Energy and Buildings 116 (2016) 263–273

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Combined air heating and ventilation increases risk of personal exposure to airborne pollutants released at the floor level

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ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form 29 September 2015
Accepted 10 January 2016
Available online 12 January 2016

Keywords:
Combined air heating and ventilation
Ventilation effectiveness
Personal exposure
Air distribution
CFD predictions

ABSTRACT

Combined air heating and ventilation systems are often used in low energy buildings. However, operating these systems in the heating mode increases vertical air temperature gradient in rooms and can have negative effect on indoor air quality. The effectiveness of ventilation and personal exposure of the occupants to airborne pollutants generated at the floor level in rooms with the combined air heating and mixing ventilation was analyzed in this paper. The dispersion of pollutants was evaluated under three air distribution methods (in-ceiling four-way and one-way air supply, and high level wall grille air supply) and under three air change rates (1, 2, and 3 ach). Each of these cases were tested at the supply air temperature of +20 °C and +25 °C by performing CFD simulations and experiments in the full-scale test chamber. The results of the experiments showed higher inhaled concentration of the contaminants under the heating mode. The inhaled-to-ambient pollutant concentration ratio varied in the range of 1.05–1.41 under the ventilation mode and it rose up to 1.14–1.78 under combined air heating and ventilation mode. CFD predictions confirmed that pollutants generated at the floor level are entrained into convective boundary layer of the occupant in cases when vertical air temperature gradient was present. The personal exposure to pollutants released at the floor level can increase significantly when a HVAC system runs in the combined air heating and ventilation mode; this effect will not necessarily dissolve with the increase of the air change rate.

1. Introduction

Energy efficiency, thermal comfort, and indoor air quality (IAQ) should be considered when designing heating, ventilation, and air conditioning (HVAC) systems for low energy buildings. Energy demand for space heating in such buildings is comparatively low, therefore ventilation systems can be used for heating purposes by introducing warm air even with the low air change rates [1]. However, vertical air temperature asymmetry in rooms with combined ventilation and air heating may result in either a stratification of contaminants, or a short-circuit air flow pattern [1–4]. Furthermore, the stratification of air can have effects on the concentration of pollutants in the breathing zone and ventilation effectiveness may be significantly affected by air distribution method and the position of the pollution source.

Three air distribution methods were investigated in the study presented by Varodompun and Navvab [5]. The authors concluded that displacement ventilation performed best in the case when ventilation effectiveness index was calculated, however it failed from the perspective of ventilation performance index as the zone of stratification discomfort was exceeded in 36% of room area. Mixing ventilation suffered from low ventilation effectiveness and excessive draft, yet it did not have significant negative effect on IAQ. It was stated, that impinging jet ventilation was efficient from the energy conservation point of view, while still maintaining good IAQ. Overall, this study demonstrated that air distribution strategies are the key to enhance IAQ.

Contaminant distribution under different isothermal steady flow conditions, such as the air change rate, contaminant source location, and contaminant density was analyzed in a full-scale test room by Heiselberg [6]. The results of the study showed that the contaminant distribution in a room will always depend on the location of the contamination source, supplied air flow and the contaminant density. It was also reported that the contaminant stratification is possible at lower flow rates and higher density of contaminants. A study performed by Mundt confirmed that contaminant removal effectiveness in rooms differs with the ventilation flow rate and is very sensible to the position of the pollutant

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http://dx.doi.org/10.1016/j.enbuild.2016.01.011
0378-7788/

source [7]. It was stated by the author that both the level of the source and its position relative to the heat sources present in the room influences the contaminant removal effectiveness. However, these experiments did not indicate the contaminant dispersion patterns in relation to the temperature of the supplied air.

Ventilation effectiveness and thermal comfort in rooms with warm air heating system combined with mixing ventilation was analyzed by Krajčík et al. The results of the study showed that warm air heating and floor heating systems did not show any significant risk of thermal discomfort due to vertical temperature asymmetry or draught [3]. However, increased ventilation rate did not always result in better ventilation effectiveness when using warm air heating. The effect of increasing nominal air change on the ventilation effectiveness was found to depend on the position of the air terminal devices, and varied between 0.4 and 1.2. Numerical simulations performed by Cho and Liu revealed that the near-optimal discharge air temperature can prevent short-circuit air circulation at different heating load conditions and air change rates [8]. The results of CO_2 measurements showed that reduction of the minimum airflow set point did not have negative effect on indoor air quality.

Interaction between human convective boundary layer (CBL) and airflows in rooms can play a significant role in contaminant transport into the breathing zone of the occupants. The direction and magnitude of the surrounding airflows considerably influence the airflow distribution around the human body [9]. CBL needs to be considered to achieve accurate predictions of personal exposure, as it can transport the pollution surrounding the human body into the breathing zone [10]. It was also proved that a particle source at the floor level and in near proximity to an occupant increased the concentration of inhaled particles by up to four times compared to the ambient concentrations [11]. A study of behaviour of particles ranging from 2.5 μm to 10.0 μm with a density of 1400 kg/m^3 by Chen et al. showed that the surface temperature of the heat source and the gap between the heat source and the near wall affects particle deposition on surfaces [12].

CFD simulations of contaminants dispersion in a single-family house showed high degrees of contamination as well as thermal stratification during the winter months. The conclusion was done that in the cases with low ventilation rates the system mimic displacement ventilation and leads to lower contaminant exposure of the occupants, compared to the case with completely mixed air [13].

The effects of air pollution source location and air distribution method on ventilation effectiveness are extremely complex. Previous studies revealed significance of low level pollution on personal exposure, however, there are no reported studies outlining entrainment of these contaminants into CBL of the occupants in relation to air heating. The aim of this study was to analyze dispersion of pollutants released at the floor level of the room with combined ventilation and air heating system by performing full-scale experiments and CFD predictions. Entrainment of the pollutant into the CBL of the occupant was evaluated by calculating personal exposure index as well as the ratio between ambient and inhaled contaminant concentrations. Eighteen case studies were analyzed overall, including three air distribution methods and three air change rates with air heating function on and off.

2. Methods

2.1. Experimental methods

2.1.1. Test chamber and facilities

A test chamber (the floor area of 13 m^2 and a volume of 35.8 m^3) representing a standard room was used for the experimental study. The walls, floor and ceiling of the chamber were fabricated using conventional construction materials, such as painted dry-wall, PVC lining and a panel ceiling. The chamber was equipped with in-ceiling air exhaust diffusers as well as air supply system, consisting of in-ceiling diffusers and a high level wall grille. One wall of the test chamber was designed to imitate an external wall. Water-borne cooling system was installed to keep the surface temperature of this wall at the desired value. Supply and exhaust airflows, as well as supply air temperature were controlled using the air handling unit (GOLD 04, Swegon AB, Sweden). The supply air temperature during the experiments was set to either +25 °C or +20 °C, depending on the analyzed case. The scheme of the chamber are presented in Fig. 1.

A heated dummy of rectangular geometry was installed in the chamber to simulate a seated person with the inclusion of "legs" considering that this was previously documented as an important factor having influence on air flows around a person [14]. The surface area of the dummy was equal to 1.7 m^2, it was covered with a textile fabric and the surface temperature of the dummy was in the range of +31 °C to +34 °C, similar to the human body surface temperature. The dummy was seated on the wooden chair. The distance between the dummy and the wall was 0.2 m to avoid disturbance of the CBL by the physical presence of the wall as well as air supply jet.

2.1.2. Experimental setups and measurement equipment

Three types of mixing ventilation air distribution cases (four-way air supply, one-way air supply, and high-level wall grille air supply) and three air change rates were analyzed (1, 2 and 3 ach). Two multi-nozzle air supply diffusers of 0.5 × 0.5 m with plenum boxes were used for the in-ceiling air supply cases. One-way mixing air supply was achieved by directing all of the 47 nozzles of the diffuser towards the closest wall. The four-way mixing was created by directing the nozzles in four directions. Wall grille of 0.3 × 0.1 m with plenum box was used for high level horizontal air supply. Air distribution patterns were tested before the experiments by using the smoke.

Experimental parameters for all 18 analyzed cases are presented in Table 1.

The air pollution source was located in the centre of the test chamber floor imitating strong localized source of contamination at the floor level. The distance between the pollution source and the dummy was equal to 1.2 m. Such experimental approach was selected with the aim to identify possible paths of volatile organic compounds (VOCs) contaminants at different temperature gradients and ventilation conditions in the entire volume of the test chamber. Pollutants emitted at a floor level may include flooring materials, carpets, household cleaning products etc. In our study, a Petri dish filled with a liquid glue (TOTALSEAL 34B, Le Joint Français, France) was used as a surrogate pollution source of VOCs. The passive release of pollutants was conducted by the evaporation of VOCs (e.g. 1,2,4-trimethylbenzene, naphthalene, xylene, polypropylene glycol, etc.) from the adhesive [15].

Concentration of released compounds was measured using seven air quality sensors based on micro-machined metal oxide semiconductor (MOS) technology (iAQ2000, AMS Sensor Solutions Germany GmbH). The metres are sensitive to various non-methane hydrocarbons, including aliphatic hydrocarbons and aromatic hydrocarbons, alcohols, ketones, organic acids, amines, as well as methane. The quantitative response of these sensors was obtained by using manufacturers provided calibration based on the Reversed Metabolic Rule technology, which calibrates measured VOC concentrations to CO_2-equivalent ppm values, thereby achieving compatibility to CO_2 standards. The seven sensors were tested for the precision of their readings in the full range of response; the coefficient of variation of the readings did not exceed 7%.