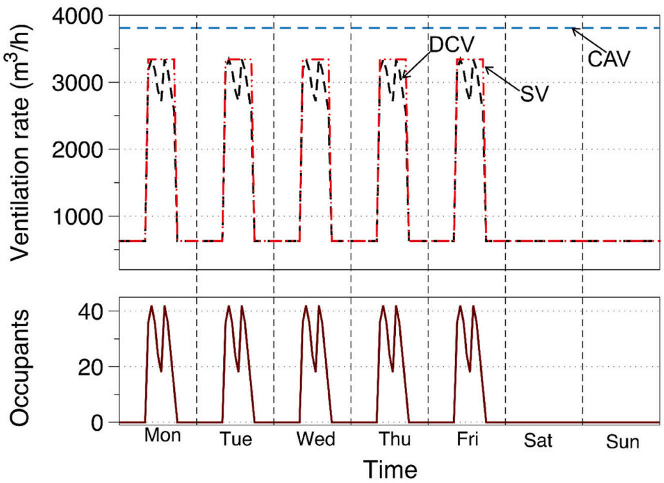

Fig. 7. Weekly ventilation rates for different ventilation strategies with a nominal occupant number of 60.

14, arrow 2).

3.2. Influence of efficiency loss due to the LHC effect on ventilation for various ventilation strategies

Fig. 5 and 6 present the efficiency loss due to LHC in a rotary heat exchanger for a DCV. This subsection compares the LHC effect on energy use for different ventilation control strategies.

We simulated three different ventilation control strategies to investigate LHC's influence on ventilation energy use:

DCV: The ventilation rates respond ideally to the hourly occupants' diversity factors. The hourly ventilation rates are calculated using the Norwegian specification NS3031 [38].

Scheduled ventilation (SV): The ventilation rate is set to a high constant (maximum value in DCV) when the building is occupied and another constant (minimum value in DCV) when unoccupied. This easily controlled strategy of scheduled ventilation is compared with the ventilation energy used in DCV.

CAV: The ventilation rate is constant. The rate is calculated based on the nominal maximum occupants in compliance with TEK17 [14].

The ventilation rates for these three strategies are illustrated in Fig. 7.

The annual energy used to heat ventilation air for these three strategies was calculated using Eqs. (10) and (11) (Fig. 8). For DCV and SV, the estimate of annual energy use is about one-third of the true value for both occupancy profiles when the LHC influence is not considered (Fig. 8). The difference in energy use between the two occupancy profiles is insignificant for all three ventilation strategies. For CAV, the annual ventilation energy use is independent of the occupancy profiles, as the ventilation rate is dimensioned for the expected maximum occupants in the ventilated space. The underestimation of annual energy use when neglecting LHC for CAV is about 40% lower compared to an optimal heat exchanger design with no LHC. These results show that the influence of the efficiency loss due to LHC in aluminium is significant and cannot be neglected for the studied case. They also indicate that commonly used building energy calculation software tools that neglect LHC (e.g. EnergyPlus [28] and IDA-ICE [36]) overestimate recovery efficiency, thus underestimating ventilation energy use and resulting carbon emissions from the operation of the ventilation system. Moreover, if the LHC effect is neglected, there may be a risk of thermal discomfort caused by drafts because the heating coil may be undersized. The total fan energy use is unchanged for the same ventilation strategy since the profiles of ventilation rates and SFP are identical for a single strategy. Once the LHC-induced inefficiency of the rotary heat exchanger at lower airflow rates is considered, the energy used for heating ventilation air becomes comparable to fan energy (Fig. 8).

Next, the annual energy used for heating ventilation air using the NS3031 occupancy profile (see Fig. 7) was broken down to monthly data excluding and including the influence of LHC for these three ventilation control strategies. Fig. 9 shows that DCV and SV use similar amounts of energy each month. SV may be preferable because rule-based control strategies are more straightforward than DCV and may require less maintenance. However, the fan power required for DCV and SV should also be taken into account when evaluating the two options. Moreover, the occupancy in this case is presumed to be known and repeated weekly; in practice, the profiles are likely to be unknown and to vary from week to week.

3.3. Comparison between different ventilation strategies considering the LHC effect

Fig. 10 and 11 show the relative difference (RD) results for different exchanger depths and design occupant load. In most cases, DCV and SV use similar amounts of energy for ventilation heating (Fig. 10). The highest energy savings for using DCV compared to SV is 27%. The

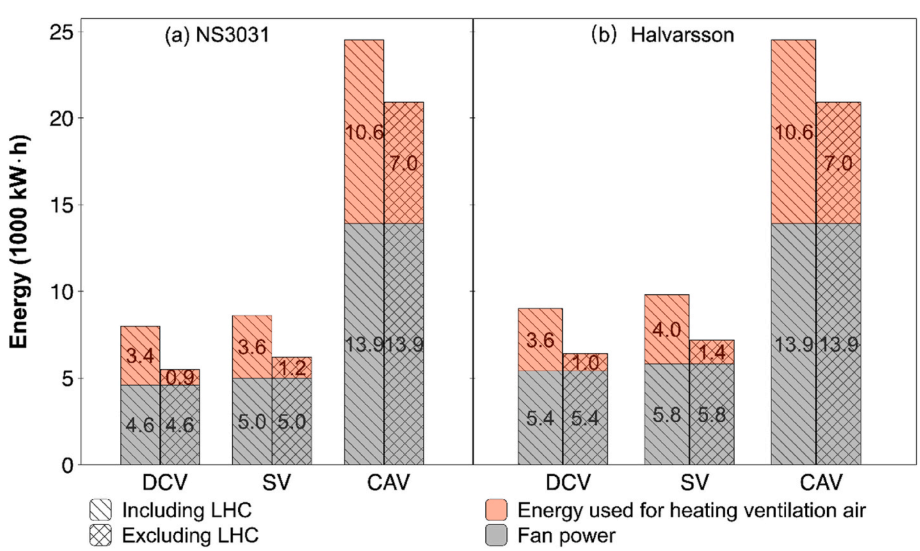

Fig. 8. Ventilation energy use including and excluding the influence of LHC for different ventilation strategies and occupancy profiles with a maximum occupant number of 60.

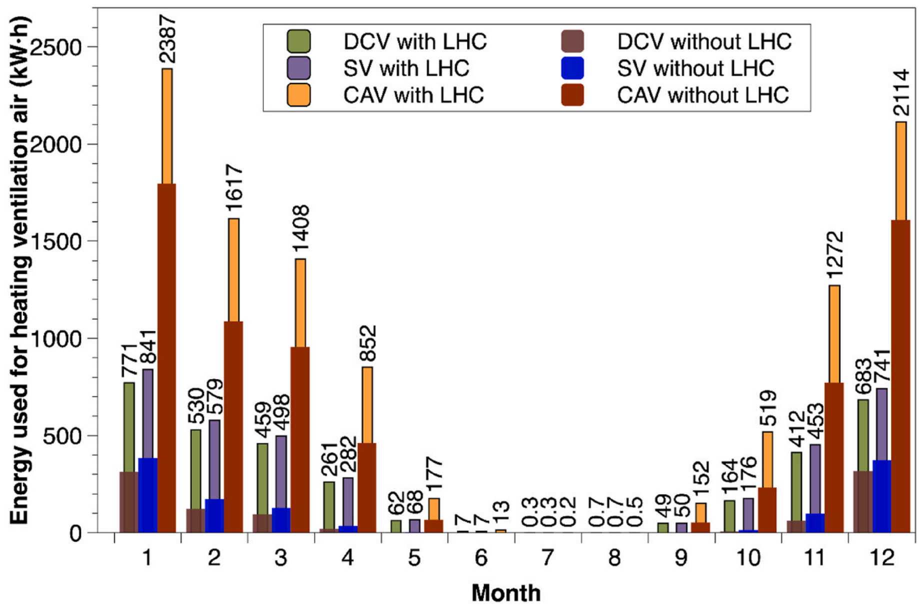

Fig. 9. Monthly energy use for heating ventilation air including and excluding the influence of LHC for three ventilation strategies (DCV, SV, and CAV).

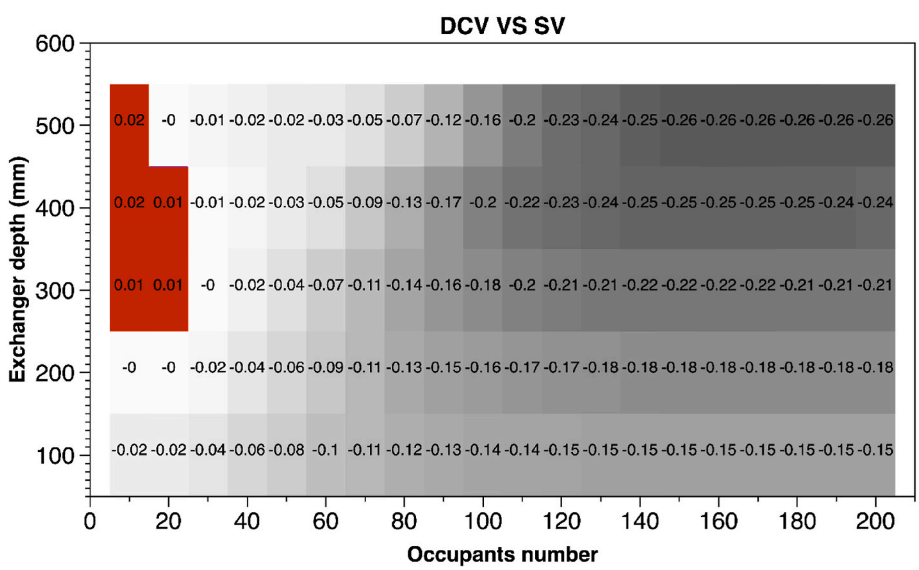

Fig. 10. Relative difference $\left(\frac{Q_{heating,DCV}-Q_{heating,SV}}{Q_{heating,DCV}}\right)$ in energy use for heating ventilation air between DCV and SV for various exchanger depths and design occupant numbers. Red cells represent conditions under which DCV requires more heating energy than SV. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

energy-saving potential of DCV, which is indicated by the negative RD values, increases with the number of occupants. Compared to SV and CAV, DCV always has the lowest ventilation airflow rates (see Fig. 7).

One might expect that DCV would use the least energy for heating due to its lower ventilation rate and higher recovery efficiency. However, as aluminium rotary heat exchangers suffer from the LHC effect, DCV may use more energy to heat the ventilation air than SV under certain conditions (as illustrated by the positive RD values in red in Fig. 10). This possibility arises when the depth of the exchanger exceeds 250 mm and the occupant numbers (building area) are low (Fig. 10). Moreover, deep exchangers are unfavourable as the pressure drop is proportional to the depth of the exchanger, and thus they need more fan power. It should be noted that the fan power is not included in the comparison of the relative difference; only the energy used for heating ventilation air is considered.

Similarly, the positive values in red in Fig. 11 show that less energy is used to heat ventilation air in CAV than in SV, despite CAV's higher constant ventilation rate. This is caused by the presence of LHC at low airflow rates, as explained above. Nevertheless, there are significant differences in the RD of ventilation heating energy use between SV and CAV compared to DCV and SV, respectively. This is because the difference between ventilation rates and the resulting LHC varies substantially between these two comparisons. SV can save more than six times as much ventilation heating energy as CAV under certain conditions (Fig. 11).

In contrast to earlier studies, this study shows that DCV may use more energy to heat ventilation air under certain conditions because LHC limits heat recovery efficiency at low airflow rates. This issue is more likely to occur for deep rotary heat exchangers. Hence, deep rotary heat exchanger designs should be avoided because of their high

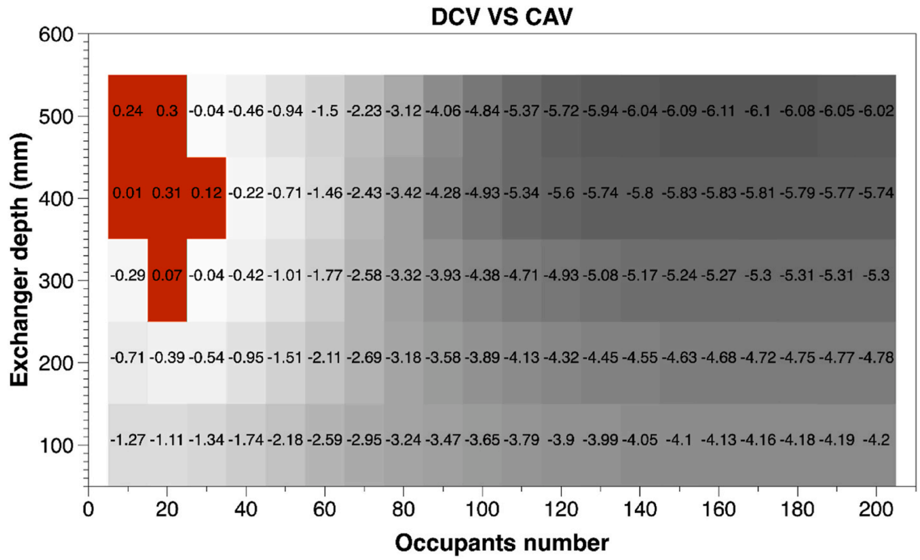

Fig. 11. Relative difference $\left(\frac{Q_{heating,CAV} - Q_{heating,SV}}{Q_{heating,SV}}\right)$ between CAV and SV in energy use for heating ventilation air for various exchanger depths and design occupant numbers. Red cells represent conditions under which CAV requires more heating energy than SV. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

ventilation energy due to the LHC effect. The energy use of deep heat exchangers can be even higher given their higher pressure penalty and the resulting need for more fan power.

4. Conclusions

Longitudinal heat conduction (LHC) in aluminium rotary heat exchangers is a commonly overlooked factor that causes significant temperature efficiency loss. This work presents a methodology to investigate the possible limitations of designing and using rotary heat exchangers in DCV, SV and CAV. We investigated the effect of LHC in a rotary heat exchanger on recovery efficiency and energy use when heating ventilation air by simulating a virtual office building for different ventilation strategies and two occupancy profiles. As a result of the LHC effect, the average annual temperature efficiency is reduced by about 10% compared to the ideal case without LHC.

The influence of LHC on both temperature efficiency and ventilation energy use cannot be neglected. In this study, the rotary heat exchanger could not achieve its expected recovery efficiency due to the presence of LHC. Indeed, the energy use for heating ventilation air was underestimated by approximately three times for DCV and SV and 40% for CAV. For the first time, this study demonstrated that heating ventilation air with DCV may consume more energy than CAV under specific heat recovery design conditions because LHC reduces efficiency at low airflow rates. Deep and oversized rotary heat exchangers are more likely to experience this issue. As a result, such exchangers should be avoided since they require more heating energy and fan power due to a higher pressure drop through the deep wheels.

In light of this study's findings, assessing the LHC effect for building energy performance evaluation is essential, especially for buildings targeting zero emissions. In future work, the efficiency loss due to rotary heat exchangers should be included in building energy calculation software. Moreover, the contribution of LHC in rotary heat exchangers should be considered when evaluating or reducing the building performance gap.

CRediT authorship contribution statement

Peng Liu: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Maria Justo Alonso:** Writing – review & editing. **Hans Martin Mathisen:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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