System Design and Energy Performance of Ventilation Systems in Small Residential Buildings

A Comparison Study of FTX-Ventilation and Termite Ventilation with Demand and Seasonal Controlled Ventilation

Master's thesis in Structural Engineering and Building Technology

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ABSTRACT

Ventilation is one of several subsystems that are necessary for a building to function as intended from an indoor climate and energy point of view. FTX-ventilation are advocated in low-energy buildings, both from an energy and indoor climate perspective. Some actors in the industry claim that Termite ventilation in combination with demand and seasonal controlled ventilation is to be equally energy efficient as FTX-ventilation and provides a better indoor climate, but with less technology and installations. This study has evaluated and compared system design and energy performance of Termite ventilation and FTX-ventilation with demand- and seasonal controlled ventilation in small residential buildings, with regard to ensuring a good indoor climate. A case study has been done where a literature review and energy calculations have been applied to an ongoing housing project.

The study shows that exhaust air ventilation with ground duct (FK-ventilation) is a suitable type of Termite ventilation for small residential buildings. Both a FK- and FTX-system ensure a good indoor climate if designed, operated and maintained correctly and if seasonal controlled ventilation is used. A FTX-system is though known to be noisier. The energy performance largely depends on the choice of heat exchanger for a FTX-system and choice of heating system. The energy demand of a FTX-system during heating season is more than 50 % lower than a FK-system but when using a heat pump it is about the same. A FTX-system with plate heat exchanger and a FK-system has about the same power demand meanwhile a FTX-system with rotary heat exchanger has about 50 % lower.

The energy demand is not the decisive factor in the choice of ventilation system, if using a heat pump. Then there are other indicators that determine the choice of system such as power demand, maintenance, user-friendliness, indoor climate, cost, etc.

Key words: Termite ventilation, FTX-ventilation, Demand and seasonal controlled ventilation, Indoor climate, Energy efficiency

Systemutformning och energiprestanda av ventilationssystem i små bostadshus
En jämförelsestudie av FTX-ventilation och termitventilation med behovs- och årstidsanpassad ventilation

Examensarbete inom masterprogrammet Konstruktionsteknik och byggnadsteknologi

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SAMMANFATTNING

Ventilation är ett av flera delsystem som är nödvändig för att en byggnad ska fungera som planerat ur inomhusklimat- och energisynpunkt. FTX-ventilation förespråkas i lågenergibyggnader, både ur ett energi- och inomhusklimatperspektiv. Några aktörer i branschen påstår att termitventilation är lika energieffektivt som FTX-ventilation samt ger ett bättre inomhusklimat, men med mindre teknik och installationer. Denna studie har utvärderat och jämfört systemutformning och energiprestanda för termitventilation och FTX-ventilation med behovs- och årstidsanpassad ventilation i små bostadshus, med hänsyn till att säkerställa ett bra inomhusklimat. En fallstudie har gjorts där en litteraturstudie och energiberäkningar har tillämpats på ett pågående bostadsprojekt.

Studien visar att frånluftsventilation med markkulvert (FK-ventilation) är en lämplig typ av termitventilation för små bostadshus. Både ett FK- och FTX-system säkerställer ett bra inomhusklimat vid rätt utformning, drift och underhåll och om årstidsanpassad ventilation används. Ett FTX-system är däremot känt för att vara bullrigare. Energiprestandan beror till stor del på val av värmeväxlare för FTX-system och val av värmesystem. Energibehovet för ett FTX-system under uppvärmningssäsongen är mer än 50 % lägre än för ett FK-system men vid användning av värmepump är energibehovet nästan samma. Ett FTX-system med plattvärmeväxlare och ett FK-system har ungefär samma effektbehov medan ett FTX-system med roterande värmeväxlare har cirka 50 % lägre.

Energianvändningen är inte den avgörande faktorn i val av ventilationssystem, om värmepump används. Då är det andra indikatorer som bestämmer val av system så som effektbehov, underhåll, brukarvänlighet, inomhusklimat, kostnad, etc.

Nyckelord: Termitventilation, FTX-ventilation, Behovs- och årstidsanpassad ventilation, Inomhusklimat, Energieffektivisering

Contents

Preface

This report is a study of a master thesis project in the Master's Programme of Structural Engineering and Building Technology at Chalmers University of Technology. The study comprises 30 credits and was done during spring 2022.

The origin of this work is based and applied on my previous master's thesis in architecture, *Grow together: Exploring collaborative building & living in the countryside*, where a design proposal of small ecological residential buildings in an ecovillage was developed for a joint building venture. This was done in a co-creation design process with the ecovillagers.

I want to give warm thanks to my examinator and supervisor Angela Sasic Kalagasidis for her dedication, guidance and expertise throughout this work and for constantly helping me limit my workload when I want too much. Secondly, I want to thank my supervisor John Helmfridsson for his enthusiasm, guidance, expertise and for pushing and challenging me to think beyond boundaries towards a sustainable development.

I also want to give a special thank you to Charlotta Berggren at ByDemand who aroused my curiosity about termite ventilation through interesting guest lectures, study visits and external supervision during my former master's in architecture. Thank you for letting me interview you during this master thesis and for sharing your expertise and experience about termite ventilation.

Finally, I want to thank my opponent Alice Allinger for great feedback of the report.

Göteborg, June 2022
Rebecka Larsson

1 Introduction

The basic purpose of ventilation is to provide an exchange of air so that polluted, humid and hot air is replaced with clean outdoor air at a suitable temperature. Ventilation is one of several subsystems that are necessary for a building to function as intended from an indoor climate and energy point of view (Ekberg et al., 2022). Air is an essential foodstuff. During a day, an adult needs 25 kg of air, 3 kg of water and 1 kg of food. Swedes spend about 90 % of their time indoors which places demands on good air quality indoors. In Sweden, buildings account for about 40 % of the total energy use. Energy efficiency is one of the most important measures to reduce climate impact and limit global warming to 1,5 degrees. Energy efficiency is achieved by building airtight and insulated, and by making technical installations as ventilation systems more energy efficient (Installatörsföretagen, 2020). Ventilation systems are divided into three main groups with associated subgroups

- Natural draft ventilation (S)
  - Fan-reinforced natural draft (FFS)
- Exhaust air ventilation (F)
  - Exhaust air ventilation with exhaust air heat pump (FX or FVP)
- Exhaust and supply air ventilation (FT)
  - Exhaust and supply air ventilation with heat recovery (FTX)

The S-system is categorized as natural ventilation driven by natural forces while F- and FT-systems are fan controlled and are therefore categorized as mechanical ventilation. The ventilation in residential buildings is mainly F-, FX- or FTX-ventilation (Ekberg et al., 2022). In the case of low-energy buildings, FTX-ventilation is advocated, both from an energy and indoor climate perspective. (Energimyndigheten, 2022)

1.1 Background

The Swedish Energy Agency's buyer's group and network, BELOK, carried out a pilot study in 2016 on the theme Innovative ventilation systems. The study was a mapping of innovative solutions, products and concepts for ventilation in premises. The purpose of the mapping was to generate proposals for projects that will result in innovative technology for ventilation coming onto the market faster and becoming conventional. In the study, interviews were conducted with property owners to determine their needs for innovative ventilation systems (Belok 2016a). Many of the interviewed property owners first stated that improved ventilation technology primarily means better technical performance in terms of efficiencies, pressure drops, advanced technology with smart control functions, etc. However, the discussion often ended up being that there are other, more difficult-to-quantify factors, such as robustness, simplicity and reliability, which should be a priority in order to achieve significantly better ventilation systems. A recurring wish was that the systems also should be easy to build, operate, maintain and preferably be proven. Some stated that they feel that the ventilation industry is generally slow and that old proven solutions take precedence over innovative improvements (Ekberg et al., 2022).

In the ecovillage Utsikten at Orust there is an ongoing housing project of small residential buildings. The housing project is run by a joint building venture[1]. The joint building venture has a wish for ecological housing, preferably with simpler and more user-friendly technical solutions which can be self-built, installed, operated and maintained on your own to varying degrees (Joint building venture, personal communication, 7 October 2022).

There are some actors in the industry who advocate a ventilation system often called Termite ventilation. Termite ventilation is a ventilation system with passive heating or cooling in ground ducts and resembles how the termites ventilate and climate-regulate their habitat. This is an old passive technology where heat exchange takes place between the intake air and the soil layer. Today there are some schools and some residential buildings that have been designed with ground ducts in Sweden. The actors claim that termite ventilation in combination with demand and seasonal controlled ventilation is to be equally energy efficient as FTX-ventilation and provides a better indoor climate, but with less technology and installations. Demand and seasonal controlled ventilation mean that the ventilation flow is regulated according to the need and season. Before mechanical ventilation came, homes and premises were always ventilated according to need and season to save energy and provide a good indoor climate. Demand and seasonal controlled ventilation however, requires more advanced control systems. (C. Berggren, personal communication, 9 December 2021).

1.2 Aim

The aim of the study is to evaluate and compare system design and energy performance of Termite ventilation and FTX-ventilation with demand- and seasonal controlled ventilation in small residential buildings[2], with regard to ensuring a good indoor climate.

1.3 Research questions

The study will be answering following three questions:

1. What are the benefits and drawbacks in terms of system design for Termite ventilation and FTX-ventilation in small residential buildings?

2. What is the energy performance of Termite ventilation and FTX-ventilation in relation to each other and what is the energy saving potential with demand- and seasonal controlled ventilation?

3. What indoor climate is provided by Termite ventilation and FTX-ventilation and how is the indoor climate affected by demand- and seasonal controlled ventilation?

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[1] A joint building venture is defined as ”a group of people who, based on their own ambitions, plan together, have a building built and use a building”.

[2] In this study, small residential buildings include single-family dwellings, twin houses, row houses and multifamily dwellings of about six dwellings.

1.4 Audience

The study is primarily aimed for the ventilation industry, both academics and practitioners, and laypersons, who are faced with choosing ventilation systems in new construction of housing. Laypersons lacks a technical background and it is therefore important to present a thorough review of the ventilation systems available on the market and to present the results in the study in an intuitive manner. Furthermore, the study is also directed to other stakeholders in the housing sector.

1.5 Methodology

The study has used methods as literature review, case study, calculations and visual communication. First a literature review was made to collect knowledge from previous research in the field. The review includes system design and performance of the concerned ventilation systems and energy efficiency measures. Requirements and general recommendations on the indoor climate and energy efficiency are also stated. Secondly a case study was carried out on a small housing project where the system design and calculations on the energy performance of the concerned ventilation systems were performed. Visual communication in terms of 3D modeling by the tool SketchUp was used to present the system designs of each ventilation system in an intuitive way, adapted to the audience.

The methodology is described in detail in chapter 4, Implementation and Method.

1.6 Scope & Delimitations

The study is focusing on two main parts, the system design and the energy performance of the two ventilation systems.

The system design of the ventilation systems includes the design of air handling unit and ductwork but also what the system designs entail in energy performance, maintenance, space requirements and indoor climate, in terms of thermal comfort, air quality and noise. The system design is chosen to be applied to one dwelling in the housing project.

The energy performance of the ventilation systems is calculated for the heating demand and electricity demand regarding both energy and power. The calculations are performed for the heating season, comfort cooling is not calculated but considered and discussed. The heating demand do not consider heat gains. The calculation methods of energy performance are simplified based on monthly mean values and where guide values for efficiencies and specific fan power (SFP) are used. The routines have been developed in Excel. A more advanced calculation method is, however, used for termite ventilation where the efficiency is calculated from scratch. There is not much basis for the efficiency today, neither measured nor calculated. The efficiency is also dependent on local site conditions. The termite ventilation is partly modelled and simulated in the program COMSOL Multiphysics 6.0, which using the finite element method. The model in COMSOL is simplified to 2D. The calculations are based on regulations, general recommendations and guide values of the authorities Swedish National Board of Housing, Building and Planning, The Public Health Agency and the Swedish Energy

Agency's buyer's groups and network, BeBo and BELOK. User data is used from BEN 2[3] and Sveby[4] and climate data is used from Sveby.

1.7 Thesis outline

The report is structured in six chapters. The introduction is followed by a literature review in chapter 2. Chapter 3 presents the implementation and methodology. In chapter 4-6 is the result presented, discussed and a conclusion is determined.

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[3] The Swedish National Board of Housing, Building and Plannings regulations and general advice on determining the building's energy use during normal use and a normal year.
[4] Sveby stands for "Standardize and verify energy performance in buildings" and is an industry standard for energy in buildings.

2 Literature review

The basic purpose of ventilation is to provide an exchange of air so that polluted, humid and hot air is replaced with clean outdoor air at a suitable temperature.

Clean and, where possible, moderately temperate air must be supplied to areas where people stay, such as workrooms, living rooms and bedrooms. Exhaust air is sometimes evacuated directly from these rooms, but normally some of the air is transferred as so-called excess air to other rooms, for example to the corridor and on to hygiene rooms. Air should not be spread to other rooms from spaces that produce the most moisture and odors, such as bathrooms, kitchens, or spaces where requirements for air quality are not particularly high. Air must always be evacuated as extract air and leave the house as exhaust air. The intention is for the air to be supplied and removed through intended openings such as fresh air valves or supply air devices, exhaust air devices and cooker hoods etc.

Ventilation is one of several subsystems that are necessary for a building to function as intended from an indoor climate and energy point of view.

For the ventilation to work correctly, it is required that (Ekberg et al., 2022):

- The airflow is correct to meet the requirement for air change rate
- The supply air is clean, has the right temperature and is supplied draft-free
- The entire stay zone is efficiently ventilated
- The operating time of the ventilation correspond to the operating time of the activity.
- The air takes the right path through the building.

2.1 Ventilation systems

Ventilation systems are divided into three main groups with associated subgroups:

- Natural draft ventilation (S)
  - Fan-reinforced natural draft (FFS)
- Exhaust air ventilation (F)
  - Exhaust air ventilation with exhaust air heat pump (FX or FVP)
- Exhaust and supply air ventilation (FT)
  - Exhaust and supply air ventilation with heat recovery (FTX)

S-systems are categorized as natural ventilation driven by natural forces while F- and FT-systems are fan controlled and are therefore categorized as mechanical ventilation. The ventilation in residential buildings is mainly exhaust air ventilation (F), exhaust air ventilation with exhaust air heat pump (FX or FVP), or exhaust and supply air ventilation with heat recovery (FTX). In residential buildings before 1970, natural draft ventilation (S) is most common. Exhaust and supply air ventilation (FT) systems are not that common (Ekberg et al., 2022).

Ventilation systems are made up of four subsystems (Dahlblom & Warfvinge, 2010):

- Room system

  - supply and exhaust air diffusers in the rooms
- Distribution system
  - the ducts that distribute supply and exhaust air
- Air handling unit (AHU)
  - in its simplest form only a fan but usually it also contains heaters, filters, heat recovery, etc.
- Control and regulation systems
  - for temperatures, pressures or airflows

2.1.1 S – Natural draft ventilation

Natural draft ventilation is driven mainly by thermal forces but also wind pressures. Warm room air rises in the exhaust air ducts due to the density difference between the outdoor air and the indoor air and new air is sucked in through fresh air valves and leaks. The driving force becomes greater with an increased height difference between inlet and outlet. The air exchange is therefore greatest on the ground floor and lowest on the top floor. In summer, the temperature difference between indoors and outdoors is small, which reduces the ventilation flow (Dahlblom & Warfvinge, 2010). In the past, when boilers were used to prepare hot water or wood stoves for cooking, the flue heated the exhaust air ducts, which increased the ventilation flow in summer. The principle still works in single-family dwellings with wood boiler (Häggbom, 2021). During winter, houses are instead over-ventilated and causes comfort problems and unnecessary energy consumption for heating. Even though the radiators at the fresh air valves are dimensioned to be able to heat the ventilation air, drafts often occur in winter. The draft problem can be eliminated with humidity-controlled or outdoor temperature-controlled fresh air valves (Dahlblom & Warfvinge, 2010).

2.1.1.1 System design

Each exhaust air diffuser is connected to a separate duct to reduce the risk of air spreading between rooms and apartments. To reduce air resistance, the ducts are large and therefore take up a lot of space. Since it is partly the height difference that creates the driving force, horizontal ducts and sharp bends must be avoided. In older houses the ducts are masonry but also ducts in wood, cardboard, eternit and gypsum occur (Dahlblom & Warfvinge, 2010).

2.1.1.2 Maintenance

Natural draft ventilation is basically maintenance free. The low air velocity means that the ducts do not become contaminated and rarely or never need to be cleaned. Contamination increases with increasing air velocity (Dahlblom & Warfvinge, 2010).

2.1.1.3 Noise

Natural draft ventilation is quiet because it lacks fans but noise from outside can enter through fresh air valves. In natural draft ventilation cannot fresh air valves be fitted with silencers due to increased pressure resistance, the same goes for air filter and heat recovery (Dahlblom & Warfvinge, 2010).

2.1.1.4 FFS – Fan-reinforced natural draft

When the thermal forces decrease with increasing outdoor temperatures natural draft ventilation can be supplemented with a fan mounted on the exhaust air hood on the roof, which helps drive the air exchange. The system therefore works both naturally and mechanically and is often called hybrid ventilation (Dahlblom & Warfvinge, 2010).

2.1.2 F – Exhaust air ventilation

In a F-system, an exhaust fan drives the airflows and creates negative pressure indoors which brings air into the building (Dahlblom & Warfvinge, 2010).

2.1.2.1 System design

The air is supplied through fresh air valves in bedrooms and living rooms. The valve can be a slit valve mounted in the window frame, a wall vent or a ventilation radiator. With a ventilation radiator, the air is taken in through a wall valve behind the radiator and preheats the supply air to some extent, which reduces draft problems. During spring and autumn, the radiators are not always warm and the risk of draft is then the same regardless of the type of fresh air valve. The fresh air valves can be equipped with air filter. The air in bathrooms and other wet areas is evacuated through exhaust air ducts in the ceiling or wall. Several exhaust air diffusers can be connected to one and the same exhaust air duct. The number of ducts can vary but they are fewer and the dimensions are smaller than in natural draft systems. In dwellings, cooking fumes are ventilated from the kitchen stove with a separate duct, in Swedish called imkanal, or with a common duct with bathrooms. The shafts for the ducts are often placed in direct connection to the kitchen, bathroom, laundry room, etc. to avoid horizontal ducts. Exhaust fans are available either as duct fans or roof fans, less common are wall fans. In the kitchen, the air can be sucked out through a cooker hood with or without a fan by forcing when cooking (Dahlblom & Warfvinge, 2010).

2.1.2.2 Maintenance

Fresh air valves for exhaust air or natural draft ventilation should be inspected and, if necessary, cleaned 1-2 times a year. If necessary, the associated filter should be cleaned or replaced as often. The exhaust air is not normally filtered before it is supplied to the exhaust air ducts. The indoor air usually contains relatively large amounts of larger particles that get stuck more easily in the duct system, mainly through impaction in bends but also through sedimentation at the bottom of ducts. Exhaust air ducts therefore need to be inspected and cleaned quite often to maintain the exhaust airflow and not to increase the exhaust fan's electricity use. For ducts with dimensions larger than 100 mm, cleaning can be done at longer intervals, up to every six years. Exhaust air diffusers are usually easy to inspect visually and should be cleaned much more often, perhaps 1-2 times a year as for a fresh air valve. Exhaust fans in F-systems without filters also need to be inspected and cleaned relatively often, perhaps as often as once a year (Ekberg et al., 2022).

2.1.2.3 Noise

As for a natural draft system noise from outside can enter through the fresh air valves but unlike the natural draft system can these valves be installed with silencer. The exhaust fan emits sound, silencers are always used there (Dahlblom & Warfvinge, 2010).

2.1.2.4 FX/FVP – Exhaust air ventilation with exhaust air heat pump

To save energy, the exhaust air system is often supplemented with an exhaust air heat pump. The heat in the exhaust air is recovered and used in the heating system and/or for domestic hot water (Dahlblom & Warfvinge, 2010).

2.1.3 FT – Exhaust and supply air ventilation

A FT-system has both fan-controlled exhaust and supply air, known as balanced ventilation.

2.1.3.1 System design

The system design of a FT-system consists of an air handling unit (AHU) and ductwork.

2.1.3.1.1 Air handling unit (AHU)

The air handling unit treats the supply air based on the requirements set in terms of air quality and temperature. The following components may be included:

- Damper *to regulate the airflow*
- Air filter *to clean the air and protect components*
- Air heater *to heat the supply air*
- Air cooler *to cool the supply air*
- Fan *to move the air*
- Heat exchanger *for heat recovery of the exhaust air*
- Silencer *to reduce noise*
- Dehumidifier *to dehumidify the air*
- Humidifier *to humidify the air*

Usually, a heat exchanger is included which has the task of heating the supply air with the exhaust air (Dahlblom & Warfvinge, 2010). The air coming from outside must be warmed to room temperature, which requires a lot of energy. With heat recovery, a large part of this energy is recovered from the exhaust air. For comfort reasons, post-heaters can be used to heat the air to a higher supply air temperature (Ekberg et al., 2022). If it is possible to have a well-functioning system without post-heaters, both costs, space and energy are saved (Wahlström, 2014). At large heat gains and a constant supply air temperature with post-heaters, there is a risk that it will be too hot in the room. Without post-heaters, the heat gains can instead be met by the radiators (the heating system). Not using post-heaters can therefore contribute to a more even room temperature and energy savings (C. Berggren, personal communication, 22 March 2022). Exhaust air is filtered to prevent dust accumulation on surfaces in the air handling unit. This is especially important when it comes to maintaining high efficiency of heat transfer components, such as heat recovery (Ekberg et al., 2022).

The air handling unit requires space. Depending on the building size a fan room is needed. The room size depends on the size of the air handling unit but also accessibility for maintenance (Dahlblom & Warfvinge, 2010). There are basically three locations of ventilation units that have different advantages and disadvantages:

- Central unit in the basement
- Central unit in the attic or top floor
- Apartment units (apartment units provide more service points but less space)

Apartment units could be placed as a spice racket solution over the stove, over the washer and dryer, or elsewhere (Ekberg et al., 2022).

2.1.3.1.2 Ductwork

To distribute ventilation air to and from rooms, two duct systems are required, one for supply air and one for exhaust air. Large dimensions on the ducts are desirable as it provides low air velocities and thus lower pressure resistance. Fan power and the risk of noise are also reduced. Low air velocities also reduce contamination of the duct. The disadvantage of large ducts is an increased construction cost and a large need for space (Dahlblom & Warfvinge, 2010). There are two main principles to run ducts in apartments, either in the intermediate floor or in a dropped ceiling in the hall, bath, walk-in closet and/or over a wardrobe wall. Between floors, ducts are running in shafts or in walls (Ekberg et al., 2022).

2.1.3.2 Maintenance

Both the ductwork and components in the air handling unit need maintenance for the ventilation system to work efficiently. Unit parts must be checked and maintained and filters must be changed regularly. The duct system must be able to be cleaned on the inside. Therefore, the ducts are provided with cleaning hatches along the system. Dirt in ducts can give rise to (Dahlblom & Warfvinge, 2010):

- Health problem
- Reduced airflows or increased fan power if the fan is flow regulated
- Fire

Unit parts, supply air ducts and supply air diffusers placed after air filters in air handling units do not normally need to be cleaned as often. A large part of the supply air's particulate mass gets stuck in the filter and what still passes through the filter also largely passes the supply air duct and supply air diffusers. It is important that the filter is not overloaded and breaks because then the need for cleaning can soon arise in all parts of the system. It is therefore important that the supply air filters are changed regularly, 1-2 times a year. Dirty and, in the worst case, humid supply air filters can give a very poor perceived supply air quality. The intake part of the supply air duct needs to be inspected and cleaned more often as this air is not filtered. Supply and exhaust air diffusers need to be cleaned a few times a year (Ekberg et al., 2022).

2.1.3.3 Noise

There are problem areas that negatively affect the sound level in air supply systems. One problem area is self-sound generation from supply air diffusers in dwellings and its dependence on the supply air system immediately before the diffuser (Kempe, 2017). Supply air fans always emit a low noise to (Dahlblom & Warfvinge, 2010).

2.2 Indoor climate and Requirements

Regulations, recommendations and requirements from authorities are formulated as functional requirements for indoor climate and the durability of the building, without any special ventilation system being advocated. It is mainly requirements for air quality and thermal climate that determine, in addition to investment and operating costs, need of space and maintenance etc. (Dahlblom & Warfvinge, 2010).

2.2.1 Airflow

According to BBR's current regulations, dwellings should be ventilated with an airflow of at least 0,35 l/s per m^2 of floor area and premises should in addition be ventilated with at least 7 l/s per person. These figures refer to the size of the hygienic airflow, i.e. the lowest airflow required to remove disturbing substances from the indoor air. Minimum values provides that the internal pollution generation is low and not necessarily a desired value to project towards. In buildings with higher pollution generation or where the ventilation is also used for comfort cooling, significantly higher airflows may be needed.

In dwellings, the ventilation system may be designed so that it is possible to reduce the supply airflow when no one is staying in the building, but it is important that the airflow is never completely shut off (moisture needs to be transported out). The reduced airflow must be at least 0,1 l/s per m^2. There is no such restriction in premises and it is common for ventilation to be switched off during nights and weekends when no one is staying in the building, in for example offices and schools. It is thus permitted with reduced airflows or intermittent operation of the ventilation in premises as long as there are no health risks or damage to the building and its installations caused by e.g. moisture.

Table 1. BBR's regulations of airflows in dwellings.

Regulations of airflows	**l/s m^2**
Outdoor airflow	> 0,35
Reduced outdoor airflow	> 0,1

In the 1990s, attempts were made to determine the required airflow regarding the emission of pollutants from the sources of air pollutants that occur in a building (building materials, furnishings, people, chemicals, outdoor exhaust gases, etc.). However, this approach did not work in practice, for two main reasons. On the one hand, the pollutants generated have very different effects on human comfort (perceived air quality), and the connection between concentration and experience is only well known in exceptional cases. On the other hand, data on the source strength of most of the various pollutant sources are lacking.

Today, a standardized working method is used instead to determine the required hygiene flow for general ventilation. The principle that is normally applied is that the choice of building and interior design materials is quality assured to limit pollution generation indoors. In addition, if the pollution generation of the activity is limited, the idea is that the standard airflows according to the previous paragraph are sufficient from an air hygiene point of view. Several factors, such as user behaviour, indoor humidity generation and possible contamination of the duct system, affect whether the airflows will be sufficient over time or not (Ekberg et al., 2022).

2.2.1.1 The background to the standard values

In the 1940s, measurements were carried out in many naturally ventilated dwellings. The average value of the measurements was 0,5 air changes per hour. At 2,5 m room height, 0,5 air changes per hour corresponds to 0,35 l/s per m^2 floor area. Today's standard value is thus a recalculation of a typical value of the air exchange in Swedish dwellings in the 1940s. It is seldom questioned whether such a value is relevant in today's buildings. Newer buildings contain many materials that were not used 70 years ago and the indoor air is also affected by the furnishings and other products used indoors. Anyway, an airflow of 0,35 l/s per m^2 of floor area is still established as a guide value for ventilation in dwellings and as a basic flow in many types of premises. The current airflow is also an approximate upper limit that should not be significantly exceeded so that the risk of drafts does not become unacceptable in rooms that are ventilated by untreated (unheated) outdoor air, as S- and F-ventilation.

In the HealthVent project, carried out in 2008-2013, European researchers have proposed 4 l/s per person as a reasonable generally minimum outdoor airflow. The starting point is that it is a safe level regarding human health. This is the level of airflow that has been provided by the Swedish Public Health Agency for many years as advice for ventilation of dwellings. The Authority's general recommendation states that the outdoor airflow should not be less than 0,35 l/s per m^2 of floor area, 0,5 air changes per hour or 4 l/s per person (see table 2).

Table 2. The Swedish Public Health Agency's general recommendations of airflows in dwellings.

General recommendations of airflows		
Outdoor airflow	> 0,35	l/s m^2
Air changes per hour	> 0,5	
Airflow per person	> 4	l/person

Up to and including 2006, the National Board of Housing, Building and Planning's building regulations gave the advice that living rooms for sleep and rest should be ventilated with at least 4 l/s per sleeping area (Ekberg et al., 2022). Until BBR 11 have the National Board of Housing been given general recommendations regarding exhaust airflows for dwellings (see table 3). These guide values are today seen as practice. For larger dwellings, the exhaust air can therefore be dimensioning (Östlund, 2021).

Table 3. Guide values of exhaust airflows according to practice.

Exhaust airflows according to practice	**l/s**
Kitchen	10
Kitchenette	15
Bathroom without forcing	15 Continuously
Bathroom with forcing	10
Bathroom with openable window	10

In work premises, the outdoor airflow must be at least 7 l/s per person plus at least 0,35 l/s per m^2 of floor area. These values are today formulated as general requirements from the Swedish Work Environment Authority. The same figures are given by the Swedish Public Health Agency as general recommendations for schools and premises for childcare. In addition, the Swedish Public Health Agency advises that a room that in normal use regularly exceeds 1000 ppm in carbon dioxide concentration should be seen as an indication of unsatisfactory ventilation. In rooms where people stay, a characteristic "human smell" arises which is caused by substances that each person emits. In the 1850s it was shown that the concentration of carbon dioxide is proportional to the intensity of human odor. It was concluded that a carbon dioxide concentration of about 1000 ppm constituted a limit for acceptable human odor in populated rooms. This concentration corresponds to an airflow of about 8 l/s per person. During the 20th century, several studies were carried out on this topic and gradually 7 l/s per person has been established as a comfort limit regarding human odor. Carbon dioxide itself is an odorless gas. Unlike the substances that smell, carbon dioxide is easier to measure and therefore the carbon dioxide content is used as an indicator because it increases in proportion to other substances from humans which smells. Laboratory experiments on how air quality is perceived by people entering a room with a carbon dioxide concentration of 1000 ppm and an airflow of 8 l/s per person versus 4 l/s per person have been carried out. A conclusion is that an outdoor airflow of 4 l/s per person probably means that a significant percentage of those who stay permanently in a room, with more people, will find that the air not completely fresh. If the outdoor airflow is 8 l/s per person, only a few people, probably none, of those staying there will be dissatisfied (regarding human odor) (Ekberg et al., 2022).

Carbon dioxide as an indicator of the indoor climate is questioned. Research shows that human odor increases in proportion to the carbon dioxide content as mentioned, but there are more factors that affect the intensity of human odor. Human odors increase with increasing room temperature and decreasing relative humidity therefore, 1000 ppm may be a less accurate guide value as the room temperature and relative humidity are not considered here. The carbon dioxide content, on the other hand, is a good indicator of the ventilation efficiency in relation to the number of people in the room. It is also overtemperatures that give rise to tiredness not increased carbon dioxide values which is often claimed (Andersson, 1995).

What connections there are between ventilation capacity and function in relation to the quality of indoor air is an ongoing discussion both in the industry and in the academia. The discussion is about what the concept of indoor air quality really means, what criteria should be used and how much ventilation is actually needed (Ekberg et al., 2022).

2.2.2 Thermal comfort

Thermal comfort is defined as the state in which a person is satisfied with the temperature experience and wishes neither warmer nor colder surroundings. The experience of the thermal climate partly depends on the two parameters indoor air temperature and indoor air velocity (Dahlblom & Warfvinge, 2010).

2.2.2.1 Indoor air temperature

The Public Health Agency of Sweden gives the general recommendation of an indoor air temperature of 20-24 degrees and 20-26 degrees in summer (Folkhälsomyndigheten, 2014). In dwellings, 21 degrees is usually recommended and used. Research shows that mental performance and work rate decreases with increasing indoor temperature. Optimal temperature is 21 degrees (see figure 1). It is also shown that tiredness increases with increasing indoor temperature. Optimal temperature is about 20-21 degrees (see figure 2). In existing and new dwellings, comfort cooling is rarely used. With increased heat waves due to the climate changes, overheated dwellings are becoming increasingly common. Energy efficient solutions for comfort cooling is therefore important to consider in housing (Svensk ventilation, 2021).

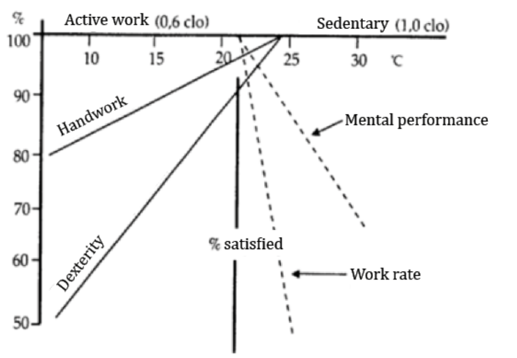


Figure 1. The chart shows how the mental performance and work rate changes with the indoor temperature. (Andersson, 2022).

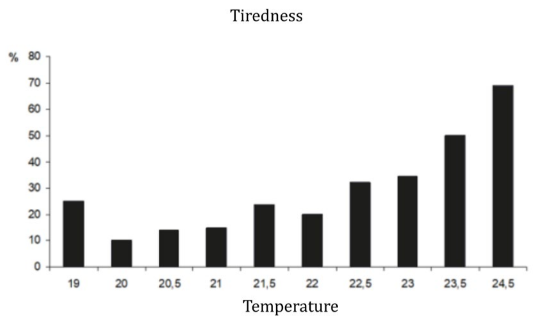


Figure 2. The chart shows how tiredness is affected by the indoor temperature. (Andersson, 2022).

2.2.2.2 Indoor air velocity

In a physical sense, draft means a local cooling of the body which leads to a lowering of the skin temperature. Problems arise when the average air velocity permanently exceeds 0,15 m/s while the operating temperature is between 20 and 24 degrees. Air jets from supply air diffusers and fresh air valves can be a cause of excessive air movements (Dahlblom & Warfvinge, 2010). The lowest possible supply air temperature depends on the size of the airflow and how the supply air is supplied in the room. The more efficient the supply air is mixed into the room air, the lower the supply air temperature can be without people being disturbed by drafts (Häggbom, 2021). According to the general recommendations of Boverket’s building regulations (BBR) the indoor air velocity should not exceed 0,15 m/s during the heating season and 0,25 m/s the rest of the year (Boverket, 2014).

2.2.3 Indoor air quality

Comfort, performance and health also depend on the quality of the indoor air such as carbon dioxide, odors, moisture and air pollution. On average, we spend around 90 % of our time indoors and therefore good air quality is particularly important (Dahlblom & Warfvinge, 2010).

2.2.3.1 Relative humidity

The indoor humidity is controlled by the outdoor humidity because the ventilation air is taken from outside. Relative humidity outdoors varies within a narrow range of 65-90 % during the year while indoor humidity can drop to low levels as 10-20 % in winter. If the relative humidity is low or high, the indoor climate is negatively affected by various factors (see figure 3). An optimal range, where the influence from the factors concerned have less impact, is at a relative humidity of 40-60 % indoors (Dahlblom & Warfvinge, 2010). During winter in Sweden, it is difficult to reach a relative humidity of around 40 % without humidification. A room temperature of 20-21 degrees and a smaller airflow, on the other hand, can keep the relative humidity around 30 % at least. For each degree the room temperature rises, the relative humidity drops by 2 % (Andersson, 1995). Humidification of air for comfort ventilation is now uncommon in Sweden due to the hygiene aspects that place great demands on care and maintenance. In suspended humidifiers, there is a risk of growth and spread of the legionella bacterium (Dahlblom & Warfvinge, 2010).

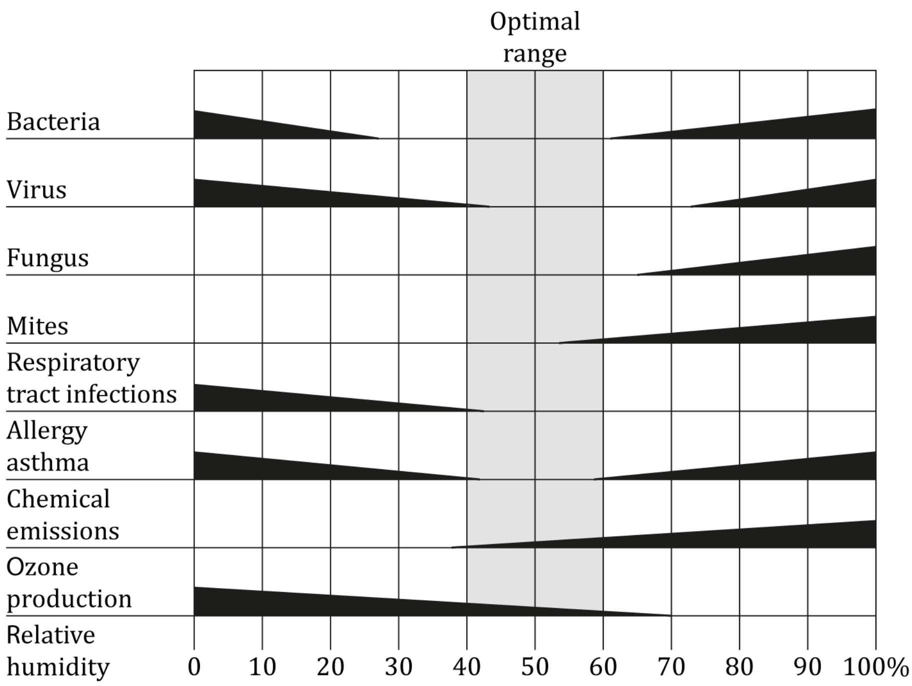


Figure 3. Factors that are affected by relative humidity (RH) and that affect the indoor climate. Redesigned chart (Dahlblom & Warfvinge, 2010).

2.2.3.2 Air pollution

To avoid air pollution or unnecessarily high temperatures being supplied to a building, the location and design of outdoor air intakes must be suitable. The outdoor air intakes are placed so that the impact from exhaust gases and other sources of pollution is minimized. Height above ground, latitude and distance from traffic, exhaust openings and chimneys are considered. The outdoor air is mainly filtered for people's health. To protect human health in places exposed to traffic exhaust fumes or other combustion-related pollutants, filters are needed that can separate small combustion particles, such as soot from diesel exhaust fumes. Filters are also needed to reduce the presence of pollen and pollen allergens indoors (Ekberg et al., 2022).

2.2.4 Noise

Noise and disturbing sounds from ventilation systems are common. In the first place, it is in quiet environments that the ventilation noise is perceived as a problem. Our increasingly well-insulated and airtight buildings attenuate sound from the outside better but increase the requirements for low noise generation from installations. There are three main noise sources in ventilation systems:

- Fans
- Ducts, dampers, bends and dimensional changes
- Supply and exhaust air diffusers.

The dominant noise source are the fans (Dahlblom & Warfvinge, 2010).

2.2.5 Energy efficiency

Energy efficiency means that we use less energy for the same benefit. Reducing energy use can partly be achieved through an improved climate shell in all its parts: walls, roof, floor, windows and doors. And partly by reducing heat losses through the ventilation. The basic driving forces for working with energy efficiency in both new buildings and renovation are governed by environmental goals, finances, security of supply and goodwill/marketing (Energimyndigheten, 2022). The demands for energy efficiency are constantly increasing and in terms of ventilation, BBR places demands on the efficient use of electricity by fans. There are also several recommendations regarding efficiencies of heat recovery (Svensk Ventilation, 2022).

2.2.5.1 Specific fan power (SFP)

Electricity for operation of the ventilation fans constitutes a large part of multifamily dwellings' electricity use (Ekberg et al., 2022). As a measure of the ventilation system's electrical efficiency, the key figure specific fan power (SFP) is used. The lower the SFP number, the less electricity the fans use (Dahlblom & Warfvinge, 2010). According to BBR must building technical installations that require electrical energy such as ventilation be designed so that the power requirement is limited and the energy is used efficiently. BBR gives the general recommendations that the electrical efficiency of ventilation systems should, in the case of dimensioning airflow, not exceed the SFP values in table 4.

Table 4. BBR's general recommendations of specific fan power (SFP).

BBR's general recommendations of specific fan power (SFP)		
FTX	1,5	[kW/(m^3/s)]
FT	1,1	[kW/(m^3/s)]
FTX + C (with cooling)	1,6	[kW/(m^3/s)]
FX	0,75	[kW/(m^3/s)]
F	0,5	[kW/(m^3/s)]

For ventilation systems with varying airflows, smaller airflows than 0,2 m^3/s or operating times shorter than 800 hours per year, higher SFP values may be acceptable (Boverket, 2020).

2.2.5.2 Heat recovery

BBR has no generally stated requirement for heat recovery. On the other hand, requirements are set for the building's specific energy use and there are power requirements for electric heating. The requirement for specific energy use is set so low that this often leads to choosing heat recovery to survive below the acceptable limit. This often means that a ventilation heat exchanger, exhaust air heat pump or any other heat pump is installed. In practice, it can be seen as that
there is an indirect requirement for heat recovery. When using ventilation heat exchangers, it is important to make power and energy calculation based on realistic data. The efficiency specified for the heat exchanger can be difficult to achieve in practice. This can, for example, be due to duct losses, soiling, defrosting or leakage in the heat exchanger (Boverket, 2012).

At EU level, there is a comprehensive ecodesign directive, which in turn has led to several binding ecodesign regulations, one dealing with ventilation units, another with fans and a third with cooker hoods. There is a regulation for a temperature efficiency of at least 73 % for plate- and rotary heat exchangers. (Ekberg et al., 2022). With today's technology, the industry organization Swedish Ventilation recommend a higher temperature efficiency of at least 80 % for rotary heat exchangers (Svensk Ventilation, 2022). The Swedish Energy Agency's buyer's groups, BeBo and BELOK, have also set various industry recommendations where the requirements in BBR have been tightened and/or further developed (Ekberg et al., 2022). In a requirement specification for Procurement of heat recovery systems with FTX-ventilation in existing multifamily dwellings, BeBo recommend at least 80 % temperature efficiency and at least 75 % annual temperature efficiency of heat exchangers (BeBo, 2017). Annual temperature efficiency indicates the calculated annual average value of the heat recovery's temperature efficiency. It is this efficiency that is to be used for further analysis of a building's energy use (Svensk Ventilation, 2013).

2.3 Energy efficiency measures

There are several measures to apply to make ventilation systems more energy efficient. Very energy efficient and profitable measures are some kind of heat recovery and demand and seasonal controlled ventilation (Svensk Ventilation, n.d.).

2.3.1 Heat recovery

The air coming from outside must be warmed to room temperature, which requires a lot of energy. With FX- and FTX-systems, a large part of this energy can be recovered from the exhaust air (Ekberg et al., 2022). Most single-family dwellings today use rotary heat exchangers, but also plate heat exchangers. In multifamily dwellings with a central air handling unit, plate heat exchangers are mainly used to avoid odor transfer between apartments (S. Ruud, personal communication, 30 May 2022).

2.3.1.1 Plate heat exchanger

A plate heat exchanger is made up of plates or plastic sheets with air gaps between each layer. Exhaust air and outdoor air pass through every other duct. The plates are heated by the exhaust air, which in turn heats the outdoor air. Plate heat exchangers are designed as cross-flow exchangers or as counter-flow exchangers. The latter is mostly used today as it has a higher efficiency of around 85 % compared to the 60 % of the cross-flow exchanger. If the moisture supplement indoors raises the dew point temperature of the exhaust air above the coldest surface temperature of the heat exchanger, condensation forms. If the surface temperature is below zero, the condensed water can freeze to ice. Ice formation must be limited as it reduces heat transfer and impedes airflow. This is the biggest disadvantage of the plate heat exchanger (Häggbom, 2021).

2.3.1.2 Rotary heat exchanger

In a rotary heat exchanger, heat is transferred from the exhaust air to the supply air by air passing through a perforated rotor. The rotor is heated by the exhaust airflow and cools down when the heat is transferred to the supply airflow. The efficiency of a rotary heat exchanger is around 85 %. In the same way as in plate heat exchangers, condensation forms on the material surfaces in the rotor if the temperature is lower than the dew point of the exhaust air and if the temperature is lower than zero degrees, ice is formed. Moisture and ice can be dried up by the outdoor airflow. This type of exchanger can thus recover moisture from the exhaust air to the supply air. A gradual accumulation of ice can occur if the outdoor air does not have the capacity to absorb the condensed moisture, but the risk of freezing is small. In case of frost, the exchanger can be defrosted by reducing the rotation speed or by preheating the outdoor air. In the same way that rotary heat exchanger can recover moisture, there is a risk of odors and other substances being returned to the supply air as well. This type of exchanger is therefore usually not used in multifamily dwellings or other mixed activities (Häggbom, 2021).

2.3.1.3 Defrosting and frost protection measurements

The heat recovery process is negatively influenced by freezing and functioning poorly. This leads to lower temperature efficiency when it is cold outdoors and needed the most. This means that a higher energy use is needed at that time and that the indoor climate is negatively affected.

Freezing is dealt with in some more or less efficient ways. In small units with rotary heat exchanger, it is sometimes not dealt with at all, which results in problems. Common defrosting strategies or frost protection strategies are:

• Turning off or blocking the supply air. This will melt the frost, but supply air will instead enter through infiltration and cause drafts and a worse indoor climate. This is a non-working solution for low-energy and airtight housing.

• Bypassing the supply air in the heat recovery unit on the outside of the heat exchanger. This gives low supply air temperatures which gives rise to drafts and poor indoor climate.

• Heating the extract air or pre-heating the supply air.

• Switching airflow direction or switching between heat exchangers in serial. This strategy has been tested but has been difficult to make reliable.

The efficiency of heat recovery is low when using the first three strategies as well as they cause problem. Defrosting is often done unnecessarily and with a too great margin of safety as the manufacturer often has poor knowledge about how and when problems arise (Johansson et al., 2019).

There are a lot of tests going on around the country with so-called Geo-FTX (or originally so-called HSB-FTX) where you preheat the outdoor air with heat from boreholes to avoid frost problems in plate heat exchangers in apartment buildings (S. Ruud, personal communication, 30 May 2022).

The annual temperature efficiency is greatly affected by geographical location, especially for plate heat exchangers (S. Ruud, personal communication, 30 May 2022). When frost problems are worst, heat recovery can be halved (Ekberg et al., 2022).

2.3.2 Heating and cooling with ground duct

Ground ducts use the fact that the earth's temperature is relatively even during the year. By taking in air through a ground duct in winter or summer, the air is heated or cooled (Törnqvist, 2011). A ground duct could be used as a heater or cooler for all ventilation systems. In combination with a FT- or FTX-system the air is taken through the duct before entering the air handling unit (Östin, 2012). In combination with S, FFS, F or FX/FVP-systems the outdoor air is taken in through the duct instead of directly through the wall or roof. The design of a duct system looks different depending on the size of the building. In larger buildings, the air is taken indoors by larger ducts through basements and distributes throughout the building from there. In smaller buildings pipes of smaller dimensions are used directly up into the building (C. Berggren, personal communication, 22 March 2022).

2.3.2.1 System design for small residential buildings

The ground duct system usually consists of an outdoor air intake, filter, dry-well, duct and supply diffusers. The outdoor air is taken in through an intake hood with filter which is placed a bit above the ground to avoid pollutions. At a dimensioned depth in the ground, the air transfer through pipes that are connected to the intake (see figure 4). The ducts are then running a dimensioning distance in the ground to the building. From there, ducts are running up through walls adjacent to rooms that require supply air. Usually, the ducts are run in interior walls or party walls but it is possible to run in the exterior wall if it is insulated correctly. It is advantageous to place ducts in as few interior walls as possible to avoid making several walls thicker and to allow flexibility. All rooms that require supply air can either be run with separate ducts from the inlet to the supply air diffuser or with a shared duct that branches to different rooms. In the case of separate ducts, problems with crosstalk between rooms are avoided and silencers are therefore not needed. In a shared duct a silencer could be used because of crosstalk even if there is no fan. In southern Sweden, the supply air is around 4-5 degrees during the coldest months. It is therefore important to choose good supply air diffusers for mixing the air with the room air to avoid drafts. Late summer, condensation can occur in the ducts. The system is then equipped with a dry well for the condensation water at the outdoor air intake, designed in the same manner as a dry well for stormwater. For the condensed water to collect in the dry well, the ducts are tilted with at least 1 % towards the dry well and the outdoor air intake (see figure 4). The ducts being used can be ordinary drainpipes in plastic with the dimension 110 mm (C. Berggren, personal communication, 22 March, 2022).

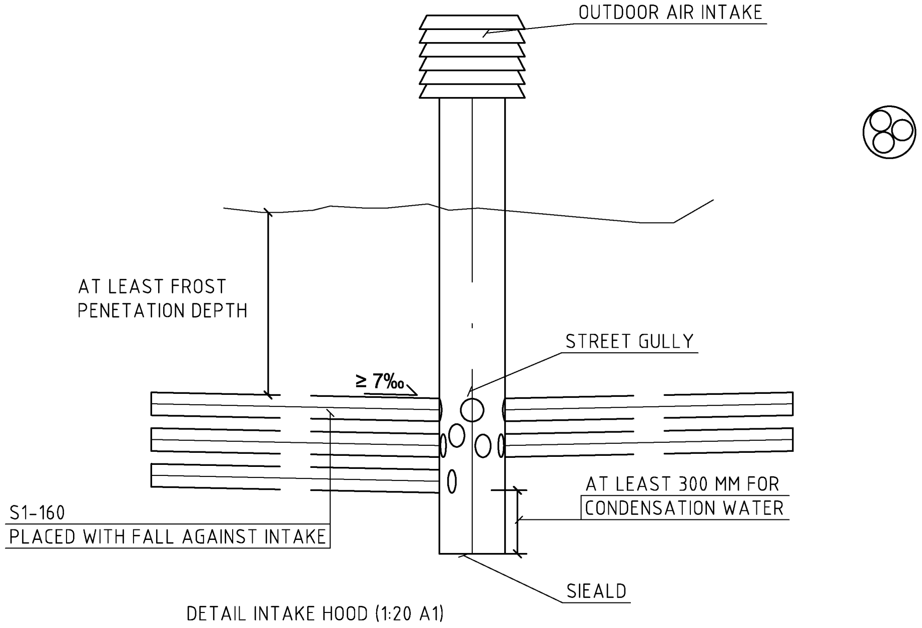


Figure 4. The detail drawing shows a design of an intake hood for a ground duct in smaller buildings. (Berggren, 2022).

2.3.2.2 Materials

Materials such as plastic (PVC and PP), metal and cement may be used for the ducts. Factors that affect the choice of material are cost, pressure resistance, corrosion resistance and durability. The choice of material has not been shown to be so important for heat transfer because convection is the dominant heat transfer and the earth's thermal properties also limits. Plastic pipes are the cheapest option and are the ones that have been used the most (Törnqvist, 2011).

2.3.2.3 Efficiency of ground duct

The efficiency of a ground duct is dependent on the four parameters depth, length, diameter and air velocity. The pipes should be at a depth of at least 1,5-2 meters depending on ground temperature and climate. Placement under the ground frost is recommended to prevent damage to the pipe system when the ground freezes. The depth should not be too deep as it can pose a risk of landslides when laying the pipes and that the system may become unstable. If the pipes are placed too shallow, there is a risk that the cooling/heating effect will not be profitable, especially in hot climates. Studies show that a deeper duct is more efficient but that the efficiency decreases markedly at 3,5 meters or deeper. Lower air velocity in the ground duct increases the temperature difference between inlet and outlet because the air has a longer time to emit or absorb heat. The energy savings will therefore be greater at a lower air speed. Most efficient is to have a long deeply placed ground duct with a small diameter and low air speed. However, investment costs must be weighed against the increase in efficiency when using a longer or deeper placed ground duct. At certain periods of the year when the temperature is within a certain range, a ground duct can give the opposite effect to the desired one, namely the duct cools the air instead of heating it. If it for example is 10 °C outdoors and 5 °C in the ground, the air is cooled to about 6 °C, which means that the supply air needs to be heated even more. This can be fixed with a bypass system for FTX-systems. During these periods, the supply air is taken directly from outside without passing through the ground duct before the air handling unit (Törnqvist, 2011).

2.3.2.4 Maintenance

The duct system needs to be cleaned every year to avoid microbial growth. This is done with advantage in the autumn after the duct has been most exposed to microbial growth. It can be a recommendation to make measurements on microorganisms every 5 years (Beiron, 2010). The ducts are cleaned most easily by flushing the ducts with water. This is done from the supply air intakes (C. Berggren, personal communication, 22 March 2022). The inside of the pipes can be covered by an antimicrobial layer. Nevertheless, the pipes must still be cleaned to prevent the antimicrobial layer from being covered by dirt and thus losing its effect (Törnqvist, 2011). If the duct system has leaks to the ground, ground air with radon can be drawn into the duct, where there is negative pressure. For this not to happen the duct should be followed up with a radon measurement (Beiron, 2010).

2.3.2.5 Performance of ground duct after field measurements

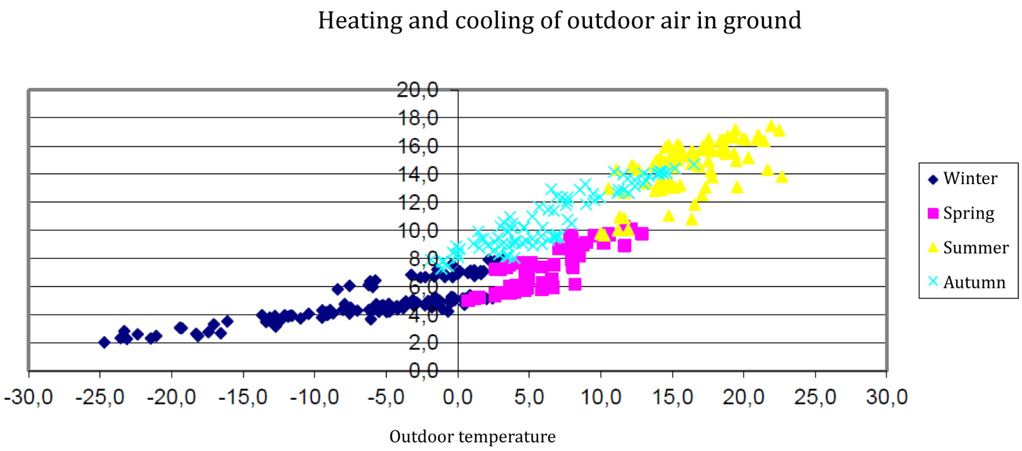


Figure 5. Air temperature after passage of ground duct. Winter: Dec-Mar, Spring: Apr-May, Summer: Jun-Aug and Autumn: Sep-Nov. (Östin, 2012).

Figure 5 shows field measures of the air temperature after passing through a ground duct. The ground duct is 36 meter long and placed in 1,5 meter depth and preheats a villa in Umeå before passing a FTX-system. Of the total length, 24 meter has a diameter of 0,2 meter and 12 meter has a diameter of 0,16 meter and the latter is located below the foundation of the house.

At outdoor temperatures down to -25 °C, incoming outdoor air to the heat exchanger is 2 °C, there is a temperature increase of as much as 27 °C. In winter, the temperature varies between about 2-7 °C and in summer the measured temperature is never higher than 18 °C, there is a cooling effect for outdoor temperatures of about 20 °C and above. The spread in temperatures is noticeable, except at outdoor temperatures lower than about -10 °C and is due to the ventilation being changed manually for different operating modes. The lowest airflow is run in winter, which increases the residence time for incoming outdoor air in the ground duct and so the air temperature. A comparison between spring and autumn (which have the same operating mode) shows that autumn consistently provides better ground preheating, which results in higher air temperatures. This is a consequence of the heat storage which surrounds the supply air duct. The ground is being charged during summer and drained of heat during winter (Östin, 2012).

2.3.3 Demand and Seasonal controlled ventilation

Before mechanical ventilation came, homes and premises were ventilated according to need and season. In winter, windows and air intakes were sealed to not unnecessarily over-ventilate and therefore increase the need for heating, create draft problems and dry air inside. In the summer the air intakes were opened and the windows were used for extra ventilation (Andersson, 1995).

2.3.3.1 Seasonal controlled ventilation

Mechanical ventilation with constant airflows does not consider the temperature differences and varying water content in the air summer and winter. High airflows in winter mean that the relative humidity drops well below the limit that is healthy for humans. Figure 6 gives a theoretical picture of how the relative humidity indoors varies with the season and geographical location. The air change rate is 0,5 oms/h (which is a general recommendation), the indoor temperature 20 degrees and the moisture supply 0 g/m^3 and 3 g/m^3 respectively.

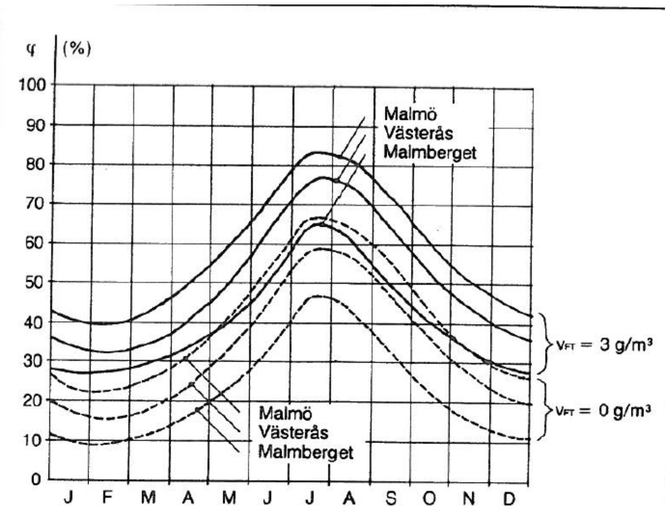


Figure 6. The chart shows how the relative humidity indoors varies with season and geographical location. (Andersson, 1995).

In summer, it can theoretically be very high relative humidity indoors. Extra heavy washing and showering significantly increases the moisture load. With a constant airflow of 0,5 air change rate, the margins will be very small and the risk is great that the relative humidity poses problems by being too high hot summer days of the year and too low cold winter days of the year. The ventilation system should be dimensioned for about 0,3 air changes per hour on cold winter days and up to 1,5 air changes per hour on hot summer days to theoretically end up around 40-60 % relative humidity.

Reduced air change rate in winter results in reduced heating needs and electricity needs for fans. A power reduction is greatest on cold winter days when it is needed the most. A common problem with too high air change rate in winter is a raised room temperature to counteract drafts. Raising the room air temperature makes the relative humidity drops further and gives rise to a drier climate than needed (Andersson, 1995). It is sometimes claimed that air leakage through the building envelope compensates for a reduced ventilation flow, especially in cold weather. However, the extent of the air leakage can in practice vary greatly. Measurements and calculations that have been made indicate that it is not generally justifiable to rely on such an effect (Ekberg et al., 2022).

As already emphasized, the size of the airflow is determined by the requirements for air quality and thermal climate, as well as the size of the internal generation of pollutants and heat. The ventilation always has the task of being responsible for the removal of pollutants so that good air quality is ensured. The internal pollution generation and the requirement for air quality or air purity determine how large the airflow must be at least. In cases where the entire heat surplus is to be removed with air, the airflow is often significantly greater than required to meet the requirements for good air quality. Then it is the requirement, that it should not be too hot, that in practice determines the airflow. In dwellings without seasonal controlled ventilation, the cooling effect is limited as the airflows are not large enough to add any major cooling effects (Ekberg et al., 2022). Adjusting the speed of the fan to the outdoor temperature is a standard control solution that is used in many single-family dwellings and especially in multifamily dwellings (C. Berggren, personal communication, 22 March 2022).

2.3.3.2 Demand controlled ventilation

There is an energy saving potential in using demand controlled ventilation in dwellings. The total heat loss in a house is largely due to the ventilation. With demand control, the heat demand can be reduced by 15–25 % depending on the complexity of the system. Demand control of ventilation means that the ventilation flow is regulated according to the need. In a home, various activities can take place, as cooking, washing, cleaning, showering, watching TV, sleeping, playing, etc. Sometimes no one is home and sometimes many are at home. The need for ventilation is affected by how many people are at home and what activities are going on. Demand controlled ventilation means that this need is measured in some way, in real time, and the ventilation flow is adapted to the measured need. In this way, energy is saved, both heat energy and electrical energy for fans.

The need for ventilation can be measured in different ways with different sensors. It is common to use carbon dioxide sensors (CO2 sensors). CO2 sensors correspond well to how large the load is dependent on human presence. This type of sensor is useful in for example classrooms, lecture halls, conference rooms and offices. However, the load in a home is more complex depending on the many different activities that take place in a home. For example, during showering, washing and cooking, moisture is generated and the moisture load will be the parameter that controls the need for ventilation. During summer, the indoor temperature is often high and on such occasions it is instead the temperature that determines the need for ventilation.

In Sweden, CAV-system is almost always used in dwellings. This means that the airflows are constant during the operating time (Markusson et al., 2018). A ventilation system can either be referred to as a CAV- or VAV-system. CAV stands for Constant Air Volume and VAV stands for Variable Air Volume. There are different divisions within these two classes (Building services engineering, 2016). DCV, Demand Controlled Ventilation is a subcategory to VAV where the airflow is controlled automatically to current needs (see figure 7) (Belok, 2016).

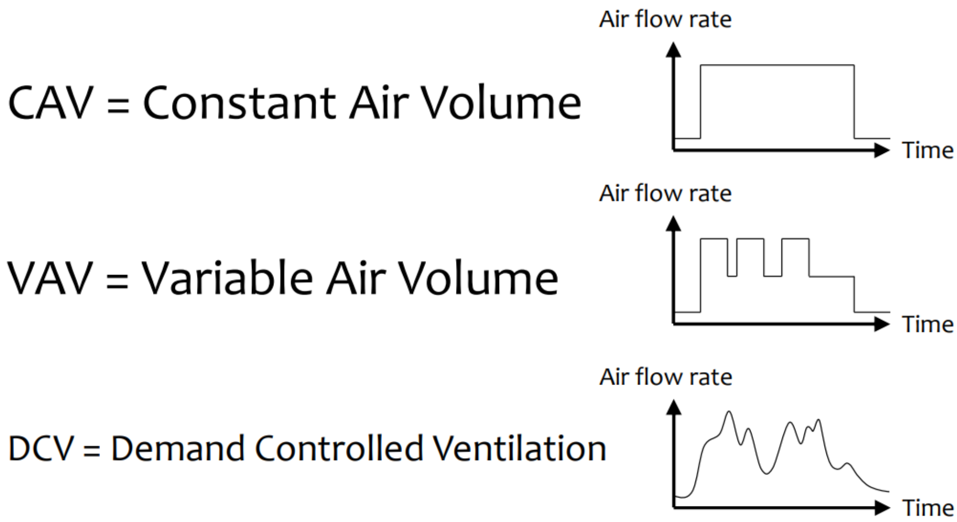


Figure 7. The principle sketch shows how CAV-, VAV- and DCV-system operate. (Building services engineering, 2016).

There are different levels of control strategies in a control system (see table 5).

Table 5. Control strategies.

Ventilation control
Manual control (no DCV)
Clock control (no DCV)
Central demand control
Local demand control
Motor & drive
On/Off & Single speed
2-speed
Multi-speed
Variable speed

The Ecodesign Directive (1253/2014) of the European Union defines the control strategies as (European Union, 2020):

Manual control means *"any control type that does not use demand control"*.
Clock control means *"a clocked (daytime-controlled) human interface to control the fan speed/flow rate of the ventilation unit, with at least seven weekday manual settings of the adjustable flow rate for at least two setback periods, i.e. periods in which a reduced or no flow rate applies"*.

Central demand control means *"a demand control of a ducted ventilation unit that continuously regulates the fan speed(s) and flow rate based on one sensor for the whole ventilated building or part of the building at central level"*
Local demand control means *"a demand control for a ventilation unit that continuously regulates the fan speed(s) and flow rates based on more than one sensor for a ducted ventilation unit or one sensor for a non-ducted unit"*.
Multi-speed drive means *"a fan motor that can be operated at three or more fixed speeds plus zero ('off')"*.
Variable speed drive (VSD) means *"an electronic controller, integrated or functioning as one system or as a separate delivery with the motor and the fan, which continuously adapts the electrical power supplied to the motor in order to control the flow rate"*.

Different control strategies of demand controlled ventilation provide different savings potentials. A more complex control system, where the ventilation to each room can be regulated individually, almost doubles the energy savings compared to a simpler system, where the ventilation is regulated for the entire building. But a more complex system is also significantly more expensive to buy, install, operate and maintain. In addition, it is more complex to get the right pressure balance in the system for each operating mode. The right pressure balance in the system is important to avoid the risk of moisture damage in the building envelope.

The percentage energy savings are apparently large in all demand controlled systems, regardless of control strategy or system design. On closer inspection of the absolute savings in energy (kWh), this is significant in dwellings without heat recovery but more modest in dwellings with heat recovery. Demand controlled ventilation has then a high potential, both economically and energy saving, to be installed in dwellings without heat recovery.

To achieve a sufficiently good indoor climate, the right control parameters must be selected. It is not enough just to choose one parameter of CO2, temperature or relative humidity, a combination of all three is preferable. A scenario where the system is run as a CAV-system during summer and a VAV-system during winter, with CO2 and RH as control parameters can also work. This because overtemperatures during summer will cause ventilation to run at maximum airflow most of the time anyway. However, this depends on what climate the dwelling is located in.

From a technical point of view, demand controlled ventilation systems for dwellings must be developed so that they enable measurement and control of the airflow over a greater airflow range, with better measurement uncertainty and without creating large pressure drops or disturbing sounds. An additional challenge is to make them sufficiently cost-effective, robust and durable at the same time (Markusson et al., 2018).

3 Implementation and Method

A case study is carried out on an ongoing small housing project. The project is in concept phase, installation system and frame system have not been decided yet. A comparison of energy performance and system design between the two ventilation systems FTX and F combined with heating and cooling with ground duct is done. The latter system will henceforth be called FK (Frånluft med Kulvert), meaning exhaust air ventilation with duct. S- and FFS-systems with ground duct are not included in the comparison in this study as natural ventilation is difficult to calculate and a S-system also has poorer performance. The FTX-system is not combined with a ground duct to avoid too many installations and components in the ventilation system.

The system design for the FTX- and FK-system is designed, dimensioned and visualized. The system design includes design of ductwork and air handling unit (AHU).

The energy performance between the two systems is compared with the energy efficiency measure demand and seasonal controlled ventilation. Two FTX-systems, one with plate heat exchanger and one with rotary heat exchanger are investigated as the efficiency differs between the two and therefore also the energy performance. The ventilation systems are compared to a reference case by a conventional F-system. The study investigates four operating modes regarding demand and seasonal controlled ventilation. The modes are a common CAV-system with constant airflow, a SCV-system with seasonal controlled ventilation, a VAV system with variable airflow and a combined case with SCV + VAV. The VAV-system is chosen to be a simple 2-speed manual-controlled system where the ventilation manually can be reduced centrally in the dwelling when the dwelling is not occupied. This simpler system is chosen to simplify calclulations and to avoid too expensive and advanced systems. The F-system with CAV is used as a reference case. A total of 16 combinations are calculated (see table 6). The combinations are calculated for 3 cases:

- Heating demand
- Heating demand + Electricity demand
- Heating demand using a heat pump + Electricity demand.

The first case looks only at the heating demand while the second case looks at both the heating and electricity demand. Since the choice of heating system affects the heating demand this is considered in the third case where a heat pump is used.

Table 6. Calculated combinations.

	F	FK	FTX-P	FTX-R
CAV	1	5	9	13
SCV	2	6	10	14
VAV	3	7	11	15
SCV + VAV	4	8	12	16

3.1.1 Case study

The small housing project is an ongoing project in the ecovillage Utsikten at Orust. The project consists of two residential buildings, one twin house in 1,5 floors and one row house, split in 2,5 and 1,5 floors.

Figure 8. The visualization shows an overview of the housing project.

Figure 9. The visualization shows an overview of the housing project.

3.1.1.1 Prerequisites and Design

The twin house consists of two dwellings with heated floor areas (A_{temp}) of 97 m^2 and 87 m^2 distributed on a ground floor and a loft (see figure 10, 11 and 12). One dwelling is 2 RoK and the other is 3 RoK. Each ventilation system is applied to the one and same dwelling. The 3 RoK in the twin house is chosen where energy performance is calculated and the system design is designed, dimensioned and visualized. The ventilation systems should be designed so that they enable flexibility in the dwellings. The small size of the housing project allows separate ventilation systems to be used for each dwelling.

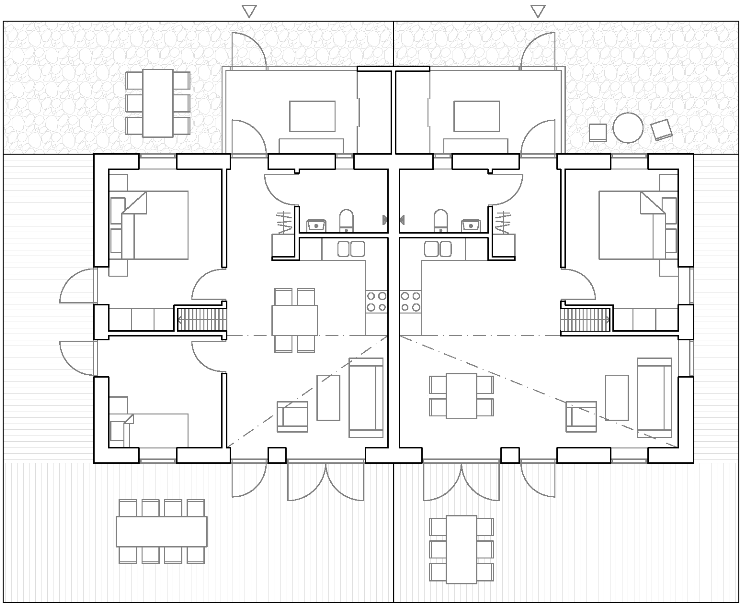


Figure 10. The drawing shows the ground floor plans of the twin house.

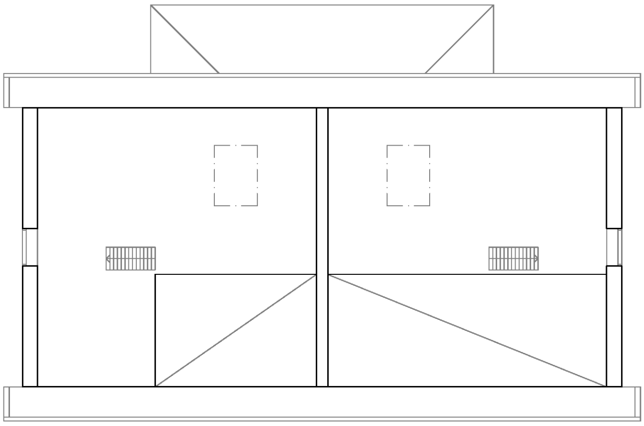


Figure 11. The drawing shows the lofts of the twin house.

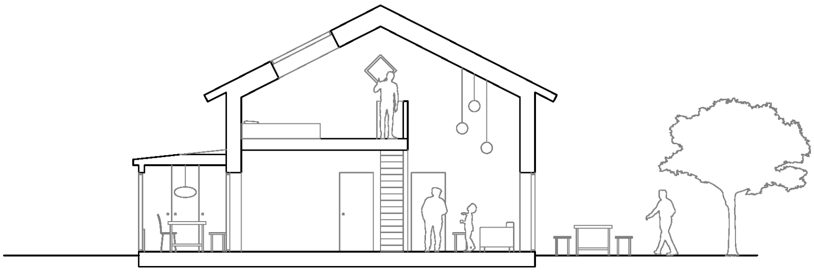


Figure 12. The drawing shows a section of the twin house.

3.2 Energy calculations

Both the energy and the power are calculated for all 16 combinations in each case. The calculations are done manually in Excel. The heating demand is only calculated for the heating season which is considered to be from October to March. The heating season is the period during the year when the heating system is running when the outdoor temperature is lower than the limit temperature.[5] Each month is calculated separately. A common COP[6] (Coefficient Of Performance) of 3 is assumed in the case used with a heat pump.

Parameters determining the energy performance are:

- Efficiencies of heat exchange for
    - Ground duct
    - Heat recovery
- Demand and seasonal control
- Specific fan power (SFP)

3.2.1 Heating demand

The heating demand due to ventilation losses are calculated according to the following equation (Dahlbom & Warfvinge, 2020):

$$P_v = q \cdot \rho_a \cdot c_{p,a} \cdot (1 - \eta) \times (T_i - T_e) \qquad [W] \qquad (1.1)$$

where q [m³/s] is the airflow, ρ_a [kg/m³] is the density of air, $c_{p,a}$ [J/Kg·K] is the specific heat capacity of air, η [-] is the temperature efficiency for heat recovery, T_i [°C] is the indoor temperature and T_e [°C] is the outdoor temperature.

[5] The limit temperature is the temperature the heating system needs to heat to, which is lower than room temperature. The temperature increase to room temperature is covered by heat gains from the sun, people and devices (Dahlbom & Warfvinge, 2020).
[6] COP (Coeffiecient Of Performance) describes the ratio between heat output to the heating system and supplied electrical power to the heat pump (Häggbom, 2021).

The energy demand for each month and the power demand are calculated according to the following equations (Dahlbom & Warfvinge, 2020):

$$P_v = q \cdot \rho_a \cdot c_{p,a} \cdot (1-\eta) \cdot (T_i - T_e) \cdot t \qquad [Wh] \qquad (1.2)$$

$$P_v = q \cdot \rho_a \cdot c_{p,a} \cdot (1-\eta) \cdot (T_i - T_{DVUT}) \qquad [W] \qquad (1.3)$$

where t [h] is the period and T_{DVUT} [°C] is the design winter outdoor temperature. DVUT refers to an average temperature for at least one day depending on the time constant, the thermal inertia of the building (Dahlbom & Warfvinge, 2020). T_i is set to 21 °C. The calculations do not consider the limit temperature. The outdoor temperature uses monthly mean temperatures of Orust (Henån) from climate data files from Sveby (see table 7). T_{DVUT} is -13,5 °C for an assumed time constant of 1 day.

Table 7. Monthly mean temperatures of Orust (Henån).

Month	Monthly mean temperature (°C)
Jan	0,0
Feb	0,5
Mar	1,9
Apr	6,2
May	11,0
Jun	14,5
Jul	18,0
Aug	16,4
Sep	11,9
Oct	8,3
Nov	3,4
Dec	0,6

3.2.1.1 Airflows

The airflow will vary depending on the four operating modes, CAV, SCV, VAV and SCV + VAV. In the CAV mode a basic airflow is used. The dimensioning and basic airflow is determined based on the largest value of airflow per area, air changes per hour, airflow per persons and the total exhaust air according to the requirements of the authorities. In the SCV mode is the airflow per area used in winter and for autumn and spring air changes per hour. In the VAV mode is the airflow reduced to 0,1 l/s m^2 those hours a day when no one is at home. Sveby's user data for dwellings assume that a person is at home 14 hours a day. These values are assumed for a person's heat load. If there are more than one person in the household, it is likely that the persons are not always at home at the same time. Therefore, it is assumed that dwellings are occupied 16 hours a day instead. For these 16 hours a basic airflow is used and for the rest 8 hours is the minimum airflow of 0,1 m^3/s m^2 according to BBR used.

3.2.1.2 Temperature efficiency for heat recovery

The temperature efficiencies for heat recovery are needed to calculate the heating demand. In the study the heating demand for both FTX with plate heat exchanger and

FTX with rotary heat exchanger is calculated. For the FTX with rotary heat exchanger it is assumed that no defrosting is needed and common guide values for the temperature efficiency is used. For the FTX with plate heat exchanger on the other hand, needs defrosting, which means that the annual temperature efficiency is lower than the temperature efficiency. Temperature efficiencies are chosen from guide values in chapter 3.2.5.2 (see table 8).

Table 8. Temperature efficiencies.

	Annual temperature efficiency	Temperature efficiency DVUT
FTX-P	75 %	50 %
FTX-R	80 %	80 %

The defrosting method for the plate heat exchanger is assumed to be two-section bypass where the heat recovery is halved at DVUT according to chapter 3.3.1.3.

The temperature efficiency for the ground duct varies during the year. Monthly mean temperature efficiencies for the duct are calculated in the following chapter.

The ability of a heat recovery unit to transfer heat is described by the temperature efficiency which defines as (Dahlbom & Warfvinge, 2020):

$$\eta_{till} = \frac{(T_{hr} - T_e)}{(T_{ex} - T_e)} \quad (1.4)$$

where T_{hr} [°C] is the temperature after heat recovery, T_e [°C] is the outdoor temperature and T_{ex} [°C] is the exhaust temperature.

3.2.2 Efficiency and dimensioning of ground duct

Following assumptions are made from the literature review to calculate the efficiency and dimensioning the ground duct.

- The duct is located at a depth of 1,5 meters
- The duct is a 110 mm drainpipe in polypropylene (PP)
- There is no snow on the ground
- The duct is partly placed below the house

3.2.2.1 Calculation of undisturbed ground temperature

The outdoor temperature varies periodically on daily and seasonal bases and is described as (Sasic Kalagasidis, 2018):

$$T_{out}(t) = \overline{T_{out}} + T_{out,A} \cdot \cos\left(\frac{2\pi t}{t_p} - \frac{2\pi t_1}{t_p}\right) \quad [°C] \quad (1.5)$$

where $\overline{T_{out}}$ [°C] is the mean temperature, $T_{out,A}$ [°C] is the amplitude, t_p is the period and t_1 is the time delay when the maximum outdoor temperature occurs. $\overline{T_{out}}$, $T_{out,A}$ and t_1 are determined by the monthly mean temperatures of Orust (Henån) in table 7.

The temperature of the ground at smaller depths from the surface varies with the outdoor temperature. The temperature of the ground at distance x from the ground surface is described as (Sasic Kalagasidis, 2018):

$$T_{ground}(x,t) = \overline{T_{out}} + T_{out,A} \cdot e^{-x/d_p} \cdot cos(2\pi \frac{t-t_1}{t_p} - \frac{x}{d_p}) \qquad [°C] \qquad (1.6)$$

where d_p is the periodic penetration depth which describes a distance from the ground surface where substantial variations of the ground temperature occur. d_p is determined as:

$$d_p = \sqrt{\frac{a \cdot t_p}{\pi}} \qquad [m] \qquad (1.7)$$

where a is the thermal diffusivity of the ground which is found as:

$$a = \frac{\lambda}{c_p \cdot \rho} \qquad [m^2/s] \qquad (1.8)$$

3.2.2.2 Calculation of transversal heat loss/gain from ducts in the ground

The temperature of the air at the outlet of the duct is calculated as (Sasic Kalagasidis, 2018):

$$T_f(L) = T_{f,inlet} \cdot e^{-L/l_c} + T_{amb} \cdot \left(1 - e^{-L/l_c}\right) \qquad [°C] \qquad (1.9)$$

where L [m] is the length of the duct, $T_{f,inlet}$ [°C] is the air temperature at the inlet, T_{amb} [°C] is the mean ambient temperature of the ground and l_c [m] is the characteristic length.

$T_{f,inlet}$ is set to the outdoor temperature calculated in equation (1.5) and T_{amb} is set to the ground temperature calculated in equation (1.6). The length of the duct iterates to achieve an air temperature close to the ground temperature at the outlet. The characteristic length is the ratio of the heat transfer through the duct by the heat loss from the duct to the surrounding found as (Sasic Kalagasidis, 2018):

$$l_c = \frac{\dot{m}_f \cdot c_{pa}}{\alpha \cdot L_c} \qquad [m] \qquad (1.10)$$

where $\dot{m}_f$ [kg/s] is the mass flow rate of the air, c_{pa} [J/(kg·K)] is the specific heat capacity of the air, α [W/(m^2·K)] is the thermal coupling coefficient (thermal transmittance) and L_c [m] is the circumference of the duct. The thermal coupling coefficient is calculated as (Sasic Kalagasidis, 2018):

$$\alpha = \frac{1}{R_{duct\_in} + R_{duct\_wall} + R_{duct\_out}} \qquad [W/m^2 \cdot K] \qquad (1.11)$$

where R_{duct_in} [m²·K/W] and R_{duct_out} [m²·K/W] are surface resistance at inner and outer wall of the duct while the thermal resistance through the duct wall is (Sasic Kalagasidis, 2018):

$$R_{duct\_wall} = \frac{ln(\frac{r_i+t_w}{r_i})}{\lambda_w \cdot 2\pi} \qquad [m^2K/W] \qquad (1.12)$$

where r_i [m] is the inner radius of the duct, t_w [m] the thickness of the duct wall and λ_w [W/m·K] is the thermal conductivity of the duct wall.

3.2.3 Calculation model in COMSOL

The undisturbed ground temperature is used as the mean ambient ground temperature when calculating the temperature of the air at the outlet of the duct in equation (1.9). The undisturbed ground temperature does not consider the thermal pillow, the warm region just below the house that is created by heat losses from the house (Hagentoft, 2001), or the heat exchange between the outdoor air transferred in the duct and the surrounding ground. To see how these two phenomena affect the ambient ground temperature around the duct, this is modelled and simulated in the software COMSOL Multiphysics version 6.0. COMSOL performs numerical calculations using the finite element method. The calculations are made as transfer in solids.

3.2.3.1 Geometry

The model is done in 2D to simplify calculations. The geometry consists of three separated solid areas, which in COMSOL is referred to as domains. A rectangle with the dimensions 20×15 m (see figure 13). A ground depth of 15 meters is chosen because temperatures below about 10 meters are stabilized. A ground surface of 20 meters is chosen for the ability to calculate both the ground temperature at the duct and the undisturbed ground temperature in the same study (then neither the thermal pillow nor the duct does affect the undisturbed ground).

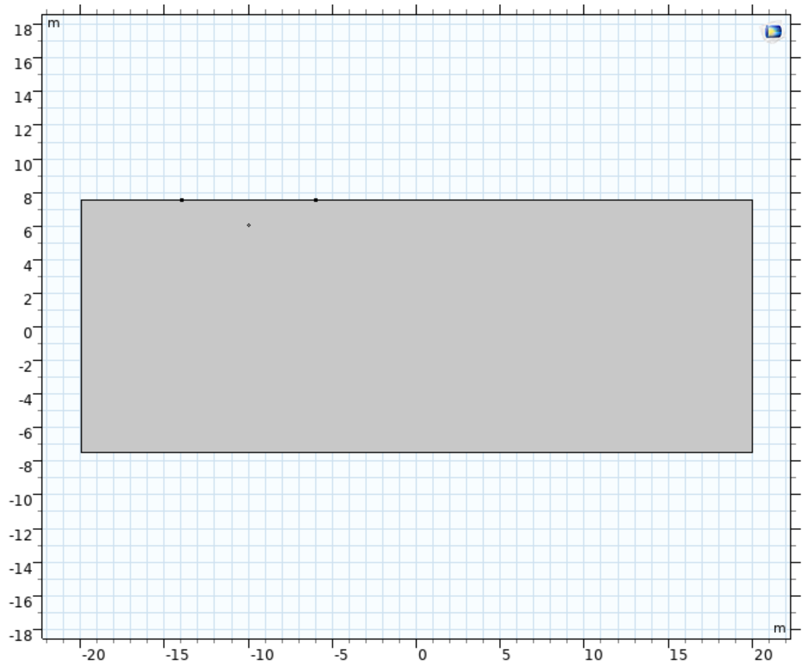


Figure 13. 2D model of the ground duct in COMSOL.

The duct is drawn as a hollow circle placed in the center of one half of the rectangle (see figure 14).

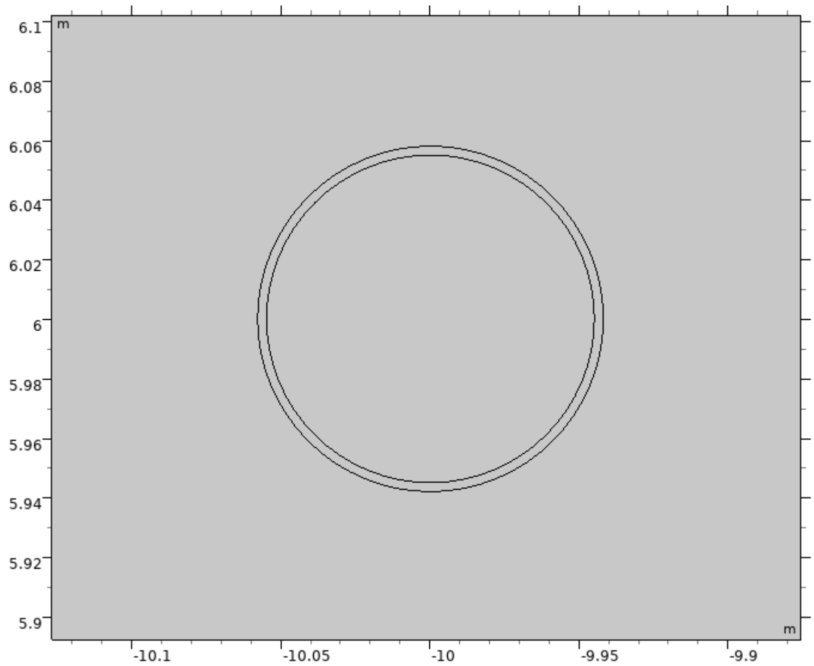


Figure 14. Zoomed in ground duct in 2D model in COMSOL.

3.2.3.2 Material

The domains consist of three different materials, clay, polypropylene (PP) and air. The material properties used are presented in table 9.

Table 9. Material properties.

	Density (kg/m³)	**Thermal conductivity** (W/m·K)	**Specific heat capacity** (J/kg·K)
Clay	2244	1	870
PP	900	0,2	1700
Air	1,2	0,025	1000

3.2.3.3 Initial values

To obtain initial values for the transient simulation, a stationary case is first run. All three domains obtain the temperature $\overline{T_{out}}$, the mean outdoor temperature as initial values.

3.2.3.4 Boundary conditions

The outer boundary conditions for the two sides and the bottom (see figure 15) are thermally insulated which means that there is no heat flow across the boundaries, the study is semi-infinite.

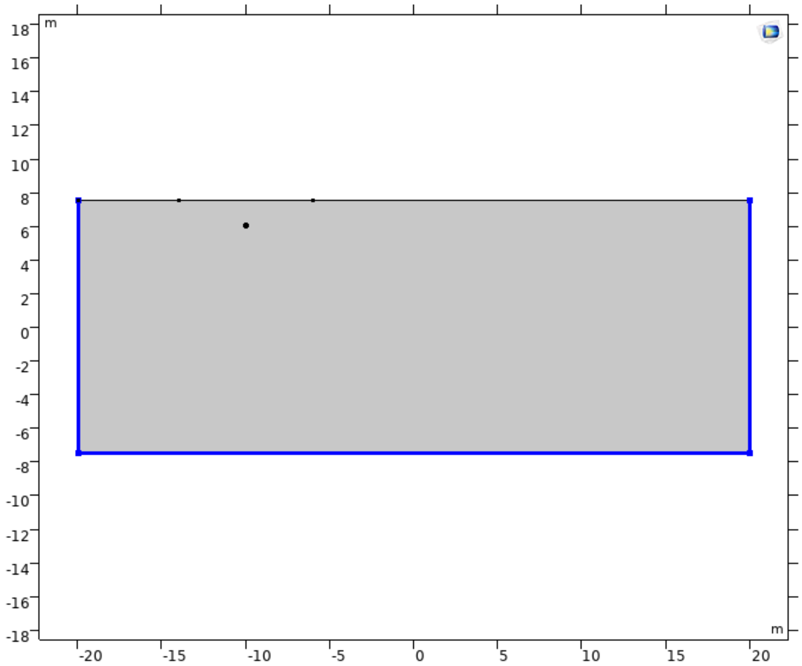


Figure 15. Outer boundary conditions in 2D model in COMSOL.

The ground surface, the top boundary, is divided into three sections. The boundary of the outer sections (see figure 16) is set to $T_{out}(t)$ according to equation (1.5).

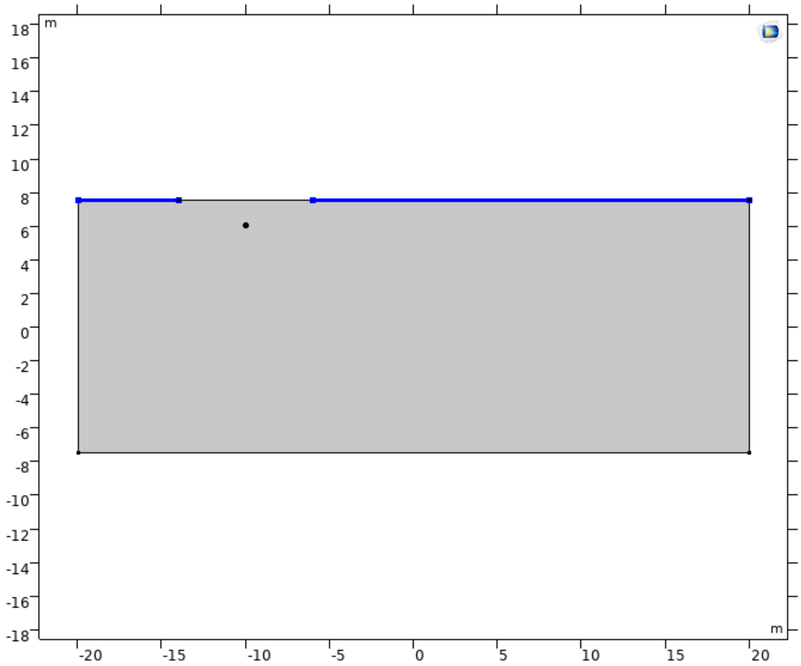


Figure 16. Top (ground surface) boundary conditions of outer sections in 2D model in COMSOL.

The middle section (see figure 17) is the width/length of the house and is placed symmetrically above the duct. This boundary is set to T_{in}, the indoor temperature.

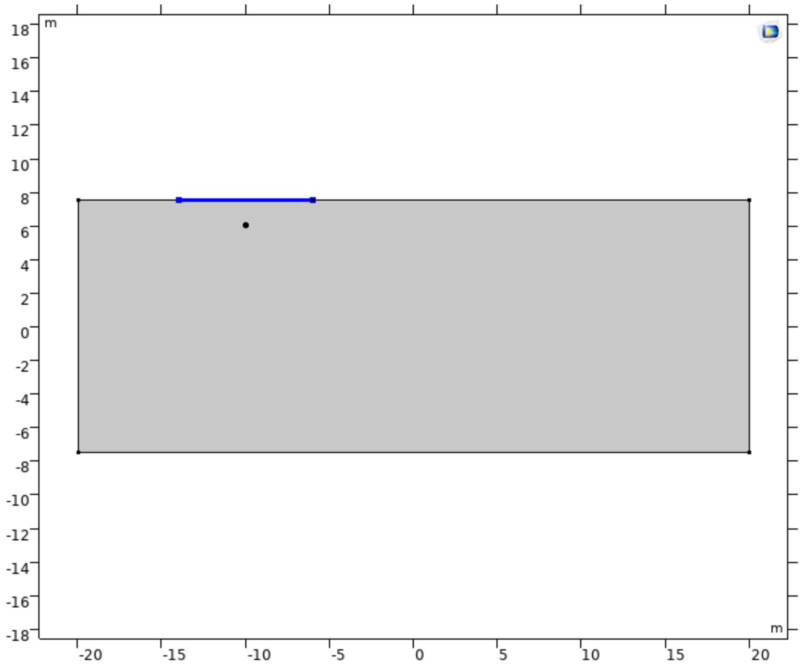


Figure 17. Top (ground surface) boundary conditions of middle section in 2D model in COMSOL.

The boundary condition of the inner circle (see figure 18) is set to the mean temperature of the air along the duct described as (Sasic Kalagasidis, 2018):

$$\bar{T}_f = T_{amb} + (T_{f,inlet} - T_{amb}) \cdot \frac{l_c}{L} \cdot (1 - e^{-L/l_c}) \qquad [°C] \qquad (1.13)$$

Equation 1.13 is adapted to a cosine curve according following equation:

$$\bar{T}_f(t) = \bar{T}_f + T_{f,A} \cdot cos\left(\frac{2\pi t}{t_p} - \frac{2\pi t_1}{t_p}\right) \qquad [°C] \qquad (1.14)$$

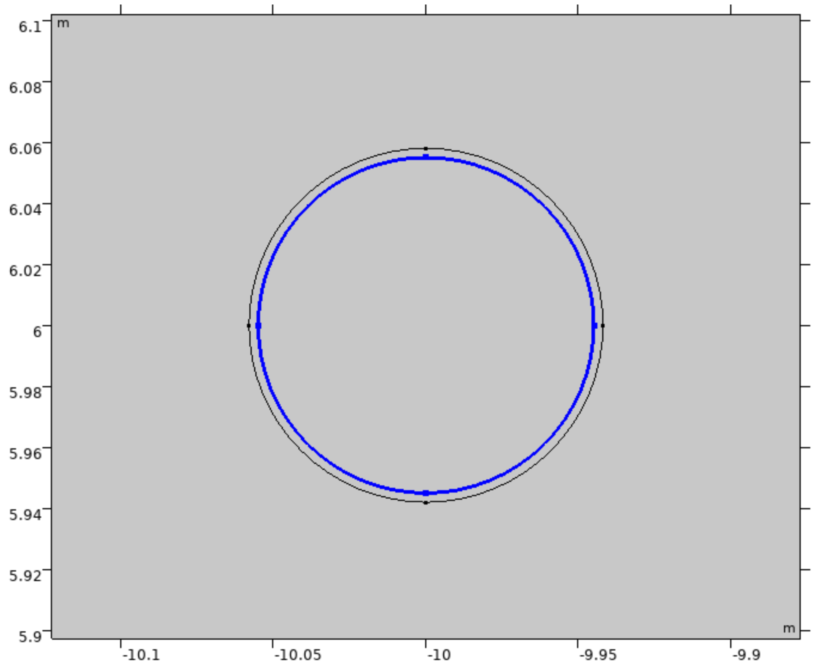


Figure 18. Boundary condition of the inner circle in 2D model in COMSOL.

3.2.3.5 Range

The simulation is a time dependent study. The simulation is run for three years to obtain a steady-state result. The time steps are days.

3.2.3.6 Results

To see the impact from the thermal pillow and the outdoor air transferred in the duct, the ground temperature at the duct is read close to the duct, in this case at a point 10 cm from the duct. The undisturbed ground temperature is read in the right part of the rectangle, in this case in the middle of the right part.

3.2.4 Electricity demand

The fan power is determined as (Dahlbom & Warfvinge, 2020):

$$P = \frac{\Delta p \cdot q}{\eta} \qquad [W] \qquad (1.15)$$

where Δp [Pa] is the total pressure drop and η [-] is the total efficiency of the fan which is assumed to be 0,5. In this study, the calculations are simplified by not calculating the total pressure drop for the ventilation systems. Instead, recommended guide values for SFP are used according to BBR to calculate the fan power. The relation between SFP and fan power is determined as (Dahlbom & Warfvinge, 2020):

$$SFP = \frac{\sum P_{total}}{q_{max}} \qquad [kW/(m^3/s)] \qquad (1.16)$$

where P_{total} [Pa] is the total fan power and q_{max} [m^3/s] is the largest airflow. As there are no guide values for SFP for FK-systems the SFP is calculated based on the guide value of a F-system. The additional pressure drop in a FK-system compared to a F-system is assumed to be the pressure drop of the ground duct. The pressure drop in straight duct sections at turbulent flow is determined as (Dahlbom & Warfvinge, 2020):

$$\Delta p = \frac{\lambda \cdot l}{d} \cdot \frac{\rho \cdot v^2}{2} \qquad [Pa] \qquad (1.17)$$

Where λ [-] is the coefficient of friction, l [m] is the length of the duct, d [m] is the diameter of the duct, ρ [kg/m^3] is the air density and v [m/s] is the air velocity. The air velocity is calculated from the following ratio between airflow and air velocity (Dahlbom & Warfvinge, 2020):

$$q = v \cdot A_{cs} \qquad [m^3/s] \qquad (1.18)$$

where A_{cs} [m^2] is the cross section of the duct. The coefficient of friction depends on the internal roughness of the duct which for polypropylene is 0,45. Since the calculations are based on SFP values, the same fan power is used for all operating modes, even though they vary. This is a chosen simplification.

4 Results

In this chapter are the results of efficiency and performance of ground duct, energy performance and system design presented.

4.1 Efficiency and performance of Ground duct

The ground duct is dimensioned according to table 10.

Table 10. Dimensions of ground duct.

Dimensions of ground duct	
Diameter of duct	110 [mm]
Length of duct	30 [m] (Computed in calculation)
Depth in ground	1,5 [m]

4.1.1 Undisturbed ground temperature

The undisturbed monthly mean ground temperature at a depth of 1,5 meter can be seen in figure 19. The temperature varies between 3,1 °C and 12,3 °C. The lowest and highest temperature occurs in February and August. The curve is shifted one month in relation to the outdoor temperature. This is because the heat is charged and stored in the ground in the summer and drained in the winter. The ground is warmer than the outdoor air from September to March and colder from March to September. Due to the storing of heat during summer the ground is warmer in the autumn than during spring. In winter the heat is released so in spring the ground is then drained of heat. The duct therefore has a better efficiency in autumn and winter. For the air at the outlet of the duct to be heated to ground temperature, the duct needs to be about 30 meters.

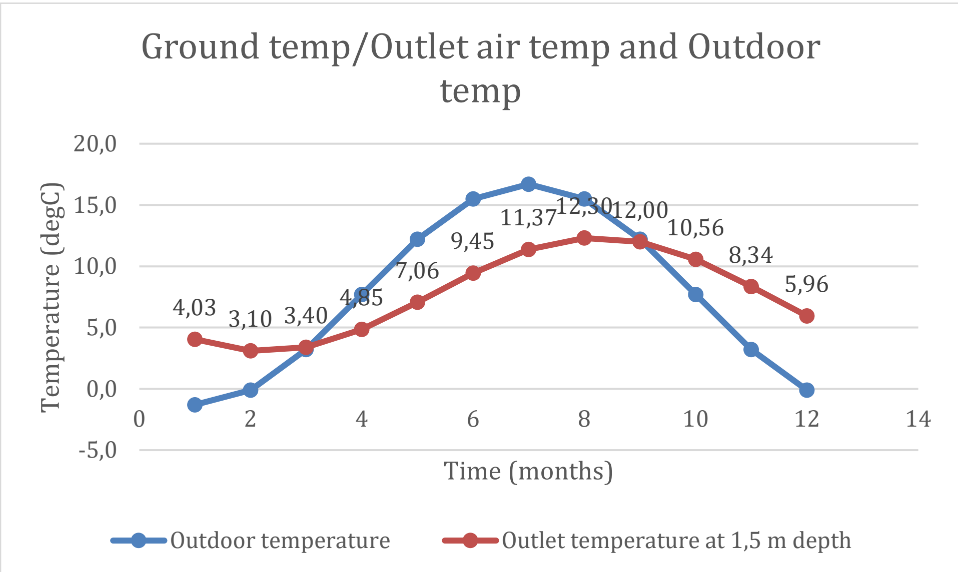


Figure 19. The graphs show the ground temperature/outlet air temperature of ground duct at a depth of 1,5 meters compared to the outdoor temperature.

4.1.2 Disturbed ground temperature

The disturbed ground temperature was calculated for the outdoor air transferred through the duct and the thermal pillow. The impact the outdoor air transferred through the duct has on the ambient ground temperature is modest. The air degrades the duct's efficiency marginally (see figure 20). Therefore, this is neglected in the calculations of the outlet air temperature of the duct.

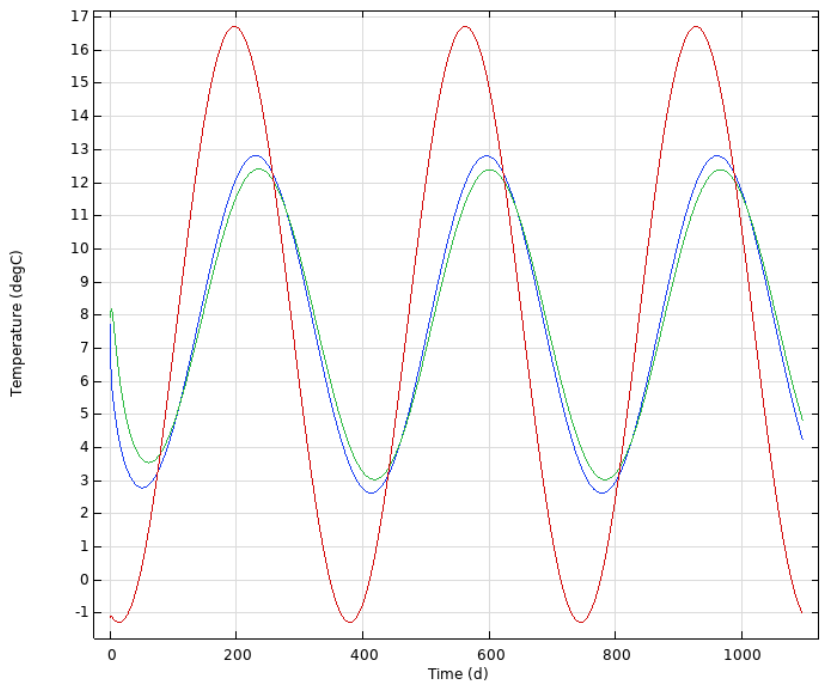


Figure 20. The graphs show the disturbed ground temperature of the outdoor air transferred through the duct compared to the undisturbed ground temperature. The blue graph shows the disturbed ground temperature, the green graph shows the undisturbed ground temperature and the red graph show the outdoor temperature.

The impact the thermal pillow has on the ambient ground temperature is large and positive (see figure 21). The impact of the thermal pillow is not taken into consideration in the calculation of the outlet air temperature in the duct either. In this case is the heat that heats the air in the duct increased transmission losses from the house. The thermal pillow can thus be seen as the equivalent of a supply air radiator for a F-system. The thermal pillow does not reduce the heating demand but increases thermal comfort with increased supply air temperatures. In the simulation, the entire duct is assumed to be below the house. In practice, the duct will only be placed partly below the house, which in turn impairs the thermal pillows impact on the outlet air temperature. Snow-covered ground in winter insulates the ground and can therefore increase the ground temperature as well but this has not been considered in the study.

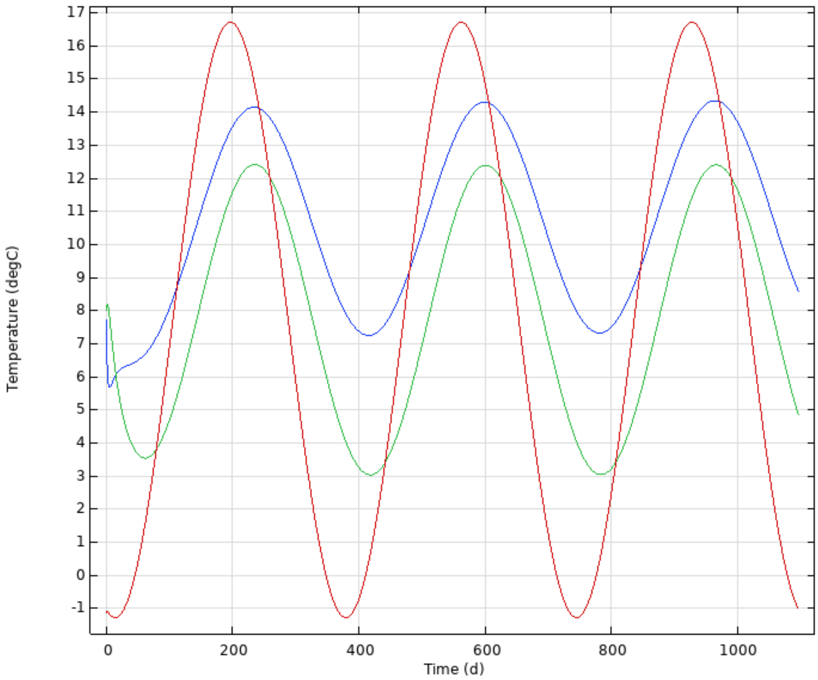


Figure 21. The graphs show the disturbed ground temperature of the outdoor air transferred through the duct combined with the thermal pillow compared to the undisturbed ground temperature. The blue graph shows the disturbed ground temperature, the green graph shows the undisturbed ground temperature and the red graph show the outdoor temperature.

4.1.3 Temperature efficiency

The calculated temperature efficiencies are based on the undisturbed ground temperature as the disturbed ground temperature, due to the impact of the outdoor air transferred through the duct and the thermal pillow, has no effect on the total heat demand of a building. During the heating season the duct adopts the temperature efficiencies according to table 11. The duct has the highest efficiency in November and December of almost 30 %. The efficiencies decrease month to month from January to March as the heat storage is decreasing and eventually is drained. Due to the heat storage during summer, the duct has as good efficiency in autumn as in winter. In March, the duct has no effect. The mean temperature efficiency of the ground duct during the heating period is 20 %. The duct has the best efficiency during DVUT of 51 %. The efficiency of the duct increases with decreasing temperatures. The duct therefore performs the best when it is needed the most.

Table 11. Temperature efficiencies of ground duct.

Month	**Temperature efficiencies (-)**
Jan	0,23
Feb	0,15
Mar	0,01
Oct	0,21
Nov	0,28
Dec	0,28
Oct-Mar (mean value)	0,20
DVUT	0,51

4.2 Energy performance

The energy and power demand for each ventilation system, FK- and FTX-system, is calculated with the input data in table 12, 13 and 14. The results are compared to the reference case of a F-system with constant air volume (CAV).

Table 12. Annual temperature efficiencies for each ventilation system.

Ventilation system	Annual temperature efficiency (%)	DVUT efficiency (%)
F	0	0
FK	20 (during heating season)	51
FTX-P	75	50
FTX-R	80	80

Table 13. Airflows for each operating mode.

Operating mode	Airflow (l/s m^2)
CAV	38
SCV *Autumn* *Winter* *Spring*	 38 34 38
VAV	29
SCV + VAV *Autumn* *Winter* *Spring*	 29 26 29

Table 14. Specific fan power (SFP) for each ventilation system.

Ventilation system	SFP (kW/(m^3/s)
F	0,5
FK	0,6
FTX	1,5

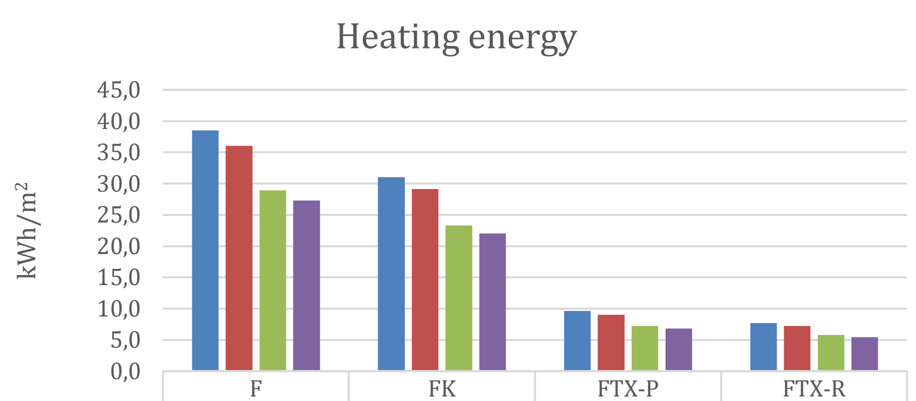
4.2.1 Energy demand

The energy demand is calculated for the three cases:

- Heating energy demand
- Heating energy demand + Electrical energy demand
- Heating energy demand using a heat pump + Electrical energy demand.

4.2.1.1 Heating energy demand

Figure 22 shows the heating energy demand for the four ventilation systems and the impact of the four operating modes. The FTX-systems have significantly better energy use due to the high heat recovery compared to the F-system and a FK-system of 20 % temperature efficiency. The seasonal controlled ventilation (SCV) has a small impact on the energy use as dwellings are dimensioned for small airflows unlike premises. There are no big differences in airflows during winter, autumn and spring. The VAV-system has the greatest impact on the ventilation systems, especially on the F- and FK-systems. Each operating modes have the same percentage effect on each ventilation system, but the effect measured in saved kilowatt hours (kWh) differs much. The operating modes have a much greater effect in saved kWh on the F- and FK-system compared to the FTX-system where the saved kWh are few. This is because the energy demand is already low for the FTX-system thanks to the high heat recovery. The heating energy demand for a FK-system is just over 3 times as large as for a FTX-system. The SCV mode saves 6 % energy, The VAV mode saves 25 % and the SCV + VAV mode saves 29 %.



	F	FK	FTX-P	FTX-R
CAV	38,5	31,0	9,6	7,7
SCV	36,0	29,1	9,0	7,2
VAV	28,9	23,3	7,2	5,8
SCV + VAV	27,3	22,0	6,8	5,5

Figure 22. The chart shows the heating energy demand for each ventilation system and operating mode.

4.2.1.2 Electrical energy demand

Figure 23 shows the electrical energy demand for each ventilation system. A FTX-system has about 3 times as much electricity use as a F-system and about 2,5 times as much as a FK-system due to a higher specific fan power (SFP).

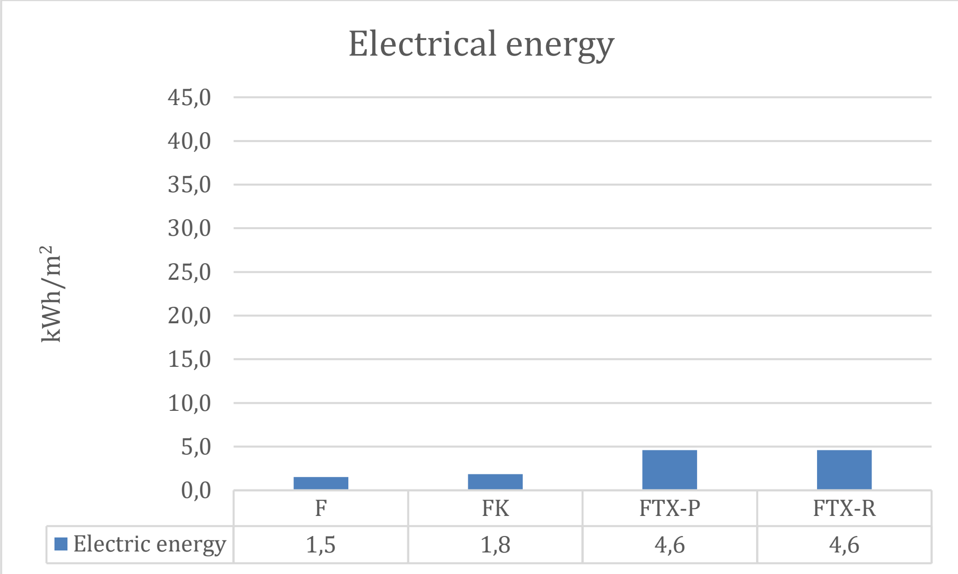


Figure 23. The chart shows the electrical energy demand for each ventilation system.

Figure 24 shows the heating energy demand with SCV + VAV and the electrical energy demand. The electrical energy demand accounts for about half of the energy demand for an FTX-system but constitutes a very small part in a F- and FK-system.

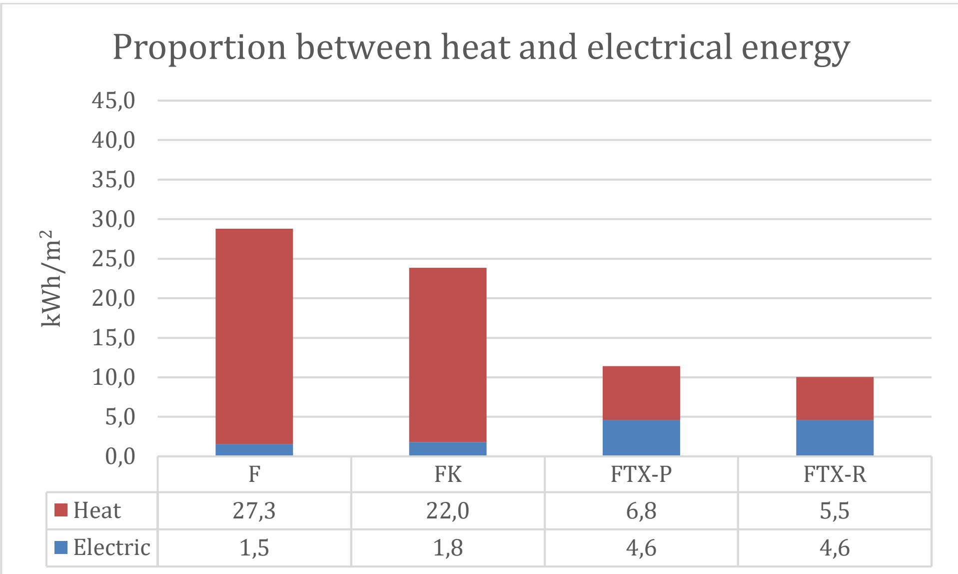
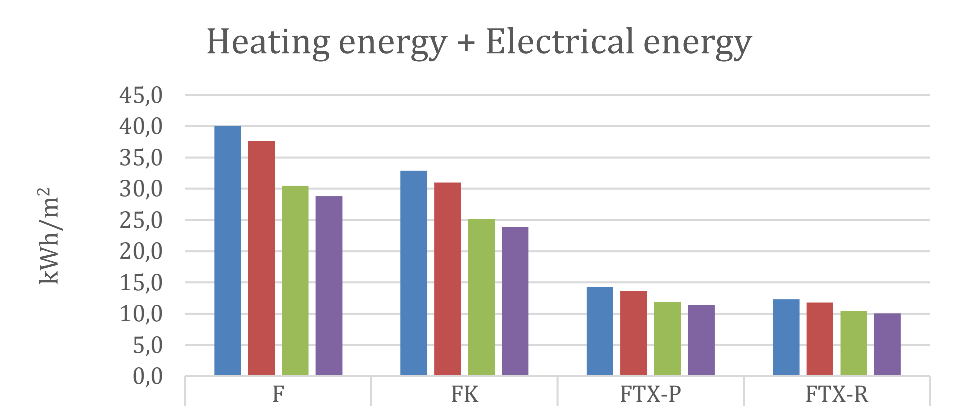


Figure 24. The chart shows the proportion between the heat energy demand with operating mode SCV + VAV and the electrical energy demand.

4.2.1.3 Heating energy demand and electrical energy demand

Figure 25 shows the heating energy demand and the electrical energy demand for each ventilation system and operating mode. Due to higher electricity use, the energy use between the FTX- and FK-system decreases. A FK-system is just over twice as much in energy use compared to a FTX.

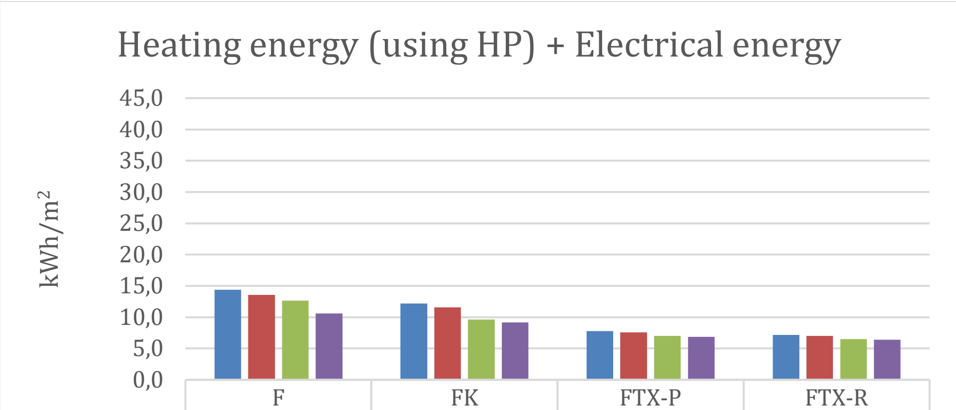


	F	FK	FTX-P	FTX-R
CAV	40,1	32,9	14,2	12,3
SCV	37,6	31,0	13,6	11,8
VAV	30,5	25,1	11,8	10,4
SCV + VAV	28,8	23,9	11,4	10,1

Figure 25. The chart shows the heating and electrical energy demand for each ventilation system and operating mode.

4.2.1.4 Heating energy demand using a heat pump and electrical energy demand

Figure 26 shows the heating energy demand using a heat pump (with a COP of 3) and the electrical energy demand. The heat pump has a great impact on the F- and FK-systems. In the SCV + VAV mode only about 4 kWh energy differs between the FTX-R- and F-system compared to 28 kWh in CAV mode and no heat pump. The energy use between a F- and FK-system is modest. A F-system with ground duct and demand and seasonal controlled ventilation using a heat pump saves 77 % energy and 31 kWh. A FTX-R-system saves 48 % energy but only 6 kWh.



	F	FK	FTX-P	FTX-R
CAV	14,4	12,2	7,8	7,2
SCV	13,5	11,5	7,6	7,0
VAV	12,6	9,6	7,0	6,5
SCV + VAV	10,6	9,2	6,9	6,4

Figure 26. The chart shows the heating and electrical energy demand using a heat pump for each ventilation system and operating mode.

4.2.2 Power demand

Figure 27 shows the heating power demand for each ventilation system. The dimensioning heating power demand at DVUT is halved using a FK-system compared to a F-system. The duct is most efficient when it is needed most and the efficiency increases with decreasing temperatures. The FK-system and FTX-P-system have the same heating power demand because heat recovery is halved when there is a need for defrosting for the FTX-P. The FTX-system with rotary heat exchanger performs the best as it can maintain the same temperature efficiency all year round.

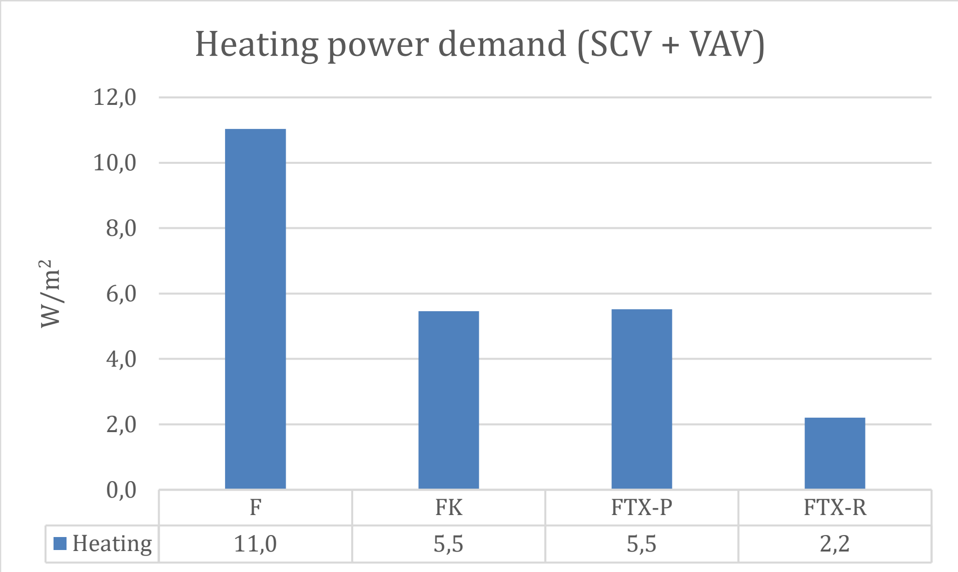


Figure 27. The chart shows the heating power demand with operating mode SCV + VAV for each ventilation system.

Figure 28 shows the electrical power demand for the ventilation systems. The electrical power demand is 2,5 times higher with FTX but, the electrical power is a small proportion of the total power demand (see figure 29).

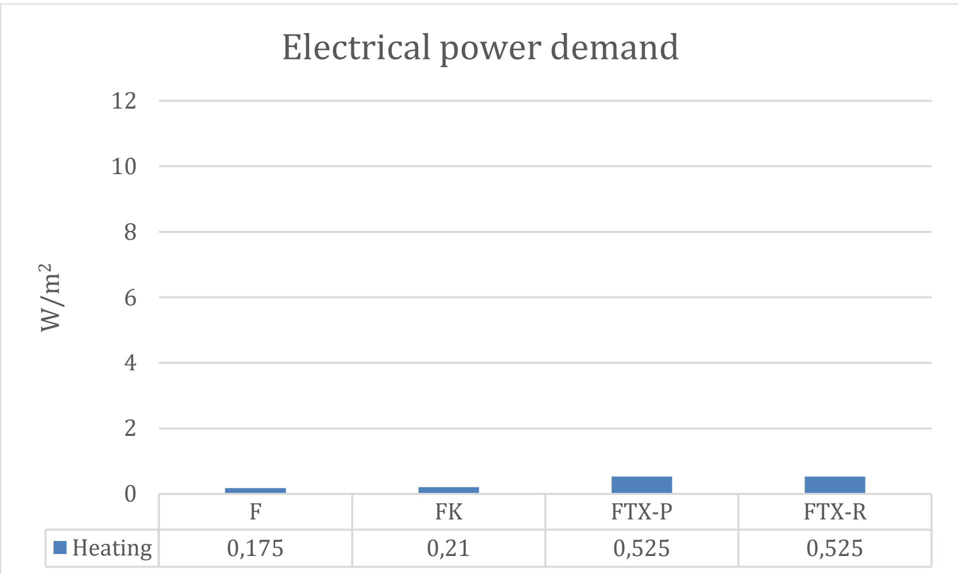


Figure 28. The chart shows the electrical power demand for each ventilation system.

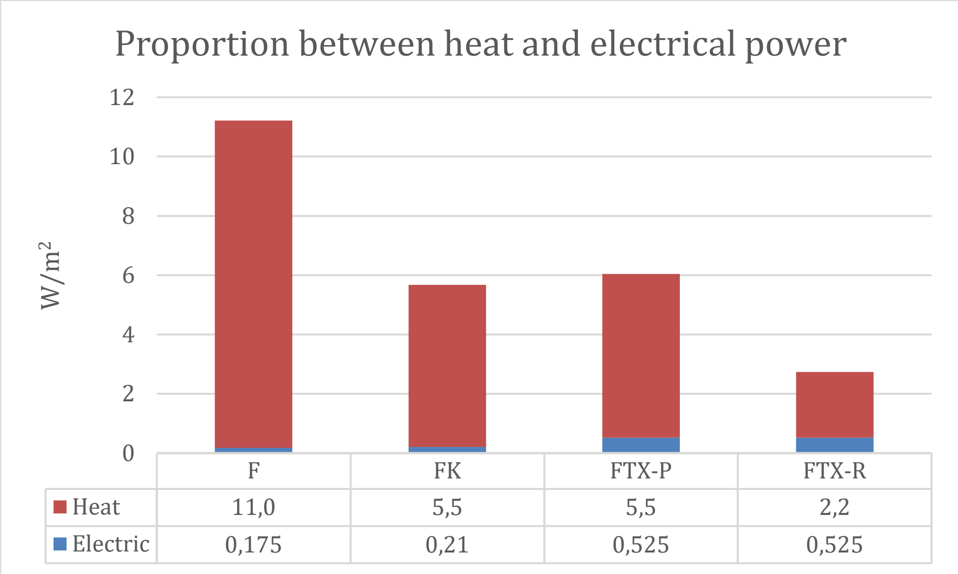


Figure 29. The chart shows the proportion between heat and electrical power with operating mode SCV + VAV for each ventilation system.

Figure 30 shows the total power demand and because of the slightly less electrical power demand the FK-system is slightly better than the FTX-P. The FTX-R, on the other hand, has half the power demand compared to the FK- and FTX-P-system.

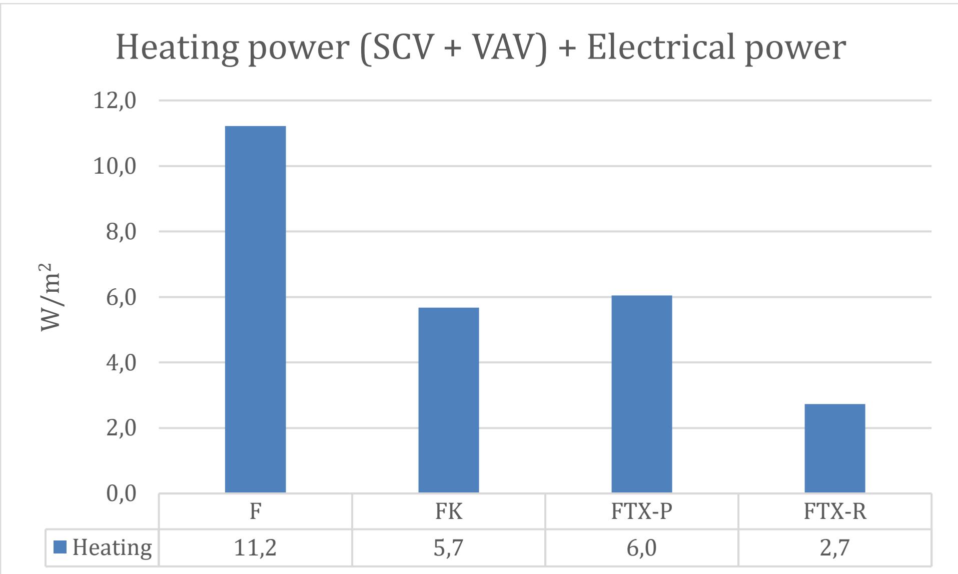


Figure 30. The chart shows the total power demand (heating power with operating mode SCV + VAV and electrical power) for each ventilation system.

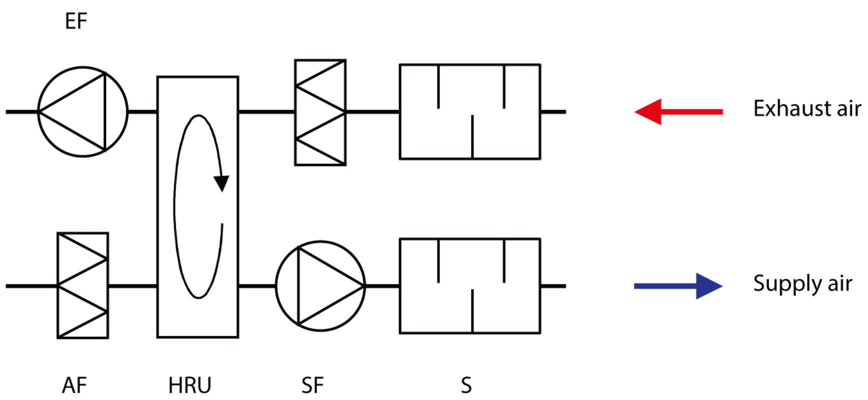
4.3 System design

The system design, air handling unit and ductwork, of a FK- and a FTX-system is presented in this chapter.

4.3.1 FTX-system

4.3.1.1 AHU

Figure 31 shows the air handling unit (AHU) and its components for a FTX-system. The system needs a double set of components, one set for the supply air side and one for the exhaust air side. The air handling unit consists of air filters, heat recovery unit, supply and exhaust fan and silencers.



AF	Air filter
HRU	Heat recovery unit
SF	Supply fan
S	Silencer
EF	Exhaust fan

Figure 31. The schematic shows an air handling unit and its components for a FTX-system.

4.3.1.2 Ductwork

Figure 32 shows the ductwork of the FTX-system in the dwelling. The air handling unit is chosen to be installed in the kitchen as a spice rack unit, which means that the unit is placed over the stove as an integrated wall cabinet, together with a cooker hood. All ductwork passes through the unit to be treated in the heat recovery unit. The outdoor air is taken into the facade through the intermediate floor. The supply air is running through the intermediate floor to the two bedrooms and the living room. The supply air to the loft is running through the party wall. The extract air is running through the intermediate floor from the bathroom and the kitchen to the air handling unit. The exhaust air is running through the party wall and exits through a roof hood.

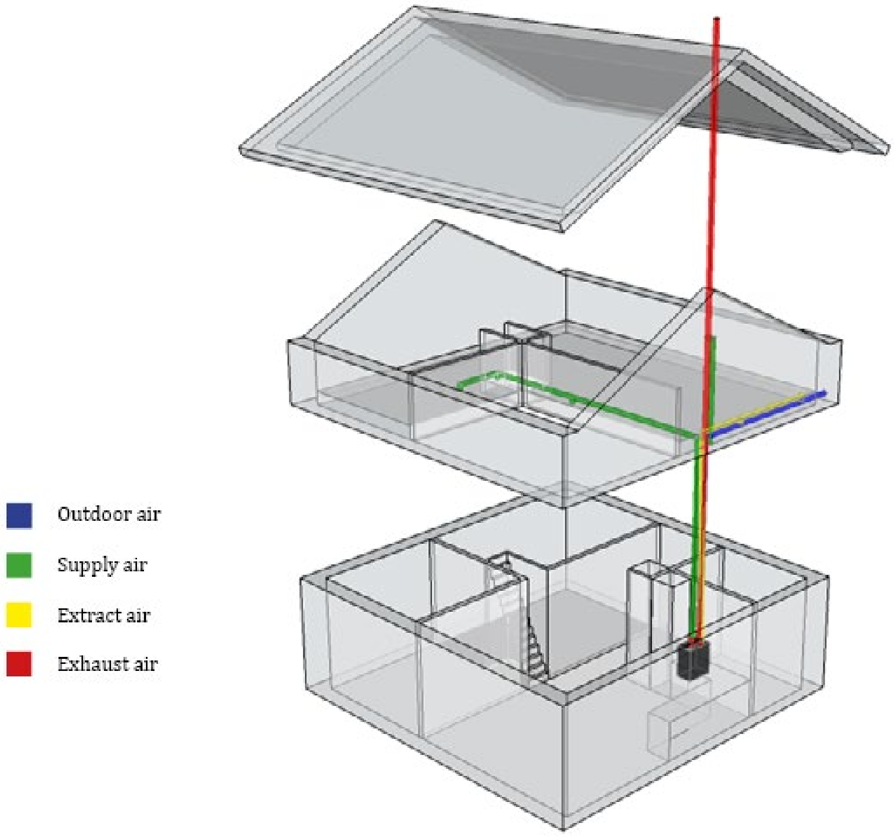


Figure 32. The principle sketch shows the placement of the air handling unit and the ductwork in the dwelling for a FTX-system.

4.3.2 FK-system

4.3.2.1 AHU

Figure 33 shows the air handling unit (AHU) and its components for a FK-system. In a FK-system, the supply air is treated by the duct with free energy and without any mechanics. In summer, the duct dehumidifies and cools the air and in winter the duct heat the air to some extent. The exhaust air side only consists of a fan and silencer. An air filter is only used on the supply side to ensure air quality. In a FTX-system an air filter needs to be used on the exhaust side as well to ensure that no particles enter the heat recovery unit.

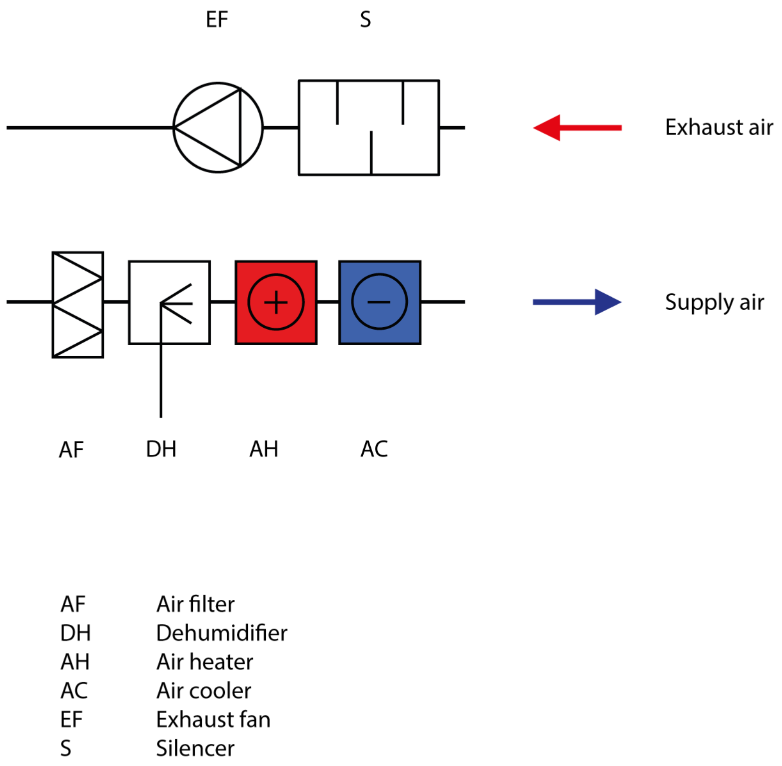


Figure 33. The schematic shows an air handling unit and its components for a FK-system.

4.3.2.2 Ductwork

Figure 34 shows the ductwork of the FK-system in the dwelling. The distribution of air is running through ducts both on the supply and the exhaust air side. The air intake with air filter is placed in the housing project's common garden at some distance above the ground where the air is cleanest in the area. From there four pipes are running 30 meters at 1,5 meters depth in the ground to the house. The pipes are pulled directly up from the ground into the interior wall between the two bedrooms. Each pipe is running to the two bedrooms, the living room and one pipe continues up to the loft with supply air. Separate pipes are chosen to avoid crosstalk and all pipes are placed in one and the same wall to increase flexibility and then only one wall needs to be a bit thicker. The exhaust air is running from the bathroom and the kitchen through the party wall and exits through a roof fan.

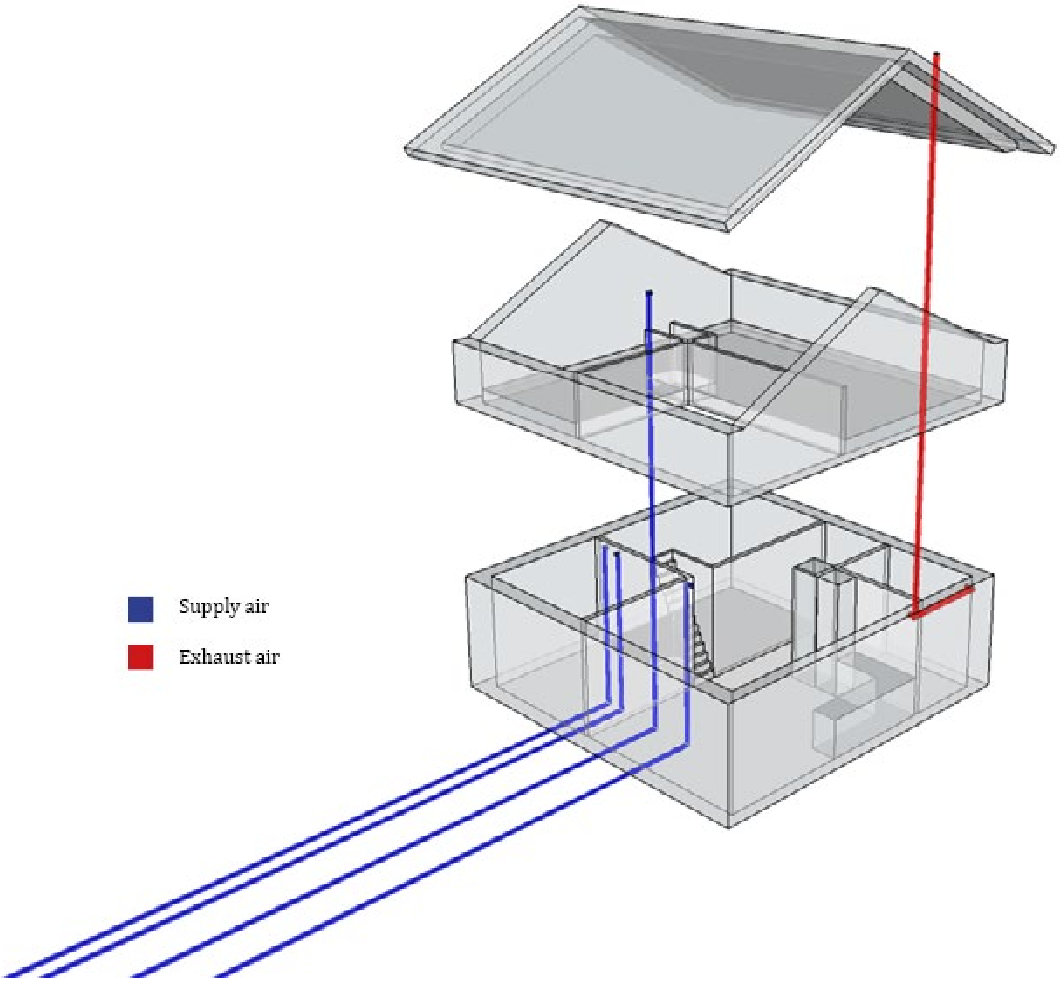


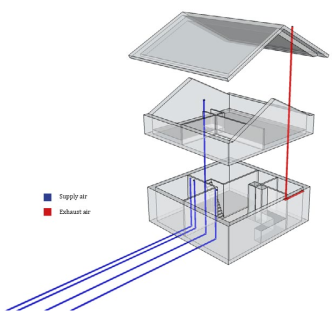
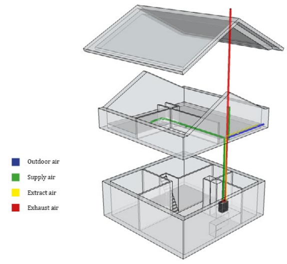
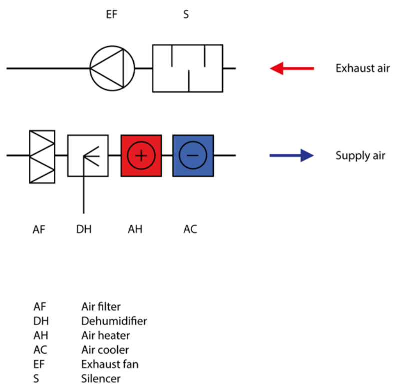
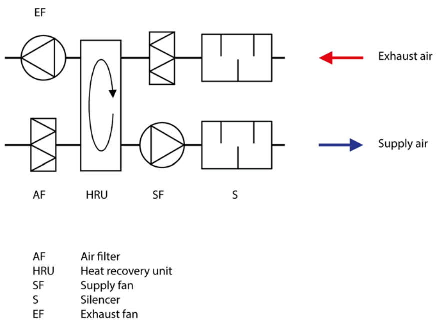
Figure 34. The principle sketch shows the ductwork in the dwelling for a FK-system.

4.4 Compilation and comparison

A compilation and comparison between FK- and FTX-ventilation with demand and seasonal controlled ventilation is seen in table 15. The compilation and comparison are made based on the 3 indicators system design, energy performance and indoor climate and their sub-indicators:

- System design
  - Ductwork
  - AHU
  - Space requirement
- Energy performance
  - Energy demand
  - Power demand
- Indoor climate
  - Air quality
  - Thermal comfort
  - Comfort cooling
  - Noise

Table 15. Compilation and comparison of FK- and FTX-ventilation with demand and seasonal controlled ventilation.

Indicators	**FK-ventilation**	**FTX-ventilation**
	System design	
Ductwork		
AHU		
Space requirement	A FK-system has no physical air handling unit as the air is treated with passive heating, cooling and dehumidification in the ground duct. The system requires lots of ductwork running in the ground and walls. Ductwork should preferably be running in as few walls as possible to increase flexibility. An intake hood on the ground is required for each dwelling.	A FTX-system requires an air handling unit which is placed most efficiently as a spice racket solution over the stove or over the washer and dryer. The system requires lots of ductwork running in walls and intermediate floors or dropped ceilings.
Maintenance	The ground duct system needs to be cleaned once a year to avoid microbial growth. Measurement	The duct system and components in the air handling unit need maintenance for the ventilation system to work efficiently. Unit

	of microorganisms are recommended every 5 years. Radon measurement in the duct system should be followed up to ensure that the duct has no leaks. Exhaust air ducts need to be inspected and cleaned up to every six years and exhaust air diffusers should be cleaned 1-2 times a year. Exhaust fans without filters need to be inspected and cleaned once a year. Filter should be replaced 1-2 times a year.	components must be checked and maintained and filters must be changed regularly, 1-2 times a year. The intake part of the supply air duct needs to be inspected and cleaned more often as this air is not filtered. Supply and exhaust air diffusers need to be cleaned a few times a year.
Energy performance		
Energy demand *(Heating period oct-mar)*	23,9 kWh/m^2 *Saving: 40 %* ______________________________ 9,2 kWh/m^2 *(with heat pump)* *Saving: 77 %*	10,1-11,4 kWh/m^2 *Saving: 75 %* ______________________________ 6,4-6,9 kWh/m^2 *(with heat pump)* *Saving: 83-84 %*
Power demand *(at DVUT)*	5,7 W/m^2 *Saving: 49 %*	2,7-6 W/m^2 *Saving: 46-76 %*
Indoor climate		
Air quality	Good air quality is provided if the system is designed, operated and maintained correctly. Seasonal controlled ventilation is a prerequisite for good air quality to maintain prescribed relative humidity.	Good air quality is provided if the system is designed, operated and maintained correctly. Seasonal controlled ventilation is a prerequisite for good air quality to maintain prescribed relative humidity.
Thermal comfort	Good thermal comfort is provided if good supply air diffusers is used that mix the supply air with the room air to avoid drafts. Seasonal controlled ventilation is a prerequisite for good thermal	Good thermal comfort is favorably provided without post-heater to maintain prescribed room temperature and if good supply air diffusers is used that mix the supply air with the room air to avoid drafts.

	comfort to favor comfort cooling and to avoid drafts.	Seasonal controlled ventilation is a prerequisite for good thermal comfort to favor comfort cooling and to avoid drafts.
Comfort cooling	Yes, cooling air in ground ducts can cover the entire cooling need in case of excess temperatures if seasonal controlled ventilation is used.	No passive/free cooling.
Noise	No disturbing noise as there is no supply air fan. No need of silencer for crosstalk if separated ducts are used to each room.	There are known problems with noise in air supply systems such as self-sound generation from supply air diffusers and supply air fans always emit a low noise.

5 Discussion

A FK-system (ground duct) has an average temperature efficiency of about 20 % during heating season (oct-mar). The energy saving potential of a ground duct is therefore significantly lower than for a heat recovery unit of 75-80 % annual temperature efficiency. A duct, on the other hand, is most efficient at low and high temperatures and therefore has the capacity to evens out power peaks. A duct halves its power demand during DVUT and have thus the same power demand as a FTX-system with a plate heat exchanger, which is in need of defrosting. A duct therefore performs the best when it is needed the most in contrast to a heat recovery unit in need of defrosting. The efficiency of a duct varies during the year. A ground duct is more efficient in autumn than in spring because of heat storage in the ground during summer and depletion of heat during winter. The low efficiency during spring could be compensated with solar gains as spring has more hours of sunshine than autumn, if the building is designed based on these conditions. This might be considered when using ground ducts. A ground duct has a supply air temperature of at least 3-4 °C during winter (in south of Sweden) but depending on how large part of the duct that is placed below the building, the supply air temperature can be raised a few degrees, thanks to the thermal pillow below the building. A FK-system has a lower supply air temperature than a FTX-system due to lower temperature efficiency but with a correct design of supply air devices the thermal climate will not be affected. As it has been shown that there may be problems with microbial growth in ducts it is assumed in the case study that the ducts are inspected and cleaned regularly according to recommendations to avoid microbial growth and ensure good air quality.

The results shows that the energy demand between a FK- and a common F-system is modest but seen from other aspects mention above, there are several reasons to advocate a FK-system. A FK-system has about a halved power demand and contributes to a better thermal climate with comfort cooling in summer and higher supply air temperatures in winter compared to a F-system with supply of cold outdoor air temperatures, which often causes problems with drafts.

A simplified calculation method based on monthly means and guide values proves to be sufficient to provide reliable results for comparing the energy performance of the ventilation systems. The results in kWh and W can, however be both better or worse but are reliable in relation to each other. If a coefficient of performance (COP) above 3 would have been used for the heat pump, the energy demand would instead be lower for a FK-system.

6 Conclusion

The aim of the present research was to evaluate and compare system design and energy performance of Termite ventilation and FTX-ventilation with demand- and seasonal controlled ventilation in small residential buildings, with regard to ensuring a good indoor climate. The study has shown that exhaust air ventilation with ground duct (FK-ventilation) is a suitable type of Termite ventilation for small residential buildings and was therefore chosen to be compared with FTX- ventilation.

The system design of a FK- and FTX-system requires lots of ductwork running in walls and floors, or as for a FK-system mostly in the ground. A FK-system has no physical air handling unit as the air is treated with passive heating, cooling and dehumidification in the ground duct. Both systems ensure a good thermal climate and air quality if designed, operated and maintained correctly. In addition, a FK-system automatically provides free comfort cooling and dehumidification in summer. There are also known problems with noise for FTX-systems unlike FK-systems.

The energy performance of the ventilation systems largely depends on the choice of heat exchanger for a FTX-system and choice of heating system. The energy demand of a FTX-system during heating season is more than 50 % lower than a FK-system but when using a heat pump it is about the same depending on the coefficient of performance (COP) of the heat pump. A FTX-system with plate heat exchanger and a FK-system has about the same power demand meanwhile a FTX-system with rotary heat exchanger has about 50 % lower.

Demand- and seasonal controlled ventilation has a great impact on FK-systems but is modest in FTX-systems. A simpler VAV-system saves about 25 % energy while seasonal controlled ventilation only saves about 6 %. Still seasonal controlled ventilation is necessary for all ventilation systems to provide a better indoor climate. A lower airflow during winter increases the relative humidity indoors and an increased airflow during summer helps preventing over temperatures. Seasonal controlled ventilation in combination with ground duct has the potential to cover the entire cooling demand.

The energy demand is not the decisive factor in the choice of ventilation system, if using a heat pump. Then there are other indicators that determine the choice of system such as power demand, maintenance, user-friendliness, indoor climate, cost, etc. FK-ventilation with demand- and seasonal controlled ventilation has potential to be used more extensively in the same manner as a FTX-ventilation, if designed, operated and maintained correctly.

6.1 Further research

- Calculate and compare a life cycle assessment (LCA) and a life cycle cost (LCC) for a FK- and FTX-system.
- Calculate the efficiency and the energy saving potential of a ground duct with and without seasonal controlled ventilation for cooling demand.
- Compare calculations and field measurements of performance and efficiency for one and the same ground ducts.
- Perform field measurements of microbial growth on multiple ground ducts.

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