Low-Temperature Heating and Ventilation for Sustainability in Energy-Efficient Buildings

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Abstract

In 2013, the building sector consumed approximately 39 % of the total final energy use in Sweden. Energy used for heating and hot water was responsible for approximately 60 % of the total energy consumption in the building sector. Therefore, energy-efficient and renewable-based heating and ventilation systems have high potential for energy savings. The potentials studied in this thesis include the combination of a low-temperature heat emitter (supply temperature below 45 °C) with heat pump and/or seasonal thermal energy storage, and variable air volume ventilation system. The main aim of this thesis was to evaluate energy savings and indoor air quality when those energy-efficient and sustainable heating and ventilation systems were implemented in buildings. For this purpose, on-site measurements, lab tests, analytical models, and building energy simulation tool IDA Indoor Climate and Energy 4 were used.

Annual on-site measurements for five new two-family houses with low- and very-low-temperature heat emitters connected to an exhaust air heat pump showed that between 45–51 $\text{kWh}\cdot\text{m}^{-2}$ energy was used to produce and transport supply water for heating and domestic hot water. Statistical data showed that these values are 39–46 % lower compared to the heating and domestic hot water consumption (that is, 84 $\text{kWh}\cdot\text{m}^{-2}$) in an average new single- and two-family house.

In order to compare the energy performance of very-low- and low-temperature heat emitters with medium-temperature heat emitters under the same condition, lab tests were conducted in a climate chamber facility at Technical University of Denmark (DTU). To cover the heat demand of 20 $\text{W}\cdot\text{m}^{-2}$ by active heating, measurements showed that the required supply water temperatures were 45 °C for the conventional radiator, 33 °C in ventilation radiator and 30 °C in floor heating. This 12–15 °C temperature reduction with ventilation radiator and floor heating resulted in 17–22 % savings in energy consumption compared to a reference case with conventional radiator.

Reducing the supply temperature to the building's heating system allows using more renewable and low-quality heat sources. In this thesis, the application of seasonal thermal energy storage in combination with heat pump in a building with very-low-, low-, and medium-temperature heat emitters was investigated. Analytical model showed that using a 250 m^3 hot water seasonal storage tank connected to a 50 m^2 solar collector and a heat pump resulted in 85–92 % of the total heat demand being covered by solar energy.

In addition to the heating system, this thesis also looked at ventilation system in terms of implementing variable (low) air volume ventilation instead of a constant (high) flow in new and retrofitted old buildings. The analytical model showed that, for new buildings with high volatile organic compound concentration during initial years of construction, decreasing the ventilation rate to 0.1 $L \cdot s^{-1} \cdot m^{-2}$ during the entire un-occupancy period (from 8:00–18:00) creates unacceptable indoor air quality when home is occupied at 18:00. So, in order to create acceptable indoor air quality when the occupants come home, a return to the normal ventilation requirements was suggested to take place two hours before the home was occupied. This eight-hour ventilation reduction produced savings of 20 % for ventilation heating and 30 % for electricity consumption by ventilation fan.

In addition, the influence of different ventilation levels on indoor air quality and energy savings was studied experimentally and analytically in a single-family house occupied by two adults and one infant. Carbon dioxide (CO_2) concentration as an indicator of indoor air quality was considered in order to find appropriate ventilation rates. Measurements showed that, with an 0.20 $L \cdot s^{-1} \cdot m^{-2}$ ventilation rate, the CO_2 level was always below 950 ppm, which shows that this level is sufficient for the reference building (CO_2 lower than 1000 ppm is acceptable). Calculations showed that low ventilation rates of 0.20 $L \cdot s^{1} \cdot m^{-2}$ caused 43 % savings of the combined energy consumption for ventilation fan and ventilation heating compared to the cases with 0.35 $L \cdot s^{-1} \cdot m^{-2}$ as a normal ventilation rate recommended by BBR (Swedish Building Regulations).

Keywords: Low-temperature heating system; Energy savings; Seasonal thermal energy storage; Variable air volume ventilation system; Indoor air quality

Sammanfattning

Byggsektorn slukade cirka 39 % av den totala energin i Sverige år 2013. Energi som används för uppvärmning och varmvattenberedning stod för cirka 60 % av den totala energiförbrukningen i byggsektorn. För hög besparingspotential och god miljöpåverkan är det därför viktigt att energieffektiva uppvärmnings- och ventilationssystem integreras med förnyelsebara energikällor. De besparingspotentialer som studerats i denna avhandling inrymmer en kombination av lågtemperaturuppvärmning (framledningstemperatur under 45 °C) med värmepump och/eller säsongslagring av energi i uppvärmningsdelen samt varierande luftflöden i ventilationsdelen. Ändamålet med avhandlingen är att utvärdera energibesparingar och luftkvaliteten inomhus då energieffektiva och uthålliga uppvärmnings- och ventilationssystem implementeras i byggnader. För detta ändamål har fältmätningar, labbförsök, analytiska modeller samt energiberäkningsprogram för byggnader IDA Indoor Climate and Energy 4 använts.

En årsbaserad fältmätning i fem nybyggda parhus med låg och mycket låg framledningstemperatur för uppvärmning som kopplats till frånluftsvärmepump visade att mellan 45-51 kWh·m^{-2} användes för uppvärmning och varmvattenberedning. Dessa värden är 39-46 % lägre än 84 kWh·m^{-2} som gäller i medeltal för uppvärmning och varmvattenberedning i nya svenska en- och tvåfamiljshus.

För att undersöka energiprestandan hos låg- och mycket lågtempererade uppvärmningssystem jämfördes dessa med medeltempererade system under identiska labbförhållanden i en klimatkammare vid Danmarks Tekniska Universitet (DTU). Mätningar visade att för att täcka värmebehovet för 20 W·m^{-2} var den behövliga framledningstemperaturen 45 °C för konventionella radiatorer, 33 °C för ventilationsradiatorer och 30 °C för golvvärme. En 12-15 °C stor temperatursänkning med ventilationsradiator och golvvärme resulterar i en primärenergibesparing på 17-22 % jämfört med referensfallet med konventionella radiatorer.

En sänkning av framledningstemperaturen i en byggnads värmesystem ger ökade möjligheter att använda lågvärdiga förnyelsebara energikällor såsom sol i olika former. I avhandlingen undersöktes också termisk energilagring i kombination med värmepump i ett hus med mycket låg, låg, och medium tempererat värmesystem. En analys gav vid handen att en 250 m^3 stor tank för säsongslagring kopplad till en 50 m^2 solfångare gav 85-92 % av totala värmebehovet.

I tillägg till värmesystem behandlar avhandlingen i någon utsträckning ventilationssystem där variabelt (lågt) luftflöde ersätter konstant (högt) luftflöde i nya och renoverade äldre byggnader. Analytiska koncentrationsberäkningar visade att halten av flyktiga organiska komponenter de första åren efter byggnadens konstruktion ökade till oacceptabla nivåer vid hemkomst kl. 18:00 om ventilationen minskades till 0.1 $L\cdot s^{-1}\cdot m^{-2}$ under hela perioden 8:00-18:00 då de boende inte var hemma. Det visade sig att för acceptabel luftkvalitet vid hemkomst måste ventilationsflödet ställas om till normal nivå två timmar före hemkomsten. Denna minskning av ventilationsflödet under 8 timmar gav 20 % energibesparing i uppvärmd mängd ventilationsluft och 30 % besparing i elförbrukning för fläktarbetet.

Hur olika luftflödesnivåer vid ventilation påverkar luftkvaliteten och energibesparingar studerades såväl analytiskt som experimentellt i ett enfamiljshus med två vuxna och ett barn i Borlänge. Koldiodidhalten (CO_2) användes som indikator för att hitta lämpligt ventilationsflöde. Mätningar visade att med ett ventilationsflöde på 0.20 $L\cdot s^{-1}\cdot m^{-2}$ var CO_2 nivån alltid under 950 ppm. Detta var följaktligen ett tillräckligt ventilationsflöde för referenshuset då CO_2 halten hölls under rekommenderad nivå på 1000 ppm. Beräkningar visar här att ett lågt ventilationsflöde på 0.20 $L\cdot s^{-1}\cdot m^{-2}$ ger acceptabel luftkvalitet och energibesparingar på 43 % för luftberedning och transport jämfört med ett normalt luftflöde på 0.35 $L\cdot s^{-1}\cdot m^{-2}$ rekommenderat av BBR (Boverkets byggregler).

Nyckelord: Låg framledningstemperatur vid uppvärmning; Energibesparingar, Säsongslagring av termisk energi; Varierande luftflöde vid ventilation; Luftkvalitet inomhus

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List of publications

The work presented in this doctoral thesis started in September 2011 and ended in September 2015. The thesis is a summary of the following papers.

List of papers appended at the end of the text:

Paper 1 Energy performance of low-temperature heating systems in five new-built Swedish dwellings: A case study using simulations and on-site measurements, A. Hesaraki, S. Holmberg, Journal of Building and Environment 64 (2013) 85–91

Paper 2 Experimental study of energy performance in low-temperature hydronic heating systems, A. Hesaraki, E. Bourdakis, A. Ploskic, S. Holmberg, Submitted for journal publication

Paper 3 Seasonal thermal energy storage with heat pumps and low temperatures in building projects — A comparative review, A. Hesaraki, S. Holmberg, F. Haghighat, Journal of Renewable and Sustainable Energy Reviews 43 (2015) 1199–1213

Paper 4 Low-temperature heat emission combined with seasonal thermal storage and heat pump, A. Hesaraki, A. Halilovic, S. Holmberg, Journal of Solar Energy 119 (2015) 122-133

Paper 5 Demand-controlled ventilation in new residential buildings: consequences on indoor air quality and energy savings, A. Hesaraki, S. Holmberg, Journal of Indoor and Built Environment 24 (2015) 162–173

Paper 6 Influence of different ventilation levels on indoor air quality and energy savings: A case study for a single-family house, A. Hesaraki, JA. Myhren, S. Holmberg, Submitted for journal publication

List of other related peer-reviewed international conference papers:

Paper 7 Energy Performance Evaluation of New Residential Buildings with a Low-Temperature Heating System: Results from Site Measurements and Building Energy Simulations, A. Hesaraki, S. Holmberg, in: Proceedings of The 2nd International Conference on Building Energy and Environment, COBEE 12, Colorado, USA, August 2012

Paper 8	An Investigation of Energy-efficient and Sustainable Heating Systems for Buildings: Combining Photovoltaics with Heat Pump, A. Hesaraki, S. Holmberg, in: Proceedings of The 4th International Conference on Sustainability in Energy and Buildings, SEB 12, Stockholm, Sweden, September 2012, and also published in: Smart Innovation, Systems and Technologies (22), 2013: 189–197
Paper 9	Demand-Controlled Ventilation in a Combined Ventilation and Radiator System, A. Hesaraki, S. Holmberg, in: Proceedings of the 13th International Conference on CLIMA 13. The 11th REHVA World Congress and 8th International Conference on IAQVEC, Prague, Czech Republic, June 2013
Paper 10	Energy-Efficient and Sustainable Heating System for Buildings: Combining seasonal heat storage with heat pumps and low-temperature heating systems, A. Hesaraki, S. Holmberg, F. Haghighat, in: Proceedings of The 10th International Energy Conference, IEC 2014, Tehran, Iran, August 2014
Paper 11	Multi-zone Demand-controlled Ventilation in Residential Buildings: An experimental case study, A. Hesaraki, JA. Myhren, S. Holmberg, in: Proceedings of 35th AIVC Conference, 4th TightVent Conference and 2nd Venticool Conference, Poznań, Poland, September 2014
Paper 12	Integrating Low-temperature Heating Systems into Energy-efficient Buildings, A. Hesaraki, A. Ploskic, S. Holmberg, in: Proceedings of The 6th International Building Physics Conference, IBPC 2015, Turin, Italy, June 2015
Licentiate thesis	Energy and Indoor Environment in New Buildings with Low-Temperature Heating Systems, A. Hesaraki, June 2013

Contents

Nomenclature

$\bar{h}$	Average convective heat transfer coefficient (W·m^{-2}·K^{-1})
$\dot{m}_{\text{poll}}$	Emission rate from pollutant source (kg·s^{-1})
4GDH	Fourth-generation district heating
$A_{\text{base, layer}}$	Base area of layer in a stratified storage tank (m^2)
ach	Air changes per hour (h^{-1})
BBR	Swedish National Board of Housing, Building and Planning
c	Pollutant concentration in a room (kg·m^{-3})
CAV	Constant air volume
c_0	Pollutant concentration in a room at start of $t = 0$ (kg·m^{-3})
CO_2	Carbon dioxide
COP	Coefficient of performance
E_{building}	Energy demand by building (kWh·year^{-1})
EU	European Union
g	Gravity (m·s^{-2})
Gr	Grashof number
HVR	High ventilation rate
IAQ	Indoor air quality
IDA ICE	IDA Indoor Climate and Energy
ISO	International Organization for Standardization
k_f	Thermal conductivity of fluid (W·m^{-1}·K^{-1})
L	Layer number in a stratified storage tank
L_c	Characteristic length (m)
LTH	Low-temperature heating
LVR	Low ventilation rate
m	Meters
n	Number of air changes per hour (h^{-1})
NMF	Neutral model format
Nu	Nusselt value
NVR	Normal ventilation rate
P_{natural}	Natural (free) convection (W)
Pr	Prandtl number
$q_{\text{ventilation}}$	Ventilation rate (m^3·s^{-1})
Ra	Rayleigh number
STES	Seasonal thermal energy storage
U value	Heat transfer coefficient of building material (W·m^{-2}·K^{-1})
VAV	Variable air volume
VLVR	Very low ventilation rate
VOCs	Volatile organic compounds
W_{HP}	Electricity consumption by heat pump (kWh)

Greek letters

η_c	Carnot efficiency of heat pump (%)
β	Thermal expansion coefficient (K^{-1})
θ_L	Layer temperature in a stratified seasonal storage tank (°C)
θ_{sin}	Temperature of heat sink in heat pump (°C)
θ_{sor}	Heat source temperature of heat pump (°C)
ν	Kinematic viscosity (m^2·s^{-1})

Chapter 1

1. Introduction

An intergovernmental panel on climate change forecasted a 6 °C increase in the average earth temperature by the year 2050 [1, 2]. The European Union's (EU) plan for long-term low-carbon development to keep temperature change below 2 °C is to decrease carbon emissions by 80 % by 2050 compared to the 1990 level [3]. In 2013, the residential and service, industry, and transport sectors consumed 39 %, 38 %, and 23 % of the total final energy demand in Sweden, respectively [4]. Therefore, the EU's aim is challenging to reach unless sustainable, energy-efficient and renewable-based heating and ventilation system is integrated into buildings. Using renewable energy would cause a great reduction in carbon dioxide (CO_2) emission and eliminate the environmental impacts of fossil fuels.

The diagram of the energy sources for heating the Swedish residential and service sector (Fig. 1) shows that oil product sources were reduced by 86 % between 2002 and 2013 [5]. This reduction could be due to environmental policy, availability, and cost, which has almost tripled since 1996 [6].

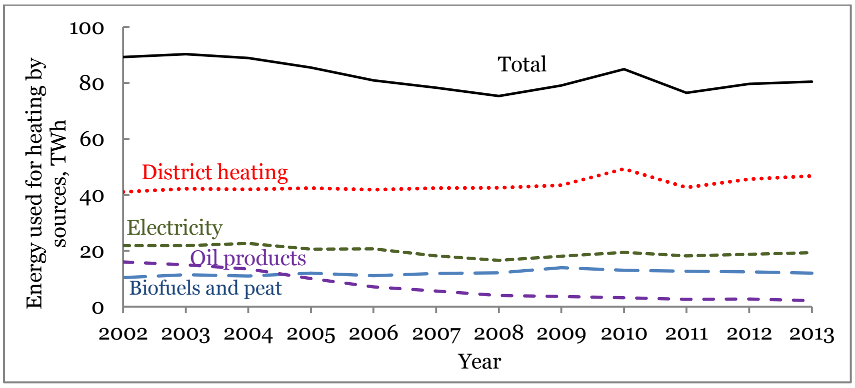

Figure 1. Energy used for heating by sources in the residential and service sector in Sweden 2002–2013 [5]

As Fig. 1 shows, by 2013, the shares of total heating demand covered by district heating and electricity were 58 % and 24 %, respectively [5]. However, these shares are totally different when it comes to the type of building; see Fig. 2. In single- and two-family Swedish houses, which together represented 62 % of the total residential heated area in 2013, 45 % of heating demand was covered by electricity, either directly or by heat pumps, followed by 34 % biofuel, 18 % district heating, and 3 % oil products. In multi-family houses, which represented 38 % of the total Swedish residential heated area in 2013, 92 % of heating demand was covered by district heating, followed by 5 % electricity, 2 % oil products, and 1 % biofuels [5].

Fig. 3 shows the average energy consumption for heating and hot water from 2001 till 2013 [7]. In Fig. 3, the total energy consumption was divided by the total heated floor area for each building type and each year. As Fig. 3 shows, energy consumption in one- and two-family houses was less than in multi-family houses throughout the studied period. One reason could be the greater use of heat pumps in one- and two-family houses compared to multi-family houses. As can be seen in Fig. 3, heating energy consumption in 2013 had dropped by 27 % in single- and two-family houses and by 20 % in multi-family houses compared to 2001 levels.

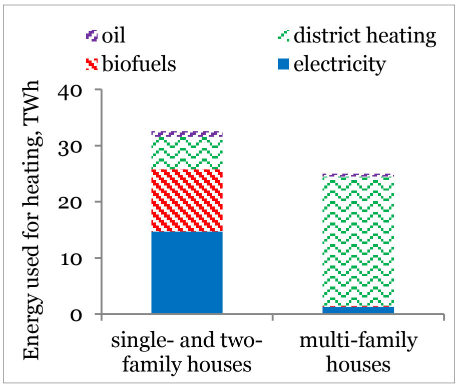

Figure2. Heat sources in Sweden in 2013

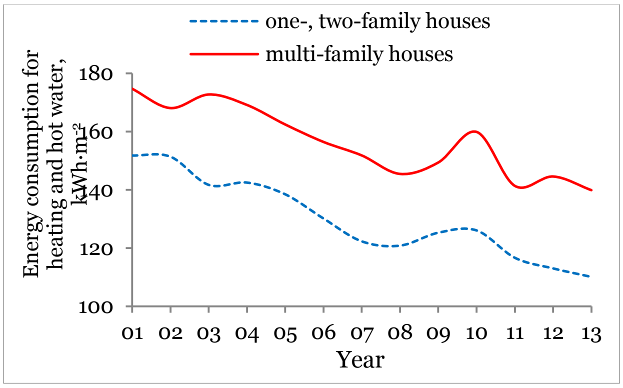

Figure 3. Average energy usage for heating and hot water

In 2007, the European Union set up a climate and energy policy called “20-20-20”. The target of this policy was to reduce energy consumption in buildings by 20 %, and to make buildings more sustainable by a 20 % share of renewable energies, and to reduce greenhouse gas emissions by 20 % by the year 2020 compared to 1990 levels. To meet the first criterion of this policy, energy consumption in buildings can be reduced through improvements in design, such as passive solar heating, using materials with low heat transfer coefficient in the building envelope, or by implementing highly efficient building services. The level of temperature supplied to the heat emitters in buildings plays a major role in primary energy consumption and environmental impacts. In 2013, energy used for heating and hot water was responsible for approximately 60 % of total energy consumption in the Swedish building sector [6]. Therefore, energy-efficient heating and ventilation systems, such as using a heat pump with low-temperature heat emitters (supply temperature below 45 °C), or variable air volume (VAV) ventilation system, have high potential for energy savings.

Moreover, there are several ways to meet the second and third criteria of the "20-20-20" target, which are to make buildings more sustainable by increasing the share of renewable energies and reducing their CO_2 emissions. Several renewable technologies are available in the market that refine renewable energies; for example, photovoltaics, which produce electricity from solar energy, or solar thermal collector for producing hot water. The problem with renewable technologies is their intermittence properties; that is, the solar energy is highest when the need is lowest, and vice versa; for example, from day to night or from summer to winter. Therefore, it is necessary to store this energy daily or seasonally in order to cover the gaps between availability and demand. Using seasonal thermal energy storage technology is one method with which to address the mismatch between the summer heat and the winter need.

The following chapters briefly introduce energy-efficient heating and ventilation systems, including low-temperature heat emitters, low-temperature heat sources, and variable air volume (VAV) and heat recovery ventilation systems.

1.1. Energy-efficient heating systems

In addition to increasing the earth's temperature every year, as more and more buildings are becoming energy-efficient due to better thermal insulation, less infiltration, and more efficient heating and ventilation systems, heat losses from buildings are decreasing. These changes have reduced the need to supply heat emitters with water at such high temperatures as was previously the case. Low-temperature heating (LTH) systems are an example of a sustainable and efficient heating system that reduces the primary energy consumption and, consequently, the production of carbon dioxide. The purpose of a LTH system is not necessarily to decrease the buildings' heat demand, but it is beneficial in terms of heat generation. Shifting to a LTH system reduces heat losses from heat production unit and also from distribution pipes. Using a LTH system also favors efficient use of energy with exergy-saving potential, as more renewable and low-quality sources could be used. By using a high-temperature heating system (for example, 90 °C) or burning fossil fuels and generating 1000 °C of flame, a great deal of exergy is destroyed as the thermal comfort temperature in the room is only 20 °C. Using LTH allows high-quality sources such as electricity or fossil fuels to become available for other high exergy purposes such as for appliances and lighting.

There are two main ways to adapt buildings with low-temperature supply: either decreasing the heat demand in buildings and using existing heat emitters with low temperature water, or using thermal-efficient heat emitters supplied with low temperature in existing buildings.

The following sections present two systems involved in low-temperature heating systems: low-temperature heat emitters and low-temperature heat sources.

1.1.1. Low-temperature heat emitters

A strict standardization of temperature ranges does not yet exist, but a heat emitter with a supply temperature below 45 °C is normally referred to as a low-temperature heat emitter. There are different types of low-temperature heat emitter in which, due to a large heated surface area or improved forced-convection heat transfer, supply water temperature can be reduced without sacrificing the heat output and, consequently, the thermal comfort. Examples of heat emitters with large heated surface area include panel heating in the floor, ceiling, or wall that are embedded in building envelope. Two examples of radiators with improved forced-convection heat transfer are ventilation radiators and add-on fan radiators. Improving the forced-convection heat transfer reduces the surface temperature of the radiator, and as a result, the radiation heat transfer is decreased. Nevertheless, the enhancement of forced convection is much larger than the reduction in radiation heat transfer [8], which results in significantly greater heat output compared to conventional radiators.

Panel heating

The supply water temperature to large surface heat emitters such as ceilings, floors, or walls is usually less than 35 °C. These types of heat emitter create a more uniform indoor temperature because of the large surface area and small temperature difference between supply and return. This requires a higher flow rate, followed by increasing pump work compared to hydronic radiator systems. In addition to higher circulation pump work, higher primary energy consumption in panel heating could occur in poorly insulated buildings due to high heat loss to the outside. The reason is that the heating system is not completely interior and is embedded in the envelope. In addition, the large mass of water flowing through pipes makes maintenance of the system challenging. However, these hidden heat emitter favor room design without interfering with the room decoration. Many occupants prefer floor heating because their feet are exposed to higher temperature and the feet usually have a lower temperature than other parts of the body.

Ventilation radiator

In a ventilation radiator, the ventilation supply is placed behind the radiator and is connected to the radiator through a channel in external walls; see Fig. 4. In this combined system, cold fresh air is forced to pass through the radiator panels, due to a constant negative pressure in the building created by exhaust fans and also partly due to buoyancy forces. This combination not only enhances the forced-convection heat transfer, but also preheats the incoming supply air before entering the room. Experimental investigations

[9] showed a double heat output in an efficient ventilation radiator compared to a conventional radiator under the same conditions. This was due to high convective heat transfer by incoming air and the great temperature difference between cold incoming air and the surface of the heating unit. These findings show that during cold days with high heating demand, when the temperature of the incoming ventilation air is low, the heat output of the radiator would increase automatically with less need to increase the supply water temperature.

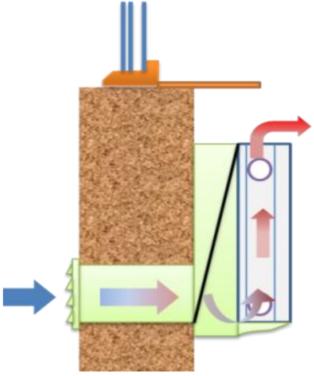

Figure 4. Schematic of ventilation radiator; that is, combination of supply ventilation with radiator to preheat the cold supply air and increase the efficiency of the radiator

Add-on fan radiator

In an add-on fan radiator, fans are placed below the radiator panels to boost the convection heat transfer along the radiator surfaces. A previous study [10] showed that having five fans below the radiator increases the heat output to almost twice that of a conventional radiator with the same water mass flow and temperature. Add-on fan radiators have several advantages with regard to energy efficiency, thermal comfort, and practicality. In terms of efficiency, the supply temperature to the add-on fan radiator can be decreased by 10 °C from 55 °C to 45 °C without reducing the heat output compared to a conventional radiator. In terms of energy consumption, added fans below the radiator consume minimal amounts of electricity; that is, the ratio of electricity consumption by the fans to the increase in the heat output of the radiator is 1–2 %. In terms of thermal comfort, the fans below the radiator help spread out the heat from the radiator in the room, thereby increasing the thermal comfort. In terms of practicality, add-on fan radiators are suitable for buildings in which it is not possible to change the conventional radiator to, for example, floor heating or ventilation radiator, which needs to change the façade by drilling a supply hole behind the radiator. In some situations, however, occupants might detect a noise with the add-on fan radiator, which means it should not be preferred in bedrooms.

1.1.2. Low-temperature heat sources

This section briefly introduces three types of heat source that are more efficient when working with low-temperature heat emitters: heat pumps, low-temperature district heating, and seasonal thermal energy storage.

Heat pumps

Heat pumps utilize three to four times less electrical energy than direct electrical heaters to deliver the same amount of heat, because they utilize renewable energies stored in earth, air or water. In the Swedish residential and service sector, the number of heat pumps sold by 2013 was 1,138,000, of which 96 % were installed in single- and two-family houses [7]. This large amount of heat pumps represented the main heat source of more than 52 % of Swedish single- and two-family houses [7]. The number of single- and two-family houses with heat pumps had increased by almost 50 % between 2008 and 2013 [7]. As can be seen in Fig. 5, 40 % of Swedish single- and two-family houses had closed-loop (ground-, lake-, or rock-source) heat pumps in 2013, followed by 34 % with air-air heat pumps, and 21 % with air-water (outdoor or exhaust air) heat pumps.

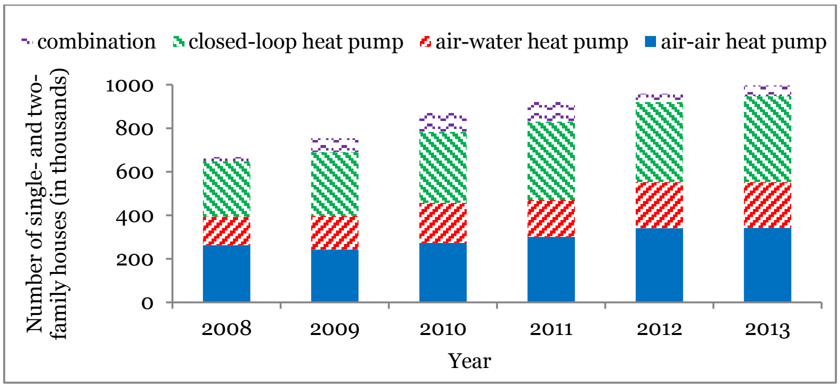

Figure 5. Number of single- and two-family Swedish houses with different types of heat pump [7]

The lower the supply water temperature to the heat emitter, the higher the coefficient of performance (COP) the heat pump has. The thermal efficiency of a heat pump improves by 1–2 % for every degree of reduction in supply water temperature. Therefore, as the number of heat pumps sold in Sweden increases, there is a need to adjust the heating systems to this change in order to attain greater efficiency; in other words, to use low-temperature heat emitters.

Low-temperature district heating

Fourth-generation district heating (4GDH) with a low-temperature network has been recognized as a sustainable heat source in which renewable sources are mainly used for heat production. Compared with current district heating network, 4GDH involves less heat losses to the ground due to a lower temperature difference between the pipes and the surroundings. However, more insulation is needed to keep heat losses as low as possible due to low-temperature water in the pipes. In this low-temperature network, which is estimated to be in use between 2020 and 2050 [11], the produced water temperature would be between 50 and 60 °C. This means that, in the near future, the supply water temperature to more than 90 % of heat emitters in multi-family buildings connected to district heating will decrease. In order to adapt to this change, it is necessary to either upgrade the heat emitters in existing multi-family buildings or to minimize the heat demand in the existing buildings. In buildings connected to a low-temperature district heating network, however, supplying hot water for domestic usage might be a challenge and could be supplied by other sources.

Seasonal thermal energy storage

In a typical house, the total amount of solar energy that reaches the roof is more than its annual heating demand, even in cold climates [12]. However, the problem with solar energy is that it is intermittent. The highest production occurs in summer and is not in parallel with the highest demand in winter. Seasonal thermal energy storage (STES) systems usually consist of an array of solar collectors to collect heat, piping network to transfer heat and storage to preserve this heat for the long term. Seasonal storage systems mainly have two types of storage medium: solid (such as soil or rock) and liquid (such as water). Both solid and liquid media have their own advantages and disadvantages. The thermal capacity of liquids is higher than that of solids and it is easier to exchange heat in liquids. However, solids can tolerate a higher range of temperatures than liquids since they will not freeze or boil, and solids cannot leak from the container. There are different ways to store heat seasonally, including hot water tank storage, water-gravel pit storage, duct thermal energy storage, and aquifer thermal energy storage. In hot water storage tanks, thermal energy is stored in the water, preferably in a tank buried under the ground. The cost of this system is quite high and can be reduced by adding gravel to the water pit storage; this system is called water-gravel pit storage. The advantages of these two systems are that they have high heat capacity and are easy to install. In addition, they do not need any special geological conditions in order to be installed. However, if the geological conditions are suitable for digging with respect to the ground type and condition of the water table, duct thermal energy storage and aquifer thermal energy storage can be used. In duct thermal energy, storage ducts are excavated into the ground and tubes of heat carrier medium are inserted into the duct. This method involves storing heat in the ground during summer for winter usage. In aquifer thermal energy storage, two wells are dug deep into the ground until they reach the aquifer. One well acts as a cold well and the other as a warm well. During the charging process in summer, the water is extracted from the cold well, heated by a heat source, and injected into the hot well. In the heating season, however, the cycle is reversed for the discharging process; that is, hot water is extracted from the warm well, cooled by the heat sink, and injected into the cold well.

The main potential challenge in seasonal storage is heat loss, which depends on the storage medium, elapsed time, temperature gradient, and volume of storage. With regard to the temperature and the volume of storage, there are different methods for decreasing thermal losses, such as optimizing the size of the system or lowering the storage temperature. Designing the system with a low surface-to-volume (loss-to-capacity) ratio is one way to keep the heat loss low. Generally, the larger STES in community is more economical and efficient than smaller ones due to lower specific construction cost and smaller relative thermal loss in larger storage volume [13]. Investigations by Fisch et al. [14] showed that the investment cost per square meter of collector area in the solar heating system for a single-family house is almost three times higher than the solar cost in a large-scale system. However, although having seasonal storage on a community-wide scale is efficient and economical, it should be noted that the single- and two-family houses constitute 64 % and 62 % of the total European and Swedish residential building areas, respectively [15]. These statistics show that it is also important to consider the application of seasonal thermal energy storage in the single-family sector. As mentioned earlier, another technique for reducing thermal loss is to have low-temperature storage. However, this type of storage is not appropriate for direct use for domestic usage or in heating systems during peak load. Hence, the storage system requires supporting equipment such as a heat pump to increase the temperature to a useful level for domestic hot water or space heating.

1.2. Energy-efficient ventilation systems

The main goal of a ventilation system is to create acceptable indoor air quality (IAQ) and thermal comfort, taking into account the health, comfort, and productivity of inhabitants. In Sweden [16], approximately 32 % of single- and two-family houses and 8 % of multi-family houses are ventilated by 0.10 $L \cdot s^{-1} \cdot m^{-2}$ or less, and only 16 % of single- and two-family houses and 42 % of multi-family houses have ventilation rates of 0.35 $L \cdot s^{-1} \cdot m^{-2}$ or more.

There are different types of ventilation system, including natural, mechanical exhaust with or without exhaust-air heat pump, and mechanical supply-exhaust with or without a heat exchanger. The ventilation type varies significantly when it comes to the type of the building and the year of construction; see Fig. 6 [16]. As can be seen in the left-hand side of Fig. 6, 46 % of one- and two-family houses built before 2005 have natural ventilation, followed by 22 % with exhaust ventilation, 16 % with exhaust-supply with a heat exchanger, 13 % with an exhaust-air heat pump, and 3 % with exhaust-supply ventilation. In multi-family houses, exhaust ventilation systems are used in 53 % of buildings built before 2005, followed by 25 % with exhaust-supply with a heat exchanger, 12 % with natural ventilation, 7 % with an exhaust-air heat pump, and 3 % with exhaust-supply ventilation (see the right-hand side of Fig. 6).

Depending on the building type and construction properties, ventilation heat loss represents 20–60 % of the total heat loss. Therefore, an energy-efficient ventilation system has high potential for reducing the total heat loss. In this chapter, VAV and mechanical exhaust-supply with a heat exchanger are introduced briefly.

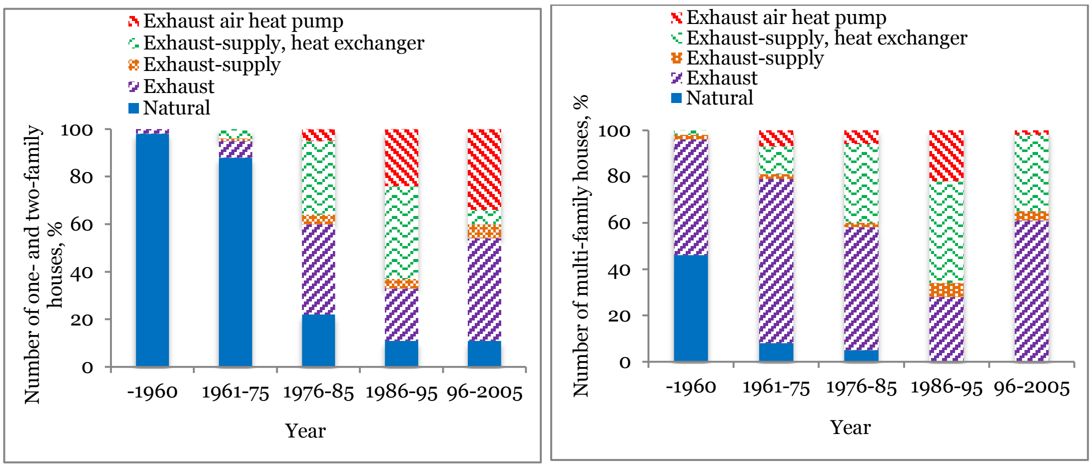

Figure 6. Ventilation type for Swedish one- and two-family houses (left) and multi-family houses (right) [16]

1.2.1. Variable air volume (VAV) ventilation systems

The ventilation rate required depends on the number of people and the emissions from the building material. Most ventilation systems in residential buildings work with a high constant air volume (CAV), which results in heating unnecessary airflow when the demand is low. Swedish building regulations, BBR [17], recommend two levels of ventilation rates for residential buildings. The first rate, for diluting contaminants generated by people and building-related source pollutant, is 0.35 $L{\cdot}s^{-1}{\cdot}m^{-2}$ of the floor area (0.50 ach in a room with 2.5 m height) in an occupied zone. The second rate of 0.10 $L{\cdot}s^{-1}{\cdot}m^{-2}$ of floor area (0.14 ach in a room with 2.5 m height) applies to building-related source pollutants for unoccupied buildings. This shows that 0.36 ach (the difference between 0.50 and 0.14 ach) is needed just to remove the pollutants from the occupants. CO_2 is a good indicator of the acceptability of IAQ since the exposure corresponds directly to the number of people and human unpleasant odor generation based on their activity level [18]. A CO_2 concentration of 700 ppm above the outdoor level has been recognized as an acceptable level of indoor CO_2 [19]. This level causes 20 % dissatisfaction of visitors or un-adapted persons in terms of body odor perception. Referring to this acceptable CO_2 concentration, the required floor area for one person can be calculated by dividing the CO_2 generation by the ventilation rate recommended for a person. A mass balance calculation showed that CO_2 level reaches 700 ppm above the outdoor level in a 32 m^2 room with 2.5 m height, which is ventilated by 0.36 ach and polluted by one person generating 0.02 $m^3{\cdot}h^{-1}$ of CO_2 during rest and low activity work. Therefore, it can be seen that, when designing a ventilation system, one person is considered to live for every 32 m^2 in Swedish buildings. However, Swedish statistics showed that, on average, there was only one person per every 48 m^2 of heated area between 2001 and 2013 [7, 20]. Therefore, in most residential buildings in which the ventilation rate is set based on the designed population density with a constant air volume, energy is wasted on conditioning unnecessary outdoor air and on the electrical energy for ventilation fans.

Furthermore, if the pollution level and demand for ventilation air vary over a day, a variable air volume (VAV) ventilation system can be used. The concept of VAV has been known since the 1970s [21]; however, some barriers such as cost, complexity, and unreliability of sensors have prevented this system from becoming popular. Nevertheless, recent technologies have shown that VAV is now cost-effective, with simple and reliable control. VAV systems are used to find a balance between IAQ by providing sufficient fresh air and saving energy by handling less outdoor air to heat, cool, or dehumidify. In current residential buildings, most people go to work or school from morning until afternoon. This provides the opportunity to reduce the ventilation rate during non-occupancy hours. However, existing residential ventilation systems with constant high ventilation rates are in conflict with ventilation on demand. Hence, in order to reduce the total energy consumption in buildings, the ventilation rate should be varied according to the demand, depending on occupancy level, pollutant emission, or IAQ requirements.

1.2.2. Heat recovery ventilation systems

The principal of heat recovery with a heat exchanger is to transfer the heat from outgoing air to incoming air. Buildings with heat recovery systems should be airtight in order to ensure that all cold incoming air is heated by passing through the heat exchanger instead of coming from the building envelope. The benefit of a heat exchanger system, however, should be considered in terms of ventilation fans' electricity consumption; that is, high specific fan power causes the energy saving potential to decrease. In addition to energy consumption by ventilation fans, savings with heat exchangers depend on the climate condition and type of the buildings. Previous studies [22, 23] have shown that, for residential buildings with a low air change rate in moderate climate zones in Western Europe with annual heating degree days of 2500–3000 °C·day·year^{-1}, heat recovery ventilation systems were not economical and caused very low or even negative energy savings. However, Dodoo et al. [24] showed that ventilation systems with heat exchangers are energy-efficient in Sweden, with annual heating degree days of 4000–6000.

1.3. Research questions

Energy consumption in residential buildings located in Scandinavian countries is mainly governed by their ventilation and heating system. To save energy, more renewable sources could be used, either directly (for example, through seasonal storage) or indirectly (by other sources, such as heat pumps or low-temperature district heating). All of these heat sources have higher efficiency when working with low-temperature heat emitters. In addition, to save energy in a ventilation system, the air flow rate can be set based on the number of occupants or indoor air quality requirements. Two main research questions were considered in this thesis:

- How much energy is saved when using a low-temperature heat emitter with heat pump and/or seasonal thermal energy storage?
- How much energy is saved when the ventilation rate is changed based on the number of occupants or concentration of pollutant gases? and how the indoor air quality is influenced by a reduction in the ventilation rate?

1.4. Objectives and contributions

This thesis presents the project objectives and contributions in the following three main parts:

1. The purpose of the first part was to evaluate the energy consumption of very-low- and low-temperature heat emitter connected to heat pumps and to compare it with medium-temperature heat emitter. For this purpose, on-site measurements, lab tests, and a simulation tool were applied for floor heating, ventilation radiators, and conventional radiator with very-low-, low-, and medium-temperature water supplies, respectively.

2. The aim of the second part was to improve the sustainability and efficiency of heating system by increasing the share of renewable sources through seasonal thermal energy storage. In addition to a comprehensive literature review of recent and previous applications, seasonal thermal energy storage combined with a heat pump was designed in a case study building with very-low-, low-, and medium-temperature heat emitters.

3. The third part deals with reducing the ventilation heat loss in new and old building by lowering the ventilation rate while maintaining an acceptable IAQ. For this purpose, energy savings and IAQ were evaluated experimentally and analytically when the ventilation rate was decreased based on the number of people or the IAQ requirement.

1.5. Limitations

In this thesis, only a few case studies were considered to evaluate energy savings and indoor air quality. Therefore, the results cannot be generalized to all applications with low-temperature heating and variable air volume ventilation systems. In addition, thermal comfort with low-temperature heat emitters was not considered in detail. However, it would be a main focus of future work.

1.6. Case study buildings

This study considered two types of buildings: five two-family new-built buildings and a single-family old building.

1.6.1. Two-family new-built buildings

The five investigated buildings were two-family houses located in Stockholm, Sweden that were built in 2011. Those buildings were equipped with very-low- and low-temperature heat emitters connected to an exhaust air heat pump, which extracted the heat from outgoing air to produce supply water for the heating system and domestic hot water usage. All buildings were identical in terms of their construction materials and geometry but different in their compass orientation. There were four inhabitants in dwellings 1 and 2, five in dwelling 3, and three in each of dwellings 4 and 5. Each building had three stories totaling 160 m^2, including hallway, living room, kitchen, bedrooms, toilet, and bathroom. The heat emitter used on the first floor was floor heating, and the ventilation supply devices were placed above the windows so the cold supply air came directly inside without preheating. On the second and third floors, the heating and ventilation systems were combined using a system called a “ventilation radiator”. The ventilation air was preheated between the radiators’ panels before entering the building. The exhaust devices were placed in the kitchen (10 $L\cdot s^{-1}$), bathroom (15 $L\cdot s^{-1}$), toilet (11 $L\cdot s^{-1}$), wardrobe (6 $L\cdot s^{-1}$), and third floor (18 $L\cdot s^{-1}$). The total airflow rate was 60 $L\cdot s^{-1}$ – that is, 0.55 ach – fulfilling the minimum requirements of BBR of 0.50 ach [17]. The plan of the building and a schematic of airflow and heat emitters are shown in Fig. 7. This case study was considered to experimentally investigate the energy performance of very-low- and low-temperature heat emitters connected to heat pumps. In addition, to improve the sustainability, seasonal thermal energy storage and a variable air volume ventilation system were designed for this case study building.

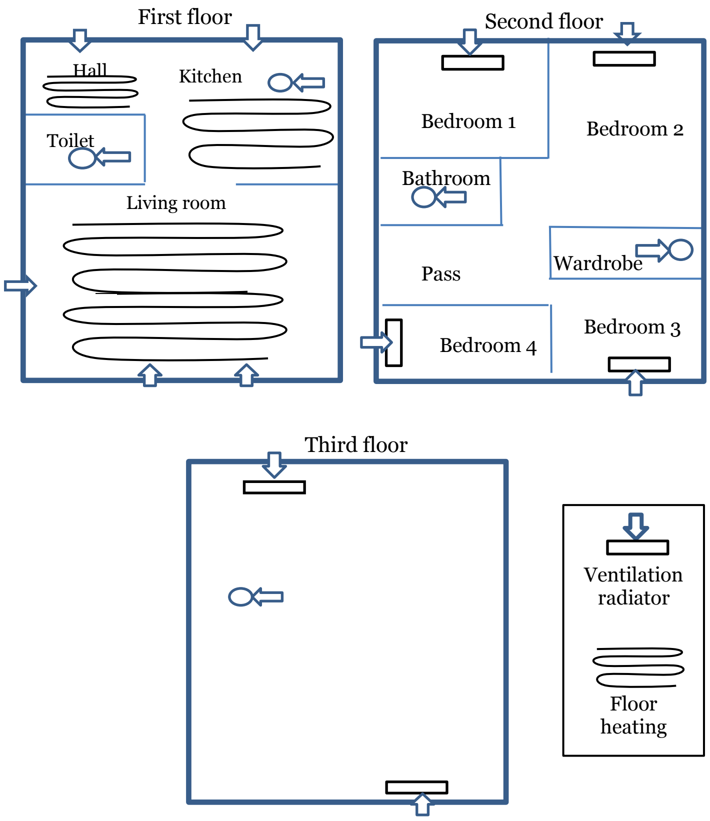

Figure 7. Two-family new-built building plan and schematic of airflow and heat emitters

1.6.2. Single-family old building

A two-story single-family house with 100 m² living area, built during 1950s in Borlänge, Sweden, was chosen; see Fig. 8. Two adults and one infant live in the house. The mechanical exhaust system in the house could be set to different flow rates. This case study was considered to investigate the energy savings potential and indoor air quality with different ventilation levels.

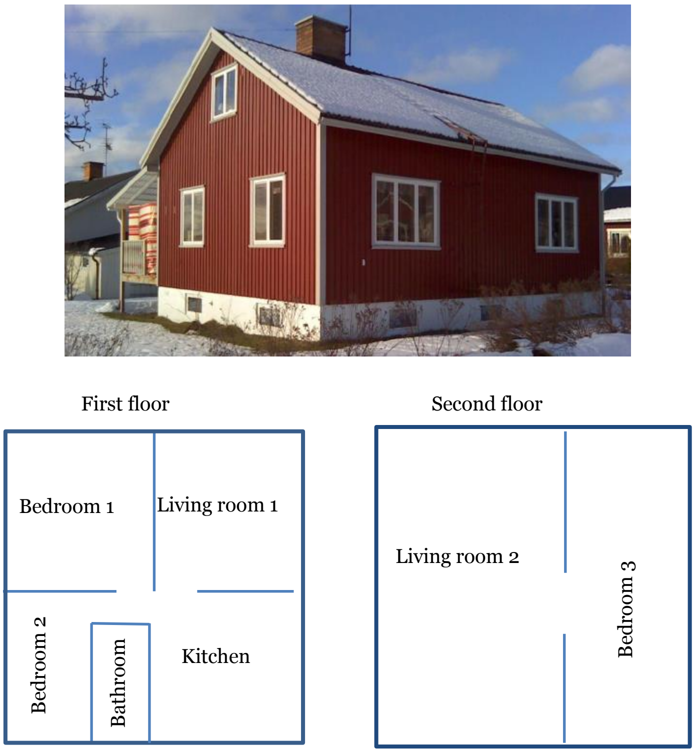

Figure 8. A two-story single-family house selected for the study

Chapter 2

2. Method

In this thesis, simulation tools, analytical models, lab tests, and on-site measurements were used to evaluate low-temperature heating and variable air volume ventilation systems in terms of energy savings and indoor air quality.

2.1. Simulation tool

IDA Indoor Climate and Energy (ICE) 4 [25] is a dynamic multi-zone simulation tool for studying energy consumption, thermal indoor climate, and the indoor air quality of the modeled building. IDA ICE 4 has a user-friendly interface that makes it easy to build and simulate different cases. In IDA ICE 4, the mathematical library is modeled with the equations from ISO 7730 [25]. The model library of IDA ICE 4 was written in neutral model format (NMF) [26]. NMF is a program-independent language that uses differential algebraic equations to model the dynamic systems. The results of IDA ICE 4 have been validated in several studies [27-31]. In IDA ICE, the ventilation system can be defined as CAV or VAV. The VAV model can be controlled by the schedule, humidity, CO_2, temperature, or pressure in each zone.

2.1.1. Description of the IDA ICE 4 model

In order to evaluate energy consumption and thermal comfort, the case study two-family new-built buildings were modeled in IDA ICE 4 similar to the actual geometry; see Fig. 9. The model was divided into 12 zones in each dwelling, and for each zone a different exhaust air flow rate was defined. A mechanical exhaust system was defined for the ventilation system and the supply devices were placed on external walls as openings.

Figure 9. Left: Four identical two-family houses in Stockholm; Right: simulation model frame of the houses in the IDA ICE 4 software

In the simulations, cooling energy was not considered since there was no cooling device supplied in the buildings. All dwellings were modeled with different orientations and different internal heat gains. The building envelope was very airtight with a low U value. Therefore, not much energy could be saved by decreasing transmission losses through building materials and space heating demand. In the investigated buildings, the occupants went to work or school on weekday mornings and returned home in the afternoon. Hence, a VAV system instead of a constant ventilation system was modeled to reduce the ventilation heat loss. In the studied building, the clock-controlled VAV system was suggested to be implemented based on step increased/decreased speed of the ventilation fan. The start time for decreasing the ventilation rate was at 8:00 when the occupants left the house. According to the defined schedule, the ventilation fan speed was decreased to 27 % of its initial speed during un-occupancy from 8:00 till 18:00, as shown in Fig. 10. The value of 0.27 shows the ratio of 0.100 $L \cdot s^{-1} \cdot m^{-2}$ as a minimum ventilation rate to 0.375 $L \cdot s^{-1} \cdot m^{-2}$ as a normal ventilation rate in the studied building.

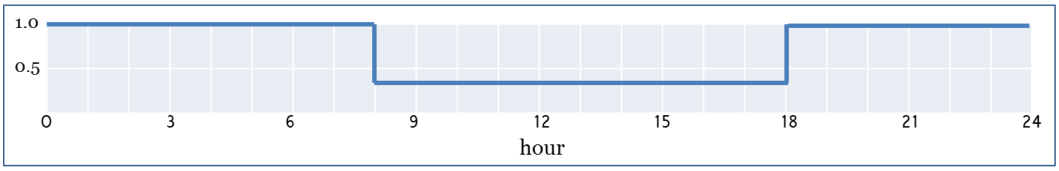

Figure 10. Profile for the ventilation fan speed for weekdays: 1.0 for working at full speed during occupancy from 18:00 till 8:00, and 0.27 for working during un-occupancy from 8:00 till 18:00 with 27 % of full speed

In order to investigate the number of hours for which the ventilation air is allowed to be decreased in terms of acceptable IAQ, four different cases with different stop times for ventilation reduction were considered; see Table 1. LVR in the table is the abbreviation for low ventilation rate, and the number after it refers to the duration of decreased ventilation rate; for example, LVR10h means that ventilation rate was decreased for 10 hours. Each VAV control was modeled in IDA ICE 4, taking into account energy savings and indoor air quality.

Table 1. Start and stop time and daily mean air change for each proposed VAV control

	LVR4h	LVR6h	LVR8h	LVR10h
Start time	8:00	8:00	8:00	8:00
Stop time	12:00	14:00	16:00	18:00
Mean air change averaged over a day, h^{-1}	0.48	0.45	0.42	0.38

2.2. Analytical models

Analytical models for energy performance and indoor air quality used in this study are described briefly in the following sections.

2.2.1. Energy performance

Total heat losses from buildings include transmission, ventilation, and leakage losses. The degree-hours method could be used to calculate building energy demand for active heating over the year. The degree hours depend on the building location and properties, the desired indoor temperature, and the base temperature depending on the internal and external heat gains. The base temperature is defined as the outside temperature above which the building does not need any active heating. In this temperature, the heat loss from the building is equal to the heat generated by the active heating system. The difference between the base temperature and the desired indoor temperature is covered by internal and external heat gains from sources such as occupants, equipment, lighting, and solar energy; this is called passive or indirect heat. A different base temperature results in different degree hours and, consequently, in various primary energy consumptions.

Energy demand in a building can be covered by a heat pump. The efficiency of a heat pump in heating mode is determined by the coefficient of performance (COP). The COP of a heat pump indicates the ratio of produced energy to used energy. Presently, the average COP of an efficient heat pump can be as high as 4.5. The COP depends on several factors, including the temperatures of the heat source and the heat sink, the efficiency of its compressor, and the type of its working medium. Above all, the temperatures of the heat source and the heat sink are very important factors that influence the COP value, as indicated by Eq. (1). As Eq. (1) shows, lowering the temperature difference between the heat source and the heat sink for a heat pump results in a higher COP value. Therefore, a low-temperature heat sink and a high-temperature heat source are beneficial. The COP improves by 1-2 % [32] for every degree of reduction in the heat sink temperature, and by 2–4 % [33] for every degree of enhancement in the heat source temperature. A high COP results in less electrical energy consumption by a heat pump, as shown by Eq. (2).

$$COP = \eta_c \left(\frac{\theta_{\sin}(t)}{\theta_{\sin}(t) - \theta_{sor}(t)} \right) \tag{1}$$

$$W_{HP} = \frac{E_{building}}{COP} \tag{2}$$

where COP is the coefficient of performance of the heat pump, η_c is the Carnot efficiency (the relation between the efficiency under real conditions and the theoretically maximum reachable efficiency), θ_{sin} and θ_{sor} are the heat sink and heat source temperatures (°C), respectively, W_{HP} is the electrical energy required by the heat pump (kWh), and $E_{building}$ is total heating demand in the building (kWh·year^{-1}).

To increase the share of renewable energy in a heating system, summer heat can be stored seasonally for the winter; namely, a seasonal thermal energy storage (STES). The energy balance between supply, loss and demand can be used to study the behaviour of the STES. Energy stored in the storage tank is equal to all heat input to the system, including energy produced by the solar collector and energy provided by the heat pump, minus all heat output from the system, including energy demand in building and energy loss to the surrounding ground [34]. In addition to the external thermal exchanges, there are internal thermal interactions between different layers due to the temperature difference inside the stratified storage tank. Heat exchanges between layers are determined using Eqs. (3–7) [35].

$$P_{natural_{L\to L+1}} = \bar{h}_{L\to L+1} \cdot A_{base,layer} \cdot (\theta_L - \theta_{L+1}) \tag{3}$$

$$P_{natural_{L+1\to L}} = \bar{h}_{L\to L+1} \cdot A_{base,layer} \cdot (\theta_{L+1} - \theta_L) \tag{4}$$

$$\bar{h}_{L\to L+1} = \frac{Nu_{L\to L+1} \cdot k_f}{L_c} \tag{5}$$

where $P_{natural}$ is natural (free) convection (W), L is the number of layers, $\bar{h}$ is the average convective heat transfer coefficient (W·m^{-2}·K^{-1}), $A_{base,\ layer}$ is the base area of layer (m^2) equal to π·(radius)^2, θ_L is the layer temperature (°C), *Nu* is the Nusselt value as a dimensionless number showing the ratio of convective to conductive heat transfer, k_f is the thermal conductivity of fluid (W·m^{-1}·K^{-1}), and L_c is the characteristic length defined as a ratio of layer's base area to its perimeter (m) equal to π·(radius)^2/ (2π·radius).

The average Nusselt number in the lower surface of the hot plate or the upper surface of the cold plate is defined as in Eq. (6) [36].

$$Nu_{Lc_{L\to L+1}} = 0.27 Ra_{Lc_{L\to L+1}}^{1/4} \qquad \text{for } 10^5 \le Ra_{Lc} \le 10^{11} \tag{6}$$

where Ra is the Rayleigh value as a dimensionless number defined as the product of the dimensionless Grashof number (Gr) and the Prandtl number (Pr); see Eq. (7). Gr shows the ratio of buoyancy to viscosity within a fluid, while Pr shows the relationship between momentum diffusivity and thermal diffusivity.

$$Ra_{Lc_{L\rightarrow L+1}} = Gr_{Lc_{L\rightarrow L+1}} \cdot \Pr = \frac{g \cdot \beta \cdot L_c^{\,3} \cdot (\frac{\theta_L + \theta_{L+1}}{2} - \theta_L)}{v^2} \cdot \Pr \tag{7}$$

where g is gravity ($m \cdot s^{-2}$), β is the thermal expansion coefficient (K^{-1}), and ν is the kinematic viscosity ($m^2 \cdot s^{-1}$).

2.2.2. Indoor air quality

The indoor air quality (IAQ) could be investigated in terms of concentration of pollutant gases such as CO_2 or volatile organic compounds (VOCs); see Eq. (8).

$$c = c_o \cdot e^{-nt} + \frac{\dot{m}_{poll}}{q_{ventilation}}(1 - e^{-nt}) \tag{8}$$

where c is the pollutant concentration in room ($kg \cdot m^{-3}$), c_o is the initial concentration at t=0 ($kg \cdot m^{-3}$), t is the time (h), n is the number of air changes per hour (h^{-1}), $\dot{m}_{poll}$ is the emission rate from pollutant source ($kg \cdot s^{-1}$), and $q_{ventilation}$ is the ventilation outdoor airflow rate ($m^3 \cdot s^{-1}$).

According to the indoor air quality requirements, it is recommended to keep the CO_2 level below 1000 ppm [19] and the VOCs concentration below 0.1 ppm [37] in an occupied zone.

To evaluate the ventilation system in terms of IAQ, the mean air age can be considered as an indicator of the freshness of indoor air. The mean air age is a measure of how long an average air molecule has spent in the building based on the ideal (full) mixing concept. Therefore, the higher the age of the air, the more stale or stuffy air there is. If a zone is ventilated only by outside air and is at steady state, this number is equal to the nominal time constant.

2.3. Measurements

On-site measurements in residential buildings and lab tests in a climate chamber facility at Technical University of Denmark were conducted to investigate energy consumptions and indoor air quality with different heating and ventilation systems.

2.3.1. On-site measurements

On-site measurements were conducted in two case studies, including two-family new-built buildings and a single-family old building. In the former case study, very-low- and low-temperature heat emitters were evaluated in terms of energy consumption. In the latter case study, indoor air quality and energy performance were investigated with different ventilation levels.

Two-family new-built building case study

To help conduct site measurements for the two-family new-built building case study, occupants of the five houses were asked to report their monthly heat pump electricity consumption for space heating, domestic hot water, fans, and pumps. The starting date for these measurements was on December 14, 2011, the date when the buildings were occupied, and the last value was reported on December 13, 2012; and thus their annual energy consumption was measured. A questionnaire was distributed to occupants to survey the perceived thermal comfort and indoor air quality. The questionnaire asked occupants how satisfied they were with the mean temperature and air quality in different rooms and whether they had felt any discomfort with respect to drafts.

Single-family old building case study

In the ventilation system of the single-family old building case study, four airflow levels were set, as shown in Table 2. In case I, the ventilation concept was set to 0.10 $L\cdot s^{-1}\cdot m^{-2}$ (0.14 ach) as a very low ventilation rate (VLVR) corresponding to the minimum required ventilation rate in BBR [17]. In case II, a low ventilation rate (LVR) of 0.20 $L\cdot s^{-1}\cdot m^{-2}$ (0.30 ach) was chosen. For case III, the flow rate was based on a value recommended by BBR for occupied building: 0.35 $L\cdot s^{-1}\cdot m^{-2}$ (0.50 ach) as normal ventilation rate (NVR). In case IV, a high ventilation rate (HVR) was used above the recommended level; that is, 0.70 $L\cdot s^{-1}\cdot m^{-2}$ (1.00 ach).

Table 2. Different ventilation rates in the single-family old building case study

Case	Ventilation rate	$L\cdot s^{-1}\cdot m^{-2}$, (ach)	Deviation from the reference (NVR)
I (VLVR)	Very low ventilation rate	0.10, (0.14)	72 % lower
II (LVR)	Low ventilation rate	0.20, (0.30)	40 % lower
III(NVR)	Normal ventilation rate	0.35, (0.50)	-
IV(HVR)	High ventilation rate	0.70, (1.00)	100 % higher

To study the IAQ, the CO_2, RH and temperature from habitable spaces were measured every 10 minutes. As these variables are never uniform in the whole room, the sensor was placed in the central exhaust in order to detect a mean value. All measurements were conducted during winter in order to consider the ventilation rate through the mechanical ventilation system alone and to exclude the influence of natural ventilation by opening windows. In order to have only exhaust from habitable spaces, the exhaust duct in the bathroom was blocked during measurements and the exhaust fan from the kitchen was not used.

2.3.2. Lab tests in climate chamber at Technical University of Denmark

To study the energy performance of very-low- and low-temperature heat emitters compared to a medium-temperature heat emitter, a climate chamber test facility at Technical University of Denmark was used.

Measurements were conducted for floor heating, a ventilation radiator, and a conventional radiator under a steady-state condition; that is, constant windows' temperature, constant ventilation supply temperature, constant ventilation flow rate, and constant internal heat gains. For floor heating and conventional radiator, a fresh air supply diffuser was placed above the window. In the case of ventilation radiator, cold ventilation air supplied into the room was preheated by passing through the radiator's panels before entering the room. The simulated room represented a living room in which two persons were at home during the evening. For this reason, no solar external heat gains were simulated. To simulate a living room, the exhaust air duct was placed at a low level, similar to the case in which the air was exhausted from below the door in the living room. The room was simulated with one external wall, including cold windows, and three internal adiabatic walls with adiabatic floor and ceiling. The U value of the windows and wall were considered to be 2.10 and 0.25 W·m^{-2}·K^{-1}, respectively, corresponding to the values in an average multi-family building built between 1976 and 2005 [38]. Two seated persons, two laptops, and two lamps were used as internal heat source generators, creating 204 W of heat; see Fig. 11. The ventilation rate was set to 12.6 L·s^{-1} with temperature of 5 °C, which is the average winter temperature in Copenhagen.

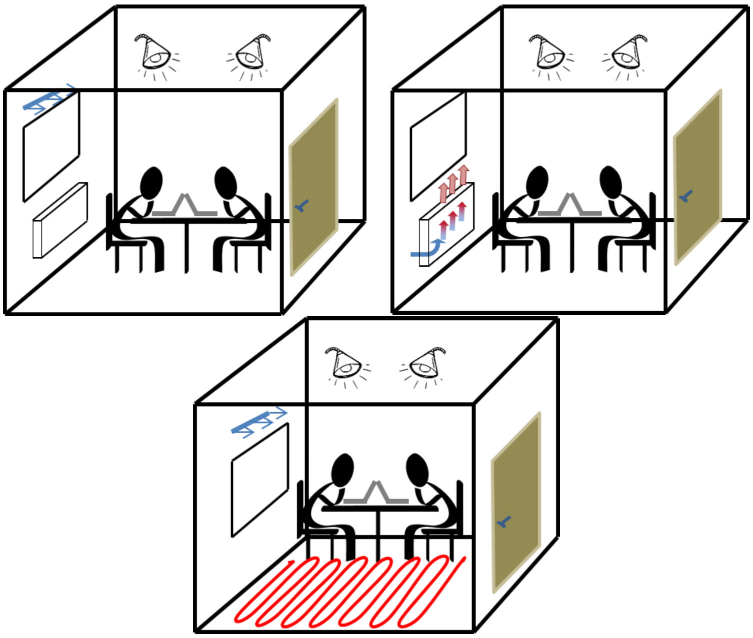

Figure 11. Conventional radiator (left), ventilation radiator (middle), and floor heating (right) used for investigation in climate chamber with internal heat gains from people, lamps, and laptops

Chapter 3

3. Results and discussion

The results of the study are presented in detail in the appended papers. This section presents the main results and discussions.

- **Energy aspect in heating systems**

The total measured annual energy consumption in the studied buildings with low- and very-low-temperature heat emitters connected to a heat pump varied between 48–54 kWh·m^{-2} of floor area, which were lower than 55 kWh·m^{-2} as a recommended value assigned by BBR. The measured energy consumption included the energy demand for heating, domestic hot water, and ventilation fan; see Fig. 12. Heating and domestic hot water consumption include energy used for production and transportation; that is, usage of electricity in the exhaust-air heat pump to extract heat from outgoing air and to transfer it to supply water, the compressor work to increase the water temperature to the suitable level, and pump work to distribute the supply water to the heating system and for domestic usage. Domestic hot water consumption was estimated from heat pump electricity consumption during the summer months, since the only reason for the heat pump to provide heating is because of domestic hot water consumption during this period. In addition, in Fig. 12, the air movement energy consumption refers to the energy used by the exhaust ventilation fan to circulate air in the building.

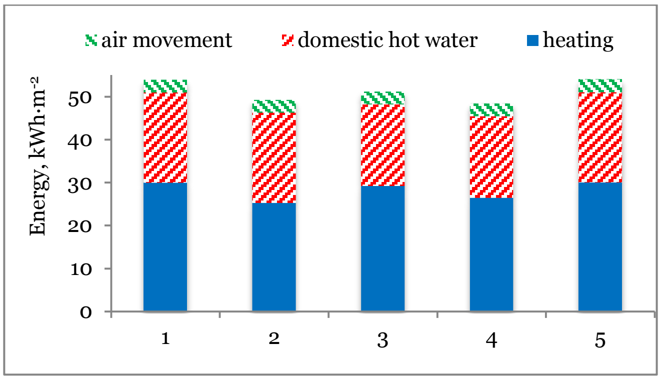

Figure 12. Measured annual energy consumption for each dwelling for heating, domestic hot water consumption, fans, and pumps

Statistical data showed that annual energy consumption for heating and hot water in an average new Swedish single- and two-family houses built between 2001 and 2012 was 84 kWh·m^{-2} [7]. This consumption is 39–46 % higher than the case studied buildings with low- and very-low-temperature heat emitters in which 45–51 kWh·m^{-2} of floor area was consumed for space heating and preparing hot water.

Climate chamber tests showed that to cover the heat demand of 20 W·m^{-2} with active heating, the mean supply water temperature for floor heating was the lowest (30 °C), but it was close to the ventilation radiator with a supply temperature of 33 °C. The supply water temperature in all measurements for the conventional radiator was 45 °C, which was significantly higher than the ventilation radiator and floor heating. The annual energy consumption for each type of heat emitters was calculated using the degree-hours method, see Table 3. In Table 3, the heat output was calculated based on the manufacture's heating power data [39, 40]. Energy consumption and CO_2 emissions were calculated assuming that the heat emitters were connected to a ground-source heat pump. CO_2 emissions were calculated based on the products of the electrical energy consumption and the specific CO_2 emission factor for electricity, which is 0.041 kg_{CO2}·kWh^{-1} in Sweden [41]. The COP of the heat pump was calculated using a commercial program called Vitocalc 2010 developed by Viessmann [42]. As Table 3 shows, the energy was reduced by 17 % in ventilation radiator and by 22 % for floor heating compared to conventional radiator. In addition, CO_2 emission savings were 18 % and 21 % for ventilation radiator and floor heating, respectively, compared to conventional radiator.

Table 3. Energy performance and CO_2 emission from each type of heat emitters

Type of heat emitter	Supply /return temp, °C	COP of heat pump	Mean heat output, W	Annual energy consumption, kWh·m^{-2} (Savings, %)	Annual CO_2 emissions, kg (Savings, %)
Floor heating	30/25	4.5	336	27 (22)	18.6 (21)
Ventilation radiator	33/29	4.2	350	28 (17)	19.3 (18)
Conventional radiator	45/40	3.5	329	34 (-)	23.4 (-)

A comprehensive literature review in previous investigations showed that combining seasonal thermal energy storage with a heat pump and low-temperature, as energy-efficient and sustainable heating systems, can contribute significantly to the need to reduce the large proportion of energy consumed by buildings. The application of seasonal thermal energy storage with very-low-, low-, and medium-temperature heat emitters for a case study building was studied theoretically. The efficiency of the system was considered in terms of the heat pump work, taking into account the COP of the heat pump and the solar fraction. Analytical simulation showed that using a 250 m^3 hot water seasonal storage tank connected to a 50 m^2 solar collector and a heat pump resulted in 85 %, 89 %, and 92 % of the total heat demand being covered by solar energy when using medium-, low-, and very-low-temperature heat emitters, respectively. Results indicated that, for very-low-temperature heat emitters, the heat pump work was less than half of that of the medium-temperature heat emitter. This was due to a 7 % higher solar fraction and 14 % higher COP in the heat pump connected to a very-low-temperature heat emitter than a medium-temperature heat emitter.

- **Indoor air quality and energy aspect in ventilation systems**

The potential for decreasing the energy consumption in ventilation heating demand should be considered with regard to indoor air quality requirements. In the newly built building case study, the energy requirements for ventilation air and electricity for the ventilation fan were decreased by 23 % and 38 %, respectively, when the ventilation rate was reduced from 0.375 to 0.100 ($L{\cdot}s^{-1}{\cdot}m^{-2}$) during the entire un-occupancy period. Fig. 13 shows how the pollutant gas concentration (that is, CO_2 and VOCs) varied over 48 hours during two consecutive working days when the ventilation rate was decreased between 8:00 and 18:00 from 0.375 to 0.100 ($L{\cdot}s^{-1}{\cdot}m^{-2}$).

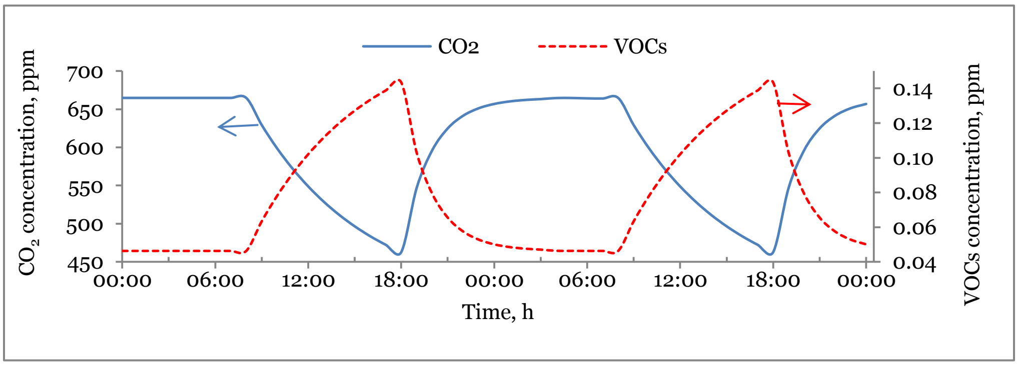

Figure 13. Pollutant gas concentration (CO_2 and VOCs) variation over 48 hours showing the effect of decreasing the ventilation rate from 8:00 till 18:00

As Fig. 13 shows, decreasing the ventilation rate throughout the entire un-occupancy period resulted in slightly higher VOCs concentration than the acceptable level of 0.1 ppm when the occupants arrived home at 18:00. Therefore, to create an acceptable level of IAQ, it was suggested to increase the ventilation rate to the normal rate of 0.375 $L\cdot s^{-1}\cdot m^{-2}$ two hours before a home is occupied. In this system, the heating requirements for ventilation air and electricity consumption for the ventilation fan were decreased by 20 % and 30 %, respectively. As Fig. 13 shows, the concentration of CO_2 was within the acceptable range every day (below 1000 ppm), since the ventilation rate was decreased at the same time as the main pollutant source (that is, humans) left the house.

The CO_2 level as an indicator of IAQ was measured during a day for an old case study building with different ventilation levels of 0.10, 0.20, 0.35, and 0.70 ($L\cdot s^{-1}\cdot m^{-2}$); see Fig. 14. The results showed that, for case I with a low ventilation rate of 0.10 $L\cdot s^{-1}\cdot m^{-2}$, the CO_2 concentration in the building reached over 1300 ppm. This level was higher than the commonly referenced threshold for ventilation control (1000 ppm), which caused poor IAQ. However, using cases II, III, and IV, which had ventilation rates of 0.20, 0.35, and 0.70 ($L\cdot s^{-1}\cdot m^{-2}$), respectively, the CO_2 level never exceeded 1000 ppm, which resulted in better IAQ. As Fig. 14 shows, the CO_2 level in case II was always below 950 ppm, which indicates that 0.20 $L\cdot s^{-1}\cdot m^{-2}$ is a sufficient ventilation rate for the reference building with two adults and one infant. In addition, the results of case III showed that a normal ventilation rate of 0.35 $L\cdot s^{-1}\cdot m^{-2}$ recommended by Swedish building regulations (BBR) was high in terms of the CO_2 concentration, with an average level of 648 ppm during occupancy. Therefore, this normal ventilation rate resulted in energy being wasted for the studied building. The high ventilation rate of 0.70 $L\cdot s^{-1}\cdot m^{-2}$ in case IV caused an average CO_2 level of 490 ppm during occupancy, which was close to the outdoor CO_2 level of 400 ppm.

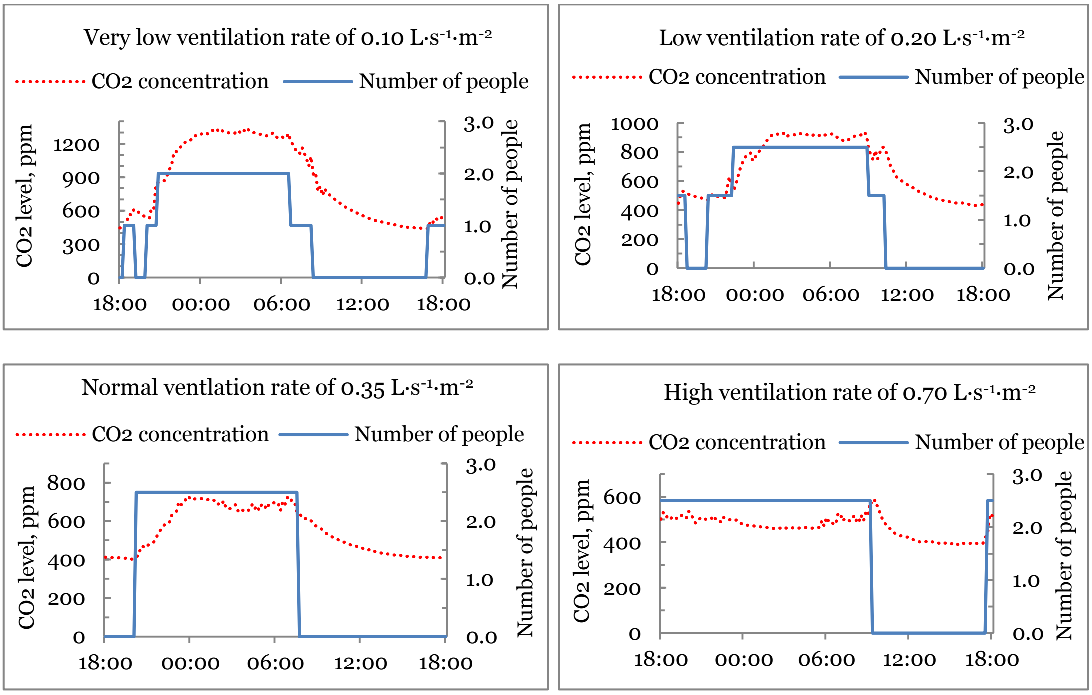

Figure 14. CO_2 concentration and occupancy level during a working day with ventilation rate of 0.10 $L\cdot s^{-1}\cdot m^{-2}$ (upper left), 0.20 $L\cdot s^{-1}\cdot m^{-2}$ (upper right), 0.35 $L\cdot s^{-1}\cdot m^{-2}$ (lower left), and 0.70 $L\cdot s^{-1}\cdot m^{-2}$ (lower right)

Annual energy savings for ventilation heat demand and ventilation fan electricity consumption with a very low ventilation rate (VLVR) were 71 % compared to the normal ventilation rate (NVR). As shown in Fig. 14, however, occupants were exposed to unacceptable indoor air quality in the case of the VLVR. For case II, which had a low ventilation rate (LVR), energy savings for ventilation heating and ventilation fan consumption were 43 % compared to the NVR. A high ventilation rate (HVR) of 1.0 ach consumed almost twice as much energy as the normal ventilation rate case.

Chapter 4

4. Conclusion

In this thesis, energy-efficient and sustainable heating and ventilation systems, including low-temperature heating integrated with renewable energy and variable air volume ventilation, were evaluated in terms of energy savings and indoor air quality. Annual on-site measurements in five new buildings with low- and very-low-temperature heat emitters indicated that in average 48 kWh·m^{-2} was used for producing and transporting supply water for space heating and domestic usage. The statistical data showed that 84 kWh·m^{-2} (that is, 43 % higher) energy was used for the same usage in an average similar building type.

In addition, climate chamber tests showed that, to cover the heat demand of 20 W·m^{-2} with active heating, the supply water temperatures required for floor heating, ventilation radiator, and conventional radiator were 30 °C, 33 °C, and 45 °C, respectively. Compared to conventional radiators, these temperature reductions of 12–15 °C with a ventilation radiator and floor heating resulted in energy savings of 17–22 %.

The need to increase the share of renewable energies, especially in northern climate countries, which lack solar energy during winter, highlights the application of seasonal thermal energy storage. Seasonal thermal energy storage was designed for different heat emitters with design supply temperatures of 55 °C, 45 °C, and 35 °C. Analytical simulation showed that between 85–92 % of total demand was covered by solar energy through a 250 m^3 hot water seasonal storage tank connected to a 50 m^2 solar collector and a heat pump. Results indicated that for very-low-temperature heat emitters, the higher COP of heat pump and higher solar fraction meant that the heat pump electricity consumption was less than half of that of the medium-temperature heat emitters.

The potential for decreasing primary energy consumption in buildings by lowering the ventilation levels was considered in this thesis with respect to indoor air quality requirement. Mathematical modeling showed that reducing the ventilation air throughout the period of un-occupancy, from 8:00–18:00, in new buildings caused intolerable VOC concentration at 18:00 when occupants arrived home, creating unacceptable indoor air quality. Therefore, it was recommended that the ventilation rate be increased to the normal level two hours before the home was occupied. This strategy caused savings of up to 20 % in energy requirements for ventilation heating. In addition, on-site measurements showed that the normal ventilation rate of 0.35 $L{\cdot}s^{-1}{\cdot}m^{-2}$ recommended by BBR is high and results in energy being wasted in the case study building. Experiments indicated that a low ventilation rate of 0.20 $L{\cdot}s^{-1}{\cdot}m^{-2}$ is sufficient to provide acceptable indoor air quality in terms of CO_2 concentration that never exceeds 950 ppm. This caused 43 % energy savings for ventilation energy consumption and ventilation fan compared to the normal rate of 0.35 $L{\cdot}s^{-1}{\cdot}m^{-2}$.

Measurements and modeling in this thesis showed that decreasing the supply temperature to the heat emitters caused higher efficiency and sustainability in the heating system. In low-temperature heating systems, losses from production units, distribution pipes, and heat emitters are reduced. In addition, renewable-based heat sources, such as heat pumps, seasonal thermal energy storage, and fourth-generation district heating networks, attain higher efficiency and sustainability when being connected to low-temperature heat emitters. Furthermore, adjusting the ventilation rate based on the demand of occupants and indoor air quality requirement would lead not only to energy savings, but also to better indoor air quality. Therefore, in order to achieve greater energy efficiency and improve the sustainability in the heating and ventilation system of buildings, it is necessary to decrease the supply temperature to the heating system and to adjust the ventilation rate to the demand. All efforts presented here show that the European goals of increasing energy efficiency by 20 %, using 20 % of renewable energy, and decreasing 20 % of CO_2 emissions in buildings by the year of 2020 are achievable.

Chapter 5

5. Future work

This study has shown that a decreased supply-water temperature to the heat emitter is a key element in renewable-based heat sources such as heat pumps, seasonal storage, or fourth-generation district heating. In addition, it is important to adjust the ventilation rate based on actual demand. Therefore, the main focus in the future could be on evaluating the buildings with low-temperature heating systems and a demand-controlled ventilation system. In future work, the following measurements are encouraged:

- Evaluating energy savings and thermal comfort in new and retrofitted buildings with low-temperature heating systems and comparing them with a reference case with a medium-temperature heating system.
- On-site measurements and climate chamber tests to evaluate low-temperature heat emitters, including add-on fan radiators and baseboard heating regarding energy savings and thermal comfort.
- On-site measurements in new and retrofitted buildings with demand-controlled ventilation system considering energy savings and indoor air quality.

In addition, as shown in this thesis, storing heat during summer for winter usage highlights the application of seasonal thermal energy storage. One type of seasonal storage is ground-duct thermal energy storage. In more than 40 % of Swedish single-family houses, ground-source heat pumps were installed by 2013. The thermal efficiency of these heat pumps can be improved significantly by increasing the temperature of the boreholes through charging the ground artificially with solar energy. Therefore, future work could expand this technology and investigate the performance of seasonally charged ground-source heat pumps with a photovoltaic–thermal collector connected to a low-temperature heat emitter.

Chapter 6

6. Overview of the appended papers

The main contribution of this thesis was to investigate the energy savings and indoor air quality of sustainable and energy-efficient low-temperature heating and ventilation systems. Collaboration with NCC as a leading construction and property development company in the Nordic region was established to evaluate the energy performance of the newly-introduced low-temperature heat emitter (that is, ventilation radiators) in NCC's newly-built building. In addition, the study showed that the normal ventilation rate recommended by BBR is high in most residential buildings due to lower occupancy level than the designed value, and also variable occupancy level during the day. The contribution of each appended paper is explained individually below.

Paper 1

Energy performance of low-temperature heating systems in five new-built Swedish dwellings: A case study using simulations and on-site measurements, A. Hesaraki, S. Holmberg, Journal of Building and Environment 64 (2013) 85–91

This paper presents the results of a study that calculated and measured energy consumption in five new-built semi-detached dwellings in Stockholm, Sweden equipped with very-low- and low-temperature heat emitters. The heat emitters were under-floor heating and ventilation radiators. The main finding of the paper was energy savings of 39–46 % in investigated buildings compared to the average energy consumption for heating and hot water in the same building type.

My contribution

I conducted all of the research, including all measurements, modeling, and drafting of the paper, under the supervision of Prof. Sture Holmberg

Paper 2

Experimental study of energy performance in low-temperature hydronic heating systems, A. Hesaraki, E. Bourdakis, A. Ploskic, S. Holmberg, submitted for journal publication

This paper presents the results of lab tests of energy consumption of conventional radiator, ventilation radiator, and floor heating with medium-, low-, and very-low-temperature supply, respectively. The main findings of the study were energy savings of 17–22 % with very-low- and low-temperature heat emitters compared to a medium-temperature heat emitter.

My contribution

I prepared the climate chamber, calibrated the instruments, fixed the boundary conditions of the tests, and conducted some pilot tests. I was the main analyzer of the raw data and wrote the drafts of the paper. Eleftherios Bourdakis contributed by conducting measurements and commenting the final draft of the paper. Prof. Sture Holmberg and Dr. Adnan Ploskic contributed with discussions and comments on the final draft of the paper.

Paper 3

Seasonal thermal energy storage with heat pumps and low temperatures in building projects – A comparative review, A. Hesaraki, S. Holmberg, F. Haghighat, Journal of Renewable and Sustainable Energy Reviews 43 (2015) 1199–1213

This paper presents a comprehensive literature review of early and recent applications of seasonal thermal energy storage with a heat pump, both on large and small scales. The main finding was the correlation between the COP of heat pumps and solar fractions with storage volume and collector area in different projects.

My contribution

I was the main driver of the work under the supervision of Prof. Fariborz Haghighat and Prof. Sture Holmberg.

Paper 4

Low-temperature heat emission combined with seasonal thermal storage and heat pump, A. Hesaraki, A. Halilovic, S. Holmberg, Journal of Solar Energy 119 (2015) 122-133

This paper investigates the impact of space heat emitter temperature (very-low, low, or medium) on the efficiency of system in terms of solar fraction, the COP of heat pumps and, consequently, electricity used by heat pumps. The main finding of the study was 31–52 % energy savings in terms of heat pump electricity consumption with low- and very-low-temperature heat emitters compared to medium-temperature heat emitters.

My contribution

I did all modeling and draft writing under supervision of Prof. Sture Holmberg and Associate Prof. Armin Halilovic. Associate Prof. Halilovic also helped with the optimization tool in MAPLE and commented on and reviewed the equations in the paper.

Paper 5

Demand-controlled ventilation in new residential buildings: consequences on indoor air quality and energy savings, A. Hesaraki, S. Holmberg, Journal of Indoor and Built Environment 24 (2015) 162–173

This paper presents an investigation of the consequences that a variable air volume ventilation system in Swedish dwellings has on indoor air quality and potential energy savings. The main finding of the paper was a 20 % saving in ventilation heating when decreasing the ventilation rate partly during un-occupancy while maintaining acceptable indoor air quality.

My contribution

I was the main driver of the work under the supervision of Prof. Sture Holmberg.

Paper 6

Influence of different ventilation levels on indoor air quality and energy savings: A case study for a single-family house, A. Hesaraki, J. A. Myhren, S. Holmberg, submitted for journal publication

This paper presents the impact of different ventilation levels on IAQ and energy savings. Experiments showed that the ventilation rate of 0.5 ach as recommended by BBR is high and decreasing it to 0.3 ach was sufficient to provide acceptable IAQ. This low ventilation rate caused 43 % energy savings for ventilation heating compared to the normal rate of 0.5 ach.

My contribution

I helped fix the boundary conditions in measurement, analyzed the raw data and wrote the paper draft under the supervision of Dr. Jonn Are Myhren and Prof. Sture Holmberg. Dr. Myhren also contributed by conducting measurements and commenting on and discussing the work.

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