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Published in:
Results in Engineering

DOI (link to publication from Publisher):
10.1016/j.rineng.2022.100619

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Nourozi, B., Holmberg, S., Duwig, C., Afshari, A., Wargocki, P., Olesen, B., & Sadrizadeh, S. (2022). Heating energy implications of utilizing gas-phase air cleaners in buildings' centralized air handling units. *Results in Engineering*, *16*, Article 100619. https://doi.org/10.1016/j.rineng.2022.100619

Results in Engineering 16 (2022) 100619

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Heating energy implications of utilizing gas-phase air cleaners in buildings' centralized air handling units

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ARTICLE INFO

Keywords:
Indoor air quality
Gas filter
Air cleaner
Volatile organic compounds
Energy use

ABSTRACT

Ventilation systems are a vital component of buildings in order to ensure a healthy and comfortable environment for the occupants. In cold climate regions, ventilation systems are responsible for approximately 30% of building heat losses. In addition to outdoor pollutants (particulate matters, NO_X, etc.), indoor emissions from materials in the form of gas pollutants and emissions from occupants are the principal indoor air quality metrics for securing an acceptable indoor concentration level. Therefore, it is of great interest to study the use of gas-phase air cleaning technologies in low-energy centralized air handling units. This study focused on reducing buildings' heating requirements by recirculating indoor air while maintaining an acceptable indoor air quality level. The heating performance of a typical residential and office building in the central Swedish climate was studied by dynamic building simulations. Indoor air recirculation rates and air changes per hour were the key parameters considered during the simulation of the building's heating demand and indoor gaseous air pollution concentration. We found that introducing indoor air recirculation reduces buildings' heating demand depending on the air change rates per hour. The results show that it is possible to reduce the energy use for heating by less than approximaytely 10% and 20% for residential and office buildings, respectively and maintain acceptable indoor air quality by using gas-phase air cleaning.

1. Introduction

Meeting occupants' indoor air quality requirements and reducing the pollutants emitted by indoor sources is important [1]. Heating, ventilation, and air-conditioning (HVAC) systems are used to ensure a healthy and comfortable indoor climate for occupants. HVAC systems can be configured in various ways, depending on the type and use of buildings, specific requirements of the residents, and climate conditions [2]. Maintaining an acceptable indoor environment and reducing the energy needed for this task in buildings are in line with several of the United Nations' Sustainable Development Goals (SDG) [3]. Thus, a transformation in the building sector towards zero-energy buildings is required without compromising occupants' health, comfort, and productivity.

In a set of countries participating in the IEA Energy Conservation in Buildings Program, all buildings' primary ventilation energy demand is approximately 9% of their total primary energy use. It is estimated that ventilating US residential buildings consumes 30% of the total energy used in these buildings, in addition to heating, cooling, and domestic hot water (DHW) needs. By increasing the air tightness of buildings, ventilation plays a more important role in maintaining acceptable indoor air quality and its share of total energy use incease [4]. In addition to ventilation energy use, carbon dioxide (CO_2) emissions have become a concern. The US annual CO_2 emissions of residential and service sector ventilation are approximately 1000 and 800 million tons, respectively [5]. Ventilation energy is utilized to heat up, cool down, filter, and dehumidify/humidify the ventilated air and to run the circulation fans. However, ventilation energy use may vary significantly based on the local climate. In Europe, most of this energy is used to heat the outdoor air for ventilation [4], while in warmer climates, the energy is used for both heating and cooling purposes. In Sweden in 2017, approximately

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https://doi.org/10.1016/j.rineng.2022.100619
Received 7 July 2022; Received in revised form 19 August 2022; Accepted 26 August 2022

Nomenclature

Abbreviations

AC	Air conditioning
AHU	Air handling unit
BBR	Swedish Building Regulations
CFD	Computational fluid dynamics
DCV	Demand control ventilation
DHW	Domestic hot water
ESP	Electrostatic precipitator
HCHO	Formaldehyde
HEPA	High-efficiency particulate air
HRV	Heat recovery ventilation
HVAC	Heating, ventilation and air conditioning
IAC	Indoor air cleaner
IAQ	Indoor air quality
KEP	Key energy performance
MERV	Minimum efficiency reporting value
MOF	Metal-organic framework
PCO	Photocatalytic oxidation
PM	Particulate matter
SDG	Sustainable Development Goals
TVOC	Total volatile organic compound
UVGI	Ultraviolet germicidal irradiation
VOC	Volatile organic compound
VRP	Ventilation rate procedure

Latin and Greek Letters

C_r	Concentration in indoor air, [μg/m^3]
C_s	Concentration in supply air, [μg/m^3]
$\dot{m}$	Strength of indoor sources [μg/h]
$\dot{V}$	Airflow rate [m^3/h]
τ_n	time constant [h]

30% of the total energy used in households was devoted to heating and hot water in multi-dwelling buildings [6]. Ventilation fans and heating and cooling equipment capacity also dictate the ventilation energy used. In order to reduce energy use to heat the ventilated air in cold climates, several practices have been implemented, such as increasing the airtightness of the building envelope, using heat recovery, and preheating outdoor air to avoid frost in air handling units (AHU) [7–9].

Because the abovementioned strategies may significantly reduce cooling/heating energy use, the reduced ventilation flow rate will increase the concentration of volatile organic compounds (VOCs), emissions from occupants (CO$_2$), particulate matter (PM), or other contaminant levels within the enclosed environment. Even the fresh outdoor air can be highly polluted in some locations and needs to be cleaned before being introduced indoors. In addition to eliminating the pollutant sources as the most effective way of improving indoor air quality such as air ions [10], cleaning the air with filters is an effective supplement to source control and ventilation. Occupants' exposure to various air pollutants causes detrimental health issues such as respiratory and cardiovascular diseases, lung cancer, and an uncomfortable indoor environment in less severe cases [11–13]. In such cases, the supplied air to the occupied zone passes through air filters, and a fraction of the pollutants, depending on the filter capture efficiency and type of pollutant, is discarded. Implementing an air cleaning technology as an extension to the ventilation system can improve air quality [14,15], reduce dependence on outdoor air [16,17], and improve energy efficiency [18,19]. However, several parameters, such as pressure losses due to filtration, fan power demand, and buildings' heating/cooling requirements, need to be studied and optimized to maximize the energy benefit of using air cleaners, while ensuring a healthy indoor environment. Typically, high-efficiency filters with a higher minimum efficiency reporting value (MERV) result in a more significant pressure drop than lower MERV filters [20]. However, Stephens et al. showed that the energy use of high- and low-efficiency filters did not differ in a four-month-long period of detailed energy monitoring of air conditioning systems in Austin, Texas [21]. In that study, various measurements such as airflow, fan power draw, cooling capacity, and the pressure drop across filters and coils in 17 residential and light-commercial forced air cooling systems for three different MERV categories revealed a negligible difference between high- and low-efficiency filters [22]. Montgomery et al. [23] conducted a cost sensitivity analysis of using particle filters in an HVAC air handling system. They found that particle concentration in the air stream and the electricity cost had the largest effect on annual operation cost. This is due to an increase in air pressure losses due to filtration. Willem et al. [24] examined the impact of air change rate on the indoor VOCs concentrations. They reported an inversely proportional rate between VOC concentrations and the air exchange rate for most compounds. Different ventilation strategies can have considerable impacts on indoor contaminants level and energy usage in buildings. Noh and Hwang [25] studied the effect of ventilation rate and filter performance on indoor particle concentration and fan power demand in a residential building. They also considered the impact of air exchange effectiveness on indoor particle concentration. Their results suggest that variations in the air-exchange effectiveness had a small influence on the minimum ventilation rate. In order to maintain the level of gaseous pollutants and particle concentration level below the no-ventilation case for residential buildings with the size of 150–300 m^3, a filter with a performance above MERV11 was required [25]. Nassif [26] investigated the impact of air filtration on the energy requirement of an air conditioning system by simulating the annual energy usage of a building. He concluded that the fan energy use was affected by the degree of the filter cleanliness and the MERV number.

Zaatari et al. [27] explored the ventilation and filtration strategies in retail stores in the US and their impacts on building energy use. They evaluated the energy demand of building cases considering the ASHARE 62.1 2013 ventilation rate procedure (VRP), demand control ventilation (DCV), and indoor air quality procedure with and without using particulate filters. Their results indicated that various strategies could maintain acceptable indoor air quality depending on the type of particulate matter; however, the building energy demand increased in any case [27]. In another field measurement work, Zaatari et al. [28] explored the effects of using HVAC filters on system airflow, coil pressure drop, and fan power rise in 15 rooftop units. The measured data for units without fan speed control showed that the flow, cooling capacity, and power decreased by increasing the filter pressure drop. However, for units with fan speed control, a rise in pressure drop resulted in a similar magnitude of fan power change but in the opposite direction. Therefore, they suggested that low-energy use in buildings and a healthy indoor environment can be achieved by a thorough understanding of the impact of filtration [28]. Ben-David et al. [29] provided an optimization methodology for day-average ventilation rates within varying energy use constraints. Their purpose was to maximize occupants' productive work hours by maximizing amounts of outdoor air per annum and maintaining the amount of energy use. They simulated three locations for an office building with ventilation rates of 8.5, 10, 20, and 30 l/(s, occupant). They concluded that lost productive hours due to low ventilation were halved using the optimized higher annual rates [29]. Soh et al. [30] compared the pressure drop over circulating fans in air conditioning systems using mechanical V-Bank air filters (ePMI 55%/F7) and electrostatic precipitators (ESP) (polarized filters) for a duration of seven months. Their results indicated that while ensuring adequate removal efficiency and acceptable indoor air quality (IAQ), ESP filters caused an increase in air pressure drop, but no measurable pressure drop was observed for the mechanical filter [30].

Cho et al. [31] investigated the energy implication of combining a demand control ventilation system with air cleaners. They studied a ventilation system's performance in a multi-family building aiming to reduce outdoor air supply using air cleaning while maintaining the indoor air quality at the desired level. Indoor CO_2 and Formaldehyde (HCHO) concentrations were monitored based on the IAQ code in South Korea, and the ventilation and air cleaning systems operated independently to optimize energy usage for ventilation. Their results indicated that, compared to the conventional ventilation system's continuous operation, the combined demand-controlled and air cleaning system reduced the operation rate of the induction of outdoor air by almost 50% of the operation time and reduced the energy usage by approximately 20% [31]. Blondeau et al. [32] have investigated the performance of six commercially used in-duct air cleaning devices for centralized ventilation systems installed in office buildings. Except for gas filtration, other air cleaning technologies such as mechanical filtration, ionization, electrostatic precipitation, and photocatalytic oxidation (PCO) were tested against a range of contaminants, including particles and a mixture of volatile organic compounds. They also considered the single-pass efficiency of each device for three different airflow rates. The VOC concentration in their experiments varied between 30 and 100 $\mu g/m^3$ [32]. Their results confirmed that only two devices performed acceptably in terms of energy effectiveness and particle removal in low or zero energy buildings. At the highest airflow rate of 3600 m^3/h, the energy effectiveness ranged from a few thousand m^3/kWh for VOCs, and for airflow rates of 1200 or 1600 m^3/h, the energy effectiveness was above 60,000 m^3/kWh for particles and bio-contaminants [32].

Technologies enabling air cleaning have been extensively investigated in the literature with appropriate IAQ standards regarding particle matters, VOCs, Radon, and HCHO removal. Applications of single cleaners are often reported without mentioning the integration into the complete system and energy savings/overheads. Most of the above-mentioned studies do not note the energy implications of particle filters on ventilation systems, and the performance of gas filters is largely unreported. Indeed, the energy implications of utilizing air cleaners have received less attention, limiting the implementation of these solutions. The decisive parameters regarding using centralized air phase cleaners in optimizing such systems have not been thoroughly studied. In the present article, the authors evaluate the performance of centralized ventilation systems equipped with gas-phase air cleaning technologies, with particular attention to their energy usage, and VOC and CO_2 removal efficacy. According to building regulations in Nordic countries, air recirculation is not allowed, so the ability to maintain clean indoor air is investigated. Since both the gaseous and particle pollutants should be removed from the supplied air to the buildings, in the present configuration, gas filters are always installed in ventilation systems together with particle filters, which are the primary cause of air pressure drops in the air cleaning device.

2. Objectives

Using gas-phase air cleaners makes it possible to recirculate and reuse the indoor air to partially replace outdoor air ventilation. The primary goal of this article is to investigate the impact of recirculation rates on the energy usage of buildings' centralized air handling units (AHU) and buildings' heating demand in the central Swedish climate. We also study the effect of different ACH and recirculation rates of the total VOC (TVOC) and human bio effluents (CO_2 used as a tracer) concentrations in residential and office buildings.

The following sections present detailed information regarding the simulation procedure, the recommended indoor TVOC and CO_2 concentration values, and the simulation results of the impact of important parameters on buildings' heating demand and indoor TVOC and CO_2 concentration levels.

3. Methodology

We studied the effect of using gas-phase air cleaners on the energy requirements of the centralized ventilation system in residential and office buildings. We employed a commercially available code, TRNSYS [33], to perform the annual transient simulations and investigate the buildings' heating demand, ventilation fan power consumption, and VOC and CO_2 concentrations. We also developed a MATLAB code to examine the indoor concentration of TVOCs and CO_2 with respect to the building requirements modeled in TRNSYS. Here, residential and office buildings were studied and the mass and energy balance equations for ventilation airflow rate, building heating demand, and VOC and CO_2 concentrations were solved. According to Swedish Building Regulations (BBR) [34], the centralized air handling unit of newly constructed and renovated buildings must be equipped with a heat recovery system. However, we have considered the assumptions for older buildings before renovations. Moreover, we investigated the impact of implementing gas-phase air cleaners in the absence of the heat recovery system.

3.1. Boundary conditions, building cases, and assumptions

The investigated buildings consist of one residential multi-family and one multi-story office building in Stockholm, Sweden (typical Nordic climate) [35], where the heating load of the building is more significant than the cooling load. The outdoor temperature in central Swedish climate ranges between −17 °C and 30 °C along the duration of the simulations which is a year. Thus, this methodology can be implemented in other regions with a similar feature. Both cases have a total ventilated floor area of 2000 m^2 and were equipped with a mechanical ventilation system with heat recovery. The heat recovery efficiency of the AHU was defined as a function of outdoor temperature. We have carefully validated the simulation model of this study with an actual building used in a previous study by Nourozi et al. [36]. The building annual heating demand and the thermal heat load demand were calculated and compared to the measurements in a reference building located in Stockholm. The deviation between simulation and measurements for the annual heating demand and heating power were less than 1% and 10%, respectively [36]. The ACH of the residential building is 0.5 h^{-1} to fulfill the recommended rate of 0.35 $l/s\ m^2$ by BBR [34], and this increased to 2.4 h^{-1} for the office building. In cases of recirculating the indoor air, a fraction of the mentioned values for ACH was supplied from indoors, and fresh outdoor air constitutes the rest; therefore, the total ACH values remain constant. More information regarding the buildings and their components used in simulations is provided in Table 1.

The occupancy rates in the simulations are based on the average rates in Swedish residential and office buildings, which are 40 m^2 and 15 m^2 of floor area per person [37]. The daily occupancy schedules for both buildings are illustrated in Fig. 1. The occupancy rate in residential buildings reduces to 20% during the day (between 6:30 a.m. and 6:30 p.m.) and is the maximum for the office building during this period. We assumed that recirculation of indoor air was required during the rush hours in the mornings and evenings when the concentration of outdoor pollutants may be higher than an acceptable threshold [38]. As shown in Fig. 1, the ventilation system in the office building was turned off during

Table 1
Information regarding the buildings used in simulations.

Building	Parameter				
	Area m^2	Flowrate $kg.h^{-1}$	ACH h^{-1}	Occupancy rate $person.m^{-2}$	Supply filter efficiency %
Residential	2000	3040	0.5	40	65
Office		13,900	2.4	15	60

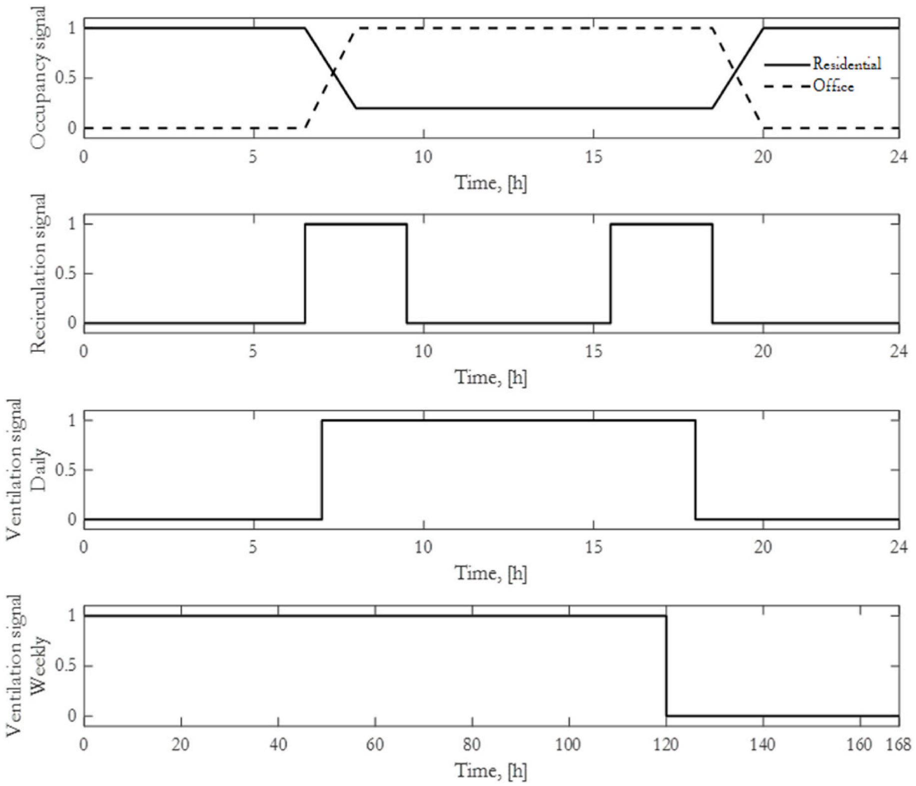

Fig. 1. Occupancy, ventilation, and recirculation schedules.

weekends and non-office hours during weekdays to reduce energy demand.

The gas filter VOC capturing efficiencies in the supply and return air streams were assumed to be 65% and 60% constant values, respectively. Since TVOC concentration has been considered in this study, these values cover the capturing efficiency for a wide range of VOC compunds [39]. We assumed that the buildings had been constructed and used for more than three years. After a steep decline, this ensures a constant TVOC emission rate [40]. Therefore, a continuous value was considered for the internal volumetric TVOC emission rate in the studied buildings where the sources are the walls, furniture, and surfaces. The emission rates and their sources for both TVOC and CO_2 are provided in Table 2. Tang et al. [41] investigated the VOC source rates in occupied classrooms and suggested that the occupant-associated TVOC emission rate was 6.3 mg/h per person. We used similar values in current simulations to evaluate the TVOC addition by building occupants to the indoor concentration of TVOC. Other two sources of TVOC emissions are the building furnishings and the ventilated outdoor air with the rate of 120 $\mu g\ m^{-3} h^{-1}$ and 110 $\mu g\ m^{-3}$, respectively.

The particle filters installed at the AHU were 20″ × 24″ × 1″ MERV13 (50.8cm × 61cm × 2.54 cm) and the initial air pressure drop when the filters were clean was about 65 Pa. The filters were changed in regular cycles when the accumulated dust and particles increased the pressure drop over the filter to approximately 80 Pa. However, detailed modelling of particulate filters in using computational fluid dynamics (CFD) can present more precise behavior of the filters as particles accumulate on their surface [42].

The presence of high TVOC concentration in outdoor air was considered for a case of combustion/use of solvents processes in nearby surroundings of the buildings [39]. In all simulations, the constant value of 110 $\mu g/m^3$ was used for TVOC concentration in the ventilation air from outdoor.

Table 2
Emission sources used jointly with schedules in Fig. 1 for intermittent/constant effect.

Air pollutant	TVOC			CO_2	
Source	Outdoor	Occupants	Interior furnishing	Outdoor	Occupants
Value	$\mu g.m^{-3}$	$mg.h^{-1}.person^{-1}$	$\mu g.m^{-3}h^{-1}$	$mg.m^{-3}$	$g.h^{-1}.person^{-1}$
	110	6.3	120	720	120

3.2. *TVOC concentration thresholds*

Several local building certifications provide guidelines to building constructors and owners to evaluate their buildings with regard to energy efficiency, land use, IAQ, etc. The indoor TVOC concentration levels recommended by a number of these certifications are provided in Table 3. In references provided in Table 3, TVOC can include all chemicals except for substances that are not found in the air at any concentration. Since each reference used its procedure for the analysis of

Table 3
Proposed guideline values for indoor TVOC concentration.

Location	Reference	TVOC concentration $\mu g\ m^{-3}$
Europe	Report EUR 14449 EN. 1992 [44]	Comfort range <300 multifactorial exposure range <3000 Discomfort range <25,000 Toxic range >25,000
Finland	Finnish Society of IAQ and Climate. 2000 [43]	Individual indoor climate <200 Good indoor climate <300 Satisfactory indoor climate <600
Germany	Federal Environment Agency of Germany [45]	Hygienically safe <1000 Hygienically noticeable <3000 Hygienically alarming <10,000 Hygienically unacceptable >1000
Germany	Seifert B [46].	300

chemicals, the list of TVOC values is not entirely comparable. However, the more conservative values provided by the Finnish classification of indoor climate [43] were used in the current study as the comparative reference to evaluate the TVOC concentration level in the studied buildings.

We assumed that the TVOC concentration and the emission source strength do not vary with time, and ventilation was the only mechanism for removing the pollutants from the indoor environment. In that case, the uniform indoor concentration can be calculated by Equation (1) [47].

$$C_r = C_s + \frac{\dot{m}}{\dot{V}} \tag{1}$$

where

C_r is concentration in indoor air, μg/m^3
C_s is concentration in the supply air, μg/m^3
$\dot{m}$ is the strength of indoor sources, μg/h
$\dot{V}$ is the airflow rate, m^3/h

In the presence of variation in indoor TVOC emission sources, which leads to a peak limit due to dense occupancy or lower ventilation rates, the theoretical TVOC concentration decay in the fully-mixed condition at time instance t is defined by Equation (2) [47].

$$C_r(t) = C_s + \frac{\dot{m}}{\dot{V}} - \left(C_s + \frac{\dot{m}}{\dot{V}} - C_r(t-1)\right)e^{\frac{-t}{\tau_n}} \tag{2}$$

where

t is time instance in transient condition, s
τ_n is the time constant and defined as below:

$$\tau_n = \frac{1}{ACH} = \frac{V}{\dot{V}}[h] \tag{3}$$

The electrical power demand, P, of the circulation fans is calculated by Equation (4) considering the total pressure losses, Δp, in the supply/return ducts including the pressure loss over the filters and the efficiency of the fans, η_{total}.

$$P = \frac{\Delta p.\dot{V}}{\eta_{total}} \quad [W] \tag{4}$$

3.3. CO_2 concentration threshold

CO_2 concentration in indoor environments has been widely considered an indoor air quality metric and a target parameter for regulating ventilation systems. A threshold of 1800 mg/m^3 (approximately 1000 ppm) is used as an indoor threshold [48]. We used Equation (2) to calculate the indoor CO_2 concentration, while we did not use any removal for CO_2. The average CO_2 generation per person in buildings was monitored by Refs. [49,50] and reported as approximately 0.0047 l/s.per (0.03345 g/h.per). The average CO_2 concentration in outdoor air in light traffic areas is approximately 400 ppm (720 mg/m^3). These values are used in simulations to evaluate indoor CO_2 concentration.

We implemented Equations (1)–(3) in Matlab to estimate the TVOC, and CO_2 concentrations, while we imported the corresponding sources and the occupancy, ventilation, and recirculation schedules from TRNSYS. Fig. 2 illustrates more details regarding the simulation model in TRNSYS.

The next section presents the results of various simulation scenarios are presented. The critical parameters are the building heating demand compared for two typical AHU cases with and without heat recovery from ventilation air. The recirculation rate ranges from 0 to 60% to determine its impact on the building space heating demand, TVOC, and CO_2 concentration levels.

4. Results

The performance of the centralized air handling units of a residential

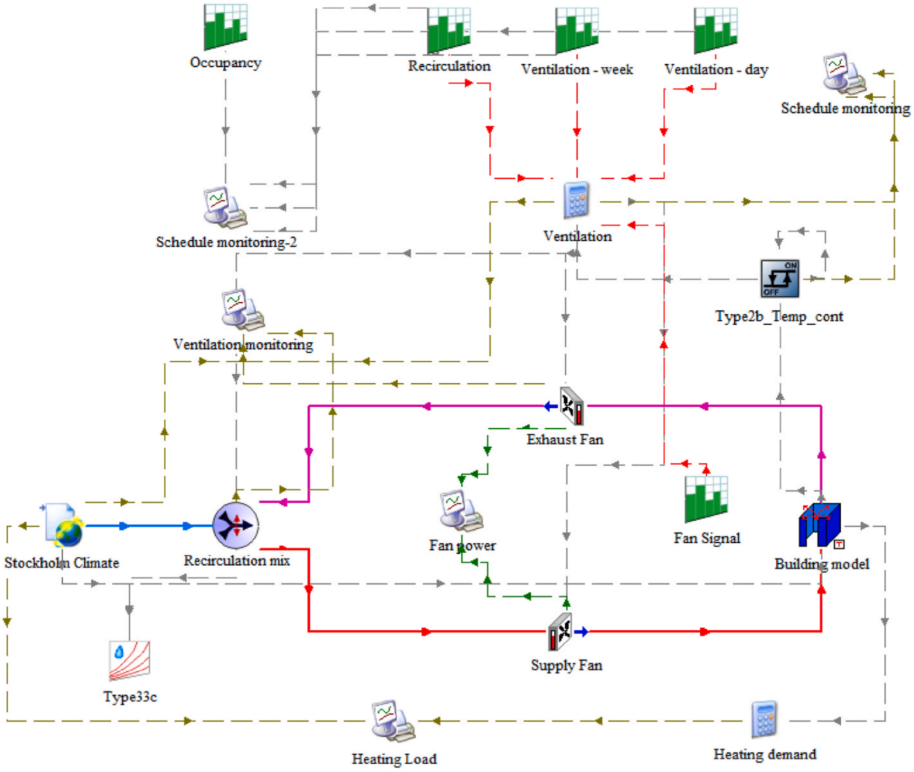

Fig. 2. Pictorial representation of the simulated model in TRNSYS.

and office building was investigated by comparing the effect of increasing indoor air recirculation on the buildings' heating demand. The TVOC and CO_2 concentrations in the buildings are also presented for the cases of recirculating the indoor air.

4.1. Buildings' heating energy demand

Fig. 3 shows the simulation results for the residential building and the annual heating energy demand of the building, as duration curves. The buildings equipped with a heat recovery ventilation (HRV) system require noticeably lower heating energy than those in which the ventilation heat recovery is not considered. The sensible heat recovery efficiency considered in these builsings is a function of outdoor temperature and ranges between 60% and 95% during winter season [36]. Recirculating a fraction of the indoor air in such buildings does not affect the required heating energy. Therefore, recirculation rate is not a decisive parameter in reducing the energy demand of residential buildings with heat recovery.

Fig. 3b shows the accumulated energy, illustrating that the annual heating demand is half that of the building without ventilation heat recovery, regardless of ventilation recirculation rate. However, the heating demand in the residential building without heat recovery is reduced by 3% increments to 97%, 94%, and 91% of the case without heat recovery and recirculation when the recirculation rate is increased in 20% increments from 0% to 60%.

Fig. 4 depicts the heating energy demand of the studied office building. Unlike the residential case, the required heating energy decreased by increasing the recirculation rate in buildings equipped with a heat recovery system. This is due to higher ACH in office buildings compared to the residential ones. In fact, a high value for ACH also affected the dependency ratio between the recirculation rate and the building heating demand. Increasing the recirculation rate in 20%-increments from 0% to 60% resulted in approximately 8% reduction increments in energy demands, which is 92%, 84%, and 76% of the heating energy need of a building supplied entirely with fresh outdoor air and without ventilation heat recovery.

4.2. Indoor TVOC concentration

The indoor air quality (IAQ) of the studied buildings is monitored by keeping track of indoor TVOC and CO_2 concentration values. Fig. 5 illustrates the residential building indoor TVOC concentration over a year. TVOC concentration constantly fluctuates between approximately 350 and 450 μg/m^3 and falls within an acceptable limit regarding the thresholds provided by the references in Table 1. The fluctuation in the concentration level is due to the number of building occupants during the day, since occupant number is the only varying parameter in the residential building following the schedule in Fig. 1. In this building, the ventilation system starts operation at the beginning of the year and continues based on the schedules introduced in Fig. 1; therefore, the average indoor TVOC concentration is mainly determined by the sum of the outdoor concentration and interior surfaces release of TVOC.

Fig. 7 shows the indoor TVOC concentration in the studied office building. As can be seen, the fluctuations in indoor concentration levels are more significant than in the residential building. This is due to both variations in the number of occupants in the building and the daily/weekly schedule for ventilation. During weekdays, concentration peaks at a maximum of 1730 μg/m^3 are observed due to switching the ventilation system off during out-of-office hours (12 h). By the beginning of the next working day, the ventilation system evacuates TVOCs to approximately 180 μg/m^3 within less than 2 h.

The peaks in TVOC concentrations during weekends are more considerable, approximately 7500 μg/m^3. According to Fig. 1, TVOCs accumulate as long as the ventilation system is switched off during entire weekends for 60 h. At the beginning of the workday in the following weeks, the decay time is 3 h when the TVOC concentration drops to the constant level of 1800 μg/m^3, which is three times the satisfactory level defined by the Finish standards. In general, while the

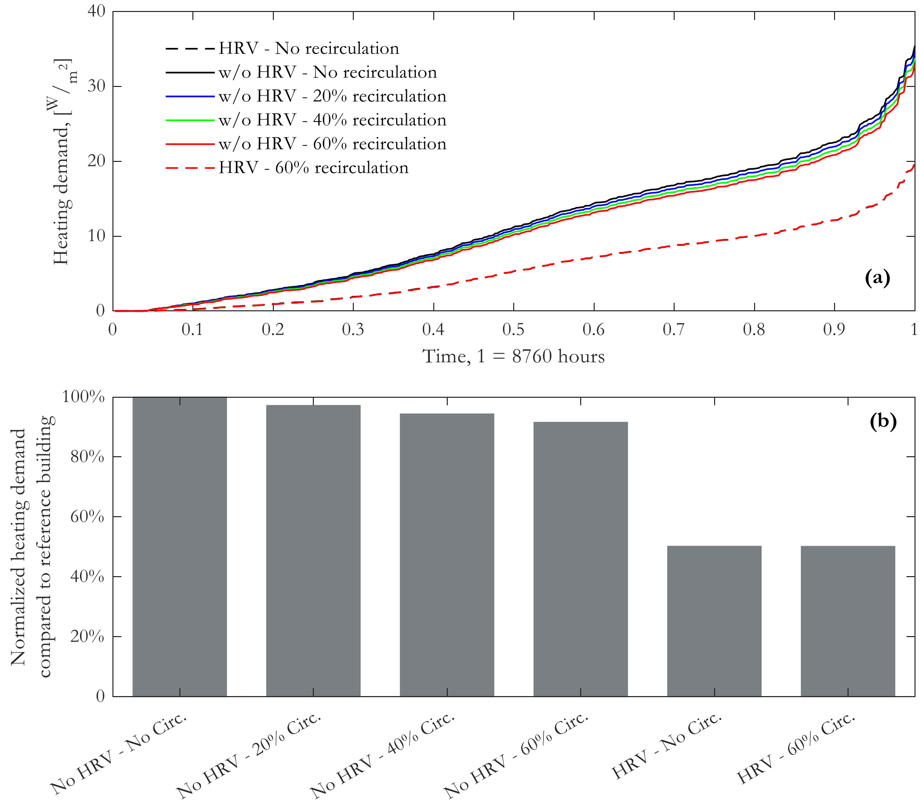

Fig. 3. Residential building heating demand.

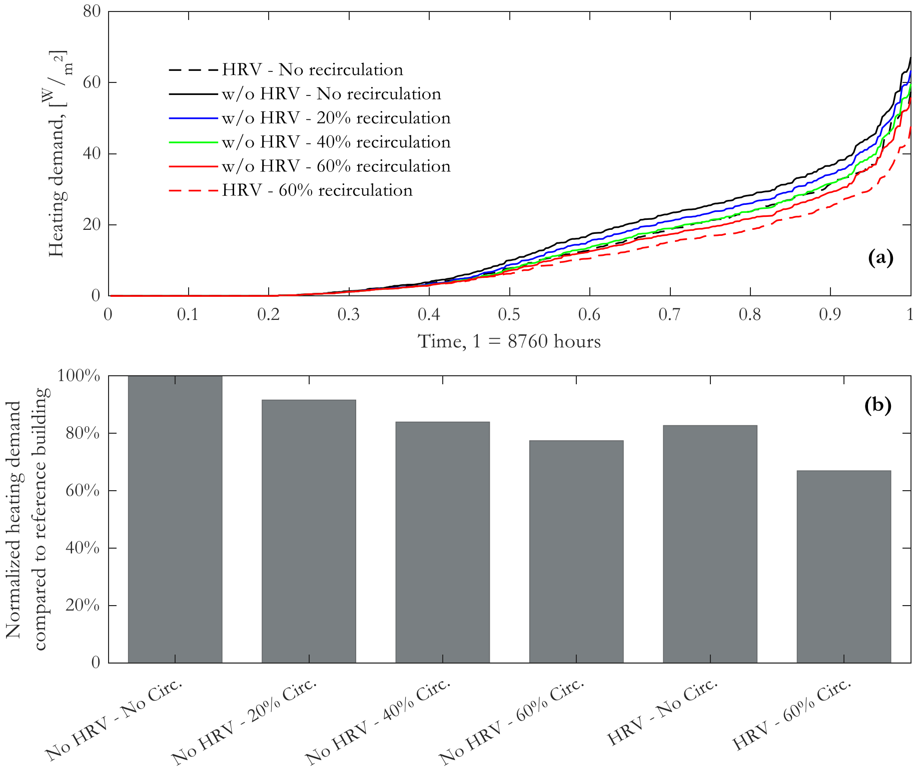

Fig. 4. Office building heating demand.

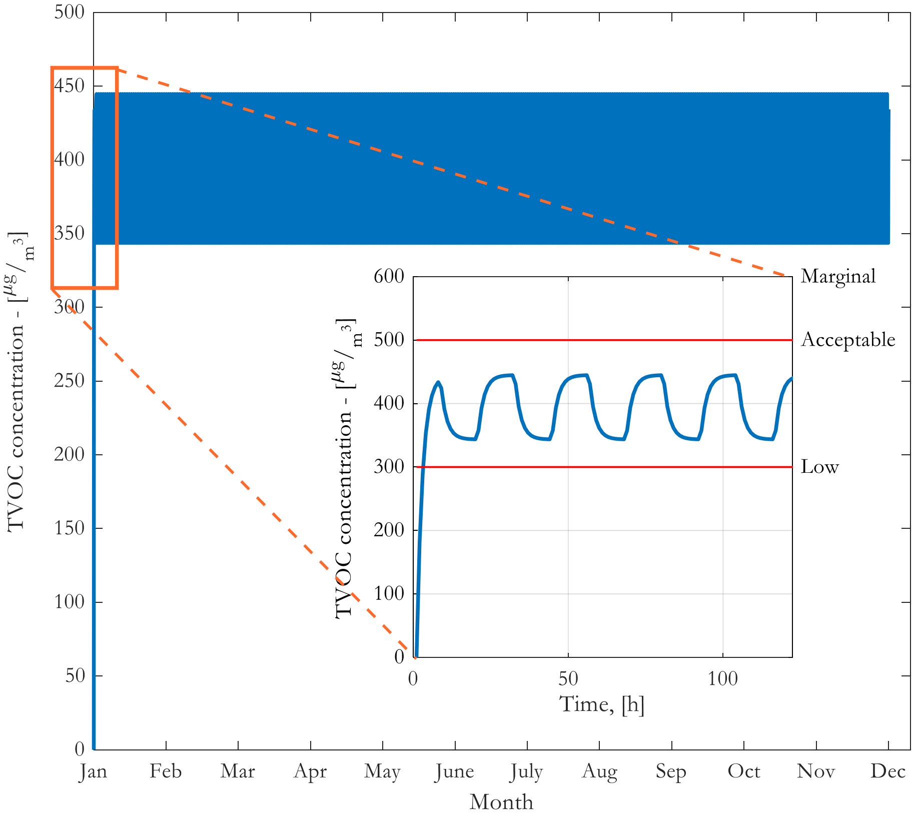

Fig. 5. Residential building without air recirculation.

building is occupied during office hours, the TVOC concentration value is within an acceptable level.

Fig. 6 illustrates the impact of the recirculation rate on the TVOC concentration in the residential building. Provided that the emission rate from the pollutant sources constantly fluctuates over time, TVOC concentration is mainly affected by recirculation rate and ACH. Despite an

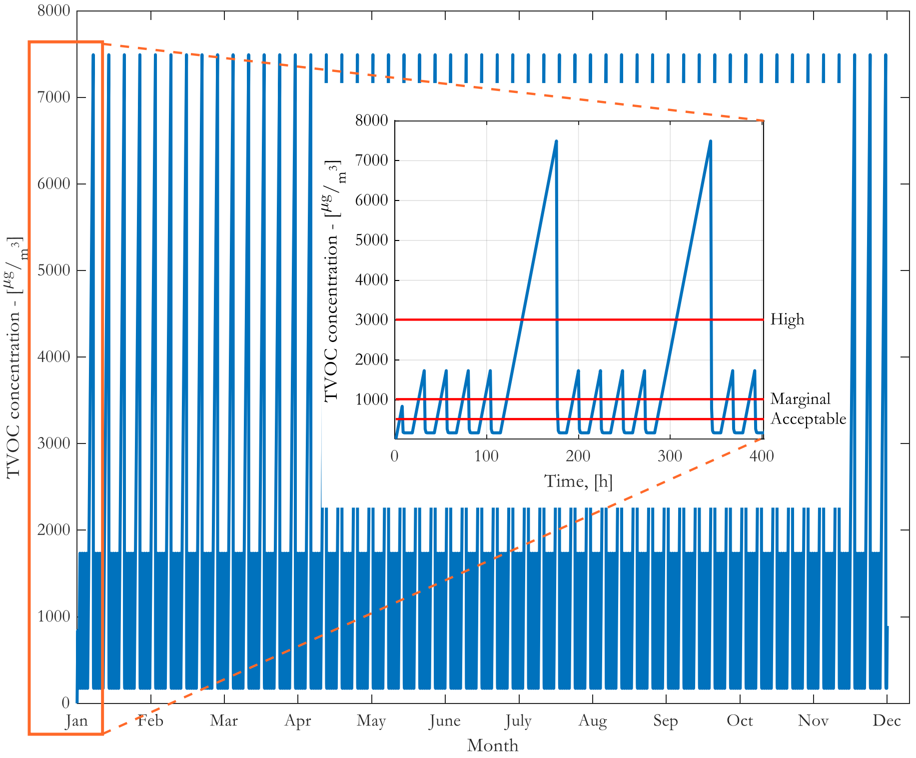

Fig. 6. Office building without air recirculation.

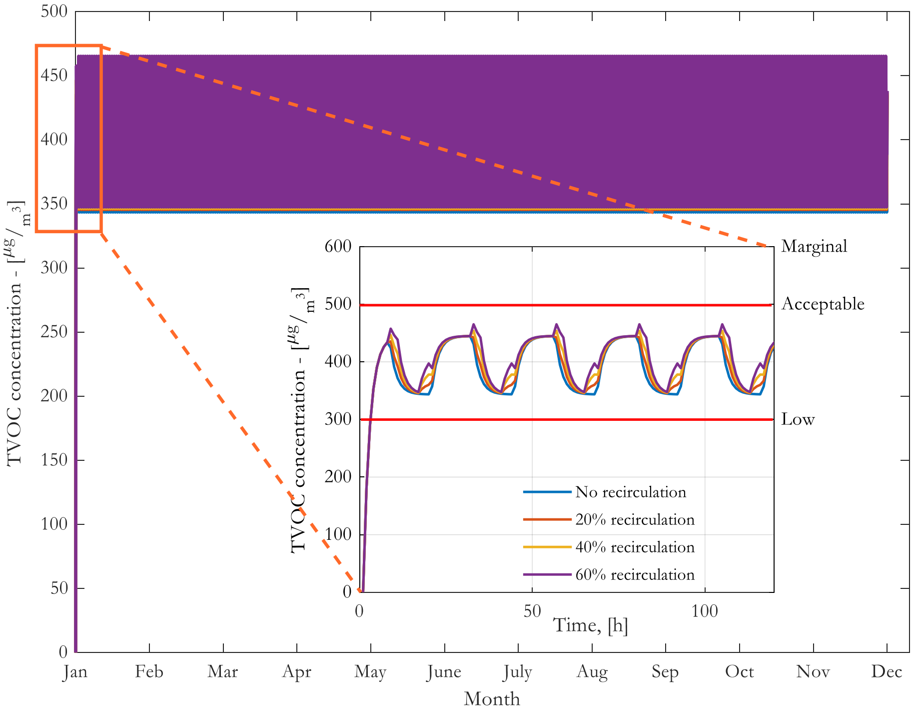

Fig. 7. Impact of recirculation rate on TVOC concentration in residential building.

increase in TVOC level as a result of a higher recirculation rate, the values remain in the acceptable range of less than 500 μg/m^3. The maximum TVOC concentration rose by approximately 5% following a 60% increase in recirculation rate.

The recirculation rate has a negligible effect on the TVOC concentration value in the office building. As can be seen in Fig. 8, a trivial change in TVOC values is observed when increasing the recirculation rate up to 60%. This is mainly due to stronger sources of TVOC in the building, such as the presence of occupants and furnishings compared to the accumulation by recirculation.

4.3. Impact of ACH and recirculation rate on TVOC concentration

Fig. 9 compares the impact of recirculation rate on the TVOC

Fig. 8. Impact of recirculation rate on TVOC concentration in office building.

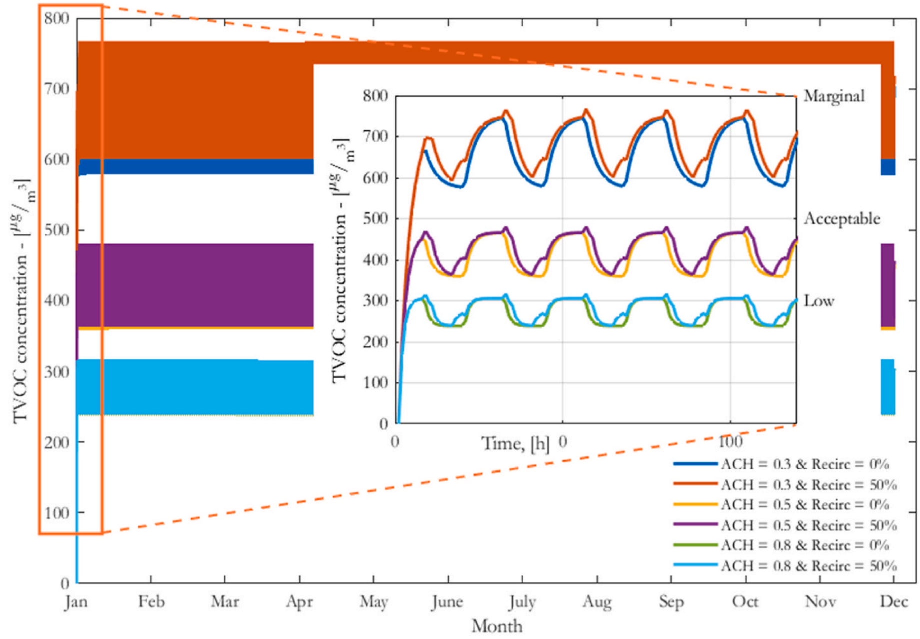

Fig. 9. Impact of recirculation rate on TVOC concentration for different ACH values.

concentration in a residential building served by an AHU with various ACH. It can be observed that increasing the ACH reduces the TVOC concentration level immensely. The required ventilation rate in Swedish residential buildings, as suggested by BBR, is ACH = 0.5 h^{-1} [34]. Introducing lower ACH escalates TVOC concentration, and increasing the ACH to 0.8 h^{-1} results in diminished TVOC values. In Fig. 9, it can also be observed that indoor air recirculation affects the TVOC concentration in the presence of higher air change rates per hour.

4.4. Indoor CO_2 concentration

Indoor CO_2 concentration is a function of outdoor concentration and the occupancy rate. Since the gas filters do not absorb CO_2, the indoor concentration is mainly affected by the more potent source, which in this study is outdoor concentration.

Fig. 10 illustrates how the CO_2 concentration varies over time in the studied residential and office buildings. For both cases, the values are within the acceptable range (less than 1800 mg/m^3). Due to considerable air change rates per hour, the indoor CO_2 concentration is

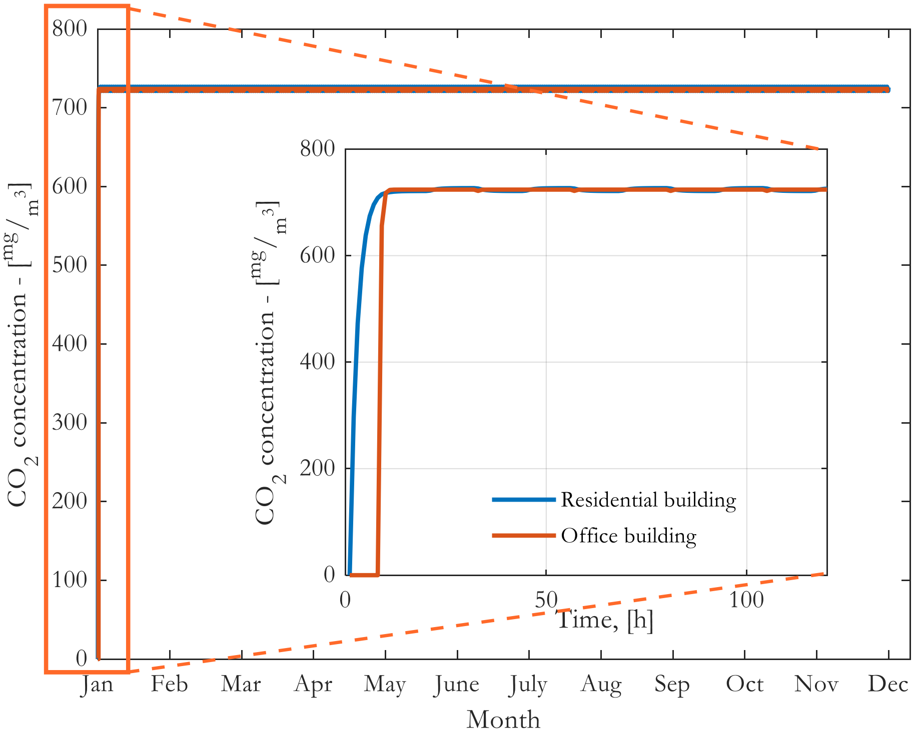

Fig. 10. CO_2 concentration in residential and office buildings.

approximately equal to the outdoor value, even though the number of occupants and ACH are different in the two cases. Due to changes in the occupancy rate in both buildings, the CO_2 level fluctuates slightly over time. Although it is negligible, this level is more visible for the residential building than the office since the ACH value is much lower. The fluctuations are negligible in amplitude since the outdoor CO_2 concentration is considerably more significant than the indoor CO_2 source. In addition, the ventilation system is always in operation in the residential building, and partly but exactly in operation when occupants reside in the office building, which converges the CO_2 level to the outdoor concentration value.

Fig. 11 shows the dependency of indoor CO_2 concentration on ACH and recirculation rate. Adopting a recirculation rate of 50% in cases where the ACH varies between 0.3 and 0.8 h^{-1} does not significantly

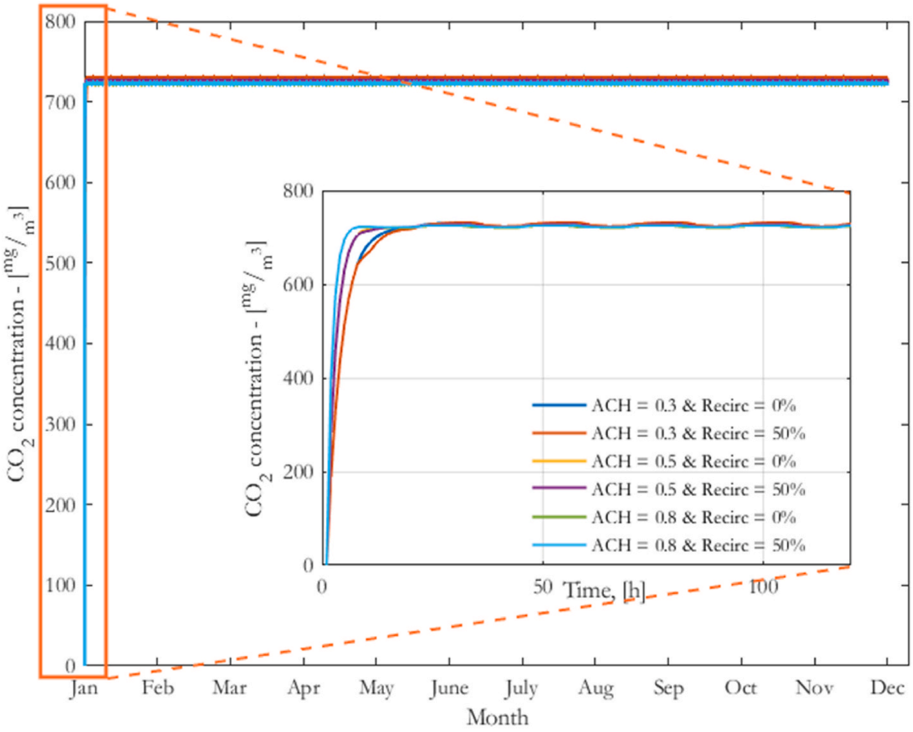

Fig. 11. Impact of recirculation rate on CO_2 concentration for different ACH values.

change indoor CO_2 concentration. This negligible effect of the recirculation rate on the indoor CO_2 level is mainly due to the dominance of outdoor CO_2 concentration over the indoor emission rate. Therefore, the recirculation rate, similar to the occupancy rate and schedule as discussed in Fig. 10, is not an influencing parameter on the indoor CO_2 level if the outdoor concentration outweighs the indoor sources.

5. Discussion

The energy usage of the simulated building [36], according to the criteria defined by the Swedish center for zero-energy buildings [51] and Boverket [34], is ranked as a mini-energy house ($\leq$75 kWh/m^{2}A$_{temp}$,yr) if the AHU is equipped with heat recovery. In the case of mechanical ventilation without heat recovery, as investigated in most parts of this paper, the building is categorized as a standard house ($\leq$90 kWh/m^{2}A$_{temp}$,yr). Since the recirculation ratio and ACH affect the ventilation heating demand, it is beneficial to investigate the impact of gas-phase air cleaning on buildings with lower energy requirements, such as passive and low-energy buildings. Further investigations on various building types reveal whether the obtained results can be scaled to buildings with lower energy demand. The effect of the ACH value, which directly affects the ventilation heat losses, is shown by the difference between Figs. 4 and 5. The energy savings by recirculation is more significant for the office building than the residential building due to higher ACH and, in turn, larger ventilation heat losses in office buildings.

Based on the obtained results, utilizing gas filters and increasing the recirculation rate of ventilated air decreases the heating demand of buildings that are not equipped with a heat recovery system. The heat recovery efficiency in the simulated case of the present work is a function of outdoor temperature and is therefore not constant. Further investigations on mechanical ventilation systems with different heat recovery efficiencies can correlate to energy savings.

Currently, a fixed schedule for recirculation of ventilated air based on the rush hours in Stockholm is utilized in all simulated cases. According to the Swedish building regulations [34], recirculation of the ventilated air is not allowed. This will be improved by the daily round real-time monitoring of various air pollutants in Stockholm and recirculating the ventilated air accordingly if required.

According to Figs. 5 and 6, TVOC concentration is within the acceptable level if the ventilation system is in operation. This is the case for the residential building during the entire simulation period; however, despite higher ACH for the office building, the TVOC concentration exceeds the recommended thresholds when the ventilation system is not in operation. It is noteworthy that these intervals are not the office hours, and the building is not occupied. Thus, it is necessary to start ventilating the building before the beginning of office hours.

Indoor CO_2 concentration level, unlike TVOC, is not significantly affected by changing the investigated parameters, the recirculation rate, and ACH value. Based on the results illustrated in Figs. 10 and 11, the observed fluctuations of indoor CO_2 levels due to occupancy and ventilation schedule are insignificant. Furthermore, the impact of different ACH and recirculation rates on the indoor CO_2 concentration is negligible. The reason is that the outdoor concentration of CO_2 is more significant than the indoor sources and the filters do not capture the existing CO_2 in the ventilated air. Despite such deficiencies, the indoor CO_2 concentration is below the recommended level during simulation time.

6. Summary and conclusions

This study evaluated the energy implication of using gas-phase air cleaners and the effect of decisive parameters on energy and indoor gas pollutants concentration was further investigated in a parametric study of the influential parameters such as the ACH and recirculation rate. TVOC and CO_2 concentrations, as two major indoor air quality metrics, were traced in a residential building and an office building where the centralized air handling units were equipped with gas filters. In general, increasing the recirculation rate, which is the ratio of indoor-to-outdoor air in the total supply to the building, decreased buildings' heating demand. Note that the energy savings were obtained for buildings without ventilation heat recovery. Further findings based on the simulation results are listed below:

- Increasing the recirculation rate decreased the required heating demand in the office building more than the residential building. This is mainly due to higher ventilation airflow rates and ACH in the office building compared to the residential.
- Increasing the recirculation rate and time during a day, from 6 h in the current study, reduces the building heating demand considerably. A 60% recirculation rate in a residential and office building decreased the required heating demand by 9% and 24%, respectively.
- Considering the occupancy rates in residential and office buildings in Sweden, our simulation results show that indoor TVOC and CO_2 concentration rates were within an acceptable range in case of increasing the recirculation rate during the rush hours in the mornings and evenings.
- Indoor CO_2 concentration value was affected less than TVOC's by increasing the recirculation rate. This is because the outdoor CO_2 concentration level dominated the indoor emission sources. Therefore, in case of monitoring only one of the targets, the TVOC concentration in buildings must be prioritized to CO_2.
- Indoor TVOC and CO_2 concentrations were less affected by recirculation in the office building than the residential one since the ventilation system in the office building with higher ACH evacuated the pollutants more effectively. Therefore, increasing the ACH value mitigated the impact of recirculation on the indoor TVOC and CO_2 concentration level. Increasing the ACH in a residential building by 60% from the BBR recommendation (from 0.5 h^{-1} to 0.8 h^{-1}) decreased the indoor maximum TVOC concentration by approximately 34%.

Credit author statement

Behrouz Nourozi: Conceptualization; Methodology; Simulation, Validation and Visualization; Main writer of Writing – original draft; **Sture Holmberg**: Editing and reviewing; **Christophe Duwig**: Editing and reviewing; **Alireza Afshari**: Editing and reviewing; **Pawel Wargocki**: Editing and reviewing; **Bjarne Olesen**: Editing and reviewing; **Sasan Sadrizadeh**: Supervision; Conceptualization; Methodology; Editing and reviewing.

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.

Acknowledgment

This work is part of "IEA EBC Annex 78 - Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications". The financial support from the Swedish Energy Agency (Grant No. P50403-1) is gratefully acknowledged.

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