Potential of Ventilation Radiators:

Performance assessment by numerical, analytical and experimental investigations

Doctoral Thesis

by

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Imagine there was a combined heating and ventilation system that could help us lower energy consumption in the world, and at the same time ensure a comfortable, healthy indoor climate...

And imagine that the system was simpler - and more user friendly - than any other system on the market…

Abstract

Energy consumption for heating and ventilation of buildings is still in 2011 considered far too high, but there are many ways to save energy and construct low energy buildings that have not been fully utilised. This doctoral thesis has focused on one of these - low temperature heating systems. Particular attention has been given to the ventilation radiator adapted for exhaust-ventilated buildings because of its potential as a low energy consuming, easily-operated, environmentally-friendly system that might also ensure occupant health and well-being.

Investigations were based on Computational Fluid Dynamics (CFD) simulations and analytical calculations, with laboratory experiments used for validation.

Main conclusions:

- Low and very low temperature heating systems, such as floor heating, in general create an indoor climate with low air speeds and low temperature differences in the room, which is beneficial for thermal comfort. A typical disadvantage, however, was found to be weakness in counteracting cold down-flow from ventilation air supply units in exhaust-ventilated buildings.
- with ventilation radiators, unlike most other low temperature systems, it was found that the risk of cold draught could be reduced while still maintaining a high ventilation rate even in cold northern European winters.
- ventilation radiators were found to be more thermally efficient than traditional radiators.
- design of ventilation radiators could be further modified for improved thermal efficiency.
- at an outdoor temperature of -15 °C the most efficient models were able to give double the heat output of traditional radiators. Also, by substituting the most efficient ventilation radiators for traditional radiators operating at 55 °C supply water temperature, it was found that supply water temperature could be reduced to 35 °C while heat output remained the same and comfort criteria were met.
- lowering the supply water temperature by 20 °C (as described above) could give combined energy savings for heating and ventilation of 14-30 % in a system utilising a heat pump.
- supply water temperatures as low as 35 °C could increase potential for utilising low temperature heat sources such as sun-, ground-, water- or waste-heat. This would be particularly relevant to new-built “green” energy-efficient buildings, but several advantages may apply to retrofit applications as well.
- Successful application of ventilation radiators requires understanding of relevant building factors, and the appropriate number, positioning and size of radiators for best effect. Evaluation studies must be made at the level of the building as a whole, not just for the heating-ventilation system.

This work demonstrated that increased use of well-designed ventilation radiator arrangements can help to meet regulations issued in 2008 by the Swedish Department of Housing (Boverket BBR 16) and goals set in the Energy Performance of Buildings Directive (EPBD) in the same year.

Preface/Acknowledgement

Fluid and Climate Technology is a division at the Royal Institute of Technology in Stockholm (KTH), where I have had the privilege to contribute to the work of creating a sustainable environment by developing energy efficient heating and ventilation systems. This doctoral thesis combines previously published licentiate work on ventilation radiators carried out at the School of Technology and Health (KTH STH) with new findings from work carried out at the School of Architecture and Built Environment (KTH ABE). Throughout the work the aim has been to achieve energy savings without compromising thermal comfort, ventilation levels or other health aspects of the indoor environment.

The project was made possible by financial support from the Swedish Energy Agency (Energimyndigheten), Haninge Kommun, Rettig Heating ICC and IVT Industrier AB. Their contributions are gratefully acknowledged. I would also like to thank my supervisor Professor Sture Holmberg for his confidence in me and for his enthusiasm. He supported me not only as a PhD student but also as a sportsman in orienteering, which was very encouraging and made me work all the harder. I would also like to thank my other colleagues at KTH for teamwork, support and for being good friends, in particular Adnan Ploskic, for the constant flow of knowledge passing my way as we sat in our office having daily discussions about HVAC-systems and heat transfer mechanisms. In addition, my thanks go to Jan-Erik Nowacki of the Swedish Heat Pump Association (SVEP), Nowab and KTH, for support and help in the mentor4research program, a program made to help researchers commercialise their ideas. I also wish to thank Heather Robertson for improving on my English, and thereby boosting my confidence when presenting my work.

Further thanks must also go to people within the industry. First and foremost, Jerry Borander at Acticon AB, who called one day, gave support through the rest of my work and inspired me to continue with ventilation radiators even after my studies. I look forward to continuing with these constructive discussions in the future. I must also thank Fredrik Bergner at Flomerics Nordic AB, Jim Fredin at IVT AB and Mikko Iivonen at Rettig ICC, all with great expertise in the various areas covered, who have taken time to teach me just what I needed to know in their respective fields.

The border between work and spare time has often been indistinct during the last six years, and so I wish to thank my orienteering colleagues for their patience, and above all my family for being so understanding over all the time I have spent at my computer.

Jonn Are Myhren

List of papers

This doctoral dissertation is based on the following papers:

Journal papers

Paper 1 Flow patterns and thermal comfort in a room with panel, floor and wall heating, Journal of Energy and Buildings, 40 (2008) pp.524–536

Paper 2 Design considerations with ventilation-radiators: comparisons to traditional two-panel radiators, Journal of Energy and Buildings, 41 (2009) pp.92–100

Paper 3 Improving the thermal performance of ventilation radiators - The role of internal convection fins, International Journal of Thermal Sciences, 50 (2011) pp.115-123

Paper 4 Performance evaluation of ventilation radiators, submitted to International Journal of Thermal Sciences 2010

Conference papers

Paper 5 Comfort temperatures and operative temperatures in an office with different heating methods, in proceedings of Healthy Buildings Conference, Vol. 2: Indoor Climate, Portugal (2006) pp.47–52

Paper 6 Summer time cooling with ventilation-radiators, in proceedings of Indoor Air Quality, Ventilation and Energy Conservation in Buildings (IAQVEC) conference, Japan (2007) p.236

Paper 7 Energy savings and thermal comfort with ventilation-radiators - a dynamic heating and ventilation system, in proceedings of Clima07, Well-Being Indoors, Finland (2007) p.110

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1 Introduction

1.1 Background

In 2006 the European Union (EU) proposed a series of ambitious climate and energy targets to be met by 2020 [1]. These are often referred to as the "20-20-20" targets, because the main aims are:

- A reduction in greenhouse gas emissions to at least 20% below 1990 levels
- 20% of energy consumption to come from renewable resources
- A 20% reduction in primary energy use compared to projected levels, to be achieved by improving energy efficiency

If these targets are to be realized, a wide range of cost-effective energy initiatives need to be implemented. It will be necessary to mobilize all working in this field and to transform the internal energy market, with the objective of providing EU citizens with the most energy-efficient buildings, appliances, processes, cars and energy systems available. Here the building sector can play a key role. Heating, ventilation and cooling of buildings is responsible for 40% of total energy consumption and a considerable amount of CO_2 emission [2, 3]. Three basic measures towards meeting these EU targets are to reduce the overall energy demand of buildings, increase the energy efficiency in the building sector and increase the use of renewable energy.

In 2008 the Energy Performance of Buildings Directive (EPBD) was launched as a mean of encouraging member states to adapt their building regulations and to introduce energy certification schemes for buildings [3]. Sweden's National Board of Housing (Boverket) responded by bringing in special building regulations (Boverkets Byggregler, BBR 16, BFS 2008:20), which set limits for total allowed energy consumption for a building, depending on its type and location and whether or not electricity is used directly for heating [4]. Owners are as a general rule free to choose between heating and ventilation systems as long as the building energy requirements are met. Table 1 lists these requirements. Note that Sweden is divided into three climate zones as shown in Figure 1, at left. In addition, secondary goals for the year 2020 regarding indoor climate, sustainability in the building sector and impact of buildings on the environment were listed in the publication "A Good Built Environment" (God bebyggd miljö) by Boverket [5].

Table 1. Swedish energy requirements, (BBR 16, BFS 2008:20), set by the Swedish National Board of Housing (Boverket).

Climate zone (Figure 1)	**1**	**2**	**3**
Buildings heated by other means than electricity:			
Total energy consumption, kWh/(m^2·year)	150	130	110
Mean heat transfer coefficient (U-value), W/(m^2·K)	0.50	0.50	0.50
Buildings heated fully or partly by electricity:			
Total energy consumption, kWh/(m^2·year)	95	75	55
Mean heat transfer coefficient (U-value), W/(m^2·K)	0.40	0.40	0.40

Figure 1. Left: Swedish climate zones; Right: Schematic diagram of a ventilation radiator.

In 2005 the annual energy demand for heating, ventilation and household electricity in multi-family dwellings in Sweden was still as high as 175 kWh/m^2 [6]. General ways to meet the new energy requirements include a) better insulated building envelopes to avoid transmission heat losses (e.g. through walls and windows), b) so-called “smart” and energy efficient heating and ventilation systems to reduce energy consumption, and c) heat exchangers and heat pumps to recover energy from exhaust air or utilize heat sources from nature such as ambient air, ground (geothermal power) or water.

The majority of Swedish buildings have since the mid 1900s had some sort of exhaust ventilation system, either with or without heat recovery. Such systems are often referred to as FX or F-systems. It was not until the 1980s that balanced ventilation systems having both supply and exhaust air ducts and with heat recovery, often referred to as FTX systems, were commonly installed as a means of saving energy. But the trend turned back, as these systems were difficult to control and their efficiency was found to be lower than expected. Further, there were complaints about noise from air supply units and a widespread belief that transportation of air through supply ducts gave more health problems compared to simple F or FX-systems where ventilation air was brought in directly from outside through the building wall. For a period during the 1990s there were even restrictions on the use of FTX-systems [7, 8]. It was not until recently, with the advent of the new regulations, that the trend turned back in favour of simpler systems and towards FTX-systems again (apparently, as before, in the belief that the change would mean energy savings). Figure 2 shows historical trends in ventilation in Sweden. Figure 18 illustrates the principle of FTX, FX and F ventilation.

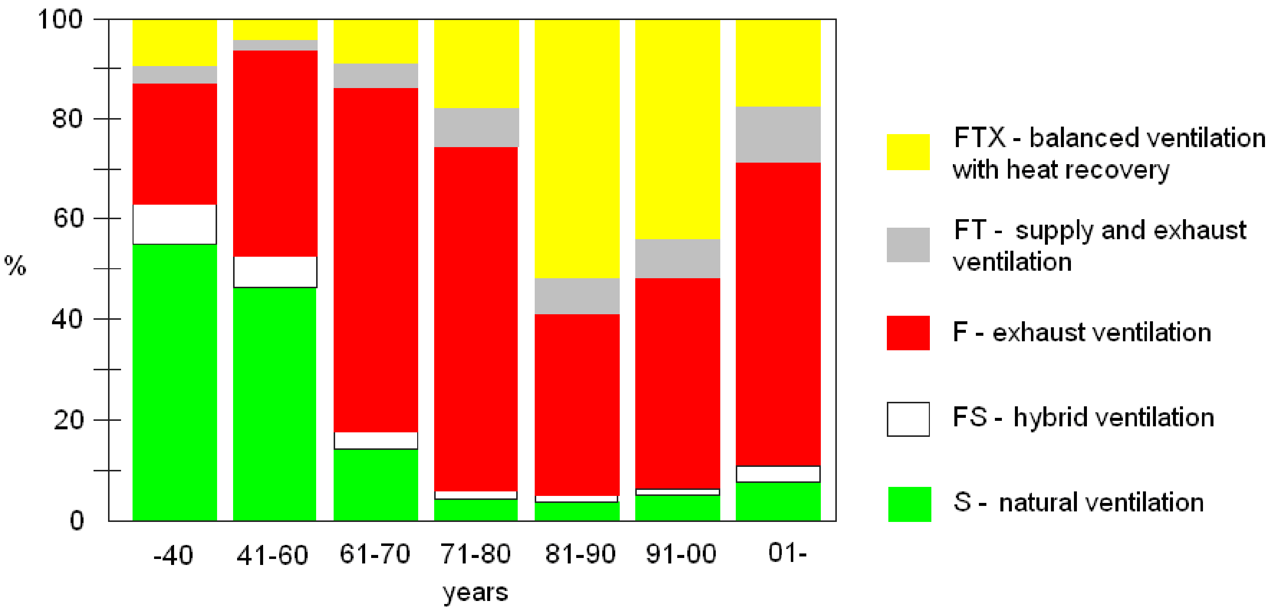


Figure 2. Historical trends in ventilation system types installed in Swedish housing stock during the last century [9].

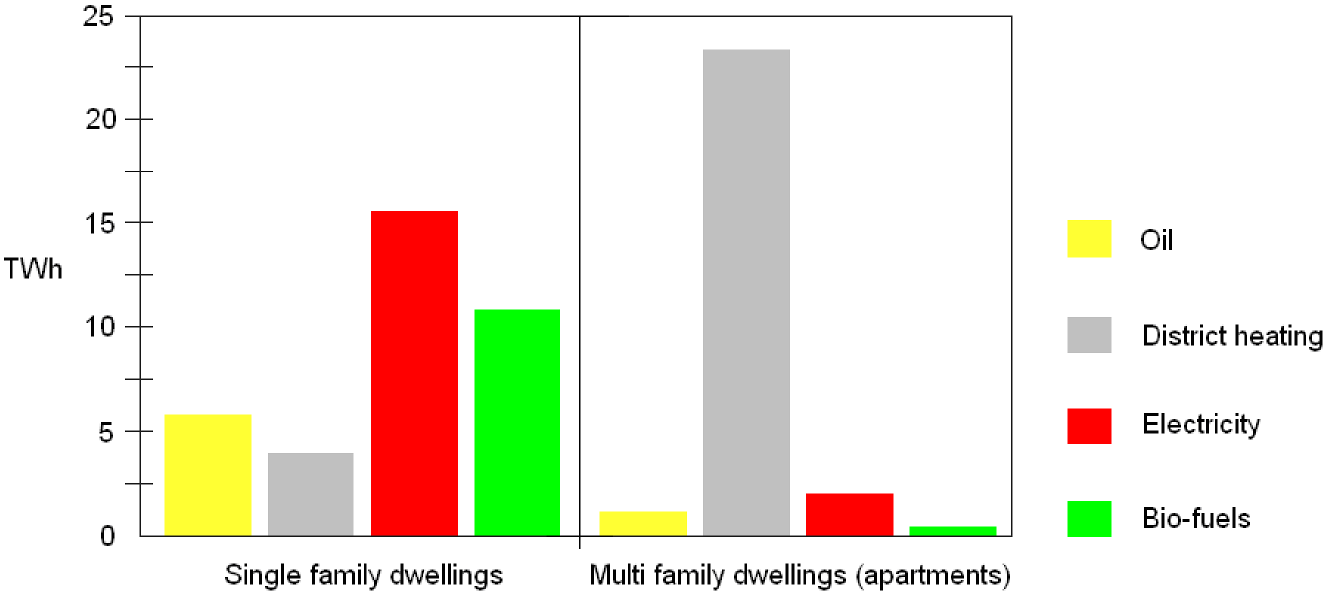


Figure 3. Proportion of different energy forms used for heating in Sweden in 2006 [6]. Note heat pumps are not shown separately but included under “electricity”.

Sweden is already a world leader in environmental friendly heat production methods utilizing heat pump technology and district heating plants (a system for distributing centrally generated warm water via well-insulated underground pipes to meet residential and commercial heating requirements), see Figure 3. In 2005 Sweden had 235 000 buildings with air-based heat pumps and 200 000 buildings with ground or water-based heat pumps. Traditional water-filled panel radiators have been the most commonly used heat emitters in both these systems. A basic national goal is to improve or develop heat emitters to allow a lower system water temperature with the same heat output as traditional radiator systems. A low water temperature leads to energy savings in heat production and distribution of heating power, especially relevant in systems adapted to heat pumps, district heating and renewable heat sources. In heat pumps, a general rule of thumb states that the thermal efficiency improves by about 1-2% for every degree the water temperature is lowered. This was confirmed in paper 2, where calculations were made using Vitocalc 2005, a non-commercial program designed to assist in the process of choosing components for heating of buildings [10].

A medium supply water temperature has been typical for district heating for a number of decades despite Sweden's cold winter climate. But heat emitters may be adapted even to low and very low supply water temperatures. In other words, there is still much potential for improvement. Table 2 presents water temperature ranges as defined for heat emitters [11].

Table 2. Four categories of water temperature range for heat emitters.

Heating system	**Supply flow, °C**	**Return flow, °C**
High temperature (HT)	90	70
Medium temperature (MT)	55	35-45
Low temperatures (LT)	45	25-35
Very low temperatures (VLT)	35	25

A range of technical methods are used to develop systems to suit a lower supply water temperature. The most commonly used methods utilize a) large heat transferring surfaces, b) technology that improves the radiation heat transfer c) convection fins shaped specially to improve convection heat transfer or d) methods that force air along heated surfaces to boost convective heat transfer. Some methods for low temperature heat emitter optimisation were discussed by Holmberg et.al. in "Space heating at low temperature difference between heating unit and ambient air" [12]. Figure 4 shows three different factors that can influence heat output from a heated surface representing a standard size radiator. It can be concluded that a low and wide radiator panel performs better than a tall radiator panel of the same surface area, that higher air velocity along heated surfaces helps to remove energy from those surfaces, and also that the temperature difference between heat emitter and surrounding air have a strong, linear effect on heat transfer (refer to the second law of thermodynamics).

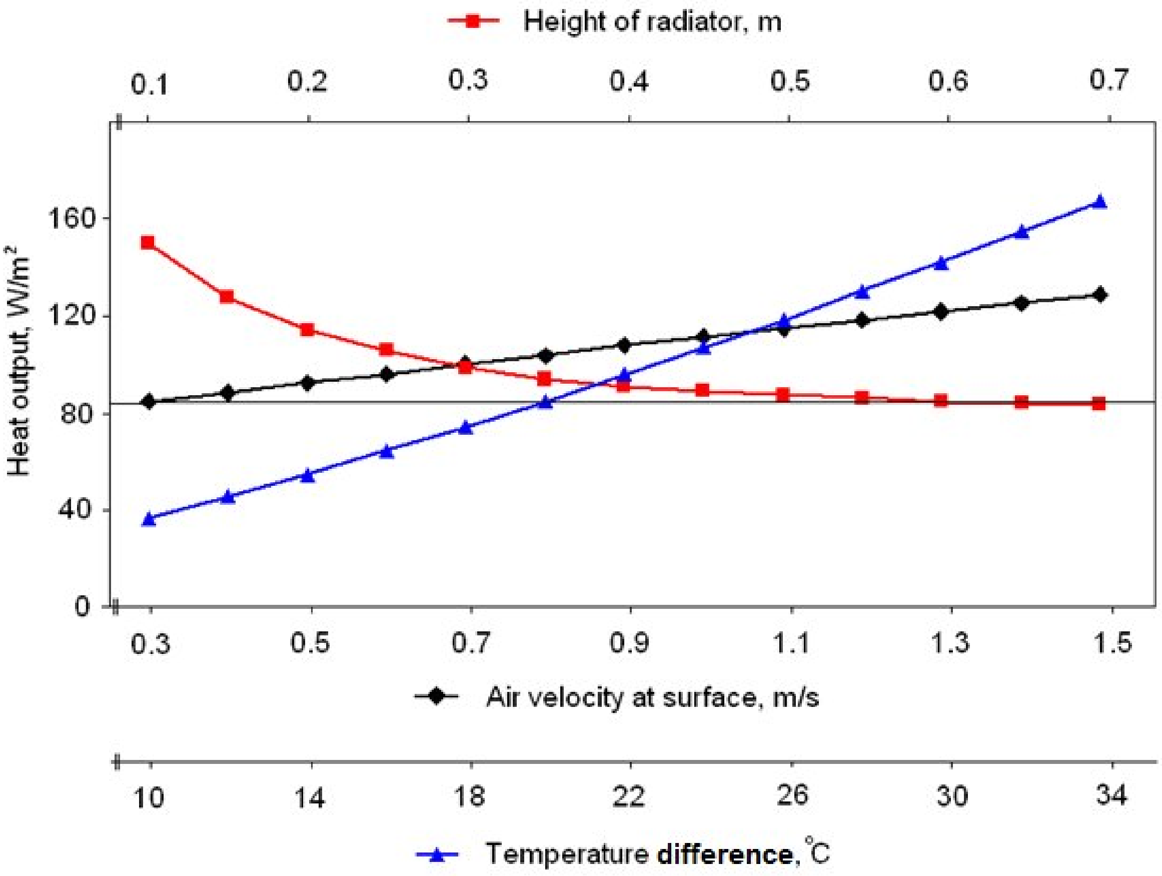


Figure 4. Variations in heat output from a vertical radiator surface according to the radiator's vertical dimension, air velocity at its surface and temperature difference to ambient air. The surface was initially 0.6 m high and heated to 40°C in a natural convection situation.

Equation 1 describes the heat transfer process from water inside a heat emitter to ambient air and the surfaces around the heat emitter. The parameters on the left hand side cover heat transfer from warm water to the solid material of the heat emitter, while the parameters on the right hand side represent heat transfer by convection (the sum of advective and diffusive transfer by air) and radiation (electromagnetic waves) from the heated surfaces to the room (illustrated in Figure 5). In papers 3 and 4, where the aim was to improve the thermal efficiency of ventilation radiators, the focus was on convective heat transfer and all three variables on the right hand side of this equation. Refer to paper 2 for a detailed explanation of Equation 1.

The Annex 37 [13] guidebook gives an overview of the most common low and medium temperature heating systems, their characteristics and the ruling heat transfer mechanisms. Other publications cover in greater detail thermal comfort and energy aspects in systems operating at low water temperatures, such as floor heating and ceiling heating [14, 15].

$$\dot{m} \cdot c_p \cdot \Delta \theta = k \cdot A \cdot \Delta \theta_m \tag{1}$$

, where the three parameters on the left side of the equation are, respectively, the mass flow of water inside the heat emitter $\dot{m}$, the specific heat capacity of water c_p, and the temperature difference between water entering and leaving the heat emitter $\Delta \theta$.

Similarly, the parameters on the right side of the equation are the total heat transfer coefficient k, which can be divided into one convective and one radiative part (α_{conv} and α_{rad}), the area of the heat emitter surface A, and the mean temperature difference between heat emitter surface and ambient air $\Delta \theta_m$.

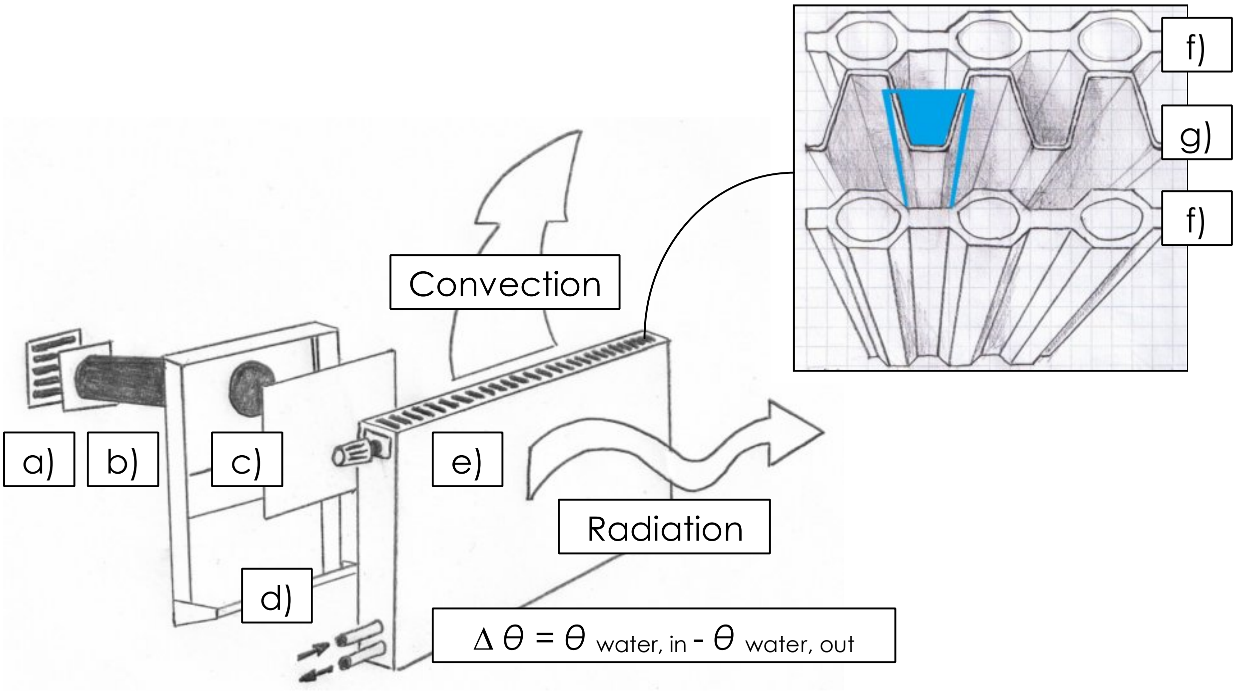


Figure 5. Main parts of a ventilation radiator: a) vent on the building wall, b) channel through wall, c) box behind the radiator (with filter) leading incoming ventilation air downwards then upwards, through an d) injector or inlet (with or without mixing of cold supply air with room air) and into a e) traditional radiator. The sketch in the upper right corner shows a typical inside geometry of a traditional "21 module" radiator. In a "21 module" the radiator consists of f) two radiator panels with water inside and g) one set of convection fins (secondary surfaces) welded to one panel. The blue section in the sketch illustrates the plane referred to when discussing flow characteristics between convection fins in Figure 9.

Heat emitters with a low system temperature have been proven not only to allow energy savings, but also to create better indoor climate conditions than traditional high temperature systems [11, 16-18]. A typical thermal climate resulting from low temperature systems is characterized by small temperature differences in the room, a larger contribution of radiant heat, and less air fluctuation caused by buoyancy forces [18-21]. Even the indoor air quality (IAQ) would appear to be positively influenced in low temperature systems. Buildings with low temperature heating tend to have fewer suspended particles, less dust and less odour [22-23].

Nevertheless, it has long been evident that people tend to experience more problems with asthma, allergy and Sick Building Syndrome (SBS) symptoms in modern, air-tightened and well-insulated buildings [24-27]. It has been strongly indicated that low energy buildings in general do not have sufficiently high ventilation rates and/or insufficient levels of fresh air in the breathing zone of occupants. Do we really want to save energy at the expense of indoor climate quality and health? EUROVEN, a group of European scientists, have reviewed scientific papers on ventilation and its effects on health, comfort and productivity in offices, schools and homes. The group found the degree of ventilation to be strongly linked to perceived air quality and health. A connection between ventilation rate and productivity in offices was also found. The main conclusion of the study was that a high ventilation rate improved perceived air quality, reduced risk of health problems and also increased productivity. Additionally, the group concluded that more health related problems were reported in buildings with air-conditioning systems compared to natural or exhaust-ventilated buildings. That a high ventilation rate was important to ensure productivity and well being of building occupants, has also been found by others [28-29].

It is obvious that we should make efforts to reach BBR requirements and create sustainable solutions. Two important measures are smart methods to allow a low water temperature in heating systems and ways to recover energy from exhaust ventilation air. However, an underlying theme of this work is that we should not forget to consider indoor air quality and related health aspects in the process as well. We need to combine heating and ventilation systems that can make our buildings energy efficient while a high ventilation rate of fresh air is allowed at the same time. It is also beyond dispute that the systems should be as uncomplicated and user-friendly as possible for occupants and building owners. The question is how to best achieve these goals.

This thesis presents a solution relevant to a large proportion of Sweden's building stock, including all residential buildings with warm water heating and exhaust ventilation. It proposes the application of ventilation radiators by utilizing traditional hydronic radiator heating brought into direct contact with incoming room air supply.

Heat transfer mechanisms that can optimise ventilation radiators for maximum heat transfer have been the main focus. In addition, many other important aspects, from thermal comfort to total energy consumption in settings with different kinds of heat pumps have been covered, including comparisons to other system solutions.

1.2 The principle of a ventilation radiator

A ventilation radiator is made for use in exhaust-ventilated buildings, preferably with heat recovery (FX system in Sweden). Figure 1 (at right) shows the principle of the ventilation radiator in such an application. Cold air (blue arrows) enters a vent in the building wall, passes through a wall channel and a filter before it is directed to a channel formed by the radiator panels. Ventilation air, typically with flow of 8-10 l/s per ventilation radiator unit, rises in this channel as it is pre-heated to room air temperature. Driving forces are partly buoyancy forces and partly the under-pressure in the building being generated by the exhaust ventilation fan. A filter prevents particles in the incoming air from reaching the indoor environment. Note that no or very little extra driving force is needed with ventilation radiators installed in this way, compared to systems bringing air in through conventional ventilation inlets (positioned above the window). This system means that a standard exhaust ventilation system can be used, with no extra energy consumption for ventilation.

The reasons ventilation radiators are more thermally efficient than traditional radiators are a) increased temperature difference between heated surfaces and air passing between the radiator panels, enhancing heat transfer, and b) higher mean air velocity between the radiator panels with increased friction velocity and additional improved heat transfer as a result.

1.3 Objectives and short presentation of each paper

This work had its starting point with a general directive from the Swedish Energy Agency; to “improve and develop low-temperature, water-based heating systems”. Low temperature heating that enables energy savings in production and distribution of warm water, is especially suited for systems that incorporate heat pumps, or that utilise alternative heating sources and heat generation methods not dependent on combustion of fossil fuels.

The direct scientific response to this request was to find ways to improve heat transfer. Our second consideration, as a division working with Fluid and Climate Technology, initially within the School of Technology and Health, was to ensure that thermal comfort and health aspects of these systems were also covered.

1.3.1 Paper 1

The goal of the first paper was to achieve a general understanding of the strengths and weaknesses of different heating systems applied in a building with exhaust ventilation. The focus was on thermal comfort, i.e. how well different systems distributed heat and managed to counteract cold downdraught from ventilation air inlets. The overall intention was to identify how best to design and position low temperature heat emitters in the indoor environment. It is known that well-balanced heating and ventilation systems may lead to energy savings and better indoor climate.

The main findings were that all four heat emitters tested, i.e. floor heating, wall heating and two traditional radiators, could create an acceptable indoor climate. However, it was found that low temperature systems had less ability to suppress downdraught from air supply units and windows. Cold downdraught may easily cause discomfort for occupants. A key conclusion was that positioning of heat emitters was the determining factor. Ideally, incoming ventilation air should be heated to room temperature as soon as possible after entering the room.

1.3.2 Paper 2

Findings from paper 1 were used as a starting point for paper 2, further investigating one of the heating systems, the ventilation radiator. The idea was to investigate how pre-heating ventilation air coming in to the heat emitter itself would affect indoor climate and energy efficiency. The interaction between heating and ventilation system thus became the main focus. To heat incoming ventilation air at an early stage had already, in paper 1, been shown to be one of the most important factors in achieving a stable and uniform thermal indoor climate. Comparisons were made to a traditional high temperature radiator in combination with a ventilation system where the air supply was situated above the window.

The main findings were a) risk for cold draught could be fully eliminated with ventilation radiators b) better thermal efficiency of ventilation radiators compared to traditional radiators allowed for a lower surface temperature with the same heat output, which resulted in energy savings, and c) a more rapid thermal response in the ventilation radiators. Thus it was apparent that ventilation radiators had a number of advantages over widely used systems and obviously this called for further investigation.

1.3.3 Paper 3

The objective of Paper 3 was to find ways to optimise ventilation radiators for maximum heat output, i.e. improve thermal efficiency as much as possible to maximize energy savings. To do this, the various parts of a ventilation radiator system, as shown in Figure 5, needed to be investigated.

Why use a traditional radiator in a ventilation radiator system? Traditional radiators are designed for maximum radiation heat transfer from outside surfaces and maximum convective heat transfer from internal surfaces. Most traditional radiators have convection fins between the radiator panels to increase convection heat output. The purpose of convection fins is to lead heat from warm water in the radiator, through the main body and out to a large surface area in contact with ambient air. The fin surfaces are vertical and smooth in order to make ambient air rise in close contact; that is, they are shaped for natural convection caused by buoyancy forces. In a ventilation radiator system, on the other hand, the flow between the radiator panels cannot be categorized as natural convection. It is more likely to be forced convection because of the extra driving force on the ventilation air due to the building's exhaust ventilation system. Under these conditions it is possible to introduce enhanced resistance to air flow between the radiator panels so as to increase heat output while maintaining the required air flow volume. This can be achieved either by enlarged heat transferring surfaces in the form of additional convection fins, or by introducing roughness or other kinds of obstacles disturbing the air flow to increase the degree of turbulence. To date, no ventilation radiators have been given an internal geometry designed to maximize convection heat transfer. Their geometry has remained like that of traditional radiators. The aim of this paper was to find out if heat transfer between the panels of a ventilation radiator could be improved, and if so, to what extent.

1.3.4. Paper 4

Results given in paper 3 indicated that significant improvements in heat output of ventilation radiators could be achieved by simple means, and several different mechanisms were studied. As Computational Fluid Dynamics (CFD) simulations preferably should be followed by real measurements to validate results, the objective of paper 4 then became to validate the results from paper 3 and to further investigate some specific heat transfer mechanisms. Several prototypes were made and tested in a climate chamber simulating a room of a modern Swedish building under cold winter conditions.

The investigations reported in paper 4 confirmed general results from the CFD simulations. It was concluded that heat output of ventilation radiators could be improved by about 20% by introducing changes to the convection fin geometry and air inlet to the radiator, without sacrificing ventilation efficiency or thermal comfort.

1.3.5 The conference papers

During the work, three conference papers were presented, studying specific aspects of low temperature heat emitters and ventilation radiators as follows:

Paper 5 *Comfort temperatures and operative temperatures in an office with different heating methods:* studying radiation versus convection heat output from various heat emitters, and influences on thermal comfort and energy aspects

Paper 6 *Summer time cooling with ventilation-radiators***:** studying whether ventilation radiators were suitable for cooling purposes

Paper 7 *Energy savings and thermal comfort with ventilation-radiators - a dynamic heating and ventilation system:* studying how the fast response time of ventilation radiators can be used to save energy (ventilation on demand)

Section 3 “Results and discussion” gives an overview of conclusions from all papers, including the conference papers. Refer to specific papers for research methodology.

1.4 Computational Fluid Dynamics (CFD) as a tool to describe, analyse and improve indoor climate

CFD was used throughout this doctoral study, as with the majority of work at the division of Fluid and Climate Theory. A major intention underlying the work was to show how CFD could be used for describing, analysing and improving indoor climate conditions and energy consumption in buildings.

One part of the work covered optimisation of the internal geometry of ventilation radiators for maximum heat output. Similar optimisation processes are common worldwide to save time in industry. Switching between simulations and measurements during several iterative steps is often the best way to reach the most favourable design in a short time. Thermal efficiency of heat emitters is not the only important factor, however, in saving energy and creating a desirable indoor climate. How heat is distributed from the heat emitters to the room and how the ventilation system transports heat within the building are also important aspects. This work demonstrated how CFD could be used in the whole design process, from shaping geometries of heat emitters to investigating the interaction between heat emitters and indoor environment. CFD could be used to predict the actual heat output, to show how and to where heat is distributed from the heat emitters, as well as to estimate how a human being standing at any particular point in the room would experience thermal climate.

Few similar studies have been reported, although Prof. Richter at TU Dresden, Institute für Thermodynamik und Technische Gebäudeausrüstung, Omori et.al. and Ploskic and Holmberg at KTH Sweden, have carried out comparable projects where thermal comfort and energy consumption with different heating systems were evaluated by CFD [30-33]. A leader in indoor CFD is the International Centre for Indoor Environment and Energy at the Aalborg University in Denmark, lead by P.V Nilsen. Computational Fluid Dynamics in Ventilation Design, by P.V Nilsen (ed), is recommended here for more information on the subject [34].

2 Method

Computational Fluid Dynamics (CFD) codes and methods were used throughout this doctoral work. Below is a short introduction to CFD in general, followed by a detailed account of methods used in each paper.

2.1 CFD simulations in general

Computational Fluid Dynamics (CFD) is a computerized system using numerical methods and algorithms to analyse the flow of fluids, liquids and gases. CFD are used where traditional flow equations cannot be solved directly, for situations ranging from internal flow in a pipe to external flow around an airplane wing. Depending on the complexity of the simulation, it is possible to include turbulent flow behaviour, energy transport through the medium, multiple face flows and particles following the flow or partly interacting with the flow. The Navier Stokes Equation (Figure 6, upper right) is always used as the basis for calculations. The four terms, from left to right, represent variation in time of the quantity observed, convection through the control volume, diffusion through the surface of the control volume and generation of the quantity per unit volume and time, respectively. This differential equation is transformed into discretization equations formulated around each grid point before being solved numerically. Different discretization schemes, turbulence models and grid types are used depending on the characteristics and complexity of the flow and solution domain.

This project had its starting point in simple CFD exercises, such as the Belays experiment for mixed convection in a two-dimensional cavity, to ensure the combined capabilities of the user and code [35]. This particular verification test shows the extent to which the CFD code predicts mixed convection conditions. A short outline of each step is given below.

Pre processing
All CFD projects start with building a Computer Assisted Design (CAD) model, see Figure 6, upper left. In this case a small cavity with two openings was constructed. Then boundary conditions were defined i.e. fluid behavior and properties at the boundaries of the problem. In this example, airflow entered at the upper left corner of the cavity, and the cavity had a floor warmer than walls and ceiling.

Meshing
The next step was to divide the solution domain into small discrete cells (together comprising a mesh or grid). The mesh could be uniform or non-uniform. In Figure 6 upper right, a Cartesian mesh was chosen. Usually nine equations, based on the Navier Stokes equation, would be solved in each cell, consisting of momentum equations in six directions, equations for generation and dissipation of turbulence and one equation for transport of energy. In situations with complex flow behaviour and steep velocity gradients the mesh often has to be non-orthogonal with denser mesh introduced in certain areas to reduce turbulence modelling errors.

Solution

The next step consisted of solving the equations iteratively. Residuals, i.e. the “leftovers” describing the degree of error, were monitored step by step, to follow progress and determine stability and convergence, i.e. continuity and mass balance.

Post processing

After making calculations, there are many ways of visualising results, such as by vectors showing velocity and direction of airflow, as in Figure 6 middle left, or by sections showing temperature distribution throughout the solution domain as shown in Figure 6 middle right. Further, films following the airstreams or iso-surfaces can be made. In this case CFD results were compared to measurements, see the lower illustrations in Figure 6.

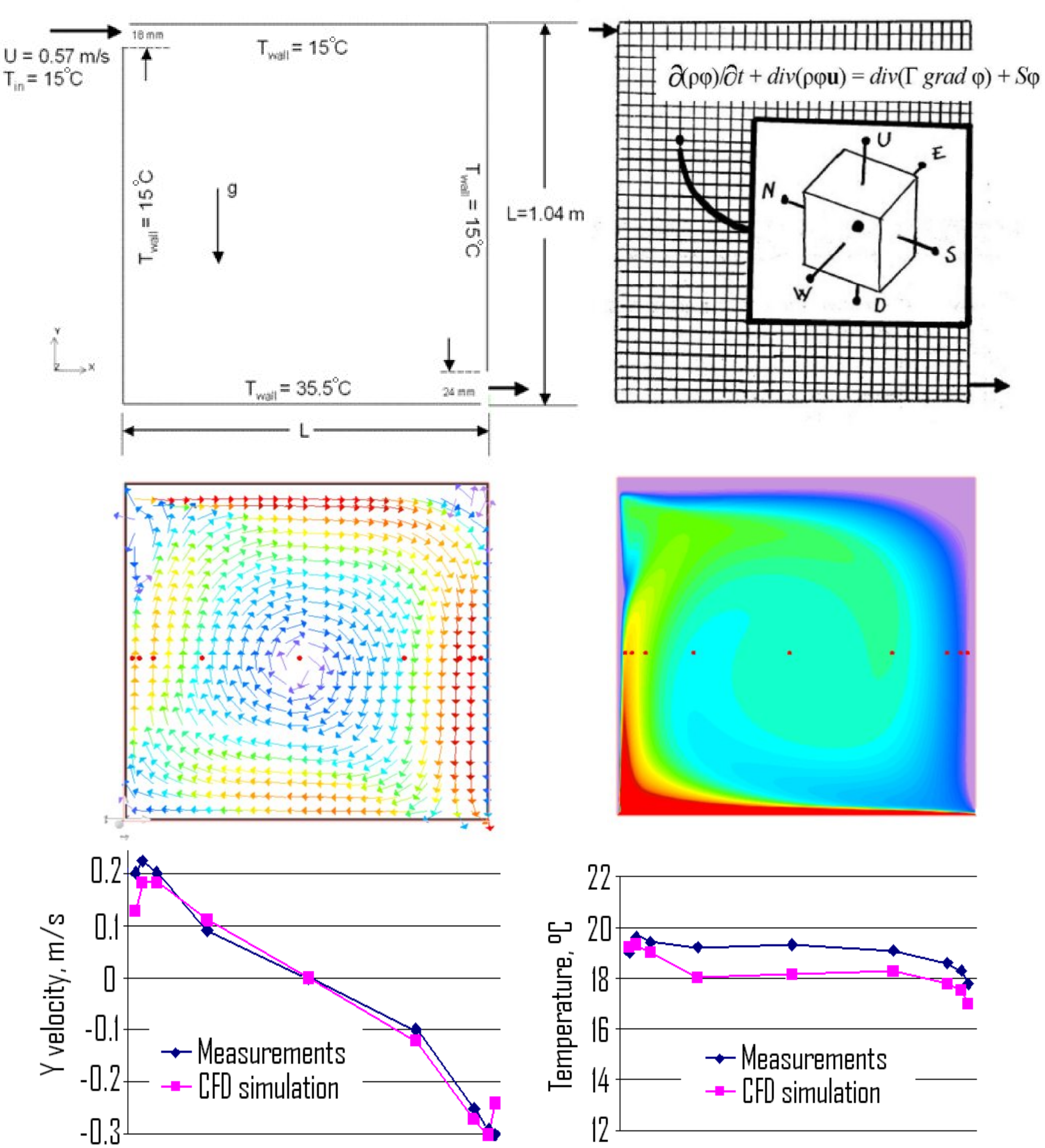


Figure 6. Illustrations showing results from Blays verification test on mixed convection in a small cavity. Upper left: solution domain and boundary conditions; Upper right: mesh; Middle left and right: velocity vectors and air temperature distribution in the simulation; Lower left and right: comparison of velocities and air temperature distribution along the line at Y = L/2 between CFD simulations and measurements.

2.2 Papers 1 and 2

The first two journal papers (Papers 1 and 2) and all three conference papers refer to a CFD model made according to descriptions of a real life test room where indoor climate conditions with different heating systems were measured by Olesen et.al. [18]. CFD simulations were made for these same heating systems, before any other kinds of heating and ventilation systems were tested and evaluated. Results from the simulations were validated by comparing results from both studies, performing standard CFD validation procedures and making comparisons to analytical models and similar CFD projects. Finally the results were evaluated with reference to Swedish and international thermal comfort standards.

2.2.1 Room model and installations

The model was a replica of Olesen's exhaust-ventilated room used for laboratory studies. It had a well-insulated window wall facing outdoor winter conditions while the rest of the room was designated as having no heat losses through walls, ceiling and floor. The various installations were designed in accordance to specifications for the model room. The upper illustration in Figure 7 is an original sketch from Olesen's work, while the lower illustration shows room dimensions and how ventilation air was brought in from different inlets, as well as positions of heat emitters in the CFD model.

In the early stages of the project, a major interest was to obtain an understanding of the interaction between different heating and ventilation, and so various combinations were evaluated. The four heat emitters described in paper 1 were two low temperature heating systems, one medium-high and one high temperature radiator. All systems were tested in combination with two ventilation systems where inlet air either came in at high velocity through many small holes in the window frame or through one single slot above the window.

Paper 2 describes one two-panel radiator only, with various geometries and positions of the air inlet in relation to the radiator studied in order to investigate related indoor climate changes. In two of these cases the inlet was placed between the panels inside the radiator to form ventilation radiator systems. Figure 1, right, and Figure 5 show the principle of a ventilation radiator and it components. Tables 3 and 4 describe all installations used in both papers 1 and 2. The surface temperature of all heat emitters was fixed at an isothermal surface temperature for simplicity.

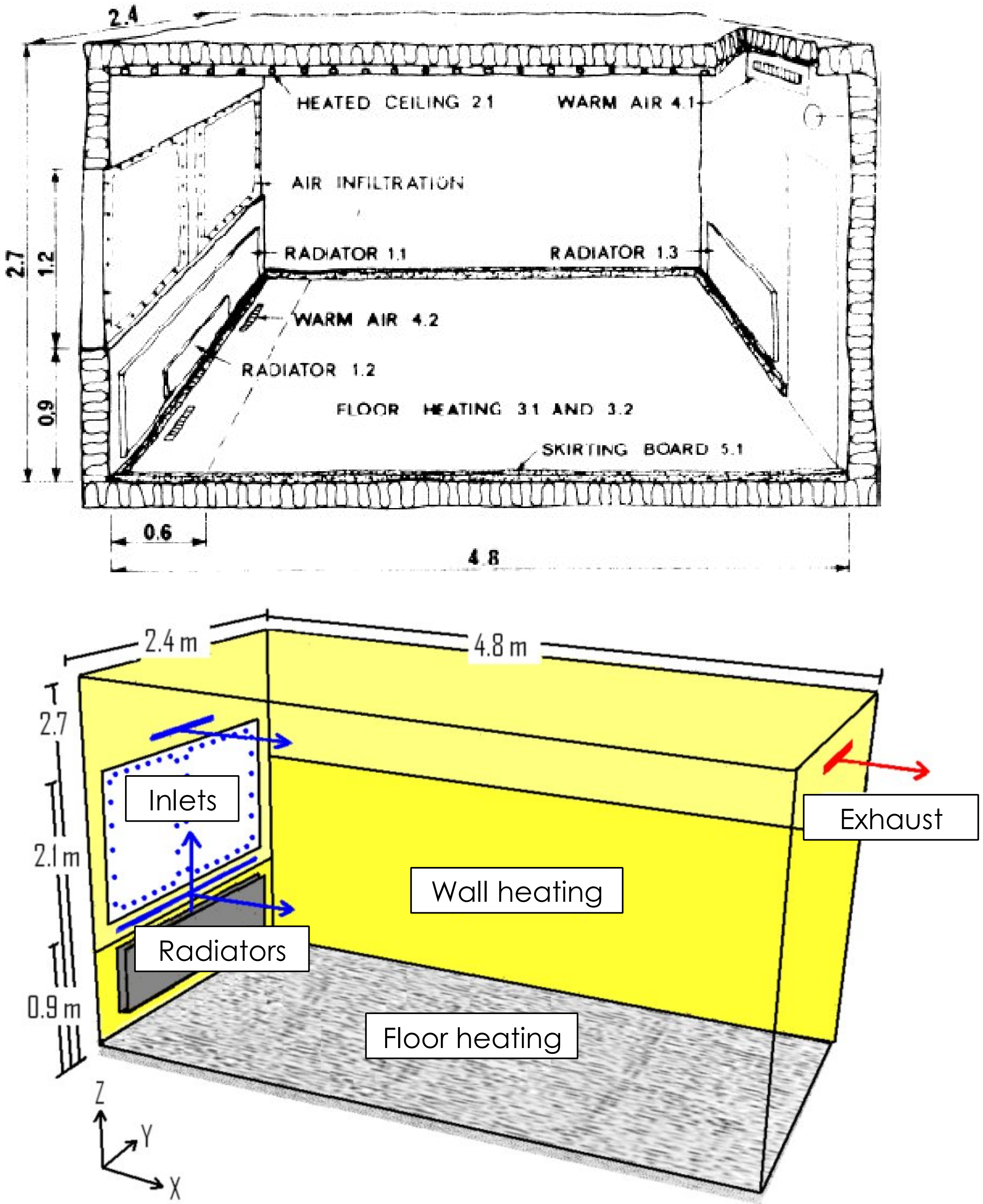


Figure 7. Above: Original sketch from [18]. Lower: Room geometries and dimensions, including ventilation openings and positions of heat emitters. Blue markings indicate positions of air inlets and direction of incoming air. Red lines indicate air being mechanically extracted through the exhaust unit.

Table 3. Description of heat emitters and temperatures (two different surface temperatures were used in paper 2)

	Description/Position	Size, m^2	Surf. Temp, °C
Paper 1			
Medium temp. radiator	Single panel, under windows	0.55 · 2.0	46.0/42.0
Floor heating	Whole floor	2.4 · 4.8	26.5/25.5
High temp. radiator	Single panel, under windows	0.40 · 1.0	76.0/67.0
Wall heating	Side walls and under windows	1.75 · 4.8	25.5/25.0
Paper 2			
Medium temp. radiator, Case A	Two-panelled, under windows	0.6 · 1.4	42.3
Medium temp. radiator, Case B	Two-panelled, under windows	0.6 · 1.4	42.3
Ventilation radiator, Case C	0.04 m wide ventilation channel	0.6 · 1.4	38.0
Ventilation radiator, Case D	0.02 m wide ventilation channel	0.6 · 1.4	34.5

Table 4. Description of air inlets and supply velocities

	Description/Position	Size, m^2	Inlet air velocity, m/s
Paper 1			
Room 1	48 openings in window frame	0.0012	5.83
Room 2	Over window, vertical	0.03 · 0.4	0.58
Paper 2			
Case A	Over window, vertical	0.02 · 0.5	0.70
Case B	Underneath window, vertical	0.02 · 1.4	0.25
Case C	Inside radiator, horizontal	0.04 · 0.5	0.35
Case D	Inside radiator, horizontal	0.02 · 0.5	0.70

2.2.2 Climate conditions

The room was studied assuming a typical Swedish winter environment, and ventilation air was brought into the room without pre-heating. To suit these conditions, the surface temperature of each heat emitter was adjusted in order to fulfil the heating requirement for certain comfort criteria in the middle of the room. Inlet air had to be heated and heat losses had to be covered.

The Swedish building regulations (BBR 16, BFS 2008:20) give directives for ventilation of buildings [4]. A ventilation rate meeting this directive was applied in the CFD room from the very beginning, even if the incoming ventilation air was relatively cold, e.g. -5°C as the air entered the room after being transported through the wall. The ventilation rate was set to 7 l/s. This resulted in an exchange rate of 0.8 h^{-1}.

2.2.3 Computational Fluid Dynamics (CFD) code and simulations

The CFD code used for these papers was FLOVENT [36]. This program was developed specifically to maximize productivity of engineers working with design and optimisation of heating, ventilating and air conditioning (HVAC) systems in the indoor environment. Drawing board, solver and post processor all are available from the same platform. The code has tools for dynamic manipulation of temperature, and flow results that enable engineers to pinpoint potential thermal and ventilation problems and visualize design improvements quickly and effectively. The progression from pre to post processing can be learnt with the help of tutorials, a special library with pre-made objects and properties, automatic grid generation and advanced help functions. The main features for indoor environment simulations are:

- Particle animation and streamlines as an aid to visualizing complex 3D airflow and contamination dispersion
- Contour animation for visualization of heat transfer paths
- Iso-surfaces and surface temperatures
- Airflow representation by vectors coloured by temperature or speed
- Easy output of flow animations such as video in AVI format

FLOVENT has a LVEL k–ε turbulence model which is specially adjusted for indoor environment simulations, see Agonafer et.al. [37]. It has embedded wall functions that automatically reduce the turbulent viscosity from the bulk value outside the wall boundary layer to zero at the wall surface. This makes meshing close to walls less complicated. It has also a “surface to surface” radiation model that accurately predicts radiation heat transfer, a very important aspect in indoor environment CFD simulations.

Yet the code has several limitations for research purposes; a) it lacks advanced-computational costly turbulence models such as SST (Shear Stress Transport) and RSM (Reynold Stress Transport) models, b) it has a simple, first order upwind discretization scheme which is stable rather than accurate and c) it handles only cubic objects and Cartesian grids.

2.2.4 Validation

The validation of a complete CFD system should be broken down into several steps, according to Chen [38]. A progressive simulation procedure does not only discover potential errors in the model or settings, but will also help to build confidence of the user performing the simulation.

Several simulations were made using either less complicated settings or subsystems of the whole system, in order to better understand the CFD code. One example was isothermal flow simulations to indicate airflow patterns. In addition, various calculations were made to ensure that heat exchange between heat emitters and indoor environment was reasonable, among them the balance between radiation and convection heat output. This was especially important in paper 2 where no reference to measurements with ventilation radiators was available.

Tests were made showing that the results from the CFD simulations were independent of the grid design (grid independent tests). The grid should always be fine enough to give similar results if the number of meshing nodes should be doubled or halved. Certain areas were meshed more densely to meet this criterion.

The grid density was especially important in the ventilation channel and around the radiator studied in paper 2. Results showed that there was up to 0.3°C deviation in the temperature distribution in the room depending on the grid density, but that the general flow patterns were always the same. This was regarded as acceptable. Figure 8 shows an example of the meshing used in one of the simulations with ventilation radiators.

Finally, the reliability of the general thermal climate conditions was established by making comparisons between simulation results and measurements by Olesen et.al.

The general flow patterns were similar. Paper 1 shows some direct comparisons between simulations and measurements.

2.2.5 Results presentation

Simulation results were described in the same way in papers 1 and 2. Temperature gradients were expressed along certain reference lines, heat output values or surface temperatures of heat emitters were presented in tables or diagrams. Results describing scalars extending throughout the room, such as air speed and perceived temperature results, were expressed as two-dimensional illustrations in the XZ plane, at Y = L/2. See Figure 8.

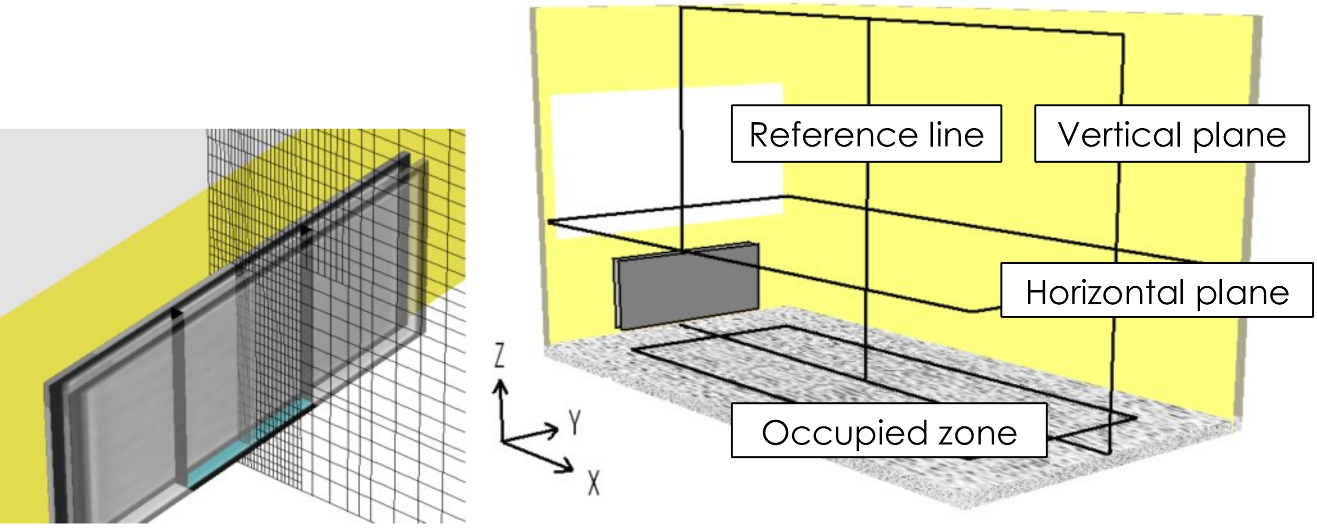


Figure 8, Left: meshing used for Cases C and D in paper 2. The area inside and around the ventilation radiator, where step gradients occurred, had finer mesh; Right: Planes and reference lines used to illustrate and describe variations in thermal climate in the room. The occupied zone, i.e. the area where people in a room normally stay, was defined as a space 0.6 m distant from all walls and up to 1.8 m above floor level.

2.3 Papers 3 and 4

The aim of these papers was to improve heat transfer of ventilation radiators as described above in sections 1.3.3 and 1.3.4. It was considered possible that the flow conditions that occur in ventilation radiators would allow another kind of design in order to enhance heat transfer. To explore this further it was necessary to study theory of heat transfer.

2.3.1 Theory of heat transfer

Flow between the two panels of a radiator is similar to channel flow. Heat transfer and pressure drop are generally closely coupled, but with a complex interaction; values are often high in the entrance region, then decreasing as the flow develops and the thickness of the viscous sub layer of air increases. The viscous sub layer (only a few mm thick) that always builds up close to heated surfaces as air rises nearby, acts as insulation between the heated surfaces and ambient air, and reduces the heat transfer. That is one of the reasons low profile radiators are more effective than tall radiator panels. Breaking the insulating sub layer without causing too much pressure drop is often the key to improving heat transfer. In fully developed flow the heat transfer coefficient and pressure drop are constant if the channel wall temperature is constant. Figure 9 shows typical flow characteristics in different parts of a channel where incoming airflow develops to fully developed turbulent flow.

The velocity boundary layer is the boundary between two regions: the first being where velocity gradients are large enough to produce considerable viscous stresses and dissipation of mechanical energy, and the second region that in which there are no velocity gradients of any note and where viscous stresses are negligible, called "free stream". The boundary layer is often defined as the distance from the wall where velocity is 99 % of the free stream velocity (U = 0.99 V). The flow is not categorized as fully developed before the velocity boundary layers meet at the centre of the channel. The length of the entrance region of the channel necessary to establish fully developed flow is called the transition length. In laminar flow, the approximate length for fully developed flow to be reached is given as

$$X^t / D \approx 0.05\ \mathrm{Re}_{\mathrm{dh}} \tag{3}$$

, where $\mathrm{Re}_{\mathrm{dh}}$ is the Reynolds number based on the hydraulic diameter and the average velocity, X^t, is the transition length and D is the diameter of the pipe.

For turbulent flow, the transition length is equal to at least 10 pipe diameters. Since radiator panels are relatively short compared to the distance between the panels, fully developed flow and temperature profiles could not be expected in this study. The flow field was only likely to develop to the extent illustrated for the traditional fin geometry as shown under design 1 in Figure 10. It was therefore important to consider the effects in the entrance region when calculating and simulating the heat transfer.

The channel Reynolds number, $\mathrm{Re}_{\mathrm{dh}}$, is a measure of the ratio of inertial forces to viscous forces and can be used to describe whether a flow is laminar or turbulent. In turbulent flow chaotic air movements reach close to the radiator walls and break up the viscous sub layer, increasing the local temperature gradient and boosting the heat transfer coefficient with improved heat transfer as a result. The velocity profile becomes almost flat as chaotic air movements reach over the whole cross-section of the ventilation channel. In laminar flow it would be parabolic.

Transition from laminar to turbulent flow depends most of all on air velocity, but also on fluid characteristics and internal geometry and roughness of internal surfaces. In smooth channels the change from laminar to turbulent flow occurs in the range $\mathrm{Re}_{\mathrm{dh}}$ = 1500-4000. A key conclusion made in this preparatory study was that the Reynolds number was not likely to exceed 2000 in the ventilation channel with hydro-dynamically smooth surfaces (point of transition to turbulent flow). In other words, if transition to turbulence was to occur at all, the transition would be slow and only present in the upper part of the channel between the radiator panels. The increase in mean heat transfer coefficient would be limited, again refer to Figure 10, design 1 and to the corresponding heat transfer coefficient graph.

Ways to trigger turbulence are many; most common are roughness or small obstacles on internal walls to disturb the air flow. Nevertheless, the idea of having roughness on the inside channel walls was rejected in this study. It is known that improvement in heat transfer due to having roughness on internal channel walls only is notable if the flow has reached a high enough Reynolds number. Reynold's analogy predicts that the driving force needed to overcome friction caused by obstacles in a channel is proportional to the square of the velocity. High velocity or changes in velocity are therefore always associated with high-pressure losses. In general the mean square velocity always becomes higher for complex internal geometries. For this reason it was decided that the investigations should be limited to thermal/hydraulic performance considering heat transfer and pressure drop, and introducing one changing feature only, i.e. the distribution of straight, longitudinal convection fins of various lengths. Accepting that the flow would be laminar and experimenting with the surface area in Equation 1 instead, in addition to finding other ways to break the viscous sub layer, would be a much more efficient way to increase the heat output. After all it is the product of α_{conv} and A in Equation (1) that should be as large as possible. Figure 10, design 2, presents a test model where the convection fin distance has been decreased in order to enlarge the total area of warm heat transferring surfaces.

Reasons for not having convection fins over the whole radiator height deserve special mention. The effectiveness of fins decreases as flow develops, with the viscous sub layer increasing and the heat transfer coefficient falling. If the array of fins could be split into two sections so as to form a mixing chamber in between, the benefit could be obtained of a new entrance region in the uppermost part, because the laminar sub layer would be broken up. In other words, thermal efficiency in the removed part would be sacrificed in order to let air flow more easily and improve efficiency in the upper part. How large a part should be removed would depend on many factors, such as the vertical dimension of the radiator, the total pressure drop, material and production costs. Such a design is also presented in Figure 10, see design 4. Observe how the typical convective heat transfer coefficient changes along with the vertical dimension of the radiator.

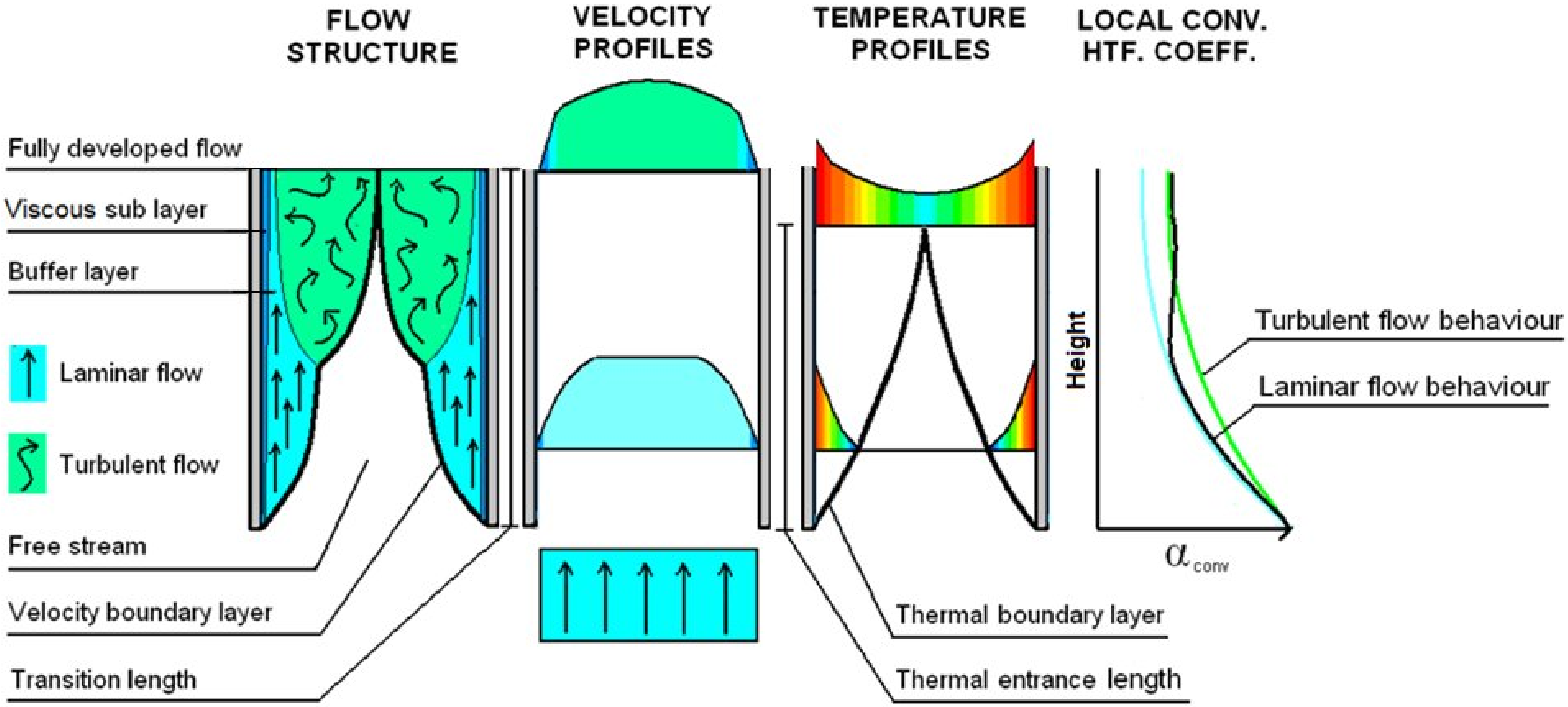


Figure 9. Flow structure, velocity profiles and temperature profiles (illustrations exaggerated in width for clarity) occurring between the entrance region and the point where the airflow would be fully developed in a channel (all relating to the blue section in Figure 5). Hydro-dynamically smooth walls have been assumed. The graph at far right shows how the local heat transfer coefficient would change as flow develops.

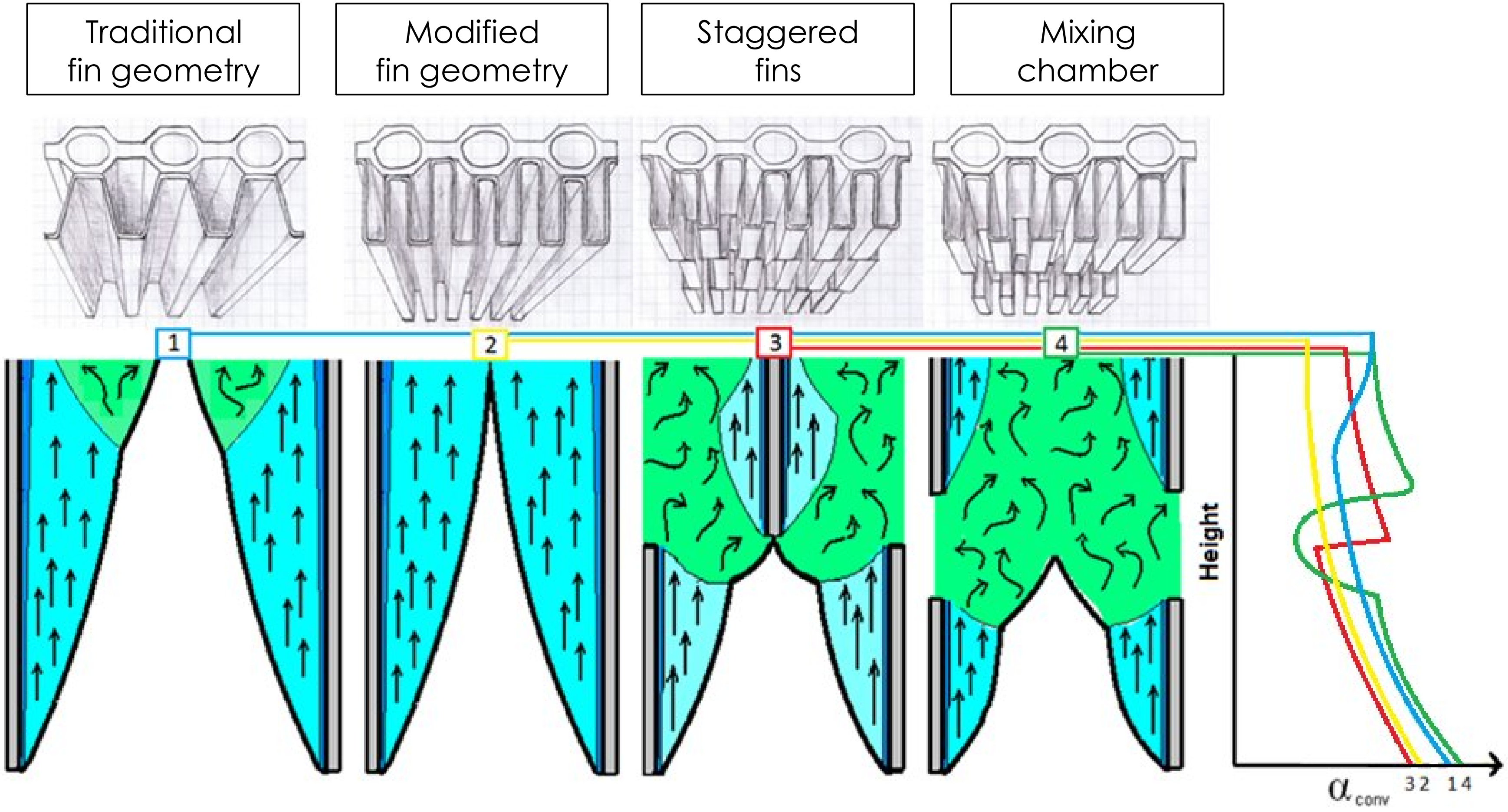


Figure 10. Above: Sections of radiator panels with different convection fin arrangements (secondary surfaces) seen aslant from above. Below: typical flow structures as air rises between vertically heated convection fins corresponding to the geometry shown immediately above (not to scale). The graph at far right shows typically changes in the local heat transfer coefficients as the flow develops (each design has been indicated by a number). Hydro-dynamically smooth channel walls were assumed.

A third alternative (design 3 in Figure 10) was to have staggered convection fins, e.g. the central part of the fin array offset in relation to fins above and below. With this arrangement, the cold cores of ventilation air would be split in two where air passes from one vertical fin section to the other, so the coldest air would come closer to heated surfaces. In addition the insulating viscous sub layer close to heated surfaces would be broken, as in a mixing chamber. This design could even trigger turbulence, as a side effect. Consequently the mean heat transfer coefficient would increase, resulting in a higher supply air temperature at the top of the radiator where air was released to the room. This design, however, meant considerable pressure drop every time air passed from one section to the next (see Paper 4).

2.3.2 Computational Fluid Dynamics (CFD) code and simulations

For the simulations in this part of the work Gambit 2.3.16 and Fluent 6.3 were chosen, together constituting a commercial package offering the broad modelling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial applications. Its large number of alternatives with their many possible settings, however, requires skilled users familiar with CFD. To avoid mistakes and ensure high accuracy in this work, simple models of channels were first made and tested, with airflow behaviour ranging from laminar to turbulent. Results were then compared to empirical values for verification, see paper 3.

Further models representing the parts between the panels of ventilation radiators were made and tested. The purpose was to examine effects given by the different convection fin designs discussed in theory in 2.3.1. For simplicity the radiator panel walls were made flat (as illustrated in the lower right diagrams in Figure 11) and had a fixed uniform surface temperature of 35°C instead of reproducing the flow of water inside the radiator panels. These simplifications meant a certain degree of error, which became larger and larger with improved efficiency, but still the relative difference between each case with different convection fin design was considered relevant, as discussed more closely in paper 4.

The integrated SST k-ω turbulence model was found to handle transitional flow conditions better than the other turbulence models. As previously proposed in the theoretical section, flow in between the panels of ventilation radiators was found to be within this range. No radiation model was used, as gas radiation was considered negligible.

2.3.3 Presentation of CFD results

Presentation of CFD results was typically done by illustrations showing the air temperature rise as a result of different convection fin geometries and arrangements, with the following example given in Figure 11 from paper 4.

2.3.4 Measurements in a climate simulator

The purpose of the laboratory measurements in paper 4 was threefold: to validate the CFD results presented above, to get a broad understanding of the heat transfer mechanisms, and to identify further possible improvements in the performance of ventilation radiators. The main focus was still on heat transfer from internal convection fins, but comfort and health aspects related to ventilation rates and air temperatures were also considered. Some illustrations from the climate simulator used for the experiment are presented in Figure 12.

The simulator was divided into a cold and a warm chamber by partition built to resemble an external building wall. In each chamber, air temperature and air pressure could be controlled separately to simulate outdoor and indoor climate. The radiator test models were attached to the building wall facing into the warm chamber. In the cases with ventilation radiators, cold ventilation air was brought in from the cold side to the warm side through the wall, then through filter and radiator just as in systems currently on the market. Air leakage through the wall itself was not measured or estimated. However, some leakage was observed even if the air-tightness level was considered similar to that of modern well-insulated air-tightened buildings.

The temperature of the warm side was set to 20 °C, the cold side was regulated at three different levels, 0.0°C, -7.5°C and -15.0°C, while the pressure difference between the chambers was controlled at 10 Pa. Both 55°C and 35°C supply water temperatures were tested with a mass flow of 0.01 kg/s.

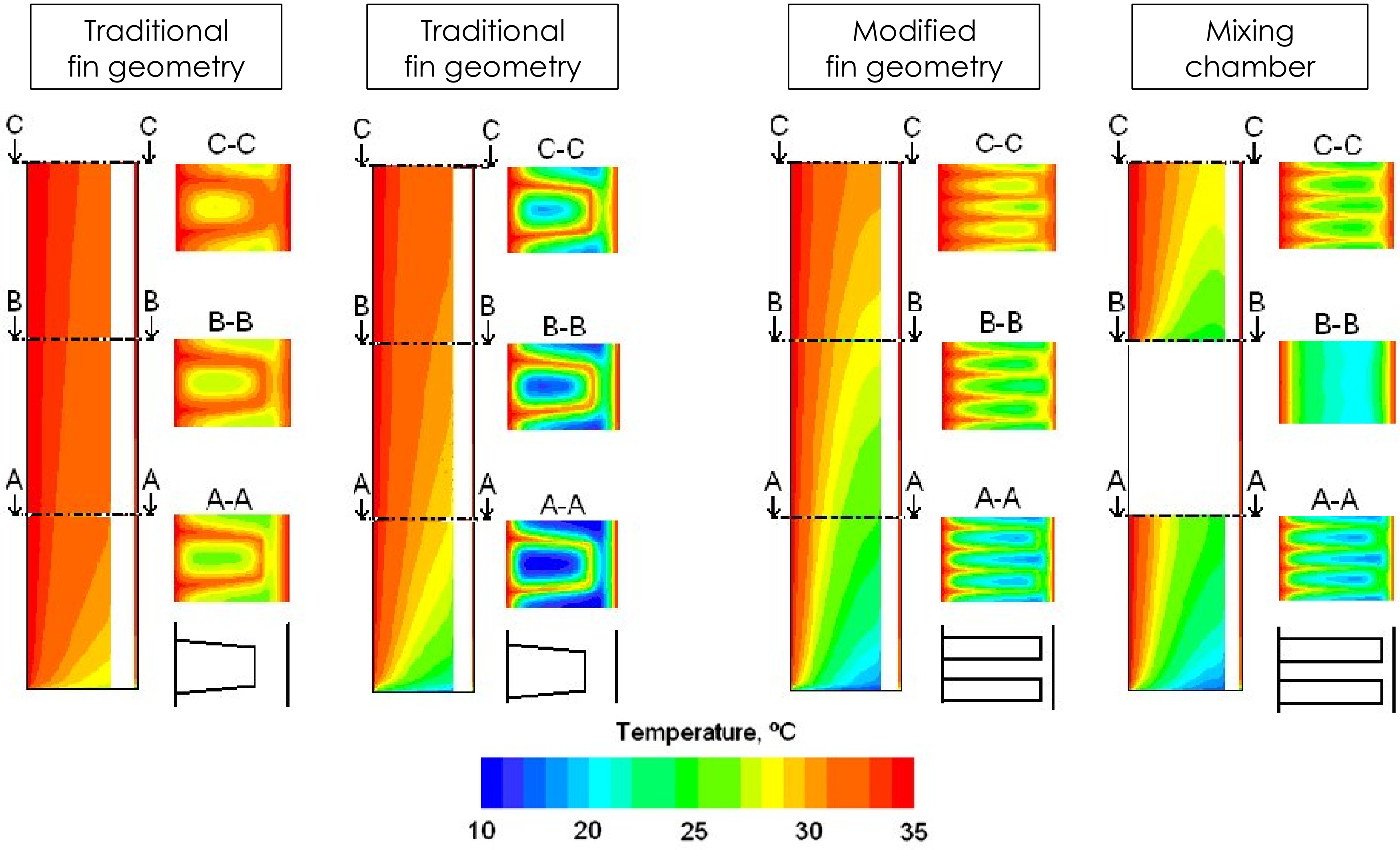


Figure 11. Vertical radiator sections showing heat distribution in fins and horizontal sections showing air temperature at three heights; at 1/3 and 2/3 up the channel (AA and BB respectively) and at the outlet (CC). A diagram showing fin geometry can be seen at bottom right of each of the four sections.

Figure 12. Illustrations from laboratory measurements. Upper left: warm side of the climate simulator where radiators were installed on the wall, together with a heater having integrated circulation pump, mass flow meter, and pressure controller; Upper right: cold side where ventilation air was taken in, measuring probes for airflow and temperature; Lower left: traditional radiator system where cold ventilation air (orange smoke) was brought in 1.5m above the radiator (no window); Lower right: ventilation radiator.

3 Results and discussion

First the performance tests of key ventilation radiator models conducted by CFD simulations and measurements in climate simulator are presented, compared and discussed. Next, the full knowledge gained about performance of ventilation radiators during this doctoral work was compared to that available for other heating systems (with previous results from the licentiate thesis included). A summary of the findings is given in Table 6 together with further discussion. Thereafter follows presentation of whole house energy analyses of systems that include ventilation radiators, a brief comparison of FX and FTX ventilation systems, a discussion on the potential of ventilation radiators, and finally some general considerations on the use of CFD for indoor environments.

3.1 Performance tests by CFD simulations and climate simulator measurements

In the CFD simulations it was confirmed that traditional fin geometry (design 1 in Figure 10) was well suitable for surface temperatures ranging from 35°C to°55 C, normal indoor conditions with buoyancy-driven laminar-flow and an ambient temperature of 20°C. The total heat output of a 0.6 m wide and 0.5 m high 21-module two-panel radiator with this arrangement and a surface temperature of 35°C was 146 W (Figure 11 far left). The result was in line with manufacturer's data. Having increased resistance in the form of more densely positioned convection fins reduced air flow considerably and thus also the heat output, since the driving force was limited.

Heat output increased to 301 W, i.e. more than doubled, when the same traditional fin geometry was used in a ventilation radiator arrangement, but where the driving force on air passing between the radiator panels was greater; the air velocity became higher and the temperature at the inlet air was 0°C. Despite this large improvement, it could be seen that a cold core of air farthest away from heated surfaces was released to the room almost unheated (Figure 11 middle left, section C-C). This gave reason to believe that the traditional fin geometry was inappropriate in this context even if the heat output had increased a great deal. After modifying the fin geometry by decreasing the fin to fin distance by half, as presented in Figure 10 design 2, and Figure 11 middle right, a new situation appeared. Now the air flow was slightly reduced, but the total heat output of the radiator had increased to 394 W (an increase of about 30%). The air was more uniformly heated at the outlet because it came into closer contact with warm surfaces.

Figure 11 far right, shows a case with a mixing region. Half way up the ventilation radiator, air was mixed to a uniform temperature before entering the upper fin array. This meant that the viscous sub layer was broken and the temperature difference between heated surfaces and ambient air became greater, resulting in improved heat transfer in the upper part. This particular case did not fully match the thermal performance of the corresponding case with fins in the whole height as the total heat output was 353 W. Nevertheless, the effect of the mixing chamber was evident and the thermal performance was comparable to the latter even when as much as 2/3 of the material was removed.

The mechanisms studied in the CFD simulations were many, and results indicated that heat output of ventilation radiators could be improved considerably. Validation by measurements with real test models, however, was needed for confirmation.

Figure 13 and 14 present results from key cases of the laboratory investigations. These included one radiator model with a traditional convection fin design exposed to typical indoor climate (traditional radiator); two where the same traditional radiator was used in ventilation radiator arrangements with and without room air mixing of incoming ventilation air (ventilation radiator A and B); and one ventilation radiator arrangement where the radiator had modified convection fin geometry and modified air inlet (improved ventilation radiator). Table 5 summarizes these differences and introduces the terms referred to later in this thesis.

Table 5. Overview of radiator models presented in Figure 13 and 14.

Terms	**Supply air inlet/injector**	**Fin configuration**
Traditional radiator	Above window	Traditional convection fin geometry
Ventilation radiator A	Injector with room air mixing	Traditional convection fin geometry
Ventilation radiator B	Inlet without room air mixing	Traditional convection fin geometry
Improved vent. rad.	Inlet without room air mixing	Mixing chamber (with decreased distance between convection fins)

The heat output more than doubled when the traditional radiator with 35°C supply water temperature was used in a ventilation radiator arrangement (ventilation radiator A) instead of having the air inlet above the window, see Figure 13. In addition, the relative difference between the traditional radiator set up and ventilation radiator became larger and larger as the outdoor temperature decreased. This agreed with the CFD simulations in paper 3 and can be explained by the boosts in $\Delta \theta_m$ in Equation (1). Further, the effect by decreasing the fin to fin distance was evident; heat output increased by an additional 20% in both cases with the improved ventilation radiator (i.e. with 35°C and 55°C supply temperature). The change reduced the heat transfer coefficient k, slightly, but this was more than made up for by the increased surface area A, as predicted in section 2.3.1. However, the outcome was not as striking as predicted in the CFD simulations, with a relative difference of 12% at most. The reason for this deviation was considered most likely to be the approximations done in the CFD simulations. Of all the simplifications made, the most influential was probably the setting of a fixed temperature on the surfaces instead of a predicted mean temperature. Another factor that could have influenced the outcome was increased air leakage through unwanted openings in the wall between the climate chambers, as the modified ventilation radiators had more resistance to incoming ventilation air.

In figures 13 and 14, both cases with decreased fin to fin distance had a mixing chamber. The difference between having a mixing chamber or not was found to be less marked than was found in the CFD simulations. As a conclusion of paper 4 it was recommended to have mixing chambers in radiators taller than 500 mm, while lower profile radiators should have staggered fins. This way one can make the most out of the material in terms of heat output compared to having straight fins over the whole radiator height.

By studying Figure 14 and Equation (1) it could be concluded that the extra heat output given by the most efficient ventilation radiators was all of a convective character, resulting in a higher incoming supply air temperature to the room.

All in all, general agreement was good in the performance tests, and all ventilation radiator models tested were found to be very efficient. How they actually would affect the total energy consumption of a building, on the other hand, wound depend most of all on the whole building organism of which they are a part. Table 6 presents the general conclusions on energy aspects and thermal comfort established though the work, with discussions following in the next chapters.

Table 6. Performance summary of ventilation radiators and various other heat emitters in relation to a high temperature radiator in the exhaust-ventilated room used in this work. Each aspect is scored from “---“ to “+++”, with 0 indicating neutral. Improved performance (e.g. lower transmission losses) is indicated by “+”. After Eijdems et.al. describing performance of low heating systems in general [12].

Performance criteria	Floor Heating	Wall Heating	Medium temperature radiator	Ventilation Radiator A	Ventilation Radiator B	Improved ventilation radiator
Thermal Comfort						
Cold draught hazard	--	---	0	++	+	+++
Vertical temp. difference	+++	--	+	++	++	+++
Air fluctuations	++	++	+	-	--	--
Radiant heat share	+++	+++	+	--	--	---
Energy aspects						
Water temperature level	+++	+++	+	++	+	++
Transmission heat losses	--	-	0	0	0	0
Thermal response	---	---	-	++	+++	+++
Pump work	---	---	0	0	0	0
Operative temperature	++	+++	+	--	---	---
Cooling possibilities	+	++	0	0	0	+

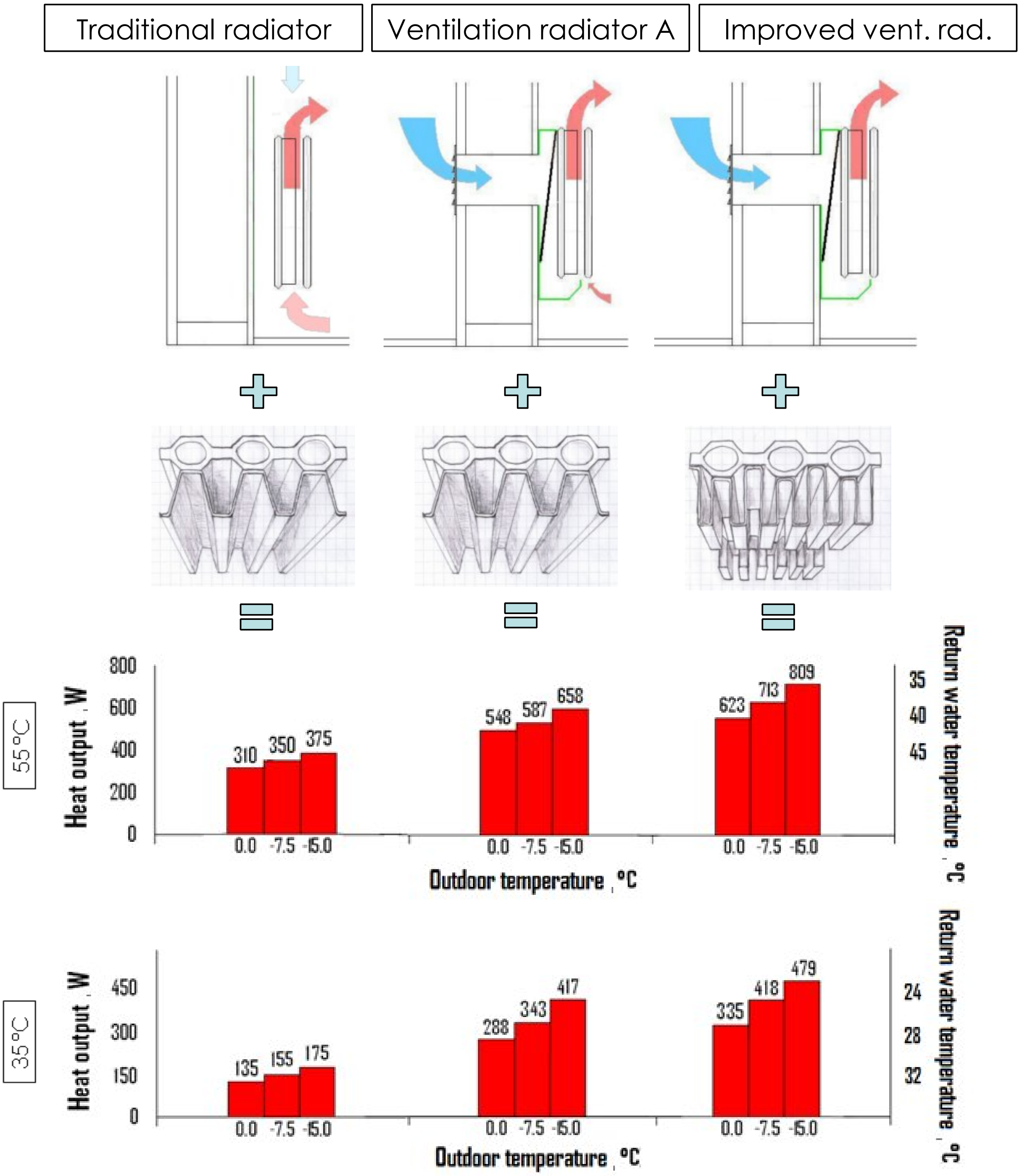


Figure 13. Heat output from three different 21 module radiators, all 600mm wide and 500 mm tall, placed in a 20ºC room, with 10 l/s of incoming ventilation air at three temperature levels, a supply water temperature of 55ºC (above) and 35ºC (below) at a water mass flow of 0.01kg/s. Radiator at left: traditional placement, inlet above the window as shown Figure 12 and table 5; Centre: ventilation radiator on the market (injector mixing incoming air with room air as denoted by the small red arrow); Right: ventilation radiator with revised geometry of internal convection fins and a modified air inlet (improved ventilation radiator).

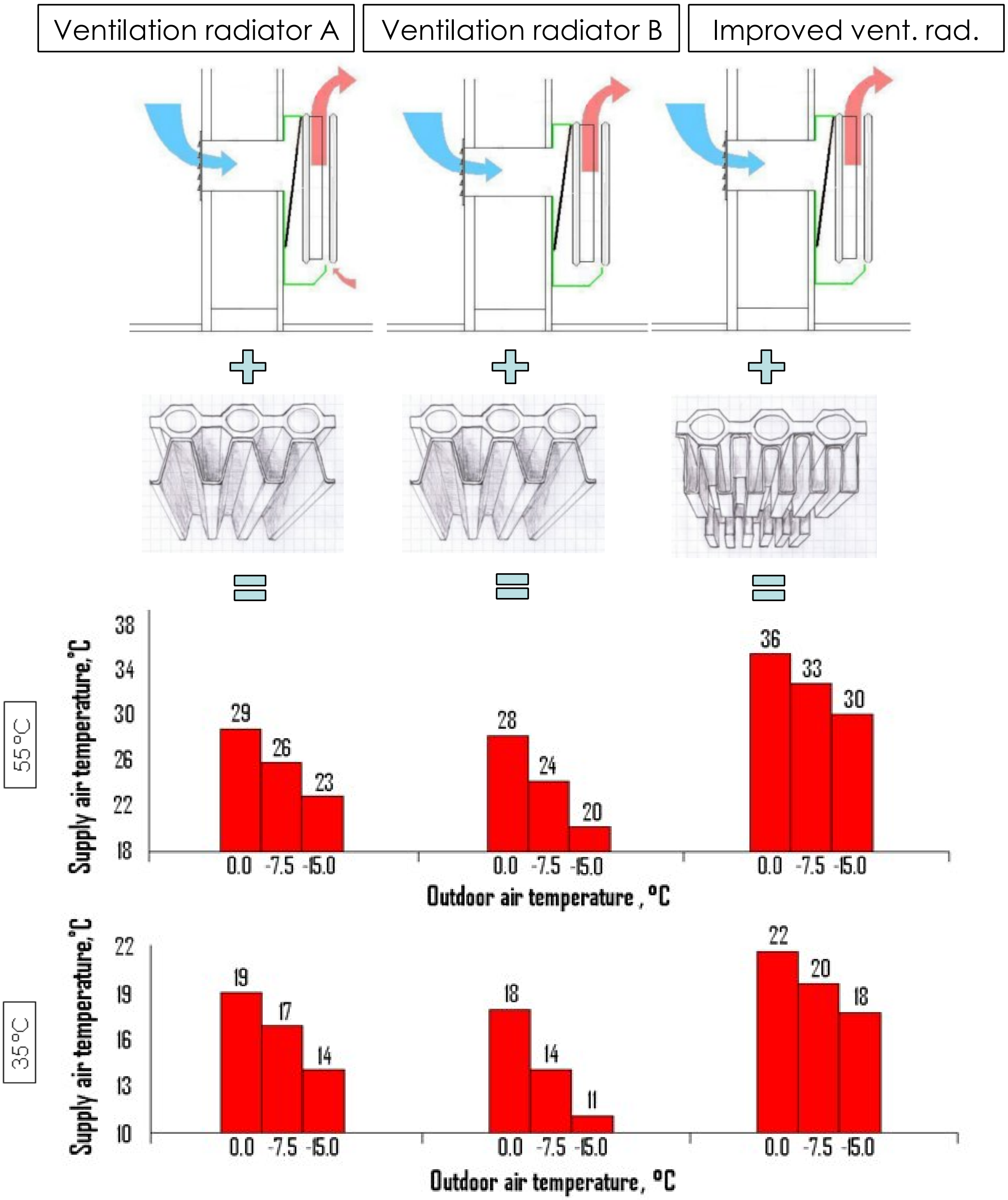


Figure 14. Supply air temperature from three different 21 module radiators, all 600 mm wide and 500 mm tall, placed in a 20ºC room, with 10 l/s of incoming ventilation air at three temperature levels, a supply water temperature of 55ºC (above) and 35ºC (below) at a mass flow of 0.01kg/s. Radiator at left: ventilation radiator on the market (injector mixing incoming air with room air as denoted by the small red arrow); Centre: Identical to left except for modified air inlet; Right: ventilation radiator with revised geometry of convection fins and a modified air inlet (improved ventilation radiator).

3.2 Thermal comfort

The claim that heating systems with low or medium-low water temperatures are able to create more stable and better thermal comfort conditions than traditional heating systems with small, high temperature radiators was in part confirmed in paper 1. It was found that:

- Low and medium-low temperature heat emitters gave fewer air fluctuations caused by buoyancy forces in the occupied zone compared to a high temperature radiator
- The wall and floor heating systems gave more radiant heat to the central parts of the occupied zone than all radiator systems tested. A large proportion of radiant heat resulted in a high operative temperature relative to the air temperature. This has been indicated to be favourable for the thermal climate, while at the same time economising on energy [14, 39]. *For a comparison of radiant heat distribution from a medium temperature radiator, a floor and a wall heating system refer to paper 5*

Air speed levels and temperature differences in the room are two important aspects for thermal comfort. In this particular room, the greatest adverse effect on indoor climate was cold downdraught from the ventilation inlets. Cold draught may readily cause discomfort in humans. Figure 15 presents Fanger's Draught Rating (DR) equation that considers the relation between air speed and Percentage of People Dissatisfied (PPD) for a range of air temperatures [40]. According to the diagram about 17% of occupants feel uncomfortable already with indoor air at 21°C and having an air speed of 0.3 m/s.

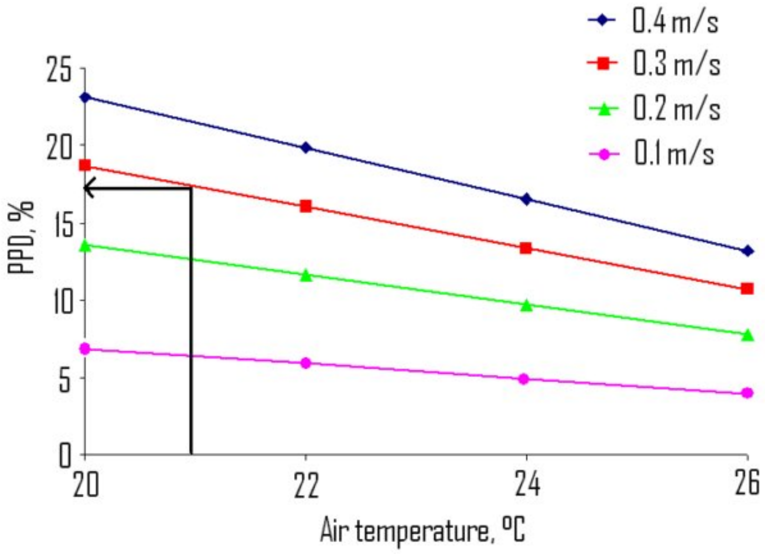
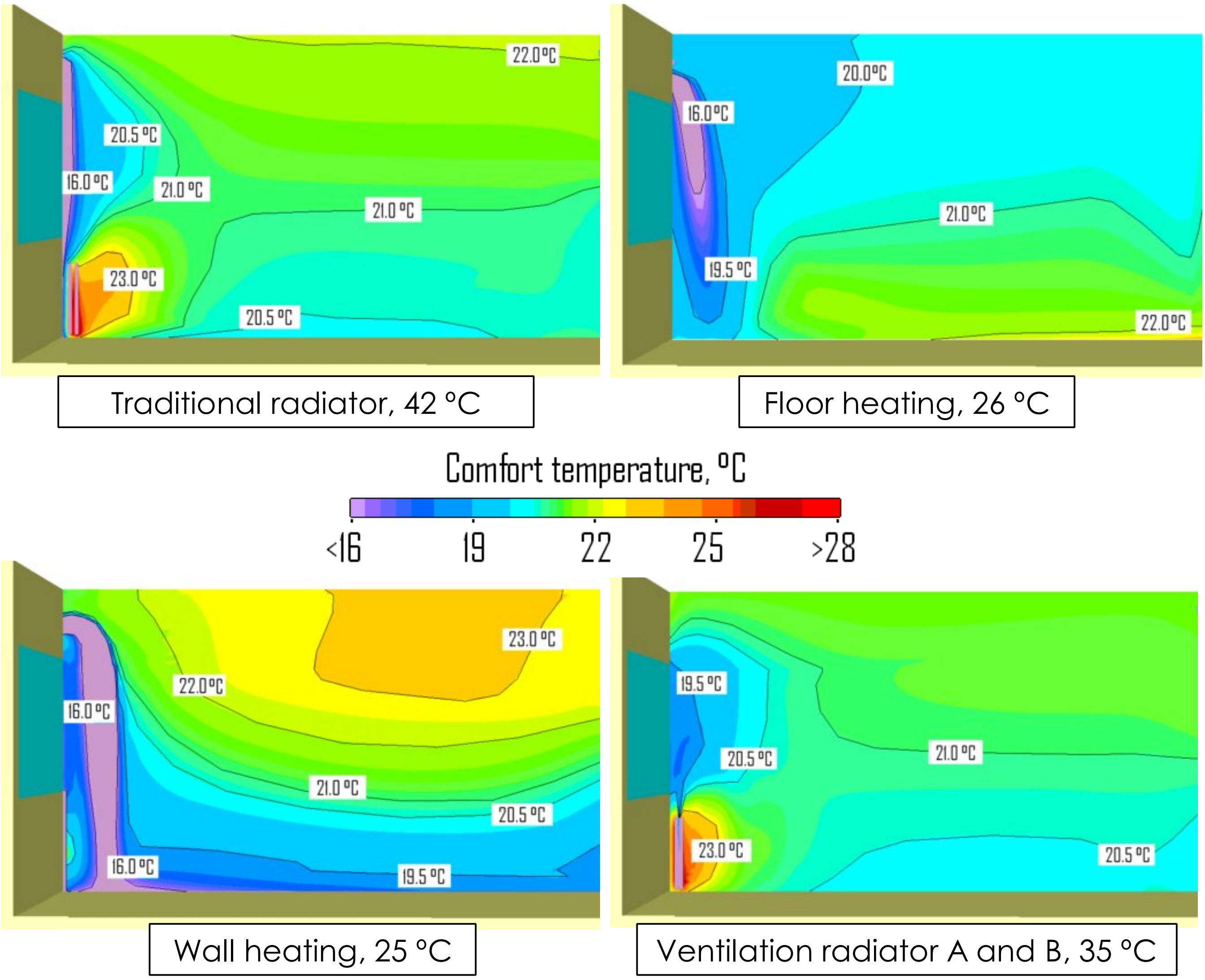


Figure 15. Percentage of People Dissatisfied (PPD) as a result of draught at different air temperatures. Turbulence intensity, a factor which influences the sensation of draught, was set to 50 % for the entire range of air speeds. It should be noted that the temperature and air speed ranges were limited and factors such as individual metabolism and clothing have not been considered here. Note also current interest in revising Fanger's Draught Rating (DR) equation [41, 42], and developing new comfort equations where effects of draught are included [43].

Whether cold down draught reached into occupied zone or not was found to be influenced most of all by the temperature of the heat emitters and their interaction with the ventilation system. Figure 16 describes perceived thermal climate with a selection of heat emitters (the comfort temperature equation is explained in section 3.5). In cases with traditional radiators positioned underneath windows, cold downdraught was blocked and prevented from reaching the occupied zone by warm air rising from the radiators. In cases with large heat-transferring surfaces at low temperatures, on the other hand, a weaker counteraction of cold down-flow from air supply units was evident. Here cold air from the inlets fell to the floor and spread into the occupied zone before it was heated to room air temperature.



Traditional radiator, 42 °C

Floor heating, 26 °C

Wall heating, 25 °C

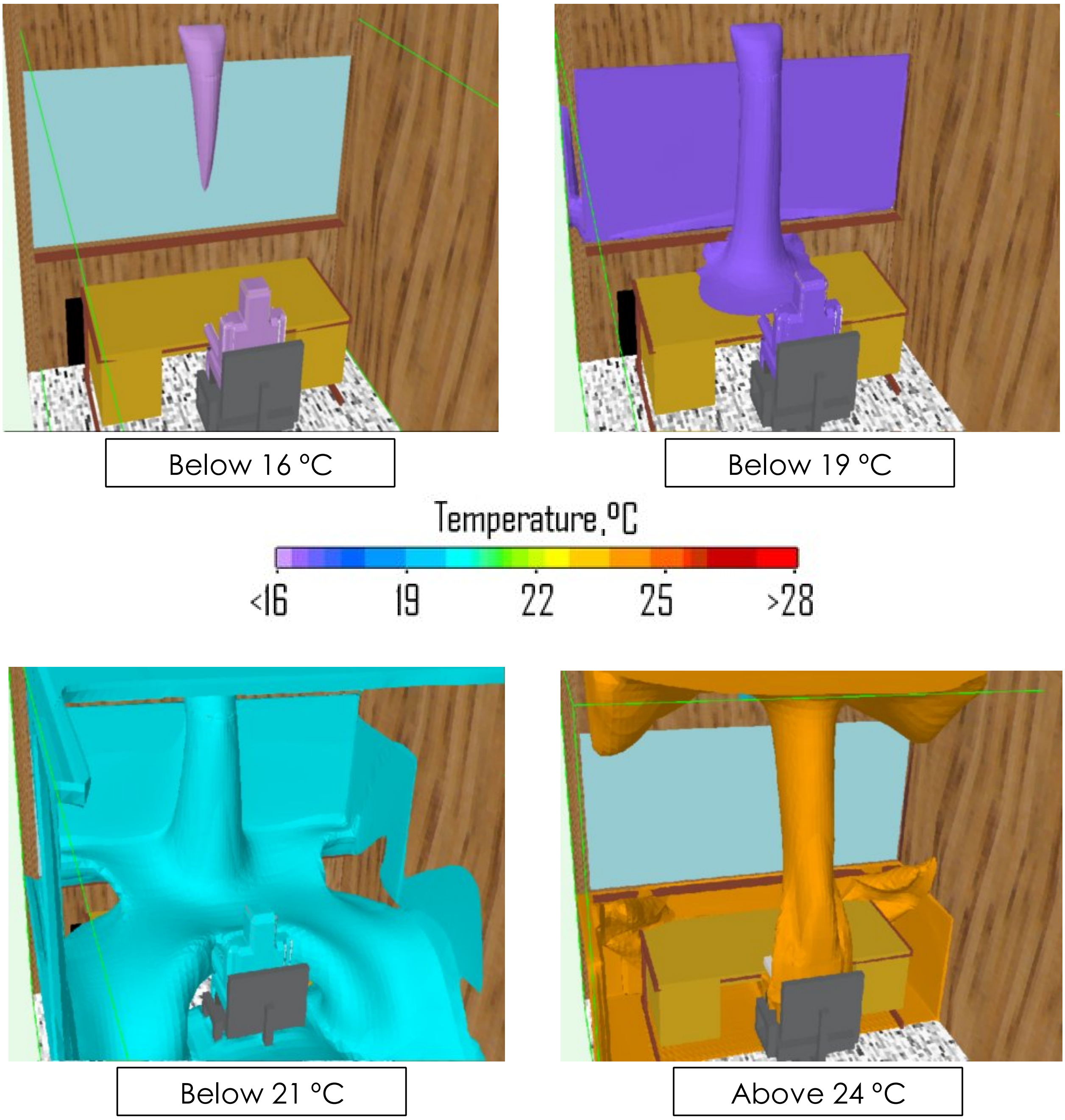
Ventilation radiator A and B, 35 °C

Figure 16. Simulated comfort temperature with four different heat emitters, along a vertical plane at Y = L/2 (Figure 8, right). Surface temperatures of the heat emitters are indicated in sub headings. Note comfort temperature was similar through the middle of the room in all cases.

It was apparent that the ability to counteract cold downdraught should be considered in buildings where cold fresh ventilation air is brought in directly from outdoors. In addition, the way ventilation inlets spread cold air into the room should also be considered and adapted to the heating system to prevent cold downdraught. Traditional radiators were found to counteract this effect better than floor and wall heating systems.

The ventilation radiator was introduced from paper 2 and onwards. Using ventilation radiators instead of traditional heating systems in exhaust-ventilated buildings proved to be a solution that could greatly reduce the risk for cold down draught. And because of their superior efficiency, ventilation radiators can be a key measure to save energy and maintain a high ventilation rate at the same time as well. The reason ventilation radiators performed equally well or better than the other systems in terms of thermal comfort, even at low supply temperatures, was because of the pre-heating of ventilation air inside the radiator. Because no cold air reached the indoor environment there was less air movement caused by buoyancy forces, and also smaller temperature differences in the room. A correctly designed system with ventilation radiators could fully eliminate risk for cold draught. A good example of this was apparent when the radiators in Figure 12 were exposed to the same conditions of water temperature and outdoor air temperature. A measuring probe located 5 cm above the radiators measured a lower air temperature in the case of the traditional radiator compared to the case of the ventilation radiator. This meant that no risk for cold draught with the ventilation radiator was found, while in the case with traditional radiator the cold incoming air needed to reach the radiator before it was heated to an acceptable level.

In the latter case there was a risk that cold air could drop into the occupied zone before it had been adequately heated. Figure 17 shows an example with a person sitting at a desk by the window. He/she became warm on the legs because of heat from the radiator, but cold on the upper body since cold incoming ventilation air fell onto the desk and flowed towards him/her before it had been heated to an acceptable level. Typically, the person would become coldest on arms and fingers.



Below 16 °C

Below 19 °C

Below 21 °C

Above 24 °C

Figure 17. Illustrations from CFD simulations showing iso-surfaces of air with constant temperatures. The ventilation air, 7 l/s at 0 °C, was released from a slot above the window. In all cases the whole air volume (different colours) had a temperature below the given value, except for that shown at lower right, where the air temperature was above the given value. Note the rising warm air plume around the occupant.

The “correctly designed system” mentioned primarily meant a system where the ventilation radiators were not over-dimensioned. Ventilation radiators are powerful; therefore it is not necessary that they be large units. In fact, it is important not to over-dimension such systems or they will over-heat rooms. In modern well-insulated buildings with great internal heat loads, heating supply ventilation air is more important than transferring heat directly to the room. The larger the ventilation radiator, the larger will be the proportion of heat from radiation and convection to the room, with less going toward heating the incoming ventilation air. Ergo, too large radiators at a very low temperature can give more heat than needed to the building without heating incoming air sufficiently to met thermal comfort criteria.

A range of minimum supply water temperatures recommended in order to avoid cold draught at various outdoor temperatures is presented in Figure 18. At an outdoor temperature of -15ºC, for instance, a supply temperature of at least 42°C for ventilation radiator A, 49°C for ventilation radiator B and 35°C for the improved ventilation radiator are recommended. By designing ventilation radiator arrangements that operate above these temperature limits, over-sized ventilation radiators can be avoided and the supply air temperature would reach at least 17-18ºC, which is satisfactory for suppressing cold down draught from windows and achieving an acceptable air temperature in the region where supply air extends into the occupied zone. This statement was based on Rehvas guidebook on displacement ventilation [44], and also CFD simulations for a comparable heating and ventilation system in [33], together with the combined conclusions of simulations presented in Figure 20 and measurements of air supply temperatures as a function of outdoor air temperatures in Figure 14. It can be observed in Figure 14 how mixing of incoming ventilation air with room air helped raise the supply air temperature (ventilation radiator A compared to ventilation radiator B).

It should be added that the supply air was directed upwards in all the laboratory experiments. Thermal climate close to a ventilation radiator if the direction of air supply is changed or deflected by the window frame, for instance, was not investigated. Nor was the influence on air exchange rate in the room by variations in air supply direction or supply air temperature investigated.

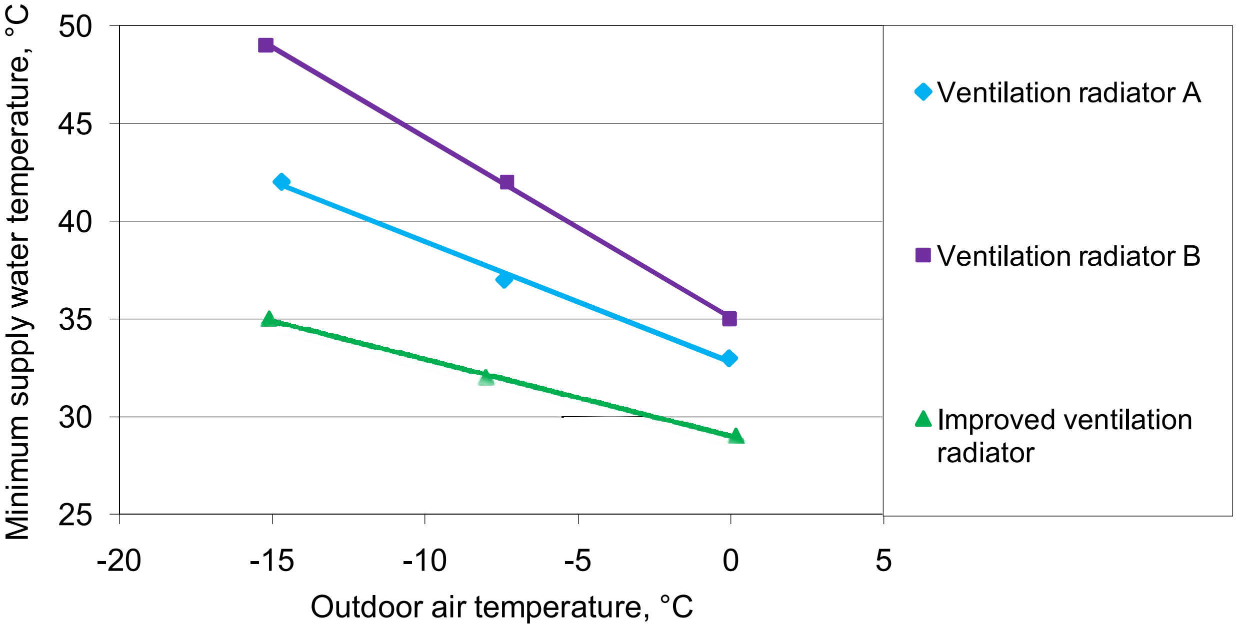


Figure 18. Minimum supply water temperature levels in order to secure a supply air temperature to the room of at least 17-18 °C.

3.3 Energy aspects

Low supply water temperature heating favours energy conservation, both in systems with heat pumps and in district heating systems. For every degree the water temperature may be lowered, energy consumption for heat production decreases and energy losses in the distribution net decrease. Further, the possibility of effectively utilizing alternative and natural heat sources increases as low temperature heat from these becomes readily available. For instance, it is much easier to heat water to 35ºC rather than 55ºC by solar power.

A major part of this work focused on methods to reduce average surface temperatures of heat emitters and thus also supply water temperatures. The average surface temperatures of heat emitters required to heat the room shown in papers 1 and 2 are presented in Table 3. Surface temperatures could clearly be seen to relate to the size of heat transferring areas, to the degree of forced airflow close to warm surfaces and also to the temperature difference between warm surfaces and ambient air (refer to Equation (1)). Thus thermally efficient ventilation radiators may have a lower mean surface temperature than less efficient radiators of the same size and still provide the same heat output.

Papers 3 and 4 confirmed the superior thermal efficiency of ventilation radiators, and further improvements were made to test models. In the case of the best performing model, it was found possible to have twice the heat output than that of a traditional radiator at a supply water temperature of 55ºC, see Figure 13. When the supply temperature of the improved ventilation radiator was lowered until it gave the same heat output as the traditional radiator, the temperature meter read about 35ºC. In the latter case both systems were placed in a room at 20ºC and the outdoor temperature was 0ºC. In other words, it should be possible in practice to lower water temperature levels in systems with ventilation radiators from 55ºC to 35ºC, considering both thermal comfort and energy aspects. This is good news, because energy usage for water heating is always the dominant consideration for energy savings in hydronic systems.

In paper 2 it was described how the theoretical coefficient of performance (COP_c) and the actual coefficient of performance (COP) of heat pumps improve with lower water temperatures. Theoretically, a decrease of 20ºC in water temperature as described above can raise COP_c by approximately 2 points. In reality, the most efficient heat pumps have a Carnot efficiency of about 0.6 (determined by the quotient of COP and COP_c). Such a 20ºC water temperature decrease would therefore mean an actual coefficient of performance (COP) increase of about 1.2 points, which can be expected to give about 30% energy savings for heating of a building. The above mentioned heat pumps have "floating condensation", meaning that the heat pump reduces its effect and produces water at the required temperature for heat emitters (down to 35°C). Whenever tap warm water is needed the heat pump produces 50-60°C warm water. This technique is much more energy effective than the alternative method relying on a constant production of 50-60°C warm water and mixing with cold water to provide the required supply temperature to heat emitters.

Other aspects affecting the total energy consumption for heating and ventilation are:

- How well the heating system interacts with the building (heat storage and transmission losses). *Floor heating systems, for example, tend to have relatively large heat losses through the floor compared to radiator systems (which may have a significant influence on the total energy consumption of the building [45])*
- How well the heating system and the ventilation system together are able to distribute heat to the indoor air and create a stable indoor climate. *In well- insulated buildings with little risk for cold draught, such as fully mechanically ventilated buildings with heat recovery, floor-heating systems create the most stable indoor climate. In exhaust-ventilated buildings ventilation radiators rapidly heat fresh ventilation air, creating an indoor climate with small vertical temperature differences, thus economising on energy.*
- How much of the time heating systems have to be turned on every day and throughout the season to give the desired thermal climate in the occupied zone. *Heat emitters with a high mass flow rate, such as floor and wall heating systems, have a slower thermal response time than small radiators and ventilation radiators. For this reason these systems are more difficult to control in relation to varying heating demands.*
- Whether direct electricity is required for heating in addition to the main heating system to meet the total heating demand on the coldest winter days
- The energy consumption of circulation pumps. *Heating systems with large surface areas, such as floor or wall heating systems require a larger mass flow of water to keep the necessary surface temperature.*

All in all, the potential for saving energy with ventilation radiators would seem great indeed. A comprehensive investigation was needed, however, in order to estimate the total energy savings for a whole building over a whole year if traditional radiators were to be replaced with ventilation radiators.

3.3.1 Whole house system energy performance

The Swedish firm Trä- och Möbelföretagen (TMF) has together with the Technical Research Institute of Sweden (SP) developed a program to evaluate the total energy consumption in a building over a year depending on factors such as building physics, the choice of heating and ventilation systems and internal heat loads [46]. The intention of the program is to help TMF to plan and construct their buildings so as to meet BBR energy requirements. The program, which is impartial and based on SS-EN ISO 13790:2008, has even been used to make comparisons and determine guidelines for different system solutions in various reports [47]. Collaboration between SP and our research group at KTH ABE has led to including ventilation radiators in the program. Table 7 shows annual energy consumption with different system combinations including some arrangements with ventilation radiators (all combinations gave the same total heat output). Figure 19 illustrates the principles of four common system combinations.

Listed below are details of building physics, specifications of the most relevant installations (performance as new and clean), climate data and user related in-data included in this analysis. The building resembled a typical single family house in the southern part of Sweden, while user related in-data was chosen according to the new Swedish building regulations [48-50].

Climate

- Climate zone 3 (see Figure 1)
- Mean outdoor temperature: 8 ºC

Building and installations

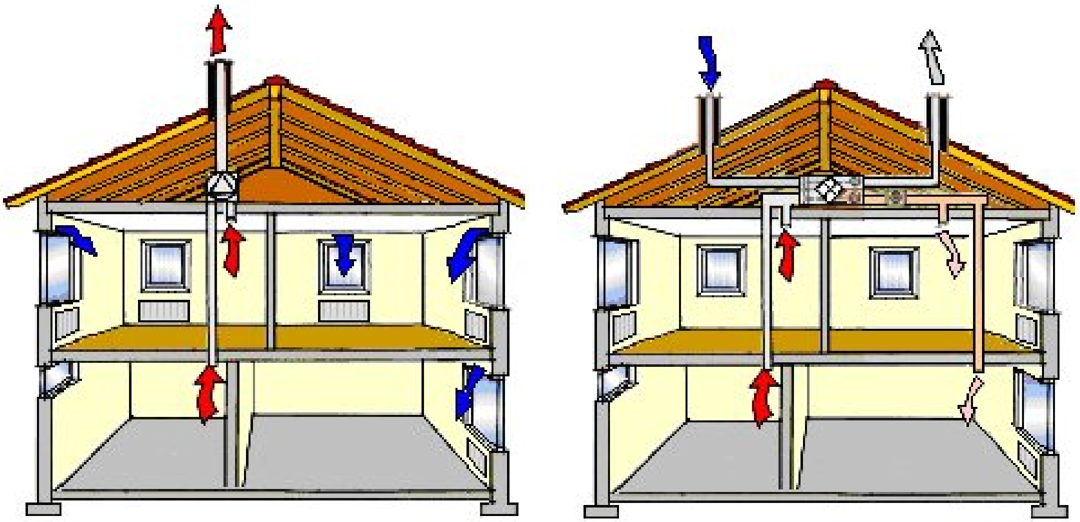
- Total floor area of building (A_{temp}): 130 m^2
- Ventilation airflow: 45.5 l/s
- Indoor temperature during heating season: 21 ºC
- Transmission losses (UA_{tot}): 89.1 W/K
- Time constant: 57 h
- Heat demand at design outdoor temperature (DUT): 4.66 kW
- Air tightness: 0.8 l/(s·m^2)
- Exhaust ventilation fan: F100
- Kitchen stove fan: F200
- Pumps and fans had the same efficiency in all cases
- Traditional radiators: Purmo Compact 21, refer to Table 5, length: 700mm, height: 500mm
- Ventilation radiators: Ventilation radiator A, refer to Table 5, same dimensions as the traditional radiator
- Improved ventilation radiators: Refer to Table 5, same dimensions as the traditional radiator
- Floor heating: covering 45 m^2 of the total floor area, the rest of the heating demand was covered by traditional radiators (all warm water was produced at 55°C, the share used in the floor heating system was mixed with cold water to an appropriate temperature)
- Mass flow rate in radiator circuit: 0.01 kg/s

User related in-data

- Internal heat load: 4 persons giving 80 W/person 14 hours per day
- Tap warm water per person and year (60 ºC): 16/m^3
- Household electricity: 6063 kWh/year

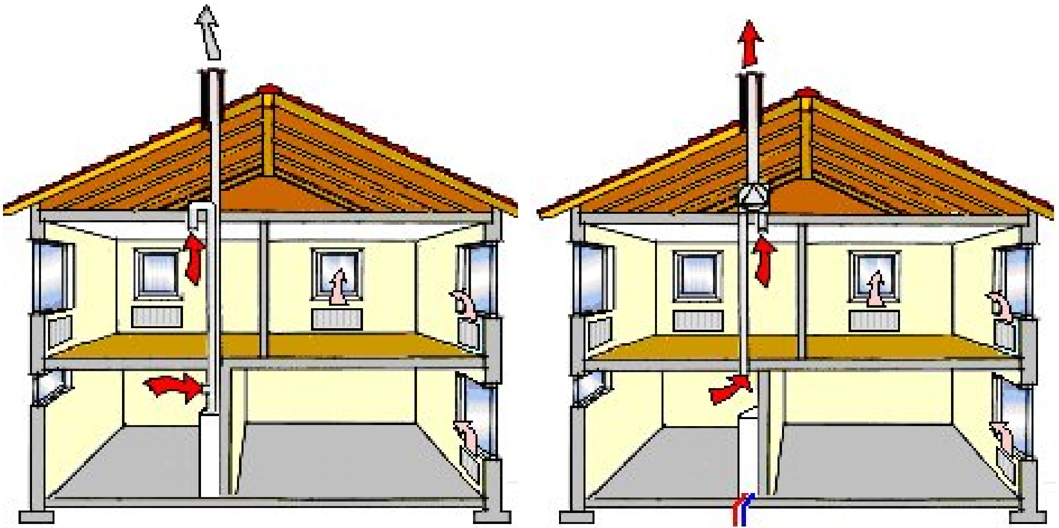
Table 7. Total annual energy consumption (Tot. Cons.) including heating, ventilation and tap warm water for various combinations of heating and ventilation systems in a single-family house. Observe that household electricity not was included. Total electricity consumption (Tot. Elec. Cons.) denotes electrical energy required for running installations such as heat pumps, circulation pumps and fans.

Case	**Heating system (Heat pump type)**	**Ventilation system (Swedish terms)**	**Heat emitters (supply/return water temperature)**	**Tot. Elec. Cons. (for fans) [kWh/m^2]**	**Tot. Cons. (BBR req.) [kWh/m^2]**
1	-	Exhaust ventilation (F)	Electrical radiators (EL)	126 (4)	126 (55)
2	District heating	Exhaust ventilation (F)	10 traditional radiators (55/45 ºC) (TRAD)	5 (4)	127 (110)
3	District heating	Supply and exhaust ventilation with heat recovery (FTX)	10 traditional radiators (55/45 ºC) (TRAD)	10 (9)	104 (110)
4	District heating, exhaust air heat pump (FJV1800)	Exhaust ventilation with heat recovery (FX)	10 traditional radiators (55/45 ºC) (TRAD)	51 (6)	79 (110)
5	Exhaust air heat pump (CZ CE50 ECO)	Exhaust ventilation with heat recovery (FX)	10 traditional radiators (55/45 ºC) (TRAD)	55 (6)	55 (55)
6	Exhaust air heat pump (CZ CE50 ECO)	Exhaust ventilation with heat recovery (FX)	5 ventilation radiators 5 traditional radiators (42/35 ºC) (VENT)	50 (6)	50 (55)
7	Exhaust air heat pump (CZ CE50 ECO)	Exhaust ventilation with heat recovery (FX)	5 improved vent. rad. 5 traditional radiators (40/33 ºC) (VENT)	49 (6)	49 (55)
8	Ground heat pump (IVT HE6)	Supply and exhaust ventilation with heat recovery (FTX)	Floor heating and traditional radiators (55/- ºC) (FLOOR)	42 (9)	42 (55)
9	Ground heat pump (IVT HE6)	Exhaust ventilation (F)	10 traditional radiators (55/45 ºC) (TRAD)	41 (4)	41 (55)
10	Ground heat pump (IVT HE6)	Supply and exhaust ventilation with heat recovery (FTX)	10 traditional radiators (55/45 ºC) (TRAD)	40 (9)	40 (55)
11	Ground heat pump (IVT HE6)	Exhaust ventilation (F)	5 ventilation radiators 5 traditional radiators (41/34 ºC) (VENT)	37 (4)	37 (55)
12	Ground heat pump (IVT HE6)	Exhaust ventilation (F)	5 improved vent. rad. 5 traditional radiators (39/32 ºC) (VENT)	37 (4)	37 (55)



Case 1 in Table 6
F + EL

Case 3 in Table 6
FTX + TRAD



Cases 6 and 7 in Table 6
FX + VENT

Cases 11 and 12 in Table 6
F + BVP + VENT

Figure 19. Some heating and ventilation system combinations as described in Table 7.

From Table 7 it can first of all be seen that installing a heat pump is an effective way to lower the specific energy consumption of a building, irrespective of whether the heat pump is an exhaust air or ground-based type. With the exhaust air heat pump (CZ CE50 ECO), energy consumption was halved, while the ground heat pump (IVT HE6) reduced consumption to one third of that required with direct electrical heating. Both systems lowered consumption to a level that met the new Swedish building requirements by Boverket (BBR 16, BFS 2008:20), see table 1.

The full potential of heat pumps can be realized when in combination with ventilation radiators. For this house the total energy saving over a year would be 8.9% (3.6 kWh/m^2) if five ventilation radiators (ventilation radiator A) replaced traditional radiators in a system with a ground heat pump (case 11 vs. case 9). Alternatively, it would be 8.4% (4.6 kWh/m^2) if the same exchange were made in a system with an exhaust heat pump (case 6 vs. case 5). Substitution of improved ventilation radiators as described would mean 2°C lowered supply water temperature and 9.5% (3.9 kWh/m^2) energy savings for the system with ground heat pump (case 12 vs. case 9) and 9.9% (5.4 kWh/m^2) for the system with exhaust air heat pump (case 7 vs. case 5).

Warm tap water heating was included in all results discussed above. The heat pumps had to heat tap water to 60°C in all cases, even if the heating systems operated at lower supply temperatures. Therefore, considering heating alone, savings would be larger, 13.2% (case 11 vs. case 9), 12.7% (case 6 vs. case 5), 14.2% (case 12 vs. case 9) and 14.6% (case 7 vs. case 5).

It should be noted that the additional savings to be achieved by using improved ventilation radiators instead of ventilation radiators of type A was noticeable, but not substantial. Neither were the results proportional to the difference in heat output between the ventilation radiator models in the performance tests presented in Figure 13. This was for the most part due to an interaction with traditional radiators in the same circuit; these had a larger relative performance drop with decreasing temperature. Other influencing reasons could be, for instance, varying heating demand due to seasonal temperature variations, operation of the heat pump and approximations in the calculations.

The maximum number of ventilation radiators to be installed is determined by the required ventilation flow to the building. Each ventilation radiator unit typically provides for an airflow rate of 8-10 l/s, so for a required flow of 45.5 l/s as in this house, five ventilation radiators were adequate. This meant that a mix of ventilation radiators and traditional radiators was needed to cover the whole energy demand. The best solution was found to be replacing traditional radiators with the same number of ventilation radiators, keeping the same water mass flow rate in the radiator circuit, but having a lower supply water temperature. This arrangement required a supply temperature of about 40ºC, which was 15ºC lower than an arrangement using traditional radiators alone.

In modern buildings where the energy demand for heating ventilation air is the dominating requirement and where transmission losses are small, the proportion of ventilation radiators could be even greater. For example, to cover energy demand in a small apartment it may be enough to have floor heating, heating ledges or similar in one room and two or three ventilation radiators in total, such as in bedrooms and living room. In this case an even lower supply temperature would be adequate. A decrease in water temperature down to 35ºC would be fully achievable without risk for cold draught with well designed ventilation radiators (discussed previously in section 3.1). In this case the total energy saving for heating and ventilation combined by using ventilation radiators instead of traditional radiators may reach approximately 20-30%.

A combination of floor heating and traditional radiators where the warm water was constantly produced at 55°C and mixed with colder water to suit the floor heating system was presented in case 8. This arrangement is fairly common in Sweden. Nonetheless, is proved to be less efficient than any of the arrangements with just radiators. It was another example showing that low and very low temperature heat emitters only are really efficient in arrangements with low or very low heat production. The reasons why the system performed even poorer than radiator systems were a) greater energy consumption for circulating water and b) larger heat loss through the building floor to the ground below.

In this whole building analysis, the focus was above all on ventilation radiators in combination with heat pumps. House owners with heat pumps can readily appreciate the energy and economic savings by changing to a more efficient heating system. Similar energy savings would also be likely in houses with district heating, but then the energy savings would be shared between the house owner and the warm water producer. The most efficient and environmental friendly way would be to produce and supply water at a lower temperature to allow the use of alternative heating methods and decrease distribution losses, but this implies that all consumers on the distribution net would have efficient heating systems such as ventilation radiators or floor heating, otherwise the heating demand will not be met. An example of a community with low temperature district heating is in Ullerödbyen in Denmark.

In Sweden the strategy of lowering the temperature of supply water from district heating plants has not been adopted. Still the authorities encourage house owners to change to more efficient heating systems. This approach leads to use of less warm water (less pump work needed) and a lower return temperature back to the plant (several other benefits emerge), another way to save energy. Typical return water temperatures in systems with traditional radiators and ventilation radiators are given in Figure 13. It should be noted that combination with either traditional radiators or floor heating or similar is often required to fulfil the heating demand, as explained above. Full energy analysis of system combinations in district heating was outside the scope of the present work, however.

3.3.2 FTX versus FX or F

Now it is often claimed that balanced mechanical ventilation with a heat exchanger (FTX) is more efficient than exhaust ventilation with or without heat recovery (FX or F), thus directing attention back towards FTX systems again. One of the major conclusions in this project was that one separate ventilation system should not be compared with another separate ventilation system. Instead, the building should be evaluated as a whole. Interaction between heating and ventilation system has to be considered when the energy performance of buildings is evaluated because heating and ventilation systems affect the performance of each other.

When district heating was assumed in the whole house analysis, FTX certainly reduced energy consumption more effectively than did F ventilation, with a reduction of 18% in case 3 vs. case 2 (refer to Table 6). However, FX ventilation (FJV1800) in combination with district heating was even more efficient, with a reduction of 24% in case 4 vs. case 3. (Note, the latter configuration is not categorised as electrical heating in the BBR requirements because of the small size of the heat pump).

It is even more important to note that in cases with a ground heat pump, a change from F to FTX systems would only mean a minor reduction in energy consumption, with a 2.5% reduction between case 10 and case 9. The reason for this is that the amount of energy recovered from the exhaust air would be small compared to the cost of producing the same amount of energy in the heat pump. Driving the extra fans needed in a FTX system might not be worthwhile, therefore. There would be little point in installing a FTX system to save an additional 6 kWh/m^2 when the extra fans required would take 5 kWh/m^2 to run (case 10 vs. case 9). Retaining the F ventilation in the building but changing from traditional radiators to ventilation radiators would be the more energy-smart decision (10% reduction).

FTX ventilation systems may be more appropriate than FX or F in large commercial buildings with high ventilation rates and cooling. Saving and reusing energy from exhaust air may have a considerable influence on the total energy consumption of a building, but in residential buildings and in combination with certain heating production methods and heat emitters there may be overriding reasons for choosing exhaust ventilation of some kind instead. A system with heat pump and ventilation radiators may be more energy efficient, as well as simpler and more user friendly to operate.

Other aspects should also be considered. For instance an exhaust system with ventilation radiators may ensure:

- Under-pressure in the building; which is important for a healthy indoor climate and avoiding dampness and moisture in walls
- Fresh ventilation air, very short supply ducts (or none) for easy cleaning and maintenance
- Noiseless air supply. Mechanical supply systems tend to have a wheezing noise where air is released to the room

3.3.3 Thermal response of ventilation radiators

The heat output from a ventilation radiator responds rapidly with changing temperature difference to air passing between the radiator panels. This results in higher heat output on cold winter days when more heating is needed and less heat output when it is warm outside. It is therefore less important to adjust the water temperature level or the mass flow rate in the radiator circuit to changing outdoor temperatures. The ventilation radiator automatically regulates its own heat output.

Moreover, a ventilation radiator is an interactive combination of ventilation and heating systems. When the room ventilation rate is increased the radiator gives more heat output simultaneously, and vice versa. If the ventilation rate in rooms is varied on a daily basis according to where people tend to sit or sleep and where fresh air and heat is needed, this fact may be utilized to save even more energy. Ventilation radiators are much more suited to so-called “intelligent” buildings with “ventilation on demand” than most other low or very low temperature systems because of their slow thermal response (as a consequence of large mass flow of water). Paper 7 describes ways of utilizing these characteristics to make ventilation radiators become even more energy efficient.

3.3.4 Cooling with ventilation radiators

Ventilation radiators became the major focus in this project on low temperature water-based heating. It was found to be easier to extract heat from water flowing inside ventilation radiators compared to traditional radiators, and the heat transfer process was then further improved.

Similar physics apply for cooling, and Equation 1 can be similarly used. Note, however, that thermal forces work in the opposite direction. It is tempting to believe that ventilation radiators could be used for cooling purposes as readily as for heating just by circulating cold water instead of warm water in the radiator circuit. The limiting factor, however, is condensation of water on cold surfaces. Water cannot be allowed to condense in the ventilation channels or between the radiator panels for reasons of hygiene. Therefore the minimum allowed surface temperature of ventilation radiators would most likely need to be the same as the dew point temperature of ambient air.

In Paper 6 a calculation was made to investigate the maximum cooling power of a standard ventilation radiator on a typical Swedish summer day. The result was approximately 200 W when outdoor temperature was 30ºC, indoor temperature 24ºC, relative humidity 65% and dew point temperature 17ºC. The conclusion was that ventilation radiators in their present forms would seem unsuitable for cooling. Even with the improved ventilation radiator shown in Figure 13 and Table 5 the cooling power would be too low. Nevertheless, cooling with traditional radiators is being studied in a research program at the Hermann Ritschel institute in Berlin, which may lead to effective ventilation radiator cooling in the future.

3.4 Future of ventilation radiators

In Sweden, heating and ventilation systems in both commercial and domestic buildings are to a large extent chosen and installed by building companies. In alterations and additions to existing housing and in custom built housing, however, owner-occupiers do have some choice, and they need to have a genuine interest in the field to be able to choose the best suitable heating and ventilation systems. Two measures are required in order to ensure that appropriate choices are made.

The first of these measures is, that potential customers whether builders or house owners, should be able to obtain objective information about the different heating and ventilation solutions available and their advantages and disadvantages in different kind of buildings. Otherwise purchasers of such systems may choose according to available marketing information, which is unlikely to be comprehensive regarding the types available, nor to fully cover the various combinations of systems possible. Ventilation and heating companies may be tempted to exploit lack of knowledge among consumers and use oversimplified sales arguments. Examples are:

- Emphasis on energy consumption only, with other aspects such as indoor air quality or variations in performance over product lifetime being disregarded.

- Promotion of complicated FTX exhaust ventilation systems as superior, even if the building energy consumption will be no different, when simpler systems would have been equally effective and easier to operate.
- Promotion of single attributes of such systems as a basis for choice, such as the low surface temperature of a radiator that is simply an extra large radiator, without regard to the combined functioning of heating and ventilation systems within the building as a whole.

The second measure would be action at a high enough political level to ensure that the building sector will be motivated to construct buildings that are truly energy efficient from "day one" and stay that way for many years into the future. In Sweden this requirement is provided for by the Department of Housings' building regulations known as Boverkets Byggregler (BBR) which set rules for regulating ventilation rates and energy consumption, together with a requirement known as "the energy declaration" (energideklarationen), which obliges owners to report building performance regularly after the building comes into operation.

In the year 2011 and probably for many years to come, the focus will be on energy consumption in the building sector, quite possible to a degree that will be to the detriment of thermal comfort and health aspects. This work has shown that ventilation radiators can be truly energy efficient and fulfill all current building regulations, without necessarily compromising thermal comfort or health aspects at all, and possibly even improving them. How energy consumption in buildings will be prioritized may well determine the future prospects of ventilation radiators, because manufacturers of ventilation radiators have so far been focusing mostly on thermal comfort and health aspects.

According to manufacturers' data in 2010, 12 % of all radiators sold on the Swedish market were ventilation radiators, with the number slowly increasing and with the radiator type even reaching new markets in other countries. It would seem that the positive contributions that ventilation radiators and exhaust-ventilation can make in certain environments are having some impact, in systems choice for both existing and future buildings. The next step in this project at KTH would be a scientific implementation study in collaboration with building industry to further illustrate the strengths and possibilities of ventilation radiators. Ideally such a study should incorporate:

- A modern, well-insulated and air-tightened building. *The air-tightness of the building influences the thermal performance of ventilation radiators as air may enter alternative inlets/small cracks in the building envelope. This aspect has not covered in the present work, but should be investigated in the future.*
- An "intelligent" ventilation system with "ventilation on demand" i.e. a system that provides fresh ventilation air when and where it is needed.
- A heat pump utilising ambient heat sources, suitable for low water temperatures.
- A modern VBX module, i.e. an exhaust air recovery unit that extracts energy from used (exhaust) air and transfers it to incoming brine from the borehole in order to complement the ground heat source.

- A combination with low or very low temperature systems such as floor heating or heating ledges if additional heating power is need to meet the heating demand

As with all developing technologies there is potential for misapplication that can bring the innovative product into disrepute, with the result that benefits never become as widely available as they might have done. With ventilation radiators this is particularly so. Not only can they be used in a wide variety of buildings, both domestic and commercial, existing and new, but they can also be used in combination with a range of heat sources and other technologies. This increases the scope for beneficial applications but at the same time increases scope for misapplication where adequate guidance is lacking. Examples of just two important challenges that may be faced by producers and sales advisors are:

Example 1. A house owner wants to change all radiators for ventilation radiators, as is the established pattern when replacing old heating systems, but in fact the optimum result would be to replace half of them, leaving existing non-ventilating radiators in the least occupied rooms e.g. bathroom, kitchen, hallway, guest room. The solution is a) better understanding of ventilation radiators by the customer, and b) a preparedness to sell only e.g. four new radiators instead of eight on the part of the sales outlet. *This is because the number of ventilation radiators should be chosen according to the required ventilation airflow, not the heating demand.*

Example 2. During a vacation the heating is turned off in a school building, but not the exhaust ventilation system, because this is what would have been done with other systems without ventilation radiators. This stops warm water flow in the ventilation radiators. Because cold air still enters through the radiators, the water inside then freezes, expands and breaks the devices, with serious water damage to the building as the outcome. The solution is that directions for management of ventilation radiators be included in care-taking directions for building maintenance. *During periods with frost there should always be a flux of warm water in the radiator circuit to avoid freezing (ventilation radiators should have certain types of thermostats, or other mechanisms, to avoid full water stop).* Freezing of water in ventilation radiators has not been covered in this work but should always be considered especially when installing ventilation radiators in intermittently used buildings such as schools.

Several further challenges may arise if ventilation radiators are modified to give more heat output. This work has identified two main modifications to traditional radiators that can be effective: a) decreased convection fin to convection fin distance and b) modified air inlet (no injector with room air mixing). It is here recommended that both be done together, not the one or the other. Having decreased distance between convection fins increases resistance on passing air, which in turn increases the risk of air entering the building elsewhere than through the ventilation radiator. Having a modified inlet alone, without modification to the fins (ventilation radiator B), would increase risk for cold draught close to the radiator.

3.5 Computational Fluid Dynamics (CFD) in indoor environment evaluation

CFD simulations were used as a tool to express indoor thermal climate produced by the various heating and ventilation systems put forward in papers 1, 2 and 5. By adjusting positions and geometries of the heating and ventilation systems, resulting changes to indoor climate could readily be followed, and an understanding gained of how different systems could be designed and positioned to achieve an acceptable thermal climate. Thus CFD simulations can be used to help eliminate airflow problems or hazards early in the design process before building or renovation begins. Whether CFD could also be used as a complement to physical airflow testing and measurements in present buildings was found to depend on the particular case.

One of the basic advantages with CFD was found to be the possibility of presenting complex variables in a nuanced way. A good example of this can be seen in Fanger's thermal comfort equations, PMV (Predicted Mean Vote) and PPD (Percentage of People Dissatisfied), that describe thermal comfort of human beings [39]. These include up to six variables; air temperature, mean radiant temperature, relative humidity, air velocity, activity level of occupants and the insulation from their clothing. Using CFD these parameters can be combined together as one unit and shown throughout the whole room as demonstrated in paper 1.

Another example of complex variables combined into one is comfort temperature, a term describing the perceived thermal climate, taking account of air temperature, heat radiation and air speed. Figure 20 illustrates how these three different variables combined together form the single variable comfort temperature. Using physical measurements it would be almost impossible, and in any case too time consuming, to include all these factors and capture the whole picture in the same way. This would be especially the case for buildings that are still in the design stage.

Comfort temperature was used for visualization of results in both papers 2 and 5. Paper 5 focused on visualization methods in CFD and how comfort temperature can be used to describe perceived temperature instead of the more commonly used operative temperature.

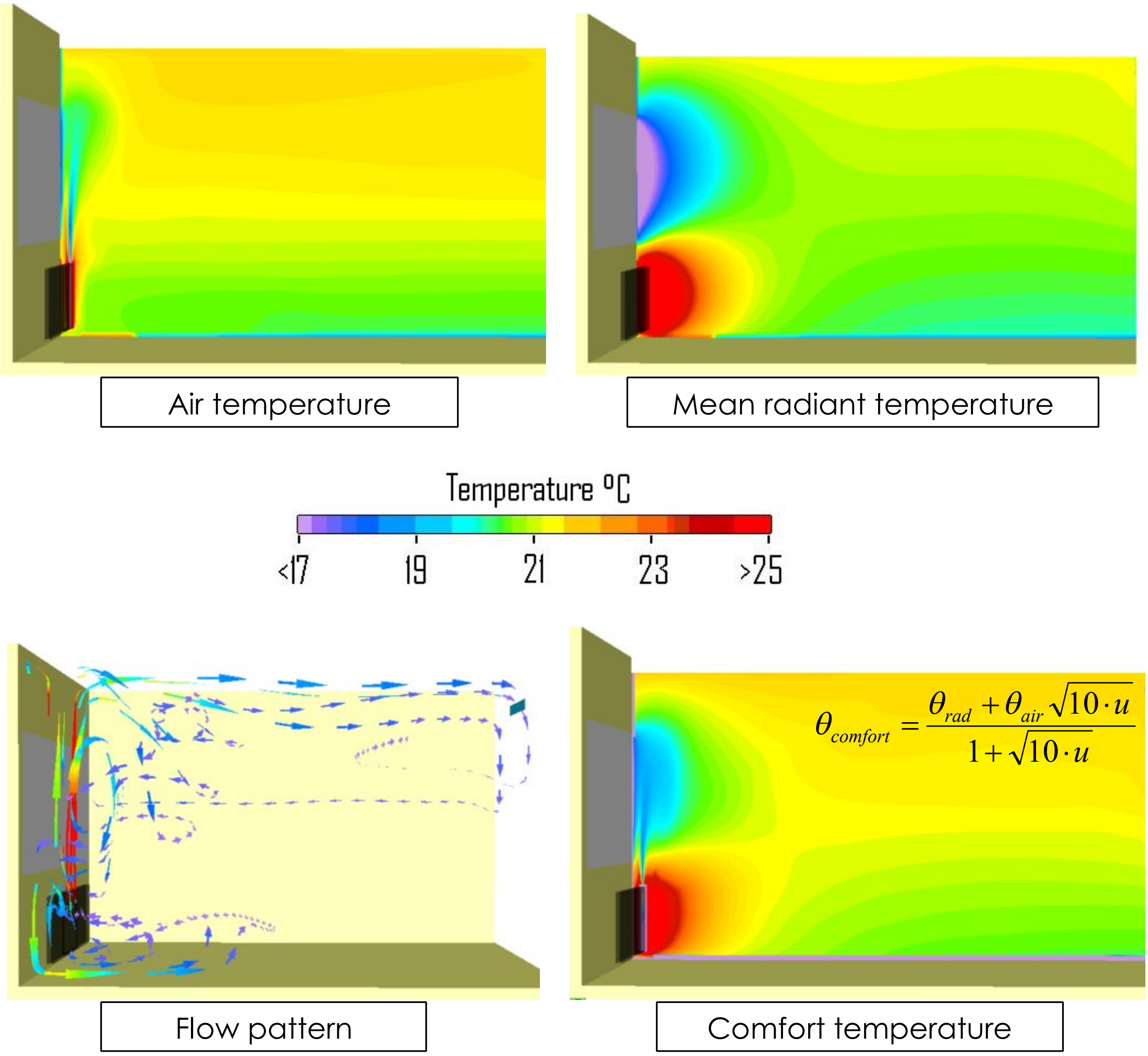


Figure 20. Examples of visualization effects in CFD, all four images relating to the same case with a ventilation radiator. From upper left to lower right: Air temperature, mean radiant temperature, air flow pattern coloured with air speed (blue indicates low velocity and red high velocity) and resulting comfort temperature.

4 Conclusion

Energy consumption for heating and ventilation of buildings is still today, in 2011, considered far too high, but there are many ways to save energy and construct low energy buildings. This doctoral thesis has focused on low temperature heating, with one particular medium given special attention, namely the ventilation radiator adapted for exhaust-ventilated buildings. The reason this particular heating system was given priority was its potential as a low energy consuming, healthy and environmentally friendly system. Thermal efficiency was the major focus, but thermal comfort and health aspects were also emphasized. This combination was a basic goal of research at the School of Technology and Health where this work started: it is important to build well-insulated buildings with energy efficient installations, but efforts should be made to ensure an adequate amount of fresh ventilation air as well.

The investigations were based on Computational Fluid Dynamics (CFD) simulations and analytical calculations, with laboratory experiments then used for validation. The work was carried out in four stages.

Stage 1. Low temperature heating in general

The conclusions from the first stage of the work were that low and very low temperature heating systems, such as floor heating, in general create an indoor climate with low air speeds and low temperature differences in the room, which is beneficial for thermal comfort. The main disadvantage with floor heating and other large-surface systems was found to be weakness in counteracting cold down-flow from ventilation supply units. For that reason other solutions may be more appropriate in certain kinds of rooms and buildings. In exhaust-ventilated buildings, for example, the advances possible by having ventilation radiators or a combination of ventilation radiators and other kinds of heat emitters may be decisive in the choice of heating and ventilation system. With such arrangements the risk of cold draught can be greatly reduced and it is possible to maintain a high ventilation rate even in cold northern European winters.

Stage 2. Ventilation radiator efficiency

The second stage of the work focused on thermal efficiency of ventilation radiators and optimization of heat transfer in between the panels of ventilation radiators. Findings showed that heat output from existing ventilation radiators already was markedly higher than that of same-sized traditional radiators where fresh air was taken in above the window.

The difference in heat output was in general 70-80 % with 55ºC supply water temperature and 110-130% with 35ºC water temperature. The exact extent would be dependent on the volume flow and air temperature of incoming ventilation air. On cold winter days, the relative difference in heat output between ventilation radiators and traditional radiators would be greater than on warmer winter days.

It was found that heat output could be further improved by approximately 20% by simple means without sacrificing ventilation efficiency or thermal comfort (improved ventilation radiator). Among the many modifications tested, the most advantageous combination was found to be decreasing the distance between convection fins and modifying the air inlet. Both modifications increased the share of convective heat output, which helped efficient pre-heating of incoming air and would make ventilation radiators even more suitable for being used in “ventilation on demand” systems.

Stage 3. Possible energy savings by using ventilation radiators

Calculations were made in order to estimate the specific energy consumption for heating in arrangements including ventilation radiators and improved ventilation radiators, and to compare this with other arrangements. The investigation showed that replacement of five traditional radiators with ventilation radiators in a single-family house would allow a lowering of the supply water temperature by about 15 ºC. The consequent energy savings for heating (excluding warm tap water heating) would be approximately 12-13 % in combination with a standard ground or exhaust air based heat pump. With improved ventilation radiators the gain would be an additional 2 %.

Stage 4. Potential of ventilation radiators

In the final stage, this study also showed that ventilation radiators (the improved version) installed in modern air-tightened buildings in combination with modern heat pump technology, can offer potential energy savings of about 30 % compared to existing reference systems. In this case the supply water temperature must be as low as 35 ºC, which was found to be the lower limit for ventilation radiators from both practical purposes and comfort perspectives (an important observation in the study). At this temperature level ventilation radiators increase the availability of low temperature heat sources such as sun-, ground-, water- or waste-heat as well. This would be particularly relevant to new-built “green” energy-efficient buildings, but many advantages may often apply in retrofit applications too.

Recommendations for further work in this field:

Future field measurements of energy efficiency are planned in collaboration with the building industry to establish general guidelines on design of ventilation radiator arrangements, and to contribute to a better understanding of the potential of ventilation radiators nationally. More attention needs to be given to advisory services if the number of ventilation radiators is to be successfully increased in owner occupied buildings such as small private homes where ventilation radiators are particularly suitable and may be more often chosen than in other building types for reasons other than heat efficiency, such as air quality and anticipated health benefits e.g. for asthmatics, by the purchaser.

Summary:

All in all, results from this four part study demonstrated that ventilation radiators can be made to achieve goals set by The Swedish Energy Agency (STEM) and regulations set by the Swedish Department of Housing (Boverket) in BBR 16, BFS 2008:20 [4].

Further this form of heating should be able to contribute substantially to the achievement of the ambitious EU goals given by directives in the European Environment Agency Report No 8/2006 [1]. Finally, this study has contributed in a number of ways, by demonstrating advantages of ventilation radiators not yet widely understood among potential buyers. Its main contributions are summed up in the following four points:

- Reduced energy consumption - meeting EU and BBR directives
- Secured occupant health and well-being
- Simplified building operation
- Improved flexibility in choice of sustainable heat sources

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