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Perceived and measured indoor climate conditions in high-performance residential buildings

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ABSTRACT

The implementation of mechanical ventilation systems with heat recovery (MVHR) in new high-performance residential buildings constitutes a fundamental change from traditional heating and ventilation strategies. A MVHR with one ventilation zone, which is commonly used in new residential buildings, will supply approximately the same temperature to all rooms and consequently contribute to balancing the room temperatures within the dwelling.

This change affects air change rates, the air distribution between rooms and temperatures, and consequently calls for an evaluation of the impact on the perceived and actual indoor climate and of to what degree the desired indoor climate conditions are provided. Therefore, a post-occupancy evaluation (POE), consisting of a user survey and long-term measurements, is performed for a high-performance residential project in Norway.

The results support earlier findings that indicated an improved indoor climate in high-performance residential buildings with MVHR compared with other building standards.

However, the findings clearly demonstrate a need for temperature zoning in residential buildings. The preferred lower bedroom temperatures appear to be difficult to achieve in common high-performance building concepts with MVHR. An important factor that influences bedroom temperatures was found to be the control strategy for the supply air temperature, where a potential for improvement was observed.
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1. Introduction

Major changes in the indoor environment have been observed over the last century, resulting from the efforts to reduce the energy use in buildings on the one hand and driven by increased requirements and changed user behaviour and comfort wishes regarding the indoor climate on the other hand.

For some of the changes, clearly useful synergy effects are exploited, in which the energy use is reduced and the indoor climate is improved at the same time. For example, the reduction of thermal bridges and the improved thermal performance of windows have unequivocally reduced energy use, improved thermal comfort and reduced the risk for mould growth.

However, with regard to changed ventilation and heating strategies in new high-performance residential buildings, such as defined in [1–5], an unconditional and distinct appraisal cannot be provided. Traditionally, fresh air and heat in residential buildings were generally controlled and supplied separately in each room by simply controlling the opening durations of windows or ventilating apertures and controlling local heat emitters, such as radiators or floor heating.

In highly insulated and airtight residential buildings, a dedicated outdoor air system with mechanical exhaust and supply ventilation with heat recovery (MVHR) is used for the provision of fresh air. The need for window ventilation during the heating season is supposed to be substantially reduced or even eliminated [6].

Regarding heating strategies, the use of a MVHR allows for a supply of heat from the heat exchanger and the heat coil, which constitutes a fundamental change compared to the traditional heat supply by local heat emitters. The heat provided through the supply air, in the following called air-heating, can cover the heating demand to a larger or lesser extent. In passive houses, air-heating is even promoted as the dominant heat source [7].

These changed heating and ventilation strategies constitute a major change compared to traditional ventilation and heating strategies. Consequently, there is a need to thoroughly investigate and evaluate the impact on the indoor climate, which comprises

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the indoor air quality (IAQ) and thermal comfort. The potential implications for the health and comfort of the occupants of high-performance buildings is not yet adequately investigated [8].

Earlier studies indicate that the use of a MVHR generally improves the IAQ due to a higher air change rate compared with a natural ventilation strategy [9–15], even though in cases an aggravation of the indoor climate is observed, generally caused by failure in planning, installation, use or maintenance [16,17]. Shortcomings regarding controllability can lead to dissatisfaction, misapplication, and ultimately to abandonment of the mechanical ventilation system [18].

With regard to thermal comfort, considerable improvements are observed in high-performance residential buildings when compared to less insulated and leaky buildings [19–21].

However, in many existing studies regarding the indoor climate in residential buildings, the dwelling is treated as a whole. Little scientific work was found regarding the impact of new heating and ventilation strategies on the indoor climate specifically in the various rooms. Some studies on residential passive houses with MVHR indicate that bedrooms are perceived as too warm even in winter [19,22,23], which may explain the substantial extent of window ventilation observed in some passive houses during the heating season [24].

There is a need for increased knowledge regarding the interaction between the user and the actual, perceived and preferred indoor climate conditions in the various rooms in high-performance residential buildings. These issues are therefore addressed in the present study. The objective is to contribute to the further development of heating and ventilation solutions that provide a good indoor climate in the various rooms in a dwelling at the lowest possible energy use.

To explore this knowledge gap, a post-occupancy evaluation (POE) was performed for the first multifamily project in Norway built according to the criteria defined in the preliminary Norwegian standard for low-energy and passive house residential buildings, prNS 3700 [25]. This project contains the most common heating and ventilation solution in new high-performance residential buildings in Norway, which makes the case project representative for new residential high-performance buildings in Norway and similar building concepts around the world.

The POE comprised measurements of indoor climate parameters, energy use as well as window opening durations. In addition, a user survey was conducted to assess the perceived indoor climate, user habits and behavioural drivers. Based on the results of the survey, a comparison with older multifamily buildings is performed to explore a tendency with regard to the perceived indoor climate. Furthermore, based on the feedback regarding the perceived indoor climate conditions in the various rooms in combination with measured indoor climate parameters, an evaluation of the heating and ventilation strategy is conducted.

2. The case project

The Løvåshagen cooperative in Bergen, Norway, was completed in 2008 and consists of 52 low-energy apartments and 28 passive house apartments according to the requirements in the preliminary version of the Norwegian standard NS 3700 [25]. This standard distinguishes between low-energy and passive house residential buildings, with a heating demand limit of respectively 30 and 15 kWh/m^{2}a for apartment buildings with a total floor area over 250 m^2 (Fig. 1).

The building structure consists of floor slabs and partition walls in reinforced concrete between the apartments and light-weight construction for interior and exterior walls as well as the roof. Regarding the air-tightness of the building envelope, a random sample of apartments was tested, which fulfilled the requirements of a maximum air change rate of 0.6 h^{-1} at a pressure difference of 50 Pa.

Each apartment is accessed via a gallery on the east or northeast side. The kitchens and living/dining rooms are oriented towards the west/southwest, whereas the bedrooms are primarily oriented towards the east/northeast. A floor plan of a typical apartment is shown in Fig. 2.

The heating system in the passive house apartments consists of hydronic floor heating in the bathrooms and one radiator in the living room area. Each passive house apartment has a 290-l water tank with a heat exchanger coil for the solar thermal collector.

In the low-energy apartments, the heating system is based on electric floor heating in the bathrooms and one electric radiator in the living room area.

Flexit SL4R MVHR units are installed in each apartment. The units are placed above the ceiling in the bathroom and equipped with a heat wheel with a maximum heat recovery efficiency of ~80% [27]. Exhaust air inlets are placed in the bathroom and kitchen. Supply air outlets are placed above the doors to the living room and bedrooms. In addition, there is a kitchen hood where the exhaust bypasses the heat exchanger. An electric heat coil with a rated power of 900 W is placed in the supply air after the heat exchanger for heating the supply air temperature to the set-point temperature. The ventilation is based on constant air volume (CAV), in which the flow rate and temperature of the supply air are adjusted by the users on a Flexit CI50 control panel, which is placed in the living room area. The user can choose between three levels for the air flow rate, where level two is intended for normal use. The set-point temperature for the supply air is adjusted on a six-point position scale in the range between 15 and 25 °C and is controlled by a sensor placed after the heat coil in the supply air duct. The factory preset for the supply air temperature is 20 °C. The set-point temperature for the supply air controls the speed of the heat wheel and the power of the heat coil when heat recovery is insufficient to reach the set-point temperature. A schematic diagram of the used MVHR system is shown in Fig. 3.

3. Methods

3.1. User survey

An occupant survey was conducted using a web-based questionnaire. The link to the questionnaire was sent on June 6th, 2012 by email to all occupants that had their email addresses registered at the board of the housing cooperative.

Of the 86 occupants to whom the questionnaire was sent, 34 responded, which corresponds to a response rate of 40%. Of these 34 respondents, 14 lived in passive house apartments and 20 lived in low-energy apartments.

The questionnaire was developed based on a previous literature study on user evaluations regarding the perception and control of the indoor climate [19,28–34] and a review on questionnaire design [35,36]. The developed questionnaire contained two parts. The first part consisted of questions based on the standardized form according to the Örebro model [29]. The Örebro model was chosen because it is well-established and widely used in Scandinavia to map perceptions, complaints and symptoms related to the indoor climate [37–42]. The Örebro model [29] assesses the thermal evaluation in an overall retrospective view. This is in contrast to other standardized methods, such as described in ANSI/ASHRAE Standard 55 [43] and NS-EN 15251 [44], in which an instantaneous thermal sensation is assessed on a seven-point comfort scale.

The results of standardized questions were compared to the results from a comprehensive study on multifamily buildings [45],

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