Potential of mechanical ventilation for reducing overheating risks in retrofitted Danish apartment buildings from the period 1850-1890 – A simulation-based study

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ABSTRACT

Advancing energy efficient renovation solutions in buildings necessitate adopting high-insulation and airtightness to avoid heat loss through transmission and infiltration, which can result in overheating. Elevated indoor temperatures have a highly negative effect on building occupants' health, wellbeing and productivity. With the possibility of remote working, people spend more time at home, and therefore addressing the elevated indoor temperatures and the overheating risks in residential buildings proves to be essential. Even more so, as these high temperatures during daytime are followed by consequent high temperatures during night-time, which distorts sleep quality. The current Danish building regulations suggest that the operative temperature in dwellings should not exceed 27 °C for more than 100 hours per year and 28 °C for more than 25 hours per year. However, in many new and renovated dwellings in Denmark the temperature during spring and summer exceeds these measures. The paper presents the first results from a larger study focused on typical Danish apartment buildings from the period 1850-1950 many of which currently undergo extensive renovation. The main objective of the project is to study facade solutions that eliminate overheating. The present paper reports an effect of different ventilation strategies on overheating in renovated apartment buildings from the period 1850-1890. The investigation showed that energy renovation in this type of buildings, including adding insulation and exchanging windows, yielded energy saving of approx. 60%, but resulted in an increase of overheating hours when no mechanical ventilation system was added. All studied mechanical ventilation systems with heat recovery were able to decrease the overheating hours below limit specified by the Danish building code in the case of the building situated in the narrow street canyon. In the absence of shading from surrounding buildings, the CAV ventilation operating with minimum airflow required by the Danish building code reduced overheating hours insufficiently.

KEYWORDS

Overheating, energy renovation, residential ventilation, apartment building, energy consumption

1 INTRODUCTION

Reduction of energy consumption and improvement of the indoor climate have been on the agenda in the building sector in recent years. The EU's goal is to reduce its total greenhouse gas emissions by 30% by 2020 compared to the levels from 1990, and by 80% by 2050 (European Parliament, 2010). Denmark has set an even more ambitious goal of being completely free of fossil fuel by 2050 (Danish Government, 2014). Energy consumption in buildings, including primarily energy used for heating, ventilation, domestic hot water and lighting, accounts for around 40% of the total energy consumption in Europe (BPIE, 2011). Efficiency of the energy use in buildings therefore plays a crucial role in achieving the political goals. At the same time, newly built constructions account only about 1% of the building stock in many developed countries. Thus, a reduction of energy use in buildings can only be achieved with focus on existing buildings. Furthermore, the residential stock is the biggest segment with an EU floor space accounting for 75% of the building stock and should consequently be in focus. Commonly applied renovation approach aims to limit heat transfer through the building envelope (thermal insulation, window replacement, tightening of building envelope). These solutions lead to energy savings during the heating season, but at the same time to high indoor temperatures during periods with higher solar heat gains.

Elevated indoor temperatures have a highly negative effect on occupants' health, wellbeing and productivity (NHBC Foundation, 2012). With the possibility of remote working, people spend more time at home, and therefore addressing overheating risk in residential buildings becomes more important. Moreover, certain vulnerable groups as infants, children and the elderly, as well as the obese and people with chronic diseases mostly stay at home. Excess heat even in shorter periods can have significant health implications for them (Brown and Walker, 2008). Additionally, higher night-time temperatures are documented to increase the risk to health due to the inability to recover from daytime heat stress (Kovats and Hajat, 2008) and interrupt sleep (Raymann et al., 2008; Strøm-Tejsen et al., 2016). It has been reported that a change of as little as 1 K in skin temperature can affect the quality of sleep obtained, particularly in the elderly (Raymann et al., 2008).

According to the Danish building regulations 2018 (BR18, 2018) the operative temperature in dwellings should not exceed 27 °C for more than 100 hours per year and 28 °C for more than 25 hours per year. However, in many new and existing dwellings in Denmark the temperature during spring and summer often exceeds these measures (Psomas et al., 2016; Larsen, 2011). Ventilation required in new and renovated Danish dwellings is designed to supply fresh air and avoid moisture related problems. It is not designed to cool. Thus, there is a risk of overheating, especially in warm months. The effect will be multiplied by the overall trend of increased external temperatures due to the climate changes (CIBSE TM36, 2005).

In Denmark 28% of the residential building area is associated with apartments (BPIE, 2011). A currently ongoing research project "Reduction of overheating in Danish dwellings by use of effective solar control without comprising visual comfort" focuses on buildings from the period 1850-1950. Energy effective solutions to the problem with overheating include limiting the solar heat gains through the glazed parts of the facade (REHVA Guidebook no. 12, 2010) and effective ventilation (IEA EBC, 2018). The project's challenge lays in identifying combinations of shading and glazing solutions that reduce overheating risk without disturbing appearance of the facade and aggravating daylight conditions. However, in the study reported in this paper the use of external solar shading is limited due to the architectural heritage value of the facades of buildings from the period 1850-1890. The paper reports results from the underlying study that had an objective to examine the impact of different ventilation strategies applicable in renovated buildings on overheating risk and energy consumption. The results will be further utilized for investigation of facade solutions.

2 METHODS

2.1 Building and its surroundings

Altogether three apartment buildings representing relevant building typologies according to Engelmark (2013) were identified. The present paper reports results for one of the buildings – a historical residential 5-storey building located in the northern area of Copenhagen – Figure 1 (left), representing a typical apartment building from the period 1850-1890 common in Danish cities. Solid masonry and bricks are the main characteristics of the facades. The inner walls are mainly made of timber construction and bricks. Floors and staircases are made of wood. The roofing material is brick, slate or metal carried by a wooden structure. All windows consist of four openable parts where the two lower parts count for 2/3 of the window size. This type of buildings comprises parts of a rectangular arrangement of similar buildings with the backside facing to the courtyard in the middle and the front facade facing the street with other buildings of the same height – Figure 1 (right).

Figure 1: Case study building (left) and outline of surrounding (right)

The IDA Indoor Climate and Energy (IDA ICE) software was used to model the building, Figure 2 (left), with and without the surrounding constructions and the greenery always omitted. The cases without shading from the surrounding buildings represent the apartments on higher floors as well as occasions where similar buildings are not located in a tight street canyon. In the model, the apartment was located on the first floor with a gross floor area of 56.6 m^2 and consisted of a kitchen, living room, bedroom, small bathroom and hall – Figure 2 (right).

The windows in the building before renovation were assumed to be clear double pane (4-12-4) with the heat transfer coefficient of glazing U_g = 2.8 W/(m^2·K), light transmittance LT = 82% and total solar heat transmittance g = 79%. The heat transfer coefficient of the window frame was set to U_f=2.0 W/(m^2·K). The fraction of the frame to the total window area was calculated to 39% for windows in the living room and the bedroom, and 28% in the kitchen.

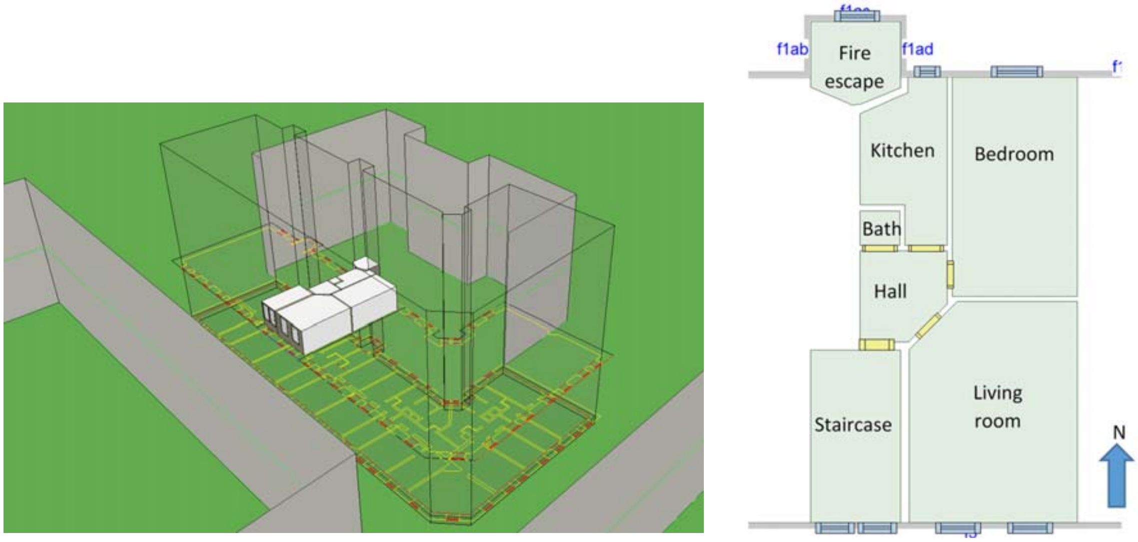


Figure 2: Building model (left) and layout of simulated apartment (right)

Energy renovation for the simulated building included an addition of 95 mm of internal thermal insulation and exchange of all windows. Internal insulation brings a risk of moisture condensation in the construction and reduction of the internal space; however, it is often used in practice due to the architectural value of the facades in this type of buildings. The Knowledge Centre for Energy Savings in Buildings (2017) recommends the thickness of the internal insulation to be below 100 mm to reduce the risk of condensation. The windows were changed to clear double pane energy windows (4-12Ar-S(3)4) with U_g=1.3 W/(m^2·K), LT = 82% and g = 65%. The U-value of the window frame was changed to 1.3 W/(m^2·K) with the same frame sizes as before the renovation.

In none of the simulated cases solar shading devices were used.

2.2 Location and weather data

The building model was located in Copenhagen, Denmark. The simulation period was set from the 1st of January to the 31st of December 2010 using weather data by the Danish Reference Year, DRY 2013.

2.3 Heat loads and schedules for occupancy

With respect to internal loads (heat from appliances, sensible and latent loads from occupants, moisture load from activities), a recent Danish guideline for indoor climate calculations (Vorre et al., 2017) was followed. Based on the apartment size and only one bedroom, the apartment was assumed to be occupied by two adults employed with standard work hours (weekdays 8:00-16:00). The occupants were assumed constantly present in the apartment during weekends. The distribution of occupancy in the particular rooms followed the guideline and is shown in Table 1. Metabolic rate of the occupants was assumed to be 1 met during the day and 0.8 met while sleeping. Occupant loads included both sensible and latent heat production. The schedules suggested by Vorre et al. (2017) include an overlap in the occupancy for common spaces and bedrooms to accommodate various users' behaviour. As this overlapping leads to relatively high occupant heat loads during afternoon/evening hours it was decided to reduce the occupancy loads to 54% in order to obtain an average load of 1.5 W/m^2 as assumed in the Danish energy frame calculations (Aggerholm, 2018).

Table 1: Occupancy schedules for different rooms for weekdays and weekends based on Vorre et al. (2017)

Weekdays	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**16:30**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Bedroom	100%	100%	100%	100%	100%	100%	100%															100%	100%	100%	100%
Living room																					100%	100%	100%		
Kitchen								100%										100%	100%	100%	100%	100%	100%		
Bathroom																									
Hall																									

Weekend	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**16:30**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Bedroom	100%	100%	100%	100%	100%	100%	100%	100%														100%	100%	100%	100%
Living room																					100%	100%	100%	100%	
Kitchen									100%	100%	50%	50%	50%	50%	50%	50%	50%	100%	100%	100%	100%	100%	100%	100%	
Bathroom																									
Hall																									

2.4 Heat loads from equipment and lighting

The heat loads from equipment and lighting in the kitchen, living room and bedroom were based on recommendations from Vorre et al. (2017). The hourly schedules for the heat loads are shown in Table 2 with the maximum internal heat loads for the kitchen 10 W/m^2 but min. 350 W, for the living room 5 W/m^2 but min. 100 W, and for the bedroom 6 W/m^2 but min. 60 W.

Table 2: Schedules for heat loads from equipment and lighting in different rooms for weekdays and weekend based on Vorre et al. (2017)

Weekdays	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Bedroom							25%														100%	100%		
Living room																				100%	100%	100%		
Kitchen	10%	10%	10%	10%	10%	10%	10%	75%	75%	10%	10%	10%	10%	10%	10%	10%	10%	100%	100%	50%	50%	50%	10%	10%
Bathroom																								
Hall																								

Weekend	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Bedroom								25%													100%	100%	100%	
Living room																				100%	100%	100%	100%	
Kitchen	10%	10%	10%	10%	10%	10%	10%	10%	75%	75%	50%	50%	50%	50%	50%	50%	50%	50%	100%	100%	50%	50%	50%	10%
Bathroom																								
Hall																								

2.5 Moisture load from activities

The moisture production from typical activities occurring in the apartment was set to 60 g/h per person based on Valbjørn et al. (2000). Since the guideline by Vorre et al. (2017) does not assume occupancy in the bathroom, the whole moisture production was added in the kitchen and was constant during 24 hours for the whole week.

2.6 Ventilation and infiltration

The building before renovation (case URNV) was assumed to be naturally ventilated. This was modelled using fixed infiltration of 0.5 l/(s·m^2) of the heated floor area (i.e. including external walls). The building after renovation was first simulated as naturally ventilated (case NV) with fixed infiltration of 0.3 l/(s·m^2) of heated floor area corresponding to the minimum fresh air supply required by the Danish building code (BR18, 2018). Additionally, four mechanical ventilation strategies were investigated for the building after renovation: two types of constant air volume (CAV_{min} and CAV_{max}) and two types of variable air volume (VAV_{RH} and VAV_{T}) systems – all systems operated with balanced supply and exhaust airflows. The CAV_{min} case represented a minimum requirement of 0.3 l/(s·m^2) fresh air supply to the whole apartment as well as each habitable room (BR18, 2018). The CAV_{max} system simulated the case when designers determine airflows according to requirements for forced extraction from a kitchen and a bathroom, as the Danish building regulations (BR18, 2018) demand possibility to increase exhaust to min. 20 l/s and min. 15 l/s in a kitchen and a bathroom, respectively. Many practitioners therefore set the CAV system to operate constantly with aforementioned airflows (Bocanegra-Yanez et al., 2017). Both VAV ventilation systems represented decentralized one-dwelling solutions with the airflows controlled by either temperature (VAV_{T}) or relative humidity sensor (VAV_{RH}) placed in the exhaust duct. The minimum airflows for both systems were the same as the airflows for the CAV_{min} system. The maximum airflows were determined to fulfil the requirements to the amount of exhaust air from a bathroom and a kitchen and therefore assumed to be 300% of the minimum airflow. The airflows for all investigated ventilation systems can be seen in Table 3.

Table 3: Airflows in CAV and VAV systems for different rooms
(in blue colour supply and in green colour extraction)

	Area	CAV_{min} Airflow		CAV_{max} Airflow		VAV_{min} Airflow		VAV_{max} Airflow	
	m^2	$l/(s \cdot m^2)$	l/s	$l/(s \cdot m^2)$	l/s	$l/(s \cdot m^2)$	l/s	$l/(s \cdot m^2)$	l/s
Bedroom	18.43	0.40	7.3	0.82	15.1	0.40	7.3	1.20	22.0
Living room	24.20	0.40	9.6	0.82	19.9	0.40	9.6	1.20	28.9
Kitchen	8.17	1.19	9.7	2.45	20.0	1.19	9.7	3.57	29.1
Bathroom	1.07	6.82	7.3	14.06	15.0	6.82	7.3	20.47	21.8
Hall	4.77	-	-	-	-	-	-	-	-
Sum	56.63								

The VAV_{RH} system was controlled by a proportional (P) controller: $RH_{set\text{-}point} = 50\%$, P-band = 20%. The VAV_{T} system was controlled by a proportional-integral (PI) controller: $T_{set\text{-}point}$ = 23 °C, K = 0.3. The control algorithm included also a condition with respect to outdoor temperature: $T_{out} \leq (T_{room} - 2)$ °C.

A typical air handling unit used in Danish residences consisting of heat recovery and two fans was simulated. Neither heating nor cooling coil was used. The dry temperature efficiency of the heat recovery was set to 85% at the maximum airflow, while the set point for the supply temperature was 18 °C. The maximum specific fan power (SFP) for each fan was assumed to be 0.5 kJ/m^3 fulfilling the requirement for a maximum total SFP = 1 kJ/m^3 (BR18, 2018). The primary energy factor for electrical power was set to 2.5 (BR18, 2018).

Infiltration of 1 $l/(s \cdot m^2)$ floor area at 50 Pa pressure difference for all cases with mechanical ventilation was assumed as the maximum allowed infiltration for new and renovated buildings according to BR18 (2018).

2.7 Heating system

Idealized heating units ensuring the heating temperature set point of 20 °C in all rooms of the apartment (16 °C in the staircase and fire escape) were used in all cases. The heating system was switched off in the summer period i.e. from the 1st of May to the 30th of September (Vorre et al., 2017). The heating was supplied by district heating with a primary energy factor of 0.8 (BR18, 2018).

2.8 Window, doors and infiltration

A crude estimate of the occupants' window opening behaviour was simulated using temperature control by a PI controller: $T_{set\text{-}point} = 23$ °C, $K = 0.3$. Additional conditions with respect to outdoor temperature: $T_{out} \leq (T_{room} - 2)$ °C and the presence of at least one of the occupants in the apartment were also applied. The effective window opening area was assumed to be 60% (15% during night-time) according to Vorre et el. (2017). It was assumed that the upper parts of the window were never open (inconvenient due to a high position of these parts), while 60% of the window opening was implemented to the lower parts. Only one of the two windows in the living room was set to open.

The VAV_T system was assumed to be used in apartments located towards polluted and noisy street as a solution allowing minimising a need for window opening. In this case, the set point for window opening was 27 °C i.e. - the occupants open the windows only when the mechanical ventilation cannot reduce the overheating.

The doors to all rooms were kept closed during the whole simulation period in order to avoid unrealistic large airflows between the rooms. A leak with an area of 0.01 m^2 and discharge coefficient $C_d = 0.65$ was placed at each door.

2.9 Energy consumption

In the present study, the energy consumption analysis included only energy demand for ventilation and heating. The energy consumption for lighting and domestic hot water was neglected.

3 RESULTS AND DISCUSSION

The results regarding energy consumption and overheating are summarized in Figure 3. Energy renovation clearly intensified overheating regardless the presence of surrounding buildings.

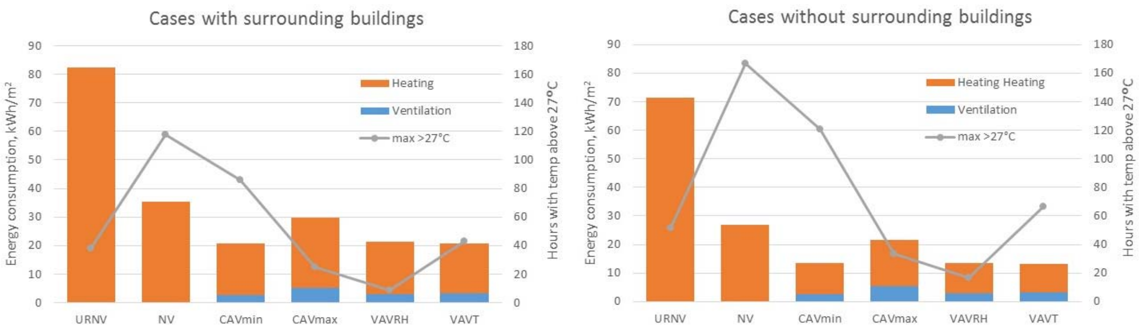


Figure 3: Energy consumption and a number of hours with indoor temperature over 27 °C in the zone with maximum overheating hours (kitchen) for the investigated ventilation strategies for cases with surrounding buildings (left) and without (right)

The mechanical ventilation system running constantly on the minimum supply airflow (CAV_{min}) could bring the overheating hours below 100 only in the case of the building in the street canyon. The CAV_{max} and both cases with VAV systems showed ability to keep overheating within the required limits.

The lack of shading from surrounding buildings (e.g. apartments on higher floors or a building facing a square) resulted in increased overheating in summer. On the other hand, reduced solar gains to the building in the street canyon led to higher energy use for heating. This effect was the highest for the building before renovation (about 11 kWh/m^{2}year more primary energy use for the shaded building), while the mean increase for the renovated building with mechanical ventilation was 7.7 kWh/m^{2}year. Energy renovation reduced the energy use for heating by 57% and 62% for the cases with and without surrounding buildings, respectively. With respect to mechanical ventilation, the CAV_{max} system used 34-105% more electricity and approx. 70-80% more energy on heating compared to the other three mechanical ventilation systems. However, it still reduced the energy use for heating by 31-39% compared to the renovated building with natural ventilation. Compared to natural ventilation, the CAV_{min} or VAV systems reduced the total primary energy use by approx. 40% and 50% for the cases with and without surrounding buildings, respectively. Both VAV systems performed equally well in regards to the total energy consumption and overheating, except that the system with temperature control for the case with the exposed building has slightly higher energy consumption for ventilation due to frequent boost of the airflows during elevated temperature in the apartment. CAV_{max} can also effectively reduce the heat excess, but it results in higher electricity use for ventilation.

In the present study, the overheating hours were evaluated for occupied hours for particular rooms of the apartment. This parameter indicated that the kitchen was the most problematic room. As the kitchen was oriented towards north, the overheating was rather caused by high internal loads from occupants and equipment per a relatively small floor area than by solar heat gains. Figure 4 (left) presents yearly duration curves for the operative temperature in all rooms for the VAV_{RH} system, which showed the best potential for reduction of overheating. It is clear from the figure that the living room had the highest amount of hours above 27 °C, when considering also unoccupied period. Moreover, it can be seen from the figure that the operative temperature in the kitchen was consistently higher than in the rest of the apartment.

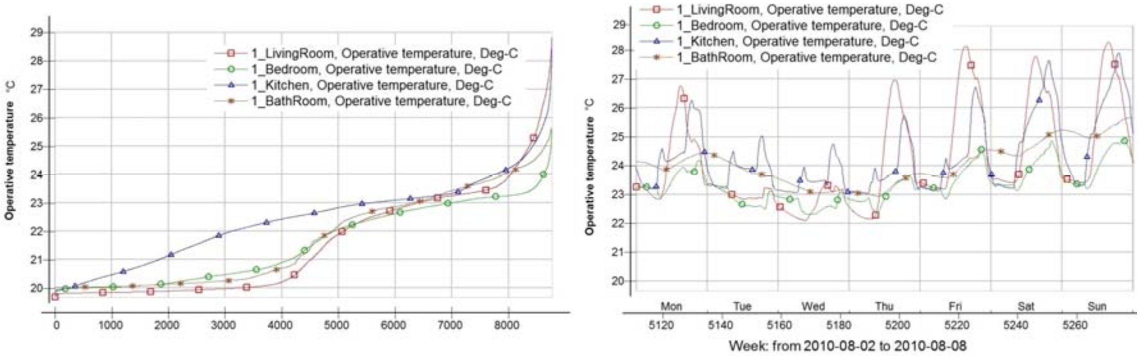
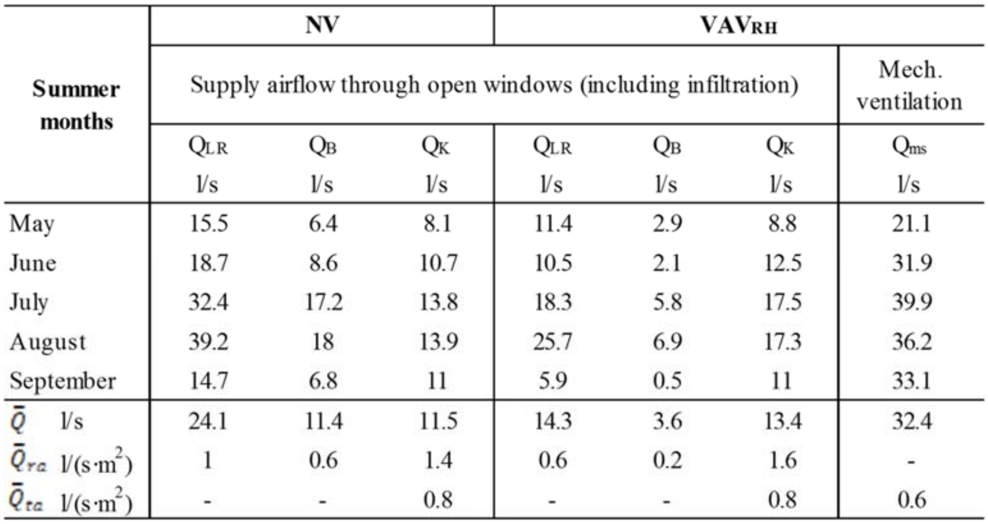


Figure 4: Duration curve for operative temperature for a whole year (left) and development of operative temperature during a week in August (right) in the case of VAV_{RH} system without surrounding buildings

Figure 4 (right) shows operative temperature development for one week in August. It illustrates that the operative temperature in the kitchen follows the occupancy schedule rather closely, while in the living room it is driven by solar gains, which besides weekend, occur when the apartment is unoccupied. This highlights the importance of occupancy schedules with respect to occupants' exposure to elevated indoor temperatures. Several alternative occupancy schedules will therefore be investigated during the continuation of the present study.

Window opening behaviour of the occupants is another crucial factor, when simulating residential ventilation. The present study applied rather crude estimate of window opening based on indoor temperature. The detailed studies focused on human behaviour, e.g. Andersen et al. (2013), show that window opening behaviour is a complex phenomenon and is not necessarily driven by indoor temperature. However, the Danish energy frame calculation assumes venting or increased mechanical ventilation in periods when the room temperature exceeds 23 °C (Aggerholm, 2018). The same approach was used in the present study. Aggerholm (2018) recommends the mean airflow through windows during warm summer months equal to 0.9 $l/(s{\cdot}m^2)$. Table 4 shows an example of the monthly mean supply airflow through open windows (including infiltration) for the NV and VAV_{RH} cases together with the monthly mean supply airflows provided by the mechanical ventilation in the VAV_{RH} case. It can be seen that the airflows provided by venting in the case of the naturally ventilated building are larger than in the case of the building with mechanical ventilation, but the grand mean normalized by the total heated floor area did not exceed 0.9 $l/(s{\cdot}m^2)$.

Table 4: Monthly mean supply airflows through windows and mechanical ventilation for summer months; Q – monthly mean, $\bar{Q}$ – grand mean. Indexes: LR – living room, B – bedroom, K – kitchen, ms – mechanical supply, ra – normalized with room heated floor area, ta – normalized with total apartment heated floor area



Summer months	NV			VAV_{RH}			
	Supply airflow through open windows (including infiltration)						Mech. ventilation
	Q_{LR} l/s	Q_B l/s	Q_K l/s	Q_{LR} l/s	Q_B l/s	Q_K l/s	Q_{ms} l/s
May	15.5	6.4	8.1	11.4	2.9	8.8	21.1
June	18.7	8.6	10.7	10.5	2.1	12.5	31.9
July	32.4	17.2	13.8	18.3	5.8	17.5	39.9
August	39.2	18	13.9	25.7	6.9	17.3	36.2
September	14.7	6.8	11	5.9	0.5	11	33.1
$\bar{Q}$ l/s	24.1	11.4	11.5	14.3	3.6	13.4	32.4
$\bar{Q}_{ra}$ $l/(s{\cdot}m^2)$	1	0.6	1.4	0.6	0.2	1.6	-
$\bar{Q}_{ta}$ $l/(s{\cdot}m^2)$	-	-	0.8	-	-	0.8	0.6

4 CONCLUSIONS

- Energy renovation (adding insulation and exchanging windows) of a Danish apartment building from 1850-1890 yielded energy saving of approx. 60%.
- At the same time energy renovation resulted in clear increase of overheating hours when no mechanical ventilation system was added.
- All studied mechanical ventilation systems with heat recovery were able to decrease the hours with overheating below the limit specified by the Danish building code in the case of the building situated in a narrow street canyon. In absence of shading from surrounding buildings, the CAV ventilation operating with minimum airflow required by the Danish building code reduced overheating hours insufficiently.
- The VAV system with a centrally located sensor for relative humidity was the most efficient system in the recent study. The temperature controlled VAV system gave worse performance than the humidity controlled one with respect to overheating while using similar amount of energy. This was probably caused by the increased set point for window opening as this system was intended to be utilized in buildings where window opening is not preferable due to outdoor noise or pollution.

- The schedules for internal loads and occupancy suggested by the Danish guideline for indoor climate calculations should be revised with respect to concurrence of occupants and loads in particular rooms.

5 ACKNOWLEDGEMENTS

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