LAURA STASIULIENĖ

COMBINED IMPACTS OF INDOOR CLIMATE SYSTEMS IN BUILDINGS ON OCCUPANT INHALED VOLATILE ORGANIC COMPOUNDS CONCENTRATION

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LAURA STASIULIENĖ

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ABBREVIATIONS

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

AH – warm air heating

BREEAM – Building Research Establishment Environmental Assessment Method

CBL – convective boundary layer

CFD – computational fluid dynamics

CRE – contaminant removal effectiveness

DPS – double precision solver

EPA – the United States Environmental Protection Agency

FH – underfloor heating

HVAC – heating, ventilation and air conditioning systems

IAQ – indoor air quality

IGCC – International Green Construction Code

LEED – Leadership in Energy and Environmental Design

MDF – medium density fibreboard

MVOC – microbial volatile organic compound

OSB – oriented strand board

POM – organic compounds associated with particulate matter or particulate organic matter

PVC – polyvinyl chloride

RH – radiator heating

RVD – relative vapour density

SBS – sick building syndrome

SVOC – semi-volatile organic compound

TVOC – total volatile organic compound

VOC – volatile organic compound

VVOC – very volatile organic compound

WHO – World Health Organization

INTRODUCTION

Background and motivation

The indoor climate in modern buildings depends on a variety of factors, such as air change rates, a presence of air pollutants, operative temperature, air distribution scheme, air velocity etc. Thermal comfort and indoor air quality in buildings are mostly influenced by the combination of heating, cooling and ventilation systems. To ensure high indoor air quality levels, it is important to either reduce emissions from pollutant sources or ensure effective removal of these emissions. The most significant air pollution sources in modern buildings are household chemicals, finishing materials and furnishings.

To accurately assess the impact of air pollutant sources on occupants, particular attention should be paid to the isothermal pollutants released at the near-floor level, because of the human convective boundary layer ability to elevate pollutants to breathing level. The most frequent sources of such pollutants are floor coverings, cleaning products, varnishes and others that emit volatile organic compounds.

Volatile organic compounds are produced by evaporation of materials at room temperature, and therefore they can be classified as isothermal pollutants. Furthermore, their density and temperature are not significantly different from the indoor air density and temperature. Therefore, the dispersion of such pollutants is influenced by indoor climate parameters (air temperature and air velocity), air distribution scheme and convective flows in rooms.

No reported results of the combined impact of heating systems and air distribution scheme on occupant inhaled pollutant concentrations were found, especially concerning isothermal pollutants (volatile organic compounds) released by evaporation at near-floor level.

The aim of the dissertation

The aim of this dissertation is to identify the factors that influence air pollutants transportation into the breathing zone in modern buildings and explore the dispersion of volatile organic compounds released at a near-floor level under different combinations of heating systems and air distribution schemes.

Objectives of dissertation

To achieve the aim of the dissertation, the following objectives are addressed:

- To investigate near-floor level emitted pollutant transportation to occupant breathing level in rooms with different combinations of heating systems and air distribution schemes under laboratory conditions;
- To perform simulations of pollutant dispersion by means of computational fluid dynamics (CFD);
- To assess the reliability of results from CFD simulations, as well as to identify factors influencing contaminant dispersion;

- To provide recommendations for the selection of heating system and air distribution scheme to ensure lower entrainment of near-floor level emitted pollutants into the breathing zone.

Scientific novelty

Quantitative differences in volatile organic compounds relative concentrations in the occupant breathing zone under different heating and air distribution conditions were identified. No studies were found reporting the combined impact of heating and mixing ventilation systems to occupant inhaled pollutant concentrations, especially regarding isothermal pollutants, such as volatile organic compounds released at near-floor level.

Practical implications

It has been determined which combination of heating system and air distribution scheme provides better air quality in the breathing zone in buildings where sedentary activities are carried out and the presence of near-floor level emitted pollutants cannot be avoided. Better air quality in the breathing zone can be ensured by combining mixing ventilation with low-temperature surface heating (i.e. underfloor heating).

It is important to emphasise that more often than not, mixing ventilation systems are designed without consideration of convective flows from occupants, heating devices or appliances (e.g. computers or lighting), assuming that temperature and pollutant concentrations will be evenly distributed in the premises. Less intense convection flows from heating devices and appliances are expected due to the energy performance of buildings as well as appliances. Therefore, convective flows from occupants, being of similar magnitude as ventilation airflow, will play an important role in room air distribution. The findings of this dissertation support the latter statements from the perspective of air quality experienced by the occupant.

Methods

The dissertation is based on experimental and numerical simulation methods. Dispersion of volatile organic compounds released at a near-floor level under different combinations of heating systems and air distribution schemes was investigated experimentally in the full-scale test chamber and simulated using computational fluid dynamics software. Statistical differences in relative concentration values were assessed employing non-parametric statistics. The computational fluid dynamics software was used to assess the effects of different factors influence on contaminant dispersion.

Structure of the dissertation

The dissertation consists of the following sections: introduction, literature review, methods, results, conclusions, discussion, references and a list of publications.

The volume of the dissertation is 96 pages. The dissertation contains thirty-seven figures, fourteen tables and provides one hundred and fifty-one reference.

1. LITERATURE REVIEW

To identify factors that influence air pollutants transportation into the breathing zone, the conducted literature review was divided into sections: indoor air pollutants of concern; sources of volatile organic compounds; health effects and indoor concentrations of volatile organic compounds; volatile organic compounds control strategies; factors influencing gaseous pollutants dispersion in rooms; human convective boundary layer.

1.1. Indoor air contaminants of concern

Indoor climate is extremely important to humans, especially indoor air quality (IAQ). Air is always more or less contaminated with various gases, particles or odours [1]. The United States Environmental Protection Agency (EPA) reported that air pollution indoors could be ten times higher than outdoors [2]. Thus, humans are always exposed to a variety of contaminants that can be seen in Figure 1. Contaminants found in indoor air are usually classified as particulate matter and gases. Indoor air contaminants can also be classified according to their origin, properties, sources, effects on human health and safety. However, the most common classification of contaminants for IAQ studies is based on physicochemical composition presented in Figure 1.

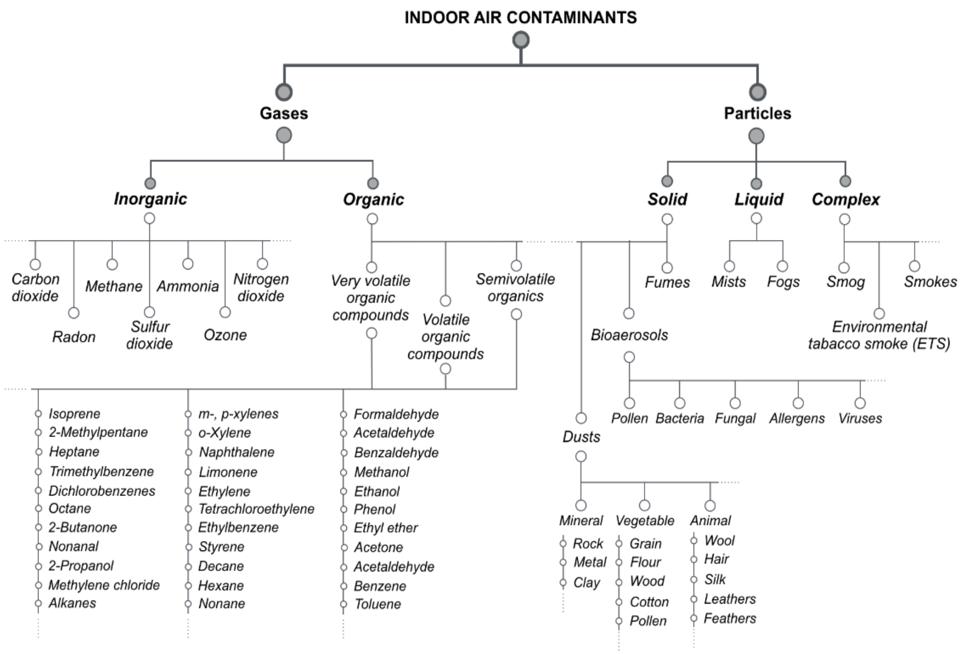


Figure 1. Main indoor air contaminants [3]

As can be seen in Figure 1, there is a wide variety of gaseous organic contaminants in indoor air. The definition of organic compound used in the European Parliament and Council directive 2004/42/EC [4] describes an organic compound as any compound containing at least the element of carbon and one or more of hydrogen, oxygen, sulphur, phosphorus, silicon, nitrogen, or a halogen, except carbon oxides and inorganic carbonates and bicarbonates.

The important fact which should be explained is that gaseous contaminants can be divided into gases or vapours. The term gas is usually used to describe a contaminant which has a gas state naturally (e.g., ammonia) and their vapour pressure is greater than the ambient pressure at ambient temperature. Vapour is described as a substance in the gaseous state, whose natural state in normal atmospheric conditions is a liquid or solid (e.g., benzene). The pressure of vapours is below the ambient pressure at ambient temperature.

Almost all gaseous organic contaminants evaporate under certain conditions. Any organic compound having an initial boiling point less than or equal to 250 °C measured at a standard pressure of 101,3kPa is termed as a volatile organic compound (VOC) [4]. The more simplified definition is given by Salthammer [5]: organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure are called volatile organic compounds. Since VOCs can evaporate under ambient temperature, they can be called isothermal contaminants. In indoor air sciences, all gaseous organic compounds are classified according to their boiling point (Table 1).

Table 1. Classification of indoor organic contaminants by volatility [6]

Category description	Acronym	Boiling-point range, °C
Very volatile (gaseous) organic compounds	VVOC	< 0 to 50-100
Volatile organic compounds	VOC	50-100 to 240-260
Semi volatile organic compounds	SVOC	240-260 to 380-400
Organic compounds associated with particulate matter or particulate organic matter	POM	>380

Regarding terminology, it is important to mention that VOCs are also produced by metabolism of microorganisms, such as fungi or bacteria, and these organic compounds are called microbial volatile organic compounds (MVOCs) [3]. Another term which is usually used is total volatile organic compounds or TVOCs. The European working group EU-LCI (European Union - Lowest Concentration of Interest) [7] defines TVOCs as a sum of VOCs in a specific range detected by a specific analysis method. This means that only a part of the volatile organic compounds is presented by the TVOCs concept. However, this concept might be useful in specific case, e.g. TVOCs can be the indicator for presence of VOCs indoors [8].

VOCs are indicated as a very important subgroup of indoor contaminants by many researchers [5, 9-11]. Zhang et al. [11] reported that exposure to VOCs could be called ‘modern exposure’ which allows claiming that VOCs are ‘modern contaminants’.

1.2. Sources of volatile organic compounds

Volatile organic compounds come from a variety of sources. The sources include occupants and their activities, building materials or outdoor air. Furthermore, VOCs can participate in reactions that form secondary contaminants, e.g. ozone-terpenoid reactions produce carbonyls such as formaldehyde and acetaldehyde [12, 13], phthalate or phosphate esters react with water and yield alcohols and acids [14]. Occupants' activities, such as the use of cleaning products, air fresheners, personal care products and smoking are classified as activities producing VOCs [14, 15]. Construction materials such as composite-wood and gypsum boards, as well as a variety of architectural finishing materials (flooring materials, carpeting, paints, varnishes), are reported as sources of VOCs [14, 16, 17]. As the aim of this work is related to pollutants released at the near-floor level, the focus will be on sources of VOCs related to the lower parts of the rooms.

Cleaning and maintenance products are probably the largest groups of VOCs sources in indoor air. These products consist of a variety of chemical compounds, which are the main sources of primary VOCs (e.g. limonene, α-pinene, a-terpinene, a-terpineol, linalool, etc.) in an indoor environment. The study of Singer et al. [18] showed that use of some cleaning products could yield high levels of VOCs (glycol-ethers and terpenes) that can react with ozone and form a variety of secondary pollutants. Bello et al. [19] reported that VOC emissions that occurred during short-term cleaning tasks remain as a source of air pollution even after the task stops.

Composite wood. Plywood, medium density fibreboard (MDF), oriented strand board (OSB) and others are types of composite wood, which are used as construction materials in buildings. Composite wood is produced by binding wood fibres, particles, strands or veneers together with adhesives. Adhesives in the composite wood are reported as a major source of formaldehyde and other VOCs [20, 21, 22, 23]. Composite wood has replaced solid wood, not only in building constructions but also in almost all furniture (wardrobes, tables, shelves, beds etc.), furnishing has become one of the major sources of VOCs in indoor air. Various textiles and filling materials, usually synthetic, are also used in furniture and are reported as a source of VOCs. Kim et al. [24] reported that materials used in mattresses (polyurethane and polyester/polyethylene) are emitters of N, N-dimethylformamide.

Gypsum boards, commonly known as drywall, are the boards made of gypsum and a paper facing. Gypsum boards are frequently used for wall, ceiling and partition systems in almost all buildings. Yang and Chen [25] suggested that gypsum walls can adsorb significant amounts of VOCs and can act as secondary sources of VOCs. Markowicz and Larsson et al. [26] found that VOCs concentrations emitted from gypsum boards increase with increased relative humidity.

Wood-based flooring materials. Two types of flooring materials frequently used nowadays are laminate and engineered flooring (Figure 2). The main difference between these types of flooring is their construction. Laminate flooring usually consists of four layers bonded together: the overlay (aluminium oxide), the decoration layer (photo printed on the film), the high-density fibre board core, and a counterbalancing layer (polymer laminate paper) [27]. Engineered flooring is also a combination of a few layers, but the layers are made of real wood. The bottom and core layers (sometimes only one layer) of engineered flooring board are manufactured of plywood, the decoration layer is made of thin veneer, and the coating layer is UV curable [28, 29]. The adhesives (urea formaldehyde resin) used in the production of laminate and engineered flooring are reported as a source of formaldehyde and VOCs [28, 30].

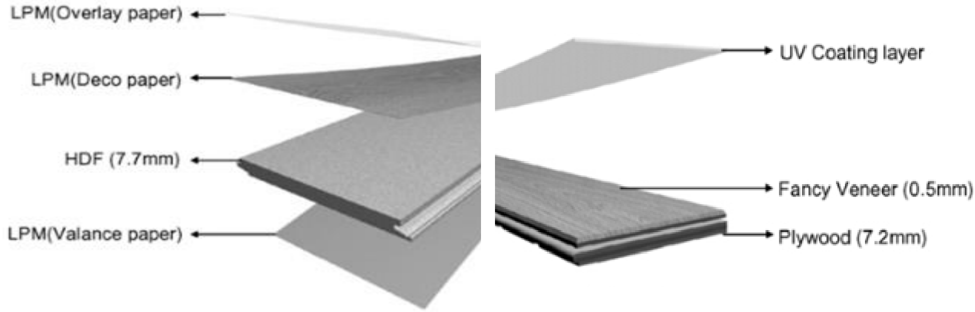


Figure 2. Layers of the laminate (a) and engineered (b) flooring [29]

Carpeting is one more common flooring material. For the production of carpets, fibres and yarns such as wool, polypropylene, nylon, polyester and other synthetic materials are used. In a study by Katsoyiannis et al. [31], VOCs emissions from four different carpets (wool, synthetic and mixed type) were evaluated. The results showed that the maximum concentrations of TVOCs were up to 2300μg/m³ in the case of the synthetic carpet. Concentrations of 4-phenylcyclohexene and 2, 2-butoxyethoxy-ethanol were up to 170, and 320μg/m³ and low concentrations of benzene, toluene, the xylenes and styrene were also registered. According to Abbass et al. [32], carpets can be both, sources and sinks of gaseous organic compounds. The authors reported that primary emissions of formaldehyde from carpets with polyester fibres were up to 16μg/m²/h, and secondary – up 29μg/m²/h. Furthermore, pollutants emissions from carpets can cause an appearance of sick building symptoms (SBS). The results of experiments in a full-scale test chamber with an old carpet and different ventilation rates showed that symptoms such as difficulty in thinking and smarting of eyes appear when an old carpet is in the chamber and ventilation rates are lower compared with the cases with high ventilation rate [33].

Vinyl flooring is used in residential buildings, usually in kitchens and bathrooms, in healthcare facilities, commercial buildings, as well as industry. Vinyl flooring is made of polyvinyl chloride (PVC) resins and various plasticizers, fillers, stabilizers and pigments. Plasticizers are additives that increase the plasticity or viscosity of a vinyl flooring, and commonly phthalate esters are used [34]. Afshare et al. [35] reported that di (2-ethyl- hexyl) phthalate and dibutyl phthalate emitted from PVC flooring and the maximum concentration was approximately 1μg/m³.

Paints and varnishes. For colouring surfaces, solvent-based and water-based paints are the most commonly used paints in indoors applications. The main difference between these two types of paints is their solvent. In solvent-based paints the binder, pigments and other additives are dispersed in an organic solvent. In water-based paints, water is used as a solvent. Organic solvents include a wide variety of VOCs such as aliphatic compounds, toluene, xylene, ketones, esters, alcohols etc. Nowadays, water-based paints are used more because they emit fewer VOCs. Varnishes are also a type of paint. The composition of varnishes is the same as paints, excluding pigments. Even in cases where low VOCs emission paints are used in buildings, they can still be considered as a pollution source [36].

Adhesives are not only used in production processes of building materials but also during the construction works, e.g. installing the floor or wallpapers, and they as well as paints are composed of materials that emit VOCs [37, 38].

Flooring materials (laminate flooring, vinyl flooring), paints, varnishes and adhesives used in floor constructions, as well as cleaning products used to keep the floor clean, are reported as important sources because of their large area [27, 39]. These materials are used in almost all buildings and particularly attention should be paid to the VOCs emissions from these materials.

1.3. Health effects and indoor concentrations of volatile organic compounds

The analysis of VOCs sources at a near-floor level in the previous subsection revealed that formaldehyde, acetaldehyde, benzene, toluene, xylenes, styrene, limonene etc. are the most commonly released compounds. These compounds are classified by the European Commission's INDEX project as the priority pollutants that should be regulated in indoor air because of their carcinogenic, sensory, toxic or reactive properties [40]. The INDEX project divides chemical compounds into three groups: high priority chemicals (formaldehyde, benzene), second priority chemicals (acetaldehyde, toluene, xylenes and styrene), and chemicals requiring further research about human exposure (limonene, α-pinene) [40].

Formaldehyde, acetaldehyde and benzene are considered as carcinogens and toluene, xylenes, styrene, limonene and α-pinene are non-carcinogens [40-43]. Short-term exposures to these compounds usually cause skin, eyes, respiratory tract irritation, as well as sneezing, coughing, headaches, dizziness and general weakness [40, 44]. Long-term exposures to formaldehyde are associated with allergy, asthma, chronic bronchitis symptoms, as well as eczema and cancer [40, 42, 45]. Exposures to benzene (long-term or higher concentrations) can cause central nervous system damage, genetic defects, aplastic anaemia, leukaemia [40, 43, 44]. Limonene, for example, is recognised as a safe compound and the health effects associated with this compound are irritation of skin, eyes, nose and throat [41]. Special concern should be taken to children and elderly exposures to VOCs. Children are more vulnerable to toxic compounds because they have a higher exposure per kilogram of body weight, are less developed immunologically, physiologically and neurologically [46]. The elderly may be more exposed to air pollutants than the rest of the population, since they spend more time indoors [47].

Furthermore, it is important to emphasise that occupants indoors are exposed to a mixture of VOCs, which is an additional concern. The study of Allen et al. [48] aimed to evaluate the effects of VOC mixtures on cognitive function in a controlled experimental environment with TVOC concentrations of 50μg/m³ ("green building") versus 500μg/m³ (conventional building). The results of the study showed that occupants had a lower cognitive function when higher TVOC concentrations were measured.

Concentrations of toxic and hazardous substances in the indoor air are limited by regulations. Usually, concentration limits are presented for individual VOCs if they are included in regulations, however the limited values vary depending on the country. For example, WHO [42] guidelines for formaldehyde concentrations are 100μg/m³ (30-minutes average concentration). In comparison, the national daily limit in Lithuania is 10μg/m³ [49]. For benzene, it is reported by WHO [42] that levels indoors should be minimised as much as possible and that there is no safe level of exposure, while in Lithuania the limited value is 100μg/m³ [49] and in South Korea (for clean and healthy buildings) – 30μg/m³ [50]. In Germany, limited values for toluene is 300μg/m³, for xylenes – 100μg/m³ and styrene – 30μg/m³, while in Lithuania the standard limited values are 600, 200 and 2μg/m³ respectively [49, 51]. Regarding TVOCs, the German Federal Environment Agency recommends a 300μg/m³ value as a limit [51]. The IGCC (International Green Construction Code) [52] has included a TVOC concentration limit of 500μg/m³.

The VOC concentrations indoors in the existing building stock systematic review was conducted by Paciêcia et al. [53]. The results from 40 published articles according to building type (schools, housing, offices and others) and season (cold or warm) revealed that the mean VOC concentrations were higher in the housing and office environments, as well as in the cold season. Higher concentrations of VOCs in cold season may be associated with lower air exchange rates. In addition, the authors evaluated indoor and outdoor concentrations of VOCs and concluded that in the majority of buildings, sources of VOCs were associated with the indoor environment. However, this review does not differentiate buildings with and without ventilation. However, different methodologies of sampling VOCs were used in the reviewed articles. The article published by Langer et al. [54] reported the concentrations of TVOCs and formaldehyde measured in 5 passive buildings with mechanical ventilation (with heat recovery) in Sweden during different seasons. The average concentrations of TVOCs were 139μg/m³ and 10.5μg/m³ for formaldehyde. The authors reported that no systematic seasonal variation was noticed. Similar results of formaldehyde concentration in a net-zero energy house were reported from the study carried out in Maryland, USA; where formaldehyde concentrations varied from 5 to 12μg/m³ [55]. In contrast, the study in 11 low energy buildings with mechanical ventilation carried out in Lithuania by Kauneliene et al. [56] revealed that the mean formaldehyde concentration was 30.7μg/m³ (higher than the national limit). The authors associated high formaldehyde concentrations with low levels of air change rates (from 0.08 to 0.69h^{-1}) and lack of professional setup after the ventilation system installation. In addition, very similar concentrations of benzene, toluene and xylene were reported by both Langer et al. [54] and Kauneliene et al. [56].

It is important to emphasise that higher concentrations of VOCs in buildings with new interior materials were also reported [56-59]. That implies that adequate ventilation rates should be assured in new buildings, particularly immediately after installation.

1.4. Volatile organic compounds control strategies

The building sector has changed significantly over the past decades. In addition to existing regulations, a number of “green” building certification programs have been developed, e.g. LEED (Leadership in Energy and Environmental Design) which is used in the United States, BREEAM (Building Research Establishment Environmental Assessment Method) used in the United Kingdom [60, 61]. A building’s impact on the environment throughout their life cycle is certified under these programs according to such criteria as energy consumption for space heating and cooling, water consumption, indoor environment, pollution, waste management, ecology, etc. Wei et al. [62] analysed "green" building certification programs from the perspective of indoor air quality and found that indoor air quality assessment takes only 7.5% of the total evaluation of the building. The main indoor air pollutants suggested to be evaluated in these certification programs are carbon dioxide (CO_2), formaldehyde and other VOCs, with only 6.7% of certification programs suggesting ozone (O_3) and SVOCs. Unfortunately, these certification programs are applied on a voluntary basis and are not mandatory for all buildings. The main pollutant suggested to evaluate in national regulations is usually CO_2 [63]. To ensure high IAQ levels, “green buildings” certification programs commonly suggest a source control and dilution of contaminants by ventilation systems. Therefore, monitoring the concentration of pollutants should be a part of its control strategy. ASHRAE [64] defines three main ways of controlling VOCs, as well as any other contaminant emissions: source control, contaminants dilution by ventilation systems as well as air filtration and purification.

Source control is the most effective way to control emissions of VOCs. In addition to an “environmentally friendly” building certification programs, there is a number of laws restricting emissions of VOCs from building materials and products used in buildings. For example, the European Parliament and Council Directive 2004/42/EC [4], which aims to limit VOC emissions in decorative paints. Limitation of emissions of pollutants is most effective when it is applied at the building design stage by choosing environmentally friendly (low VOCs-emitting) materials. Low VOCs-emitting materials are certified by third parties (usually, the state certification centres) and are marked with special characters, such as “Indoor Air Comfort®” in Germany [65]. In the building maintenance phase, limitation of pollutant emissions can be performed by removing or transposing VOC-emitting material to better-ventilated areas, by changing people's habits or environmental conditions (temperature, relative humidity). Often, it is not enough to remove the contaminants only once. For example, in the case of microbiological pollution, constant surface cleaning may be required.

Cheng et al. [66] found that "green" building materials also emit VOCs, but in much smaller quantities compared to conventional building materials. According to the authors, VOCs from "green" materials, as well as from conventional materials, can react with the ozone in the atmosphere and create a secondary emission.

Schieweck and Bock [67] conducted a study with “low VOC” and “zero-VOC” emitting materials and found that all materials emitted VOCs, even though the material was labelled as "green." Based on these findings, it can be argued that emissions of VOCs limitation cannot be used as the only tool for air quality control.

Dilution of pollutants by supplying outdoor air to the building is the most traditional way to control indoor pollution. It is widely used to control both particulate matter and gaseous contaminants. Additionally, it is identified in all sustainable building certification programs [62]. Dilution of pollutants can be ensured by both natural and mechanical ventilation systems. Concentrations of pollutants are controlled by adjusting the supply air volume, selecting a proper air distribution scheme, maintaining different air pressures or arranging working desks closer to the fresh air supply points. However, occupant’s adaptation to environmental conditions is particularly important in buildings. Due to sensibilization, poor IAQ is less likely to be identified by occupants [68]. Therefore, air quality sensors and controllers should be used to automate IAQ control. In addition, the air supplied to the ventilated space should be cleaner than the air in the ventilated space.

Air filtration and purification techniques are used in cases when the air drawn from outdoors or recirculated from indoors contain undesirable pollutants at higher than recommended concentrations. Air filtration and purification techniques differ for particulate matter and gaseous pollutants.

If air is contaminated by particles, fabric filters are usually used for cleaning the air. These filters are made from materials with different filtration class and are selected according to the requirements of air quality in the room and present outdoor air quality. Currently, filters for general ventilation (e.g. for ventilation systems used in residential or non-residential buildings) are classified according to the particle sizes that can be captured [69]. Particles smaller than 1, 2.5 and 10 microns are assigned to the PM1, PM2.5 and PM10 class, respectively, while particles larger than 10 microns are considered as coarse particles. In relation to particle classes, filter classes are as follow: ISO ePM1.0, ISO ePM2.5, ISO ePM10 and ISO coarse. The filter is assigned to a specific group if it captures at least 50 percent of the corresponding particle size range [69]. For example, if a filter captures 86% of PM2.5 particles, it is classified as ISO ePM1 85% (“e” stands for “efficiency”). However, filters for general ventilation are not capable of ensuring the very high levels of air purity that is needed for example in cleanrooms, pharma industries, micro-electronics industries, laboratories or hospital theatres. Therefore, special filters, such as EPA, HEPA and ULPA should be used [70]. These filters have efficiencies higher than 99.9% and are capable of capturing ultrafine dust, aerosols and microorganisms. The gaps between these filters fibres are very small. Therefore, these filters can trap the particles with a lower diameter than 0.3 microns.

One of the major disadvantages of fabric filters is constant care of filters. Filters become polluted and need to be changed. Otherwise, they become an additional source of pollution. Additionally, polluted filters influence energy consumption of fans used in the ventilation system. Another disadvantage is related to gaseous pollutants. Standard fabric filters cannot ensure efficient removal of gaseous pollutants. Ventilation systems with standard fabric filters simply dilute indoor air; if undesirable gaseous contaminants are present in outdoor or recirculated air, indoor air will stay contaminated.

Regarding gaseous pollutants, it is important to emphasise that complete and permanent removal of every pollutant is not necessary. There is a great variety of gaseous pollutants, and it is important to keep their concentrations at recommended levels with no harm to human health. The most commonly used purification methods to remove gaseous pollutants, as well as VOCs, from air can be divided into destructive and non-destructive (recovery) methods [71, 72]. In non-destructive methods, polluted air is passed through the material (liquid or solid) that can bond pollutant molecules, while in destructive methods; pollutants molecules react with specific materials and form new compounds.

Absorption and condensation techniques are classified as non-destructive air cleaning techniques for VOCs [71, 72]. Absorption is an ability of liquids (e.g. water or various emulsions) to absorb soluble gas or vapour molecules. When polluted air is in contact with a liquid soluble, VOCs are transferred to the liquid phase. Absorption technique is usually used in industries and has an efficiency of around 90-98% [72, 73]. However, not all VOCs are soluble and can be captured in liquid. Consequently, the disposal of VOCs is a common problem in the absorption technique. In the adsorption technique, polluted air is passed through the porous medium and VOCs are bonded to the surface of the adsorbent. By using adsorption techniques to remove VOCs, air activated carbon, zeolite, as well as silica gel, are very common adsorbents. These materials have a large surface area, which is a result of their porous structure. Additionally, materials are used in the form of granules, pellets, powder or fibres, which results in the even larger surface area. Filters with adsorbent materials can clean the air from unpleasant odours and various VOCs (e.g. toluene, benzene, n-hexane etc.). The efficiency of such filters varies between 80-95% [71, 72]. However, adsorbents after a period of time get saturated, and their cleaning efficiency reduces. Therefore, these materials need to be replaced by fresh carbon or reactivated regularly. Furthermore, dust and some compounds such as ketones or aldehydes in the air stream can clog the pores of adsorbent materials, thus decreasing filter efficiency. Condensation technique is used in the cases where high concentrations of VOCs are present (above 5000ppm) [72], i.e. in industries [74]. This cleaning technique is based on the principle that VOCs condense at low temperatures. Therefore, the air stream should be cooled and VOCs condense on the cooling surface. The efficiency of this cleaning method is between 70-85% [71, 72]. Khan and Ghoshal [72] emphasise that this method is dangerous because the concentration of VOCs can fall through the explosive range during the condensation process. Therefore, additional safety technologies should be used that consequently increases the operational costs. Also, this technique is more suitable for single compounds, because a mixture of different VOCs may have different condensing temperatures. In addition, captured VOCs should be reused or disrupted.

Thermal and catalytic oxidation, photo-catalysis as well as bio-filtration are technologies used to destroy VOCs [64, 71, 72, 75, 76]. By using these methods, VOCs are converted into CO_2, H_2O and other by-products. Thermal oxidation is used in processes where high concentrations and high airflows are present [75]. The efficiency of thermal oxidation is 95-99% [71]. VOCs are burnt at high temperatures (over 1000 °C); therefore an additional heat source is needed. One of the major limitations of this method is that an incomplete burning process may produce by-products such as carbon monoxide, sulfur dioxide and harmful compounds. Also, during the process, explosive atmospheres may occur. The catalytic oxidation process is similar to thermal oxidation except that the technique operates at lower temperatures (250-500 °C) and includes a catalyst [72, 75]. Various noble metals, non-metal oxides and mixed-metal catalyst can be used for catalysts [75]. The technique is suitable for air streams with low concentrations of VOCs and variable airflows. VOCs removal efficiency is in the range of 90-98% [71]. Catalytic oxidation process also produces combustion products. In addition, catalysts may be sensitive to specific compounds. Nath et al. [76] suggested the use of photo-catalysis technology that accelerates the natural decomposition process of pollutants under UV light at room temperature and pressure. The use of special materials, such as titanium dioxide (TiO_2) in building materials can induce the formation of oxidising reagents that can degrade pollutants such as VOCs, sulphur dioxide, carbon dioxide, nitrogen oxides and others into harmless compounds such as CO_2 or H_2O without using additional energy. The efficiency of the method depends on various factors, including the concentration of pollutants, pollutant types, ambient air parameters, surface exposed and UV intensity [76]. However, photocatalytic concrete looks attractive as a method of VOCs destruction in the perspective of sustainable construction. By using bio-filtration techniques, air is passed through a porous packed medium that contains a specific population of micro-organisms, then adsorbed by a water/bio-film phase of the medium and thirdly and finally micro-organisms convert them to CO_2, H_2O and other inorganic products as well as bio-mass [72]. This technique is effective for low concentrations of many VOCs that are found in buildings. This method is also used in exhaust air cleaning systems in agricultural, paper industries and sewerage treatment plants. VOCs removal efficiency depends on the metabolisms of micro-organisms, VOCs type and moisture level, and is in the range of 60-95% [72]. The main disadvantage of this method is that the process is slow and micro-organisms decompose only selective pollutants. Therefore, a mixed culture of micro-organisms is required.

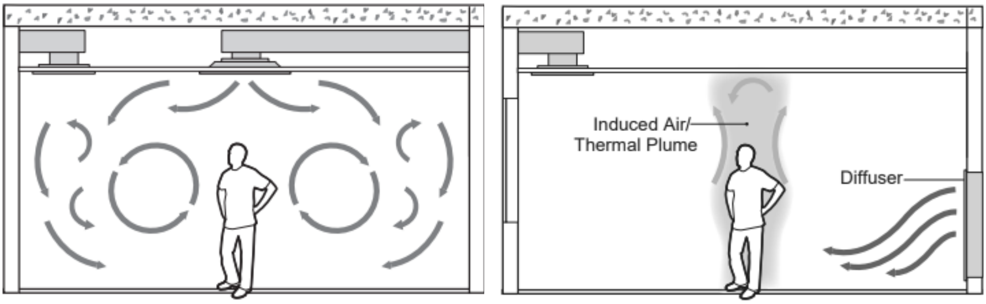
Several previous studies showed that high IAQ in buildings could be achieved by wisely combining air dilution and filtration techniques of indoor air quality control [77, 78]. Han et al. [77] presented a control strategy of IAQ that dynamically integrates ventilation and air filtration techniques, thereby reducing annual energy consumption by 11%. The idea of the study was to adjust the amount of outdoor air and air filtration operation depending on outdoor air quality and thermal conditions. Therefore, a bypass function was used. In the study of Ciuzas et al. [78], the effect of portable air filters combined with mechanical ventilation on pollutant (particulate and VOCs) removal was tested. The authors concluded that air cleaning was more efficient for removing particulate pollutants, thereby reducing the ventilation air change rate, while ventilation was more efficient in removal of VOCs. The positive effect of a combined ventilation and air filtration technique was presented; pollutant removal efficiency increased by 20% in this case.

1.5. Factors influencing pollutant dispersion in rooms

Despite the fact that pollutant concentrations are controlled using different strategies, under certain conditions the concentration of pollutants in rooms is not uniformly distributed and the effect to occupants might be higher or lower. First of all, distribution of pollutants depends on their properties, such as relative vapour density (RVD). RVD is defined as the mass of a gas or vapour compared to air, which has an arbitrary value of 1. RVD of VOC which is not significantly different from indoor air density [79]. Therefore, some of them being less dense than air tend to rise, while others are denser and tend to sink.

Distribution of gaseous pollutants is usually linked to the flow of air [80]. Airflows in indoor environments have a different origin; they can be dynamic or convective. Dynamic flows are usually generated by ventilation systems, while convective flows are generated by warm or cold surfaces. Warm and cold surfaces include outside walls of the building, windows, heating and cooling equipment, lighting fixtures, computers and other equipment. Occupants are also the source of convective flows. All these airflows affect each other and are bound by building partitions, furniture or equipment.

The purpose of ventilation is to increase air quality indoors by delivering fresh air to occupants and by removing pollutants as efficiently as possible. Air quality indoors depends not only on air change rate [81] but also on the air distribution scheme (flow pattern) [82, 83, 84]. Figure 3 shows two commonly used air distribution concepts. These are mixing ventilation and displacement ventilation. In the case of mixing ventilation, the air is supplied in the upper part of the room (outside the occupied zone). The air can be supplied by ceiling or wall units with a high momentum (approx. velocity is 1m/s). High initial velocity ensures that room air circulates and mixes. Supply air velocity should be high enough to ensure mixing and at the same time low enough to ensure that air velocity in the occupied zone would be at an acceptable level. Exhaust air units can be placed in upper or lower part of the room.



(a) (b)

Figure 3. Illustration of mixing (a) and displacement (b) ventilation [85]

In displacement ventilation, air is supplied directly into the occupied zone at floor level. Supply air velocity is low (lower than 0.2m/s), and air temperature is few degrees lower than room air temperature. Due to the low temperature of the air, it spreads along the floor and displaces the warm contaminated air. Convective flows from occupants, or warm equipment directs contaminated air towards the ceiling where exhaust units should be placed.

Figure 4 shows the performance differences between mixing and displacement ventilation. Temperature and contaminant distribution along the height of the room with mixing ventilation is uniformly distributed, while air velocities are higher in the upper part of the room. Therefore, mixing ventilation is widely used for heating and cooling of rooms. Displacement ventilation ensures uniform air velocities along the height of the room, while air temperatures are lower in the lower part of the room and higher in the upper. The concentration of contaminants is lower in the lower part of the room; however, the risk of contaminants stratification due to temperature gradients can appear. Displacement ventilation is not suitable for heating. It is important to highlight these properties of mixing and displacement ventilation presented in Figure 4 are for ideal conditions, which occur rarely.

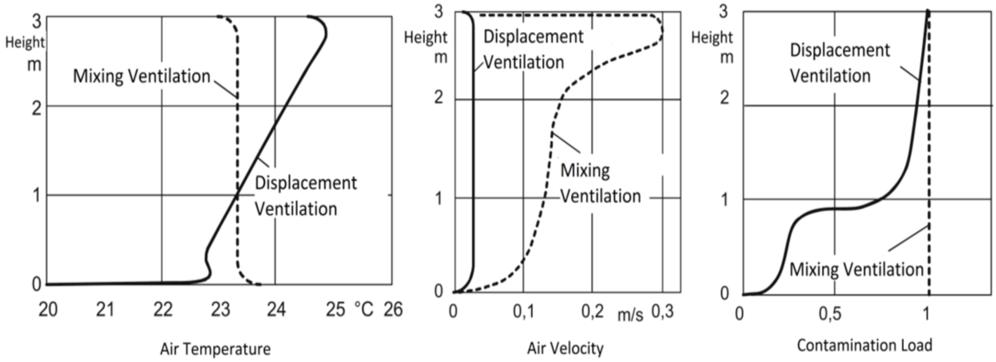


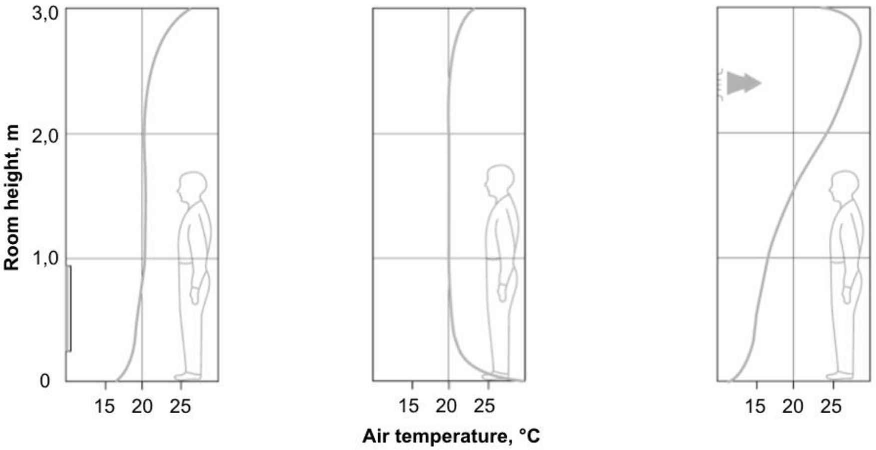
Figure 4. Properties of mixing and displacement ventilation [86]

Short circuits and stagnant air layers might be formed in real cases of mixing ventilation (usually as the result of an incorrect position of air supply or exhaust units). Lower air velocities and stagnant air zones in rooms are commonly the main reasons for higher pollutant concentrations if pollutant sources are present in those areas [80]. The effect of higher pollutant concentrations in stagnant air zones means that the location of pollutant sources is an important factor of pollutant distribution in rooms [81, 82]. It can be concluded, that airflows generated by ventilation systems have a direct impact on the dispersion of pollutants indoors.

Convective flows can be generated by cold and warm building partitions [87-89], and these flows may easily cause discomfort as well as influence dispersion of pollutants in rooms. A study of Jurelionis and Isevičius [88] showed that the near cold outside wall in the lower part of the room airflow velocities is higher compared with the upper part. In cases with warm partitions, e. g. summer season, upward air movement might be generated. This might affect the flow of supplied air units.

Convective flows are also generated by heating devices. Heating systems, being different in nature (convection and radiation), generate heat flows that lead to different temperature distribution over the height of the room. Vertical temperature gradients of the most common heating systems in buildings are presented in Figure 5.

The more convective type of heating systems (radiator and warm air heating) has higher temperatures in the upper part of the room, as well as higher air velocities. Radiant heating ensures even temperature distribution in the room and small air velocities [91]. Warm air heating systems are often combined with mixing ventilation systems. In this case, there is a risk that the air is not properly distributed, e. g. it will not reach the occupied zone and will create a stagnant air zone [92-94]. As mentioned above, stagnant air zones might be the reason for higher pollutant concentrations in specific areas.



(a) (b) (c)

Figure 5. Vertical temperature gradients under radiator (a), underfloor (b), warm air (c) heating systems [90]

Xiaozhou et al. [95] investigated different combinations of heating and ventilation systems and their impacts on indoor air distribution and ventilation effectiveness. Figure 6 shows the results of air temperature and velocity measurements in their study for the case with underfloor heating and mixing ventilation. The authors concluded that air temperature and air velocity distribution would not cause any discomfort for occupants. The authors also evaluated ventilation effectiveness and concluded that ventilation effectiveness is equal to recommended values of the ASHRAE standard 62.1 [96]. Nevertheless, no information on pollutant distribution was given.

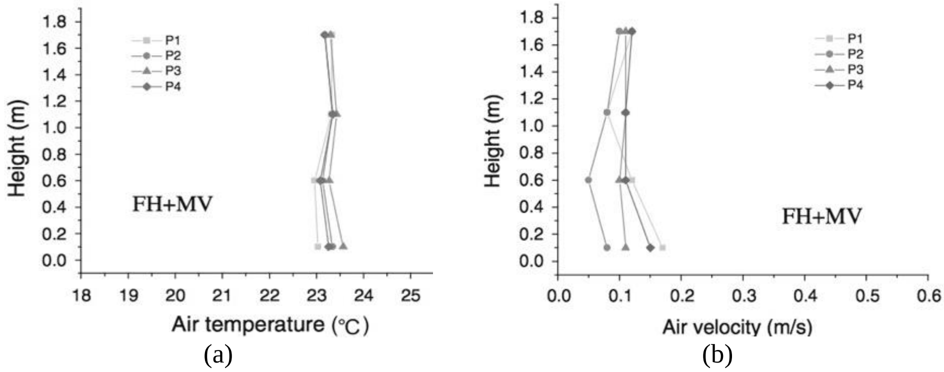


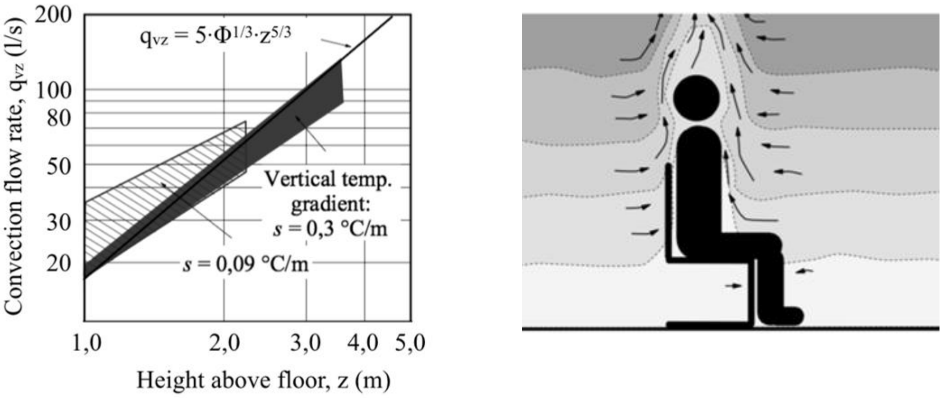
Figure 6. Vertical air temperature distribution (a) and vertical air velocity distribution (b) in a room with underfloor heating and mixing ventilation [95]

In an experimental study of Krajčík et al. [93] the thermal environment and ventilation effectiveness were evaluated for warm air heating and underfloor heating systems combined with mixing ventilation. Different positions of air supply and exhaust devices, as well as different air changes, were used. The authors concluded that no significant thermal discomfort due to vertical temperature distribution or draught were present. They also found that an increased air change rate did not always result in higher ventilation effectiveness in cases with warm air heating; ventilation effectiveness depended on the position of air terminal devices and was higher in cases when the air was supplied in the upper part of the test chamber while air exhaust was in the lower part. A positive effect of underfloor heating on ventilation effectiveness was found. In the study of Tomasi et al. [94] underfloor heating combined with mixing ventilation was investigated. Two positions of air exhaust terminals were used (in upper and lower part of the chamber). It was found that in cases with the air exhaust at low-level, ventilation effectiveness was lower compared with the cases where the air was exhausted in higher levels. Olesen et al. [97] investigated the different combinations of mixing / displacement ventilation and radiator / underfloor heating systems. The authors presented results regarding air temperature and air velocity as well as ventilation effectiveness. No issues with vertical air temperature distribution as well as with air velocities were addressed. In cases with displacement ventilation, ventilation effectiveness was always lower when radiator heating was used. Underfloor heating resulted in a higher efficiency of displacement ventilation. In cases with mixing ventilation, the radiator heating, ventilation effectiveness was slightly lower than in cases with underfloor heating. The studies of Krajčík et al. [93], Tomasi et al. [94] and Olesen et al. [97] give an important understanding about the combined impact of different heating and ventilation systems on how effectively pollutants are removed from the room. However, further investigation is needed on air quality experienced by the occupant.

Airflow in rooms is also influenced by various obstacles, such as furniture or occupants. Effects of furniture arrangement on ventilation effectiveness were investigated by Zhuang et al. [98]. A different arrangement of furniture resulted in changes in airflow and the temperature field, and caused changes in pollutant distribution and ventilation effectiveness. Since the aim of this work is not related to the effects of furniture arrangements, no further focus will be given on this topic. Obstacles such as occupants are important influencers of airflows in rooms because they generate flows by movement as well as thermal flow. More focus on flows generated by occupants will be given in the next subsection.

1.6. Human convective boundary layer

The human body, due to complex metabolic activities produces heat that must be continually rejected to keep constant body core temperature of around 37 °C [99]. The average resting adult of about 70kg and 1.73m in height, with a skin surface area of about 1.8m^2, at normal room temperatures produces about 100W of heat [100]. The amount of produced heat varies widely, depending on the person, activity level, clothing, surrounding air parameters (air temperature, radiant temperature, humidity and air velocity) and other factors such as age, gender or health condition [100]. Total heat loss from the human body is divided into heat loss from skin and through respiration [99, 100]. Heat loss from skin consists of convective, radiative and evaporative heat losses, while convective and evaporative heat losses are included in heat losses through respiration. Convective and radiative heat losses are dry heat losses [99]. Heat transfer from the human body to the surrounding environment by convection depends on the temperature difference between the human body and the surrounding air. This heat loss from the human body creates a rising natural convection flow along the body, and a convective boundary layer (CBL) is formed around the human [101, 102].



(a) (b)

Figure 7. Convection flow rate at normal room temperatures above a sedentary person (a) and scheme of air entrainment (b) [105]

CBL begins at the feet level and rises towards the head level, forming a thermal plume above the human head [103, 104]. CBL in the lower parts of the human body are thinner, airflow is slower and laminar, while in the upper parts it is thicker, the flow is faster and more turbulent [102, 103]. The width of human CBL, as well as convection flow rate, increases with height; due to entrainment of the surrounding air to the laminar flow along the body [105]. The effect of height on the convection flow rate is shown in Figure 7a. The flow rate is indicated by the continuous line and is calculated by the formula given in the figure, where Φ is the convection flux in watts from a person and z is the height above the floor level in metres. The convection flow rate at normal room temperatures above the seated human at the height of 1.1m is about 20l/s (72m^3/h) and due to the surrounding air entrainment becomes about 50l/s (180m^3/h) at the height of 2.0m. This convection flow plays an important role in room air distribution, as it has the same magnitude as air supplied by room ventilation systems. Figure 7a also shows that the convection flow rate is slightly lower when higher vertical temperature gradients exist in the surrounding air, while with lower gradients the convection flow rate is higher.

The form of human CBL might differ, depending on various factors, i.e. surrounding air temperature and human posture [102, 106], occupant clothing and furniture arrangement [104], the presence of vertical temperature gradient [105] etc.

In the study of Licina et al. [102] seated and standing human CBL was investigated, and velocity fields around the thermal manikin under a quiescent indoor environment at air temperatures of +20 °C and +26 °C were determined. Narrower CBL deflected towards the face of the manikin, as well as higher velocities were registered in the case with the seated manikin in a surrounding air temperature +20 °C. In the case of the surrounding air temperature +26 °C, the convection from the manikin was less concentrated, with lower air velocities and widely distributed between legs and body. Higher velocities in front of the standing manikin were registered with the surrounding air temperature +20 °C, while the shape of CBL was not affected by the increase of temperature.

If the temperature gradient is present in a room, the thermal plume may spread horizontally in that level of the room where the temperature difference between the plume and surrounding air diminishes [105]. As presented in subsection 1.5. temperature stratification appears in rooms ventilated by displacement ventilation. A series of studies were performed on CBL with displacement ventilation [107-111] as it has a positive effect on the transport of fresh air from near-floor level to the breathing zone (see Figure 7b). However, air quality in the breathing zone will be higher only in cases with warm air contaminants, as they tend to rise. In cases with isothermal contaminants, the human CBL may transport contaminant from lower room levels to the breathing zone, thus decreasing air quality in the breathing zone [108, 110].

Zukowska et al. [104] found that loose clothing decreases the velocity in human CBL, gives a wider thermal plume above the head and a 24% greater flow rate compared to tight clothing; no effect of tight clothing on the thermal plume was found. The absence of a gap between manikin and table gives a wider and a 50% greater flow rate above the sitting manikin [104]. Figure 8 shows the average contour maps of the vertical velocity component for thermal plumes investigated in the latter study.

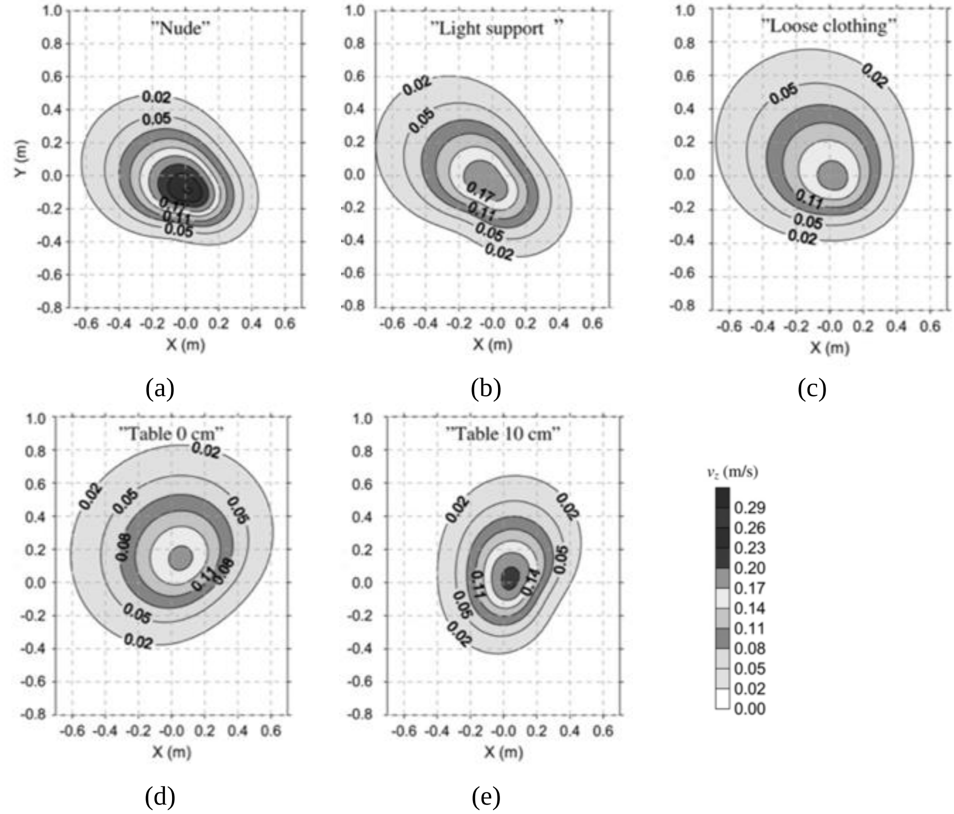


Figure 8. Average contour maps of the vertical velocity component for thermal plumes of: nude manikin (a), manikin with light clothing (b), manikin with loose clothing (c), manikin with no gap between abdomen and table (d) and manikin with a gap of 10 cm between abdomen and table (e) [104]

Rim and Novoselac [112] studied contaminant distribution in human CBL in spaces with highly mixed and stratified room airflow, with air change rates 4.5h^{-1} and 3h^{-1} respectively. The study included experiments with gaseous and particulate contaminants placed in front of a thermal manikin at 1.6m height and behind the manikin at 0.25m above the floor. The results of experiments showed that contaminant (gaseous and particulate) concentration distribution in the CBL was uniform in the case with mixed room airflow, while in the case with stratified room airflow it was non-uniform and depended on the source position. Manikin CBL transported particulate contaminants from near-floor level to the breathing zone in the case of stratified airflow.

Gaseous contaminants originated from the human body or released in its vicinity under a quiescent indoor environment are transported to the breathing zone and decreases air quality experienced by a human. Higher concentrations are registered when the temperature of the surrounding air is lower [113]. Transportation of airborne particles released at feet level to the breathing zone under uniform room airflow depends on the airflow direction relative to the person; higher concentrations are registered in cases with the airflow opposing flow from above, while transverse airflow from the front or a side can minimise or eliminate contaminant concentrations [114].

Melikov [103] discussed the importance of human CBL in personalised ventilation. Personalised ventilation is a ventilation strategy when the clean and cool air is delivered directly to each occupant [103]. It was highlighted that human CBL should be carefully considered, as it can transport contaminants. The direction of supply air should be considered as well, and airflow from the front of the face was recommended.

The above discussed studies give valuable information to understand the origin of human CBL and factors that influence it. However, previous studies on human CBL ability to transport airborne contaminants from the near-floor level to the breathing zone focused on quiescent, uniform, fully mixed or stratified indoor environment airflows, which usually were ensured by the ventilation system. In most cases, airflows in the indoor environment are generated not only by the ventilation system but also by different heating systems. No studies were found with the combined impact of heating and mixing ventilation systems to occupant inhaled pollutant concentrations, especially regarding isothermal pollutants (volatile organic compounds) that release at near-floor level.

2. METHODS

This chapter further explains in detail the methods that were used to explore dispersion of volatile organic compounds released at a near-floor level under different combinations of heating systems and air distribution schemes. The chapter is divided into four subsections. The first and second subsection explain the experimental and numerical method respectively, while the third subsection presents indices that were used to evaluate indoor air quality. The fourth subsection describes statistical methods adopted in this research.

2.1. Experimental method

2.1.1. Indoor environment chamber

A full-scale indoor environment chamber at the Energy and Microclimate laboratory of the Kaunas University of Technology was used for the experiments (Figure 9). This indoor environment chamber is mainly used for research on indoor air quality, thermal comfort and occupant productivity. Similar environment chambers are used in other research institutes for the same proposes [112, 113, 115, 116].

The HVAC laboratory is equipped with an electric boiler, air handling unit consisting of fans, filters, rotary heat exchanger (Gold04, Swegon, Sweden) in combination with a water-borne air heater and cooler, and water-borne cooling system. The air handling unit is used to control supply and exhaust airflows. The electric boiler together with the water-borne heater is used to control supply air temperature, as well as the temperature of the water-borne radiator in the test chamber. The cooling system is used to control the temperature of one of the walls in the test chamber. Figure 9 shows the layout of the laboratory equipment which was used during the experiments.

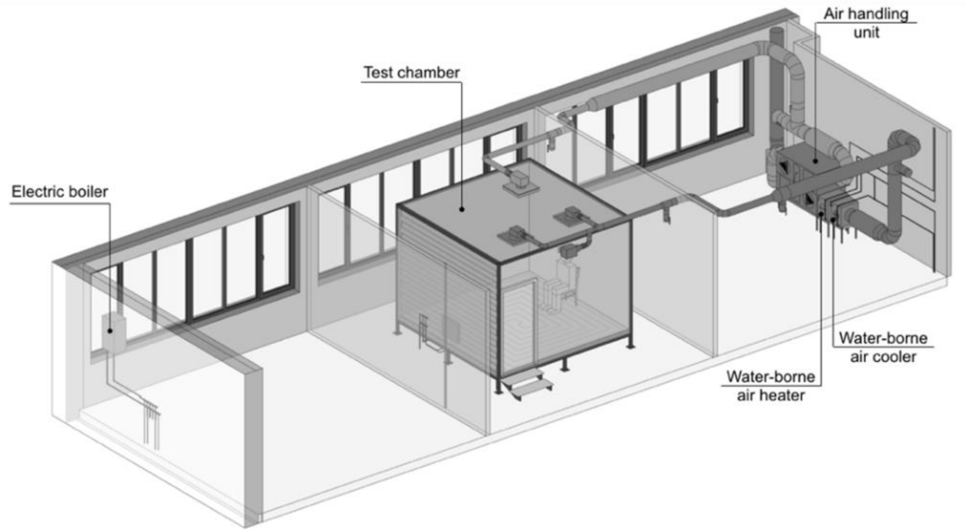


Figure 9. Schematic view of the laboratory equipment used for the experiments

The indoor environment chamber (Figure 10) has dimensions of 3.6 × 3.6 × 2.8m. The floor area of the chamber is 13m², and the volume is 36m³. The chamber has a door of 0.9 × 2.1m. Metal frames are used as supporting structures for all the chamber. The chamber is constructed using conventional construction materials. The walls are constructed of a sandwich construction of painted drywall panels and a core consisting of 50mm mineral wool. The chamber has a raised floor construction, which is a sandwich construction of chipboard panels and a core consisting of 30mm polyurethane foam. The flooring material is PVC lining. The ceiling construction is of a sandwich construction of drywall panels, mineral wool (50mm) and panel ceiling. The chamber is illuminated by two fluorescent recessed lighting fixtures, which were turned off during all experiments to avoid excessive heat.

One wall of the chamber was cooled using the water-borne cooling system during experiments. This wall imitates the external wall of the room during the heating season, i.e. created heat losses. The cold surface was also necessary to prevent overheating of the chamber and to ensure steady state conditions during the experiments. In addition, as it was outlined in the literature review, airflows from cold surfaces may affect the distribution of air-borne contaminants. Although the cold wall effect in modern buildings should be low (because of well insulated buildings) it was included into the experiments as cold surface may be, for example, a large area window.

The chamber is equipped with three different types of heating systems: underfloor heating, radiator heating and warm air heating. For underfloor heating, the floor of the chamber was equipped with an electric cable covered by the cardboard-based covering to avoid excessive uncontrolled emissions from the flooring. For radiator heating, the chamber was equipped with a water-borne radiator (500-600×11, Henrad, Belgium), which was mounted on the cooled wall. The radiator has dimensions of 0.5 × 0.6m. The distance between the floor and the bottom part of the radiator is 0.1m. The chamber was also equipped with a warm air heating system, which is combined with the mixing ventilation system. Two multi-nozzle in-ceiling air supply diffusers of 0.5 × 0.5m with plenum boxes and high-level air supply grille of 0.3 × 0.1m with plenum box were used for warm air supply. The diffusers and grille ensure two different mixing ventilation airflow patterns (four-way air supply and high-level wall grille air supply). Although both air supply units ensure mixing ventilation, the air supply momentum is different. In the case of four-way air supply, diffuser lower air velocities in the occupied zone are expected, while in the case with wall grille air, velocities will be higher. This might affect pollutant transportation to the occupant breathing level. In the case when one air supply system is in operation, the other can be disconnected and sealed. One in-ceiling diffuser is used for air exhaust from the chamber.

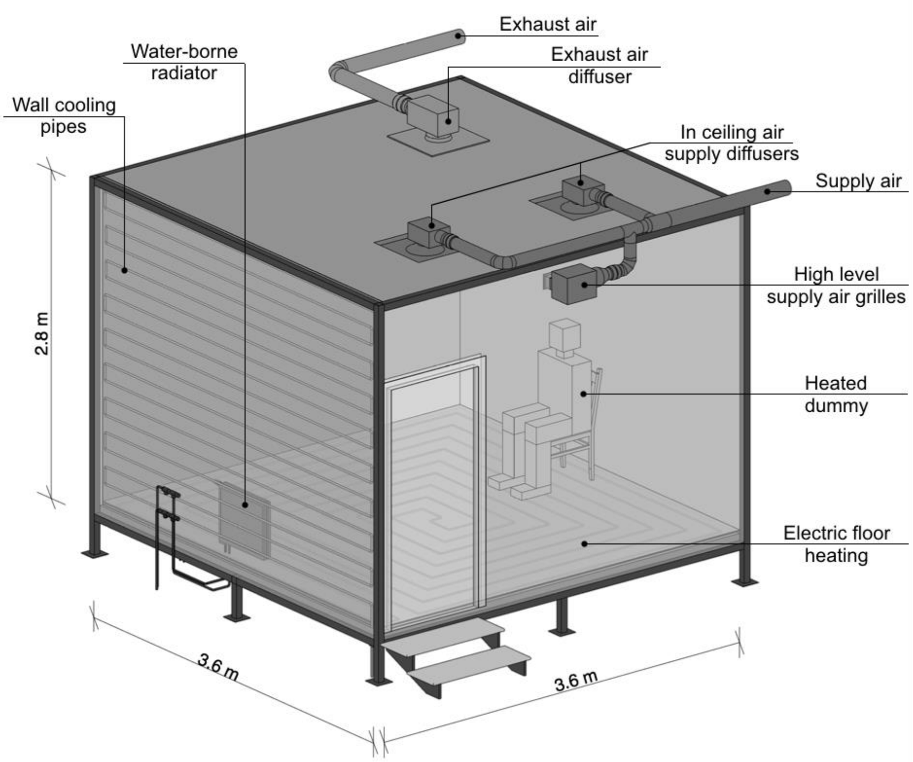


Figure 10. Test chamber with equipment used for the experiments

2.1.2. Pollutant

Various tracer gases are commonly used as pollution sources for IAQ studies. Heiselberg [81] used a table tennis ball with six small holes with a diameter of 1mm.

As a contaminant, carbon dioxide (CO_2) gases mixed with nitrogen (N_2) and helium (He) were used, to give the contaminant different densities. Krajčik et al. [93] used a perforated table tennis ball covered with sponge material, and refrigerant R134a was used as a contaminant.

For this study, a passive source of pollutants was needed to imitate VOCs emissions. It was assumed that pollution sources such as carpets emit a mixture of VOCs (e. g. a carpet itself might emit several VOCs and might be treated with cleaning products that emit other VOCs). Therefore, to imitate the passive pollutant emission from near-floor level, VOC sources polyurethane-based liquid glue (TOTALSEAL 34B, Le Joint Francais, France) was used in the experiments. The glue emits compounds such as 1,2,4-trimethylbenzene, naphthalene, xylene etc. [117]. For the simplification of experiments, a Petri dish filled with liquid glue was used as a source of VOC. This allowed for both a more precise dosing of the glue and keeping the VOC's levels in the chamber within the sensors' measurement range. It was assumed that the dispersion of pollutants from a point source would be similar to the area sources such as flooring materials or carpets. Therefore, several initial tests were performed in the environment chamber imitating a small carpet with cardboard covered by the grid of dots of adhesives. Also, this assumption was tested with CFD software and the results of the distribution of pollutant concentrations are presented in Figure 11. It was observed that the pollutant dispersion trends did not change significantly, whether the point source or the area source were used. However, concentrations may be different from these sources. The point source was used as the strong localized source. In reality, emission rates from near-floor pollution sources would have a smaller scale.

(a)

(b)

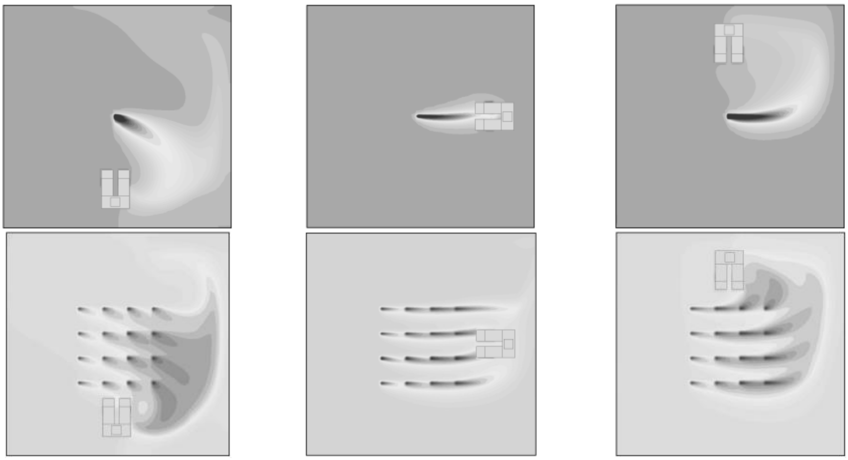


Figure 11. Distribution of VOCs in relation to pollutant geometry for cases with high-level wall grille air supply, warm air heating and thermal dummy in different positions: point source (a), area source (b)

The Petri dish with liquid glue was located on the floor, in the centre of the test chamber with the distance from the walls equal to 1.8m (Figure 13). Such an experimental approach was selected with the aim to identify possible paths of VOCs in the entire volume of the test chamber.

2.1.3. Thermal manikin

Thermal manikins or heated dummies are used in indoor environmental research for occupant imitation. There are many different types of thermal manikins, and they are used in different application areas [108, 118, 119]. The most common application areas are thermal insulation of clothing, heat transfer coefficients, flow characteristics around the human body, thermal comfort, air quality experienced by the occupant, the source of heat, contamination and momentum, the interaction between persons, etc. [108]. When thermal manikins are used for assessing the impact of heating and ventilation systems on occupants they are considered as heat sources and obstacles that influence air movement in the room [120]. In cross infection studies, when the effect of exhaled air on other occupants is studied, the manikins' breathing function is considered [149, 150].

For this study, a heated dummy (Figure 12) of simple geometry was selected to represent a seated occupant. The rectangular geometry of the "head" and the inclusion of "legs" was chosen, considering that these were previously documented as important factors influencing convection airflow around a person [119, 121]. A thermal dummy without breathing function was used, as it was reported that breathing has only a minor effect on the convective boundary layer [151]. However, the accuracy of the experiments may be improved in the future by using a thermal manikin with breathing function, as well as a more precise shape replicating the human body.

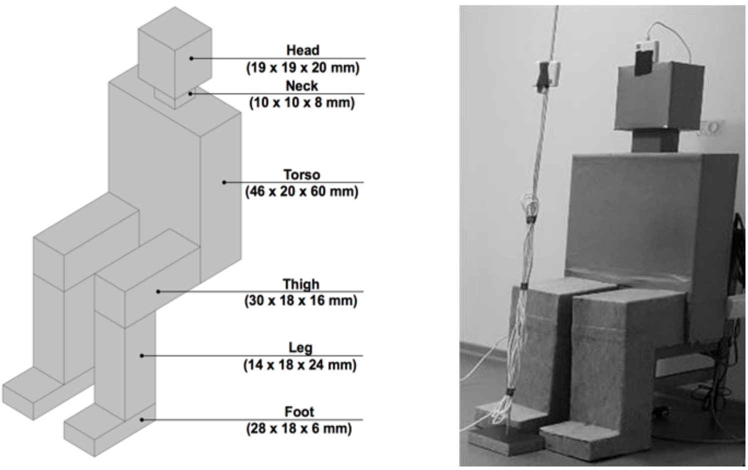


Figure 12. The geometry of the heated dummy used for the experiments

Simple geometrical shapes were used to compose the dummy. The shapes were constructed using aluminium shells of 2mm thickness. The surface of the dummy was covered with textile fabric to imitate clothing and to increase the surface roughness to airflow. The height of the seated dummy was 1.2m, and the surface area was 1.7m², which is similar to the surface area of the average person [122]. The detailed dimensions of the dummy are presented in Figure 12.

The dummy was set to a heat output of about 85W, to simulate dry heat losses through the skin [104, 113]. Before the experiments, the surface temperature of the dummy was measured and was kept within +31 to +34 °C (similarly to the human body surface temperature).

2.1.4. Experimental setups and measurement equipment

18 experiments were designed to explore the distribution of VOCs released at a near-floor level under different combinations of air distribution pattern, heating system and varying position of heated dummy. Experiments were done in three stages by heating type. The plan of the experiments is presented in Table 2.

Table 2. The plan of experiments (stages and cases)

Stage [a)]	Heating type [b)]	Air distribution type [c)]	Location of the heated dummy
1	*2*	*3*	*4*
1	AH	GR	A
			B
			C
		M4	A
			B
			C
2	FH	GR	A
			B
			C
		M4	A
			B
			C
3	RH	GR	A
			B
			C
		M4	A
			B
			C

a) 1 – experiments were performed in February of 2015; 2 – experiments were performed in April of 2015; 3 – experiments were performed in October of 2016;
b) AH – warm air heating; FH – underfloor heating; RH – radiator heating;
c) GR – high-level wall grille; M4 – in-ceiling four-way diffuser.

The temperatures of the ceiling and walls (except cooled wall) were approximately the same as the air temperature in the laboratory room where the chamber is located (in underfloor heating and radiator heating cases - +22±0.5 °C; in warm air heating cases - +20±0.5 °C). The temperatures of the ceiling and the walls were different in cases with warm air heating because of a season. Experiments with warm air heating were performed in February and the temperature of the laboratory was lower than in April or October and was not additionally controlled. Therefore, during all experiments, it was decided to maintain the same difference between the cooled wall and the rest of partitions. The temperature of the cooled wall, which imitates an outside wall, of the chamber was maintained 3 °C lower than the rest of the partitions.

Three positions of thermal dummy (A, B and C) were used during the experiments (see Figure 13) to have a different occupant position in relation to pollutant and supply air diffusers; as well as the supply air grille. The distance between the dummy and the wall was 0.2m to avoid disturbance of the convective boundary layer by the physical presence of the wall, as well as the air supply jet.

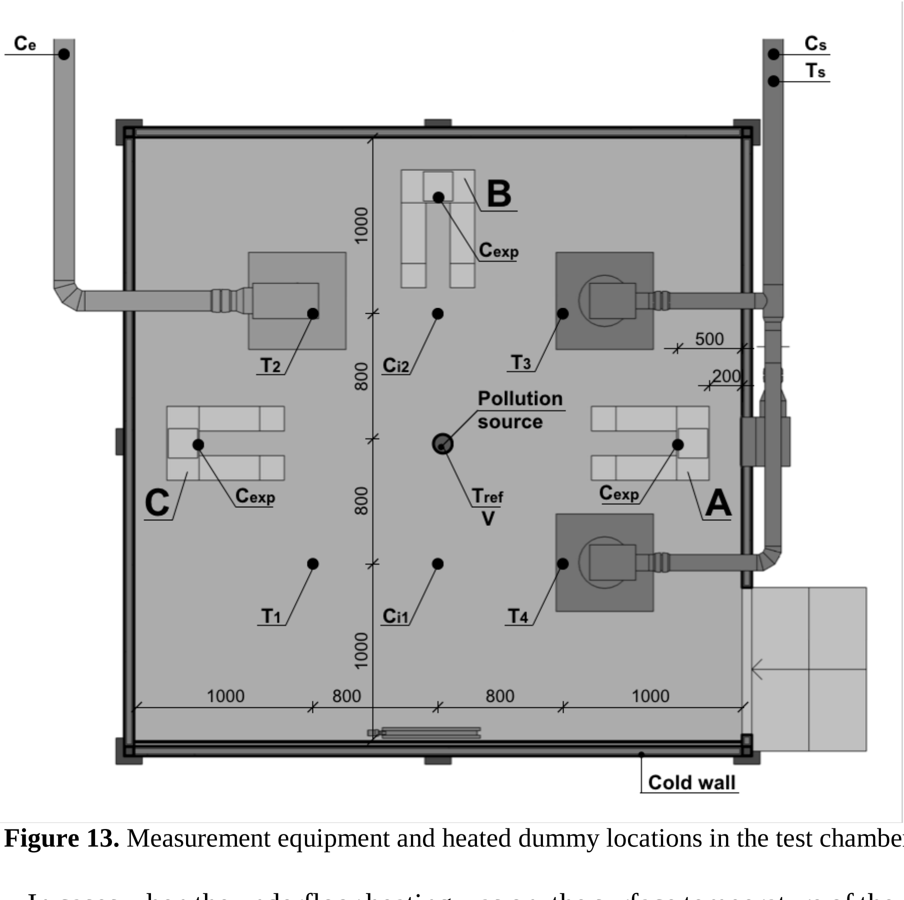


Figure 13. Measurement equipment and heated dummy locations in the test chamber

In cases when the underfloor heating was on, the surface temperature of the floor was equal to +25±0.5 °C. In other cases, approx. 20 °C. In cases when the radiator heating was on, the surface temperature of the radiator was maintained at +40±0.5 °C. Supply air temperature, in cases with warm air heating combined with mixing ventilation, was set to +25±0.5 °C. In all other cases, the supply air temperature was set to +21.5±0.5 °C and was roughly equal to the chamber air temperature.

Air change rate was set to $2h^{-1}$ for all cases and was equal to 20l/s (72m³/h) for both supply and exhaust, considering the requirements for occupancy and removal of pollutants generated by furnishing and building materials [122]. Airflow was set up in the air handling unit, as well as measured in each air supply device with Fluke 922 micromanometer (Fluke Corporation, United States) that is capable of measuring pressure (±1% + 1 Pa accuracy). Additionally, a CO_2 tracer gas decay method was applied to verify air change rate [123]; CO_2 meter IAQ-CALC 7545 (TSI Inc., USA) was used for measuring concentrations (±3% accuracy). The air distribution pattern in the in-ceiling diffusers was set up by rotating adjustable nozzles, in the wall grille – by directing the grille's vanes. Air distribution patterns were tested before the experiments by using smoke, generated by the smoke machine IMG Stage Line FM-910 (Monacor International, Germany). Only mixing ventilation was investigated in this research. Displacement ventilation was not analysed because it is not suitable for air heating. Furthermore, in specific cases displacement ventilation ensures higher pollutant removal effectiveness, as was discussed in subsection 1.5. of the literature review.

All the experiments were carried out under steady-state conditions. It took approximately 2 hours to obtain steady-state conditions (stable temperature) for each experiment. Figure 14 shows the results of temperature measurement on one of the stands during the initial experiment. It was identified that from 120mins, the temperature stabilises and only varies in a small range. It was established that the steady state conditions of approx. 99% was achieved for the presented case. Steady state condition of 95-99% was assured for the rest of the cases.

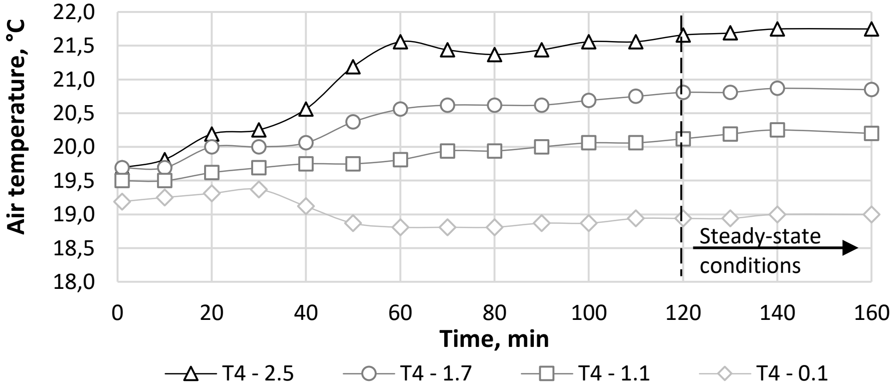


Figure 14. Temperature stabilisation during an initial experiment on a stand T_4 at four heights (0.1, 1.1, 1.7 and 2.5 m above the floor) for the case with in-ceiling four-way air supply diffusers, thermal dummy in position B and warm air heating

To ensure stable pollutant generation during the experiments, several initial tests were performed. It was determined that the VOCs concentration can be stable for 40mins when all the systems (ventilation, heating, wall cooling and thermal dummy) are ON in the test chamber. Therefore, the Petri dish was filled with liquid glue and placed in the test chamber after reaching the steady-state environmental conditions. Then the measurements were continued for 40mins. Figure 15 shows that the total measurement time was 160mins, while the interval of analysed data was 20mins. In between the experiments, the chamber was ventilated to achieve the background VOCs level.

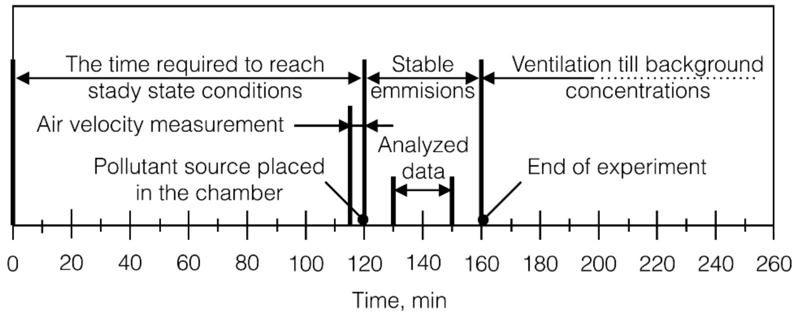


Figure 15. Plan of measurements

The layout of measurement equipment is presented in Figure 13. Three main parameters were measured during experiments: air velocity, air temperature and VOC concentrations. Air velocity was monitored using the Lumasence Innova 1221 thermal monitoring system (Lumasence, Denmark). Calibrated air velocity transducer MM0038 (±0.1m/s accuracy), which operates at a constant temperature difference anemometer principle, was placed on a tripod located at the approximate centre of the test chamber, at the height of 1.1m. Air velocity measurements were performed for 5 minutes, before introducing the pollutant source into the chamber. This was done in order to test if air velocity is lower than the recommended air velocity in the occupied zone (0.1m/s for office environment) [124].

For measurement of vertical air temperature gradient, four stands (T_1, T_2, T_3 and T_4) with temperature meters were used. The temperature was measured at four heights (0.1, 1.1, 1.7 and 2.5m) above the floor with digital temperature sensors DS18B20 (Dallas Semiconductor, United States) (±0.5 ºC (-10 ÷ +85 ºC) accuracy). The reference room temperature (T_{ref}) was measured in the centre of the test chamber, at the height of 1.1m.

The concentration of released VOCs was measured using five air quality sensors based on micro-machined metal oxide semiconductor (MOS) technology (iAQ2000, AMS Sensor Solutions Germany GmbH) [125]. The metal oxide used in the sensors changes its electrical properties when exposed to gaseous pollutants and the concentration of pollutants is obtained by measuring conductivity [126]. MOS sensing technology is conventional technology used in a variety of applications and it is relatively inexpensive compared to other sensing technologies [127]. Selected VOC sensors have a simple design, small size and low cost. These sensors are sensitive to various non-methane hydrocarbons, including aliphatic and aromatic hydrocarbons, alcohols, ketones, organic acids, amines etc. Compounds emitted from liquid glue during the experiments are attributed to aromatic hydrocarbons. Selected VOC sensors represents not the individual VOC concentrations but a mixture of gases (i.e. represent so called TVOCs). If gases are present, the sensors, because of special manufacturers provided calibration technology, translate the signal into parts per million (ppm) CO_2 (CO_2 equivalent) [128]. It allows to achieve compatibility between the measured values and recommended CO_2 concentration from standards. It is important to emphasise that by comparing VOC and CO_2 sensors it was observed that the general pattern of measured concentrations is the same, but concentrations measured by VOC sensors varies in a much wider range and has higher peaks [129]. The peaks are explained by surface chemistry and secondary reactions of VOCs. However, VOC sensors based on MOS technology have some limitations. These sensors suffer from a limit of detection that is too high for air quality monitoring [130-132]. For example, the selected sensors measure VOCs concentrations in the range of 450-2000ppm (CO_2 equivalent). However, these sensors are calibrated to reflect CO_2 concentration indoors, thus minimum detection values seem reasonable, as CO_2 concentration in outdoor air is approx. 400ppm. Not all VOCs are detected by these sensors [133]. This means that some hazardous compounds may not be detected. The sensors are non-compound specific [129]. Additionally, less information can be found on the accuracy of these sensors [129].

Despite the latter limitations, VOC sensors iAQ-2000 were used during experiments of this dissertation. As the aim of the dissertation is to explore the dispersion of volatile organic compounds measured concentration, which may be expressed as relative concentrations, without paying attention to real measured values. Consequently, this research does not evaluate health effects from VOCs exposure, thus it is better to avoid confusion by presenting real measured values.

Before experiments, the sensors were inter-tested for the precision of their readings in the full range of response; the coefficient of variation of the readings did not exceed 7%.

Concentrations of the pollutants were measured in the supply air (C_s), exhaust air (C_e), occupied zone, at the height of 1.1m above the floor (C_{i1}, C_{i2}) and in the breathing zone of the dummy (C_{exp}). Occupied zone here is defined as space between the floor and the horizontal plane at the height of 1.1m above the floor. Breathing zone is the space in front of the heated dummy's face. Thus, VOC sensor was mounted on the face area.

Temperatures and VOC concentrations were recorded at 1s intervals and 1200 values were collected from 20 minutes for each experiment.

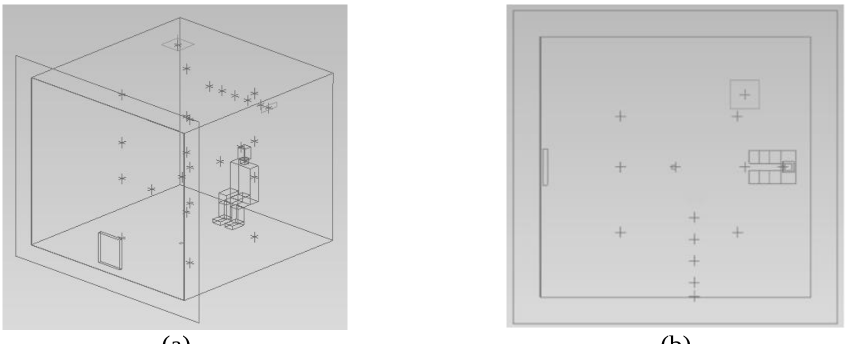
2.2. Numerical method

2.2.1. Solver settings

The Computational Fluid Dynamics (CFD) tool was selected to predict and visualise the dispersion of pollutants in the test chamber. CFD has been widely used for more than 50 years to predict indoor airflows [134]. For this study, commercial CFD tool FloVENT (Mentor Graphics, United States) was chosen. The selected software is specifically designed to investigate the airflow, heat transfer and contamination control within rooms or buildings. Airflow and heat transfer are governed by conservation laws that can be expressed in a partial differential form (Navier Stokes Equations) [135]. All conservation equations in FloVENT are converted to a finite volume form. Each value of temperature, pressure and velocity (x, y and z directions) are calculated for each volume (grid cell). For the representation of turbulence, K-epsilon turbulence model (LVEL K-epsilon) was chosen. It is reported that K-epsilon turbulence models show good performance in predicting airflows, temperatures and contaminant distribution in buildings [134, 136-138]. This turbulence model in FloVENT calculates two additional variables; the kinetic energy of turbulence and its dissipation rate (FloVENT User Guide, 2014). Double Precision Solver (DPS) was chosen to achieve steady-state simulation results.

2.2.2. Geometry and grid

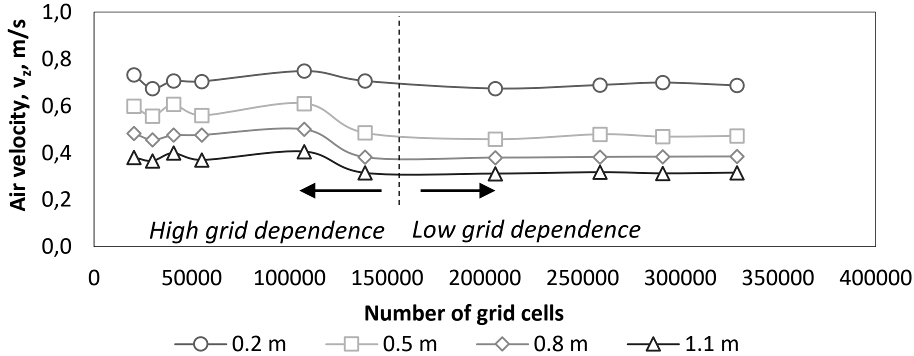
A three-dimensional geometry replicating the full-scale indoor environment test chamber used in experiments was employed in the numerical predictions. The walls were created as an enclosure. The geometry of the dummy was built according to the physical geometry of the dummy used for the experiments. Square diffusers were used to create air terminals with four sideways jets. Fixed flow openings were used to create supply air wall grille and exhaust air diffuser. Solid cuboid with thermal attribute was used to simulate the radiator, as well as underfloor heating. The example of the chamber geometry used in the numerical model is given in Figure 16.



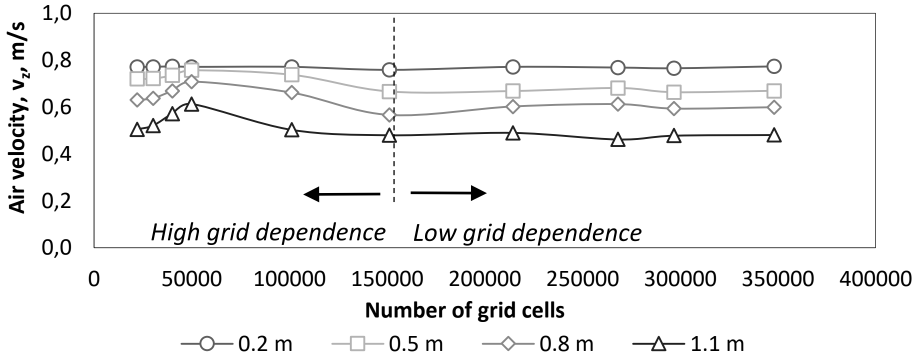
(a) (b)

Figure 16. Chamber geometry (isometric view (a) and plan (b)) used in the numerical predictions, the case with radiator heating, wall grille air supply and heated dummy in position B. "+" indicates the location of the monitor points

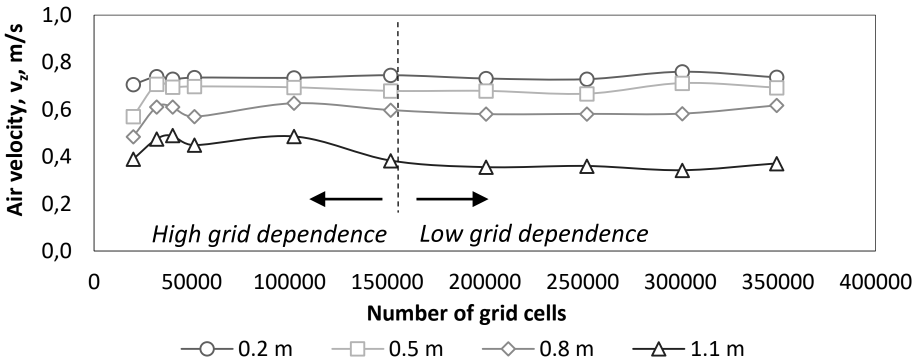
The geometry was divided into regions by using the variable Cartesian grid. The density of the grid was increased close to the air supply equipment, heated floor, radiator and cooled wall. A localised grid was used around the heated dummy. Grid aspect ratio was lower than 10. To obtain a converged steady-state solution, the smallest grid cell was kept smaller the 10^{-6} × the overall scale for the system. Grid quality in CFD simulations is an important factor that affects the results. Therefore, it is recommended to perform grid sensitivity analysis [138-140] to obtain results that would be grid independent. Grid sensitivity analysis was performed for three cases, with the same position of the heated dummy and flow pattern, but with different heating types. The results of grid sensitivity testing for warm air heating, radiator heating and underfloor heating are presented in Figure 17a-17c.



(a)



(b)



(c)

Figure 17. Air velocity comparison for different number of cells for the cases with high-level air supply grille, heated dummy position B and warm air heating (a), radiator heating (b), underfloor heating (c)

Four monitor points were used to follow air velocity in the supply stream at different distances from the air supply grille. Monitor points were at the height of 2.66m from the floor in the middle of air supply grille. The distances from the grille were selected as follows – 0.2m, 0.5m, 0.8m, 1.1m. Figure 17a-17c presents air velocity for direction z. It was determined that approx. a 150,000 cells grid is appropriate for this study because refining the grid further gives negligible changes in results. It is assumed that this grid will give grid independent results and later the results will be presented with the number of grid cells varying in the range from 100,000 to 200,000. The example of the typical grid used in the numerical model is given in Figure 18.

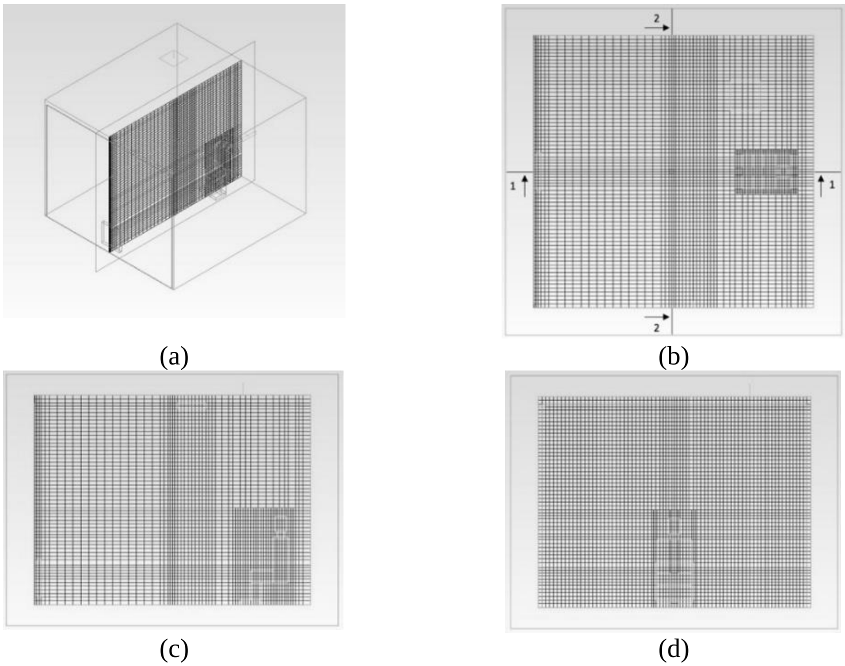


Figure 18. Typical grid (isometric view (a), plan (b), section 1-1 (c), section 2-2 (d)) used in the numerical predictions, the case with radiator heating, wall grille air supply and heated dummy in position B

2.2.3. Boundary conditions for numerical model

All boundary and initial conditions were chosen to replicate parameters achieved in experiments. The external ambient temperature for all the walls of the chamber, except for the cooled one and floors, was set to +20 °C or +22 °C, depending on the case. For the cooled wall, the temperature was set 3 °C lower than other partitions. In cases with underfloor heating, the temperature of the floor was set at +25 °C. The heated dummy was simulated as a combination of simple cuboids with 85W thermal attribute in total. Additionally, the dimensions of the heated dummy were identical to the heated dummy used in experiments. In cases with ceiling diffusers, the nozzle diffusers were replaced by the uniform air jets by using the "Box method"

[140]. The jet angle was set at 20 degrees. Supply airflow was set to 36m³/h for each diffuser. Wall grille air supply opening was designed with the 0.71 free area ratio and supply airflow was set to 72m³/h. Supply air temperature in cases when underfloor heating and radiator heating was used was set at +21.5 °C and +25 °C in cases with warm air heating. In all cases, the air exhaust diffuser was designed with the 0.5 free area ratio, and exhaust airflow was set at 72m³/h. These airflows ensured an air change rate of $2h^{-1}$. As it was mentioned in the previous chapter, solid cuboid with thermal attribute was used to simulate the radiator, and the thermal attribute was set at 200W. In cases with underfloor heating, a thermal attribute for warm floors was set at 25 °C. As the CFD tool FloVENT does not have a function that allows for creating a pollutant source of a mixture of different gases, properties of the pollutant source were selected similar to benzene. Benzene has a similar density as the gases emitted from liquid glue during the experiments. Furthermore, the emission rate of pollutants released from liquid glue during the experiments was not measured. For this reason, several initial simulations were performed with the CFD software and the results showed that the pollution source simulated as a very small isothermal air jet (0,1l/s) with 80,000ppm concentration of benzene, which gave the closest concentrations to those obtained from experiments. Pollutant concentration in the supply air was set similar to the measured concentrations in the experiments depending on the case. Monitor points were used to follow the temperatures, velocities and concentrations in the same positions as sensors in the experiment.

2.3. Ventilation effectiveness and personal exposure indices

For evaluation of air quality and efficiency of the ventilation system in removing contaminants, both in experiments and in simulations, two main parameters were selected: ventilation effectiveness and personal exposure index.

Ventilation effectiveness was evaluated as contaminant removal effectiveness, CRE, ε^c, index. As Mundt et al. [80] pointed out, the CRE index is a measure of how quickly an airborne contaminant is removed from the room. This index is used when detailed information, (e.g., position) is known about the contaminant sources. Contaminant removal effectiveness is defined by the equation (1) [80]:

$$\varepsilon^c = \frac{C_e}{\langle C_{oc} \rangle} \tag{1}$$

where ε^c is contaminant removal effectiveness, C_e is contaminant concentration in the exhaust air and $\langle C_{oc} \rangle$ is the mean contaminant concentration in the occupied zone. The occupied zone in this research is defined as the area up to 1.1m above the floor level.

Air quality in the inhaled air was evaluated as the personal exposure index, ε^c_{exp}. This index reveals the real effectiveness experienced by a person in the ventilated room [108]. Personal exposure index is defined by the equation (2):

$$\varepsilon_{\exp}^{c} = \frac{C_e}{C_{\exp}} \tag{2}$$

where ε^{c}_{exp} is personal exposure index (exhaust to inhaled), C_e is contaminant concentration in the exhaust air, and C_{exp} is contaminant concentration in the inhaled air (CBL of a person).

In a fully mixed situation concentration, the exhaust air will be equal to the mean contaminant concentration in the occupied zone and this will give CRE equal to 1.0; as well as a personal exposure index. The high values of CRE and personal exposure index demonstrate that ventilation works effectively for the locations where these indices were calculated. These two indices also show that air quality experienced by a person and the mean air quality in the occupied zone can be different.

Air quality in the inhaled air was evaluated by the additional relative value inhaled to ambient concentration ratio, ε^{*}_{exp}. This ratio reveals air quality in the inhaled air compared to average air quality in the occupied zone. This personal exposure index (inhaled to ambient) is defined as:

$$\varepsilon_{\exp}^{*} = \frac{C_{\exp}}{\langle C_{oc} \rangle} \tag{3}$$

where ε^{*}_{exp} is the personal exposure index (inhaled to ambient), C_{exp} contaminant concentration in the inhaled air (convective boundary layer of a person) and $\langle C_{oc} \rangle$ is the mean contaminant concentration in the occupied zone.

Low values of personal exposure index (inhaled to ambient) contrary to personal exposure index (exhaust to inhaled) demonstrate that the ventilation works effectively for the location where this ratio was calculated.

2.4. Statistical analysis

Descriptive statistics were used to summarise and visualise the relative concentrations of VOCs. Mean (or the arithmetic average of measured values) and median (or the middle value of a measured values) were selected as central tendency measures; while standard deviation, minimum and maximum values were used as measures of data variability.

To indicate statistical difference between different experimental cases, a mean comparison test was used. The test type (parametric or non-parametric) was selected according to data distribution. Therefore, it was essential to identify if the data was normally distributed around a central value.

It is assumed that data is distributed normally (has Gaussian distribution) if the values cluster around the central value forming a symmetrical bell-shape curve [141]. It was possible to conclude this when analysing two additional measures of descriptive statistics, i.e. skewness and kurtosis. The skewness and kurtosis provide information to the curve (or the histogram) form of the measurements. Skewness indicates the symmetry of the data. The skewness in a normal distribution is equal to zero, and in other cases, the curve (or the histogram) is shifted to the right or left. The kurtosis provides information about the curve (or the histogram) form, which identifies the sharpness of the graph peak and tails. In a normally distributed data case, the kurtosis is equal to 3.

However, additionally, a Shapiro-Wilk test was conducted as it is a recommended testing normality [142]. The null hypothesis (H_0) for the Shapiro-Wilk test was that the distribution of relative concentrations is normal, while the alternative hypothesis (H_A) was that the distribution is not normal. The significance level, or alpha, of 0.05 was used; as it is widely used in academic research. If the calculated p-value was less than 0.05, the hypothesis of normality (H_0) was rejected. Otherwise, it should be assumed that the distribution is normal. The Shapiro-Wilk test was implemented with the statistical software *STATISTICA 10.0* (StatSoft, United States). The results of the Shapiro-Wilk test are presented in subsection 3.2.

The data was not normally distributed. Therefore, a non-parametric test to compare the mean difference between experiments was used. More precisely, a Kruskal-Wallis test was used to compare the relative concentration groups between themselves. This test is capable of assessing significant differences with more than two independent groups without assuming that data is normally distributed. The null hypothesis (H_0) for the Kruskal-Wallis test was that there is no difference between values from different experiments. In other words, the mean ranks of the values are the same. The alternative hypothesis (H_A) was that there is a difference between values from different experiments. The significance level of 0.05 was used. In this case, the significance level indicates that there is a 5 percent risk of concluding that the difference exists while there is no difference. If the calculated p-value was less than 0.05, the null hypothesis (H_0) was rejected. Otherwise, it was assumed that there is no difference between values from different experiments. The Kruskal-Wallis test was implemented on the ranked values with the statistical software *STATISTICA 10.0* (StatSoft, United States). The results of the Kruskal-Wallis test are presented in subsection 3.2.

2.5. Validation of CFD models

If the computational fluid dynamics tools are used as a numerical method in research, it is recommended that the numerical calculations should be validated by comparing with measurements from experiments [138]. The main parameters that are usually compared during the validation procedure are air velocity, air temperature and pollutant concentrations [143-146]. Parameters should be measured in several locations and after that compared with results of numerical calculations in the same locations. During the experiments, the main measured parameters in this research were temperatures and VOC concentrations. Air velocity measurements were performed before experiments to verify that air velocity does not exceed the recommended values in the occupied zone.

Air velocity in the occupied zone usually has small values (<0,02m/s). Therefore, comparison with velocity calculated during numerical simulations is inadequate. Villafruela et al. [143] outlined that the airflow pattern is significantly influenced by the air momentum flow produced by the supply openings. Therefore, supply airflow patterns should be compared during the validation procedure. In this research, two air supply patterns were used (high-level wall grille air supply and four-way in-ceiling diffuser air supply). Air velocities in the supply air jets were measured with a hot wire anemometer (Testo 425, United States) that is capable of measuring flow velocity (±0.03m/s + 5 % of reading accuracy) and temperature (±0.5 ºC) before experiments. Air velocities in the supply air jet from the grille were measured along a horizontal line at 2.66m from the floor at the centre of the grille. The measurements were performed for 15 seconds at every five centimetres, one metre away from the grille. The nozzles of the in-ceiling diffuser were rotated in such a way that the air would be spread in four directions. Air velocities in the supply air jets from the in-ceiling diffuser were measured along a horizontal line at 0.01m from the ceiling at the centre of each side of the diffuser. The measurements were performed for 15 seconds at every five centimetres, forty centimetres away from the diffuser. Measured values, later on, were compared with values from the steady state simulations.

Warm air heating, radiator heating and underfloor heating were analysed in this research. As it was mentioned in the literature review, these heating systems generate different heat fluxes that affect air movement, leading to a different temperature distribution over the height of the room. Therefore, temperature distribution obtained in experiments and numerical predictions were compared during the validation procedure.

Direct comparison of VOC concentrations was impossible, because the exact emission rate of VOCs from liquid glue was unknown. Therefore, ventilation effectiveness and personal exposure indices were used to validate results obtained by numerical simulations.

The differences between experimental and numerical results were evaluated according to the relative percentage error, defined as:

$$PE = \left| \frac{(x_e - x_{cfd})}{x_e} \right| \times 100\% \quad (4)$$

where PE is relative percentage error, x_e is experimentally obtained value and x_{cfd} is numerically obtained value.

According to Zhang et al. [147], if the relative percentage error when comparing experimental and CFD results are less than 10%, it is assumed that the accuracy of the CFD model is good, less than 30% - acceptable.

Additionally, in cases of comparing air velocities, linear regression analysis was used to estimate the relationship between experimental and CFD results.

3. RESULTS AND DISCUSSION

The first subsection of the results chapter will present the results of pollutant dispersion in the test chamber, as well as results of air temperature distribution and air velocities. Both experimental and numerical results will be presented together. In the second subsection, results of the statistical analysis performed for experimental data will be presented. The third subsection of this chapter will assess the reliability of the numerical model. The last subsections will provide an analysis of factors influencing pollutant transportation into the breathing zone by means of CFD.

3.1. Experimental and numerical results of pollutant dispersion

Concentrations of VOCs measured in the exhaust air (C_e), occupied zone, at the height of 1.1m above the floor (C_{i1}, C_{i2}) and in the breathing zone of a heated dummy (C_{exp}) were converted to relative concentrations according to the highest concentration registered during twenty minutes of each experiment. This research does not focus on health effects and concentrations presented in actual units are not comparable with the standard requirements. Therefore, it was decided to use relative concentrations to avoid confusion for the reader. It is important to note that VOC concentrations in the occupied zone were measured at two positions, while further they are provided as a single average $C_{i,1.1}$ value.

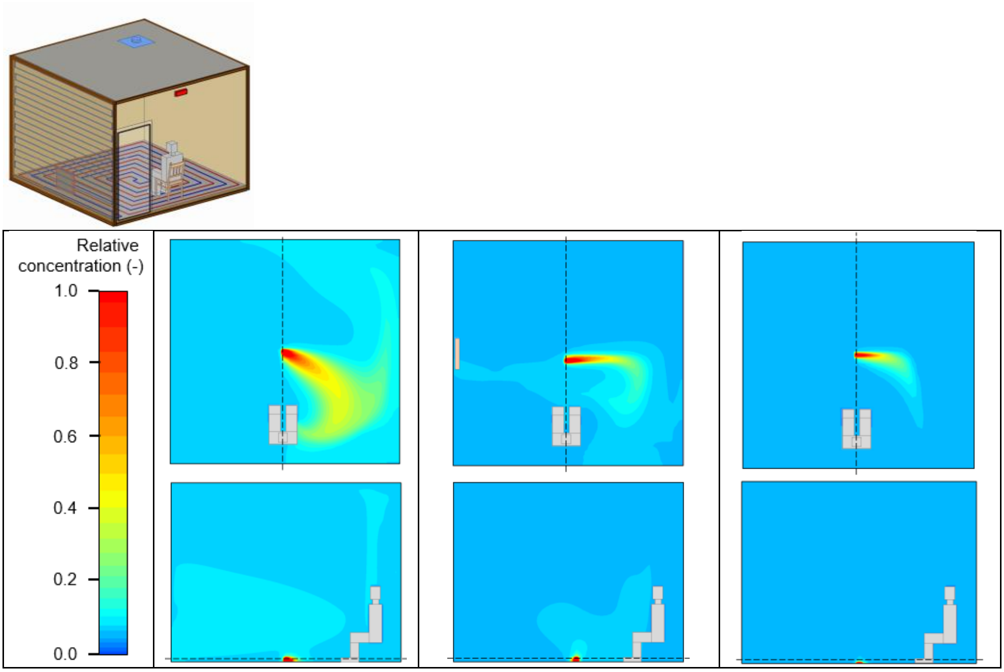
The range of the relative concentration values ($C_{i,1.1}$, C_e, C_{exp}) median and inter-quartile interval, as well as minimum and maximum values for each experimental case, are presented in Figures 19b-24b. CFD prediction results of near-floor level released pollutant dispersion in the test chamber are presented in Figures 19a-24a. CFD simulations were performed to supplement the experimental results and provide the spatial patterns of pollutant transport. Figures 19a-24a provide the sections of the CFD models at the height of 0.1m above the floor and through the heated dummy.

Each chart and sections of the CFD model in Figures 19-24 compares results from the cases with different heating systems. Figures 19, 21 and 23 present results from the cases with high-level wall grille air supply, while results from the cases with four-way in-ceiling diffusers are presented in Figures 20, 22 and 24. Pairs of the Figures 19 and 20, 21 and 22 and 23 and 24 present results from the cases with a heated dummy in position A, B and C respectively.

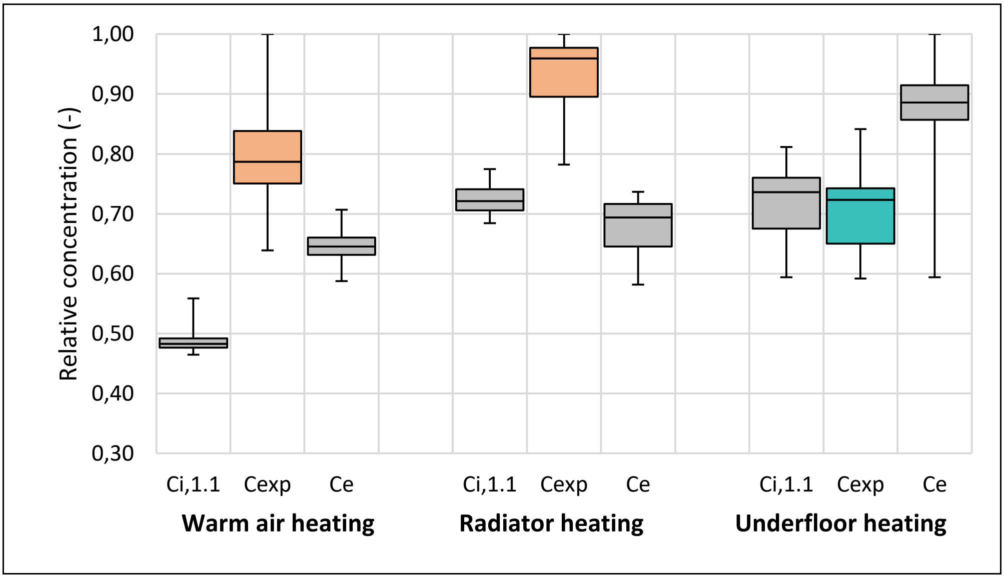
Vertical air temperature gradients between 0.1 and 2.5m above the floor for the experimental cases are presented in column five of Table 3, for numerical cases in column five of Table 4. CFD prediction of temperature distribution in the test chamber is provided in Figure 25-30.

The ventilation effectiveness, ε^c, and personal exposure indices, ε^c_{exp}, ε^*_{exp}, calculated for the main 18 experimental cases are presented in Table 3. Numerical results for the same 18 cases are presented in Table 4. Ventilation effectiveness and personal exposure indices were calculated by using the average relative concentration values from 20 minutes of the experiment.

The average air velocity measured in the middle of the test chamber at the height of 1.1m were lower than values recommended by ISO 7730 and varied from 0.02 to 0.06m/s during all experimental cases. As air velocity was measured in order to test if it was lower than the recommended air velocity in the occupied zone (0.1m/s for office environment) (ISO 7730), detailed results of measurements are not provided.

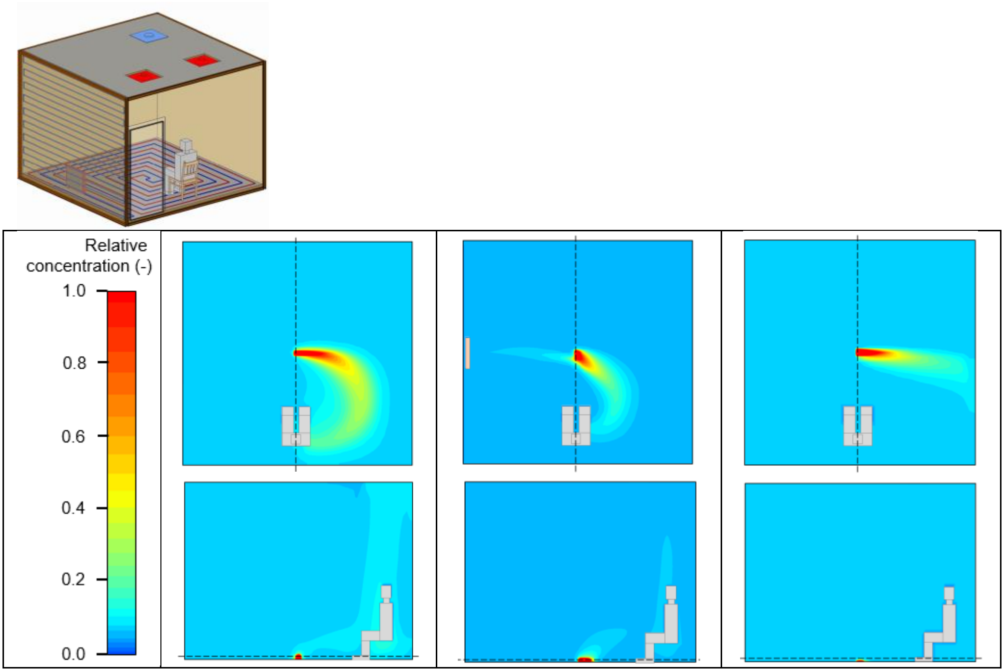


(a)

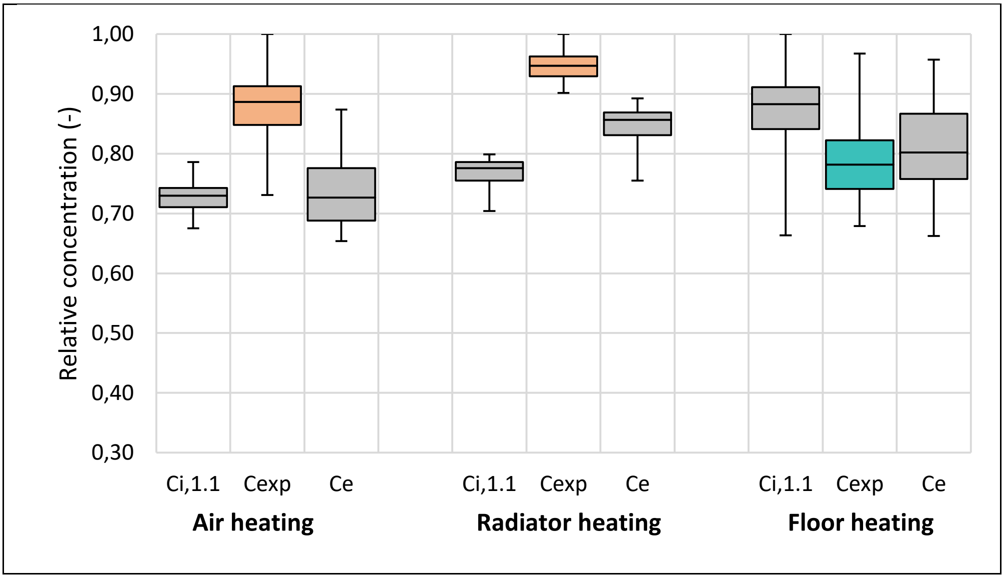


(b)

Figure 19. Relative pollutant concentrations for the cases with heated dummy in position A and high-level wall grille air supply: (a) results of numerical simulation (upper picture – sections of CFD models at the height of 0.1m, lower picture – sections through the heated dummy); (b) experimental results ($C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air)

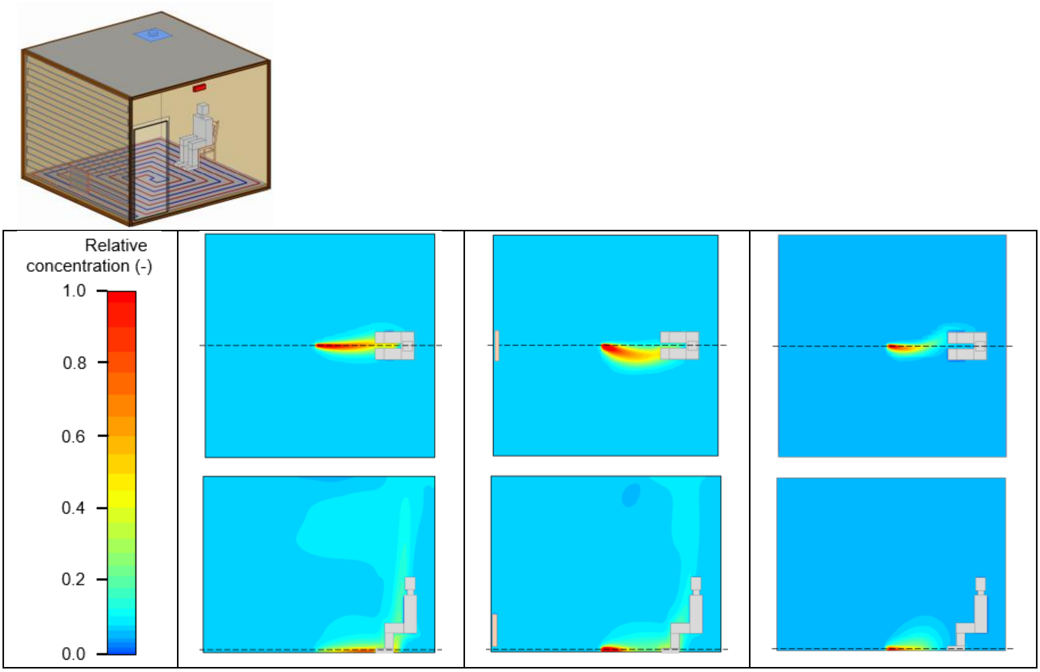


(a)

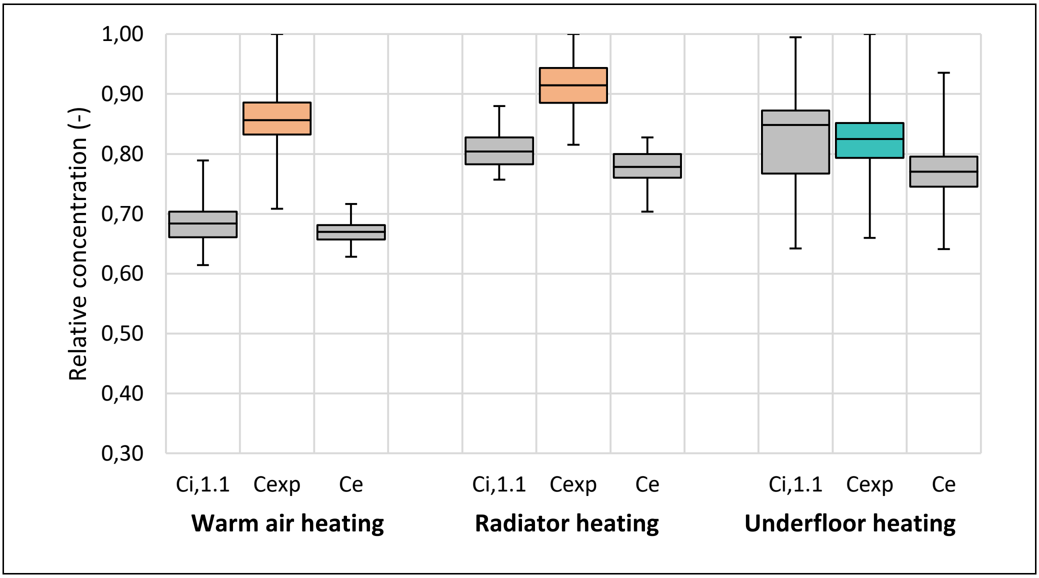


(b)

Figure 20. Relative pollutant concentrations for the cases with heated dummy in position A and in-ceiling four-way air supply: (a) results of numerical simulation (upper picture – sections of CFD models at the height of 0.1m, lower picture – sections through the heated dummy); (b) experimental results ($C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air)

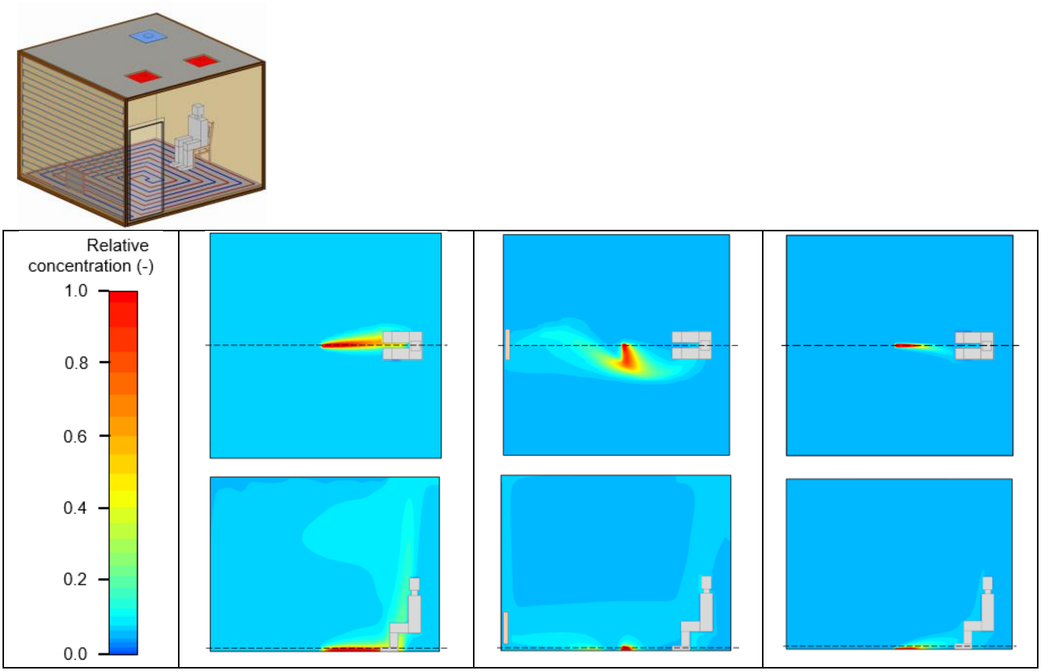


(a)

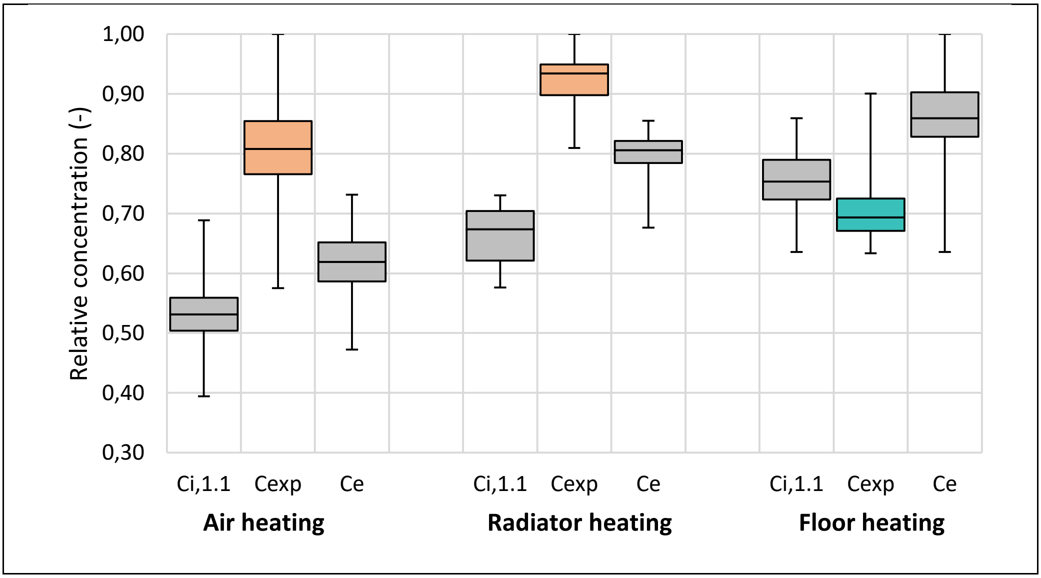


(b)

Figure 21. Relative pollutant concentrations for the cases with heated dummy in position B and high-level wall grille air supply: (a) results of numerical simulation (upper picture – sections of CFD models at the height of 0.1m, lower picture – sections through the heated dummy); (b) experimental results ($C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air)

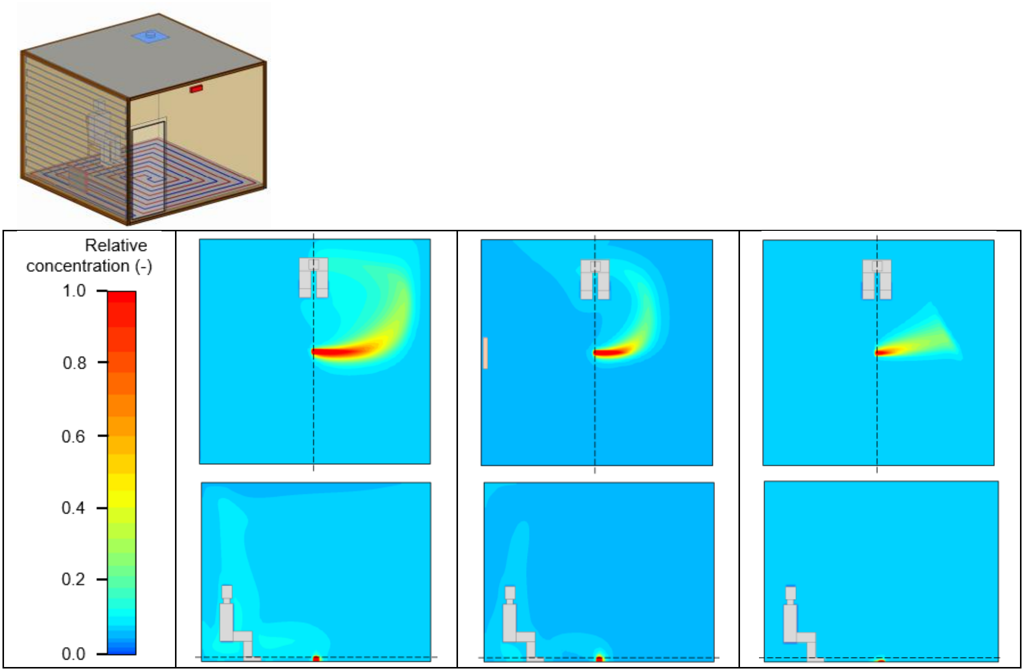


(a)

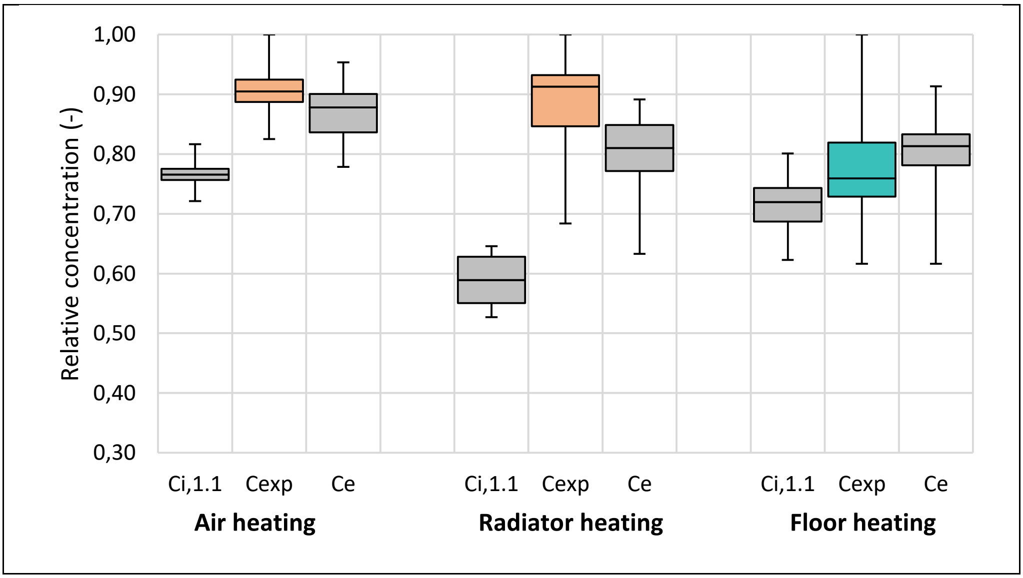


(b)

Figure 22. Relative pollutant concentrations for the cases with heated dummy in position B and in-ceiling four-way air supply: (a) results of numerical simulation (upper picture – sections of CFD models at the height of 0.1m, lower picture – sections through the heated dummy); (b) experimental results ($C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air)

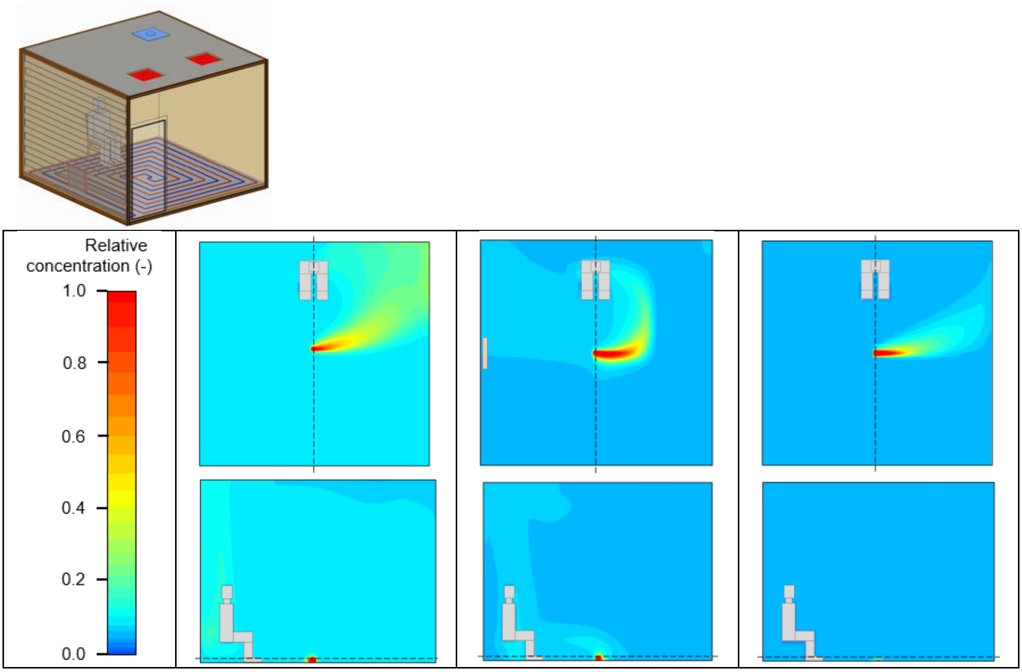


(a)

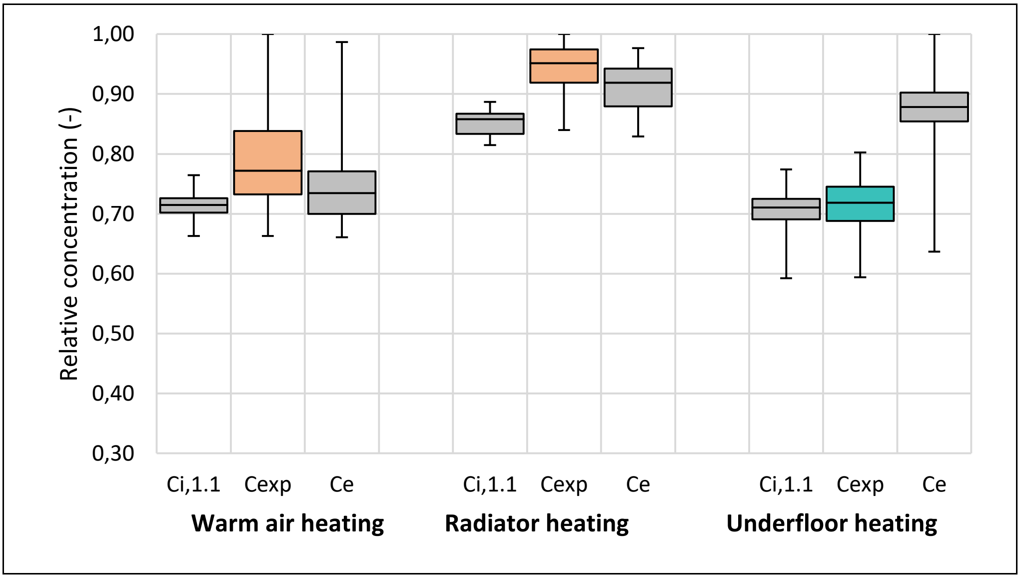


(b)

Figure 23. Relative pollutant concentrations for the cases with heated dummy in position C and high-level wall grille air supply: (a) results of numerical simulation (upper picture – sections of CFD models at the height of 0.1m, lower picture – sections through the heated dummy); (b) experimental results ($C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air)



(a)



(b)

Figure 24. Relative pollutant concentrations for the cases with heated dummy in position C and in-ceiling four-way air supply: (a) results of numerical simulation (upper picture – sections of CFD models at the height of 0.1m, lower picture – sections through the heated dummy); (b) experimental results ($C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air)

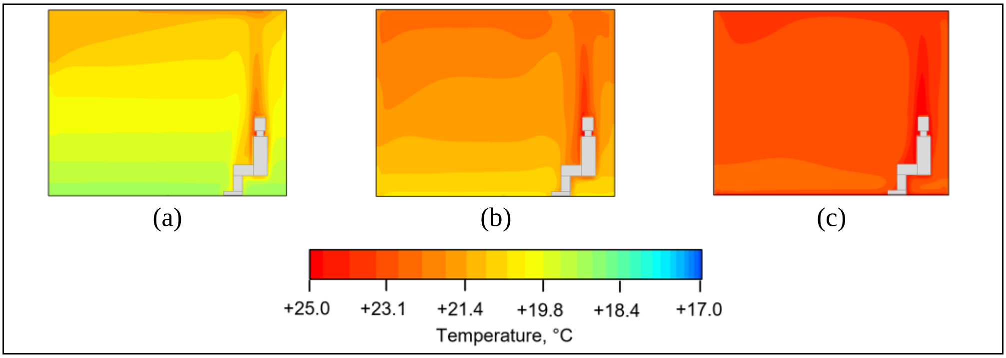


Figure 25. Temperature distribution for the cases with heated dummy in position A and high-level wall grille air supply: (a) warm air heating; (b) radiator heating; (c) underfloor heating

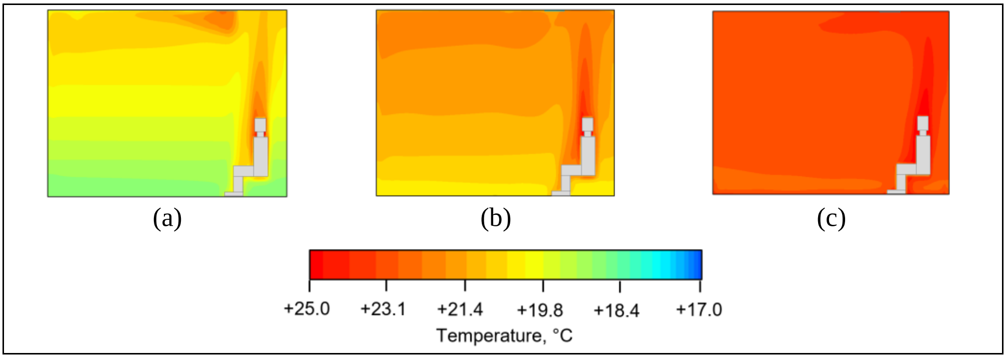


Figure 26. Temperature distribution for the cases with heated dummy in position A and in-ceiling four-way air supply: (a) warm air heating; (b) radiator heating; (c) underfloor heating

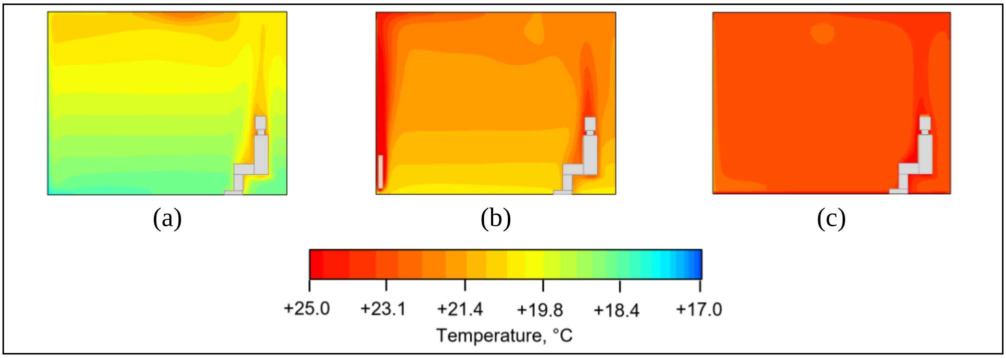


Figure 27. Temperature distribution for the cases with heated dummy in position B and high-level wall grille air supply: (a) warm air heating; (b) radiator heating; (c) underfloor heating

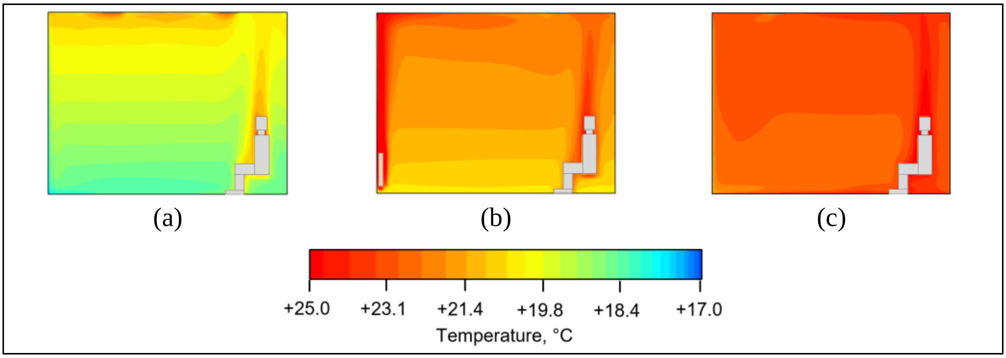


Figure 28. Temperature distribution for the cases with heated dummy in position B and in-ceiling four-way air supply: (a) warm air heating; (b) radiator heating; (c) underfloor heating

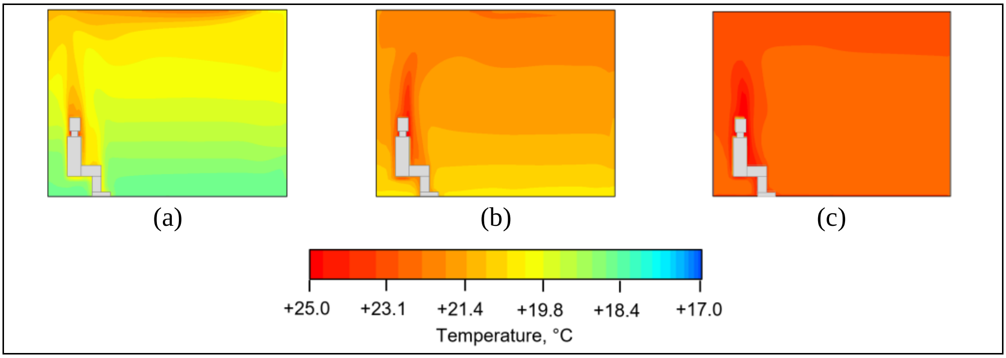


Figure 29. Temperature distribution for the cases with heated dummy in position C and high-level wall grille air supply: (a) warm air heating; (b) radiator heating; (c) underfloor heating

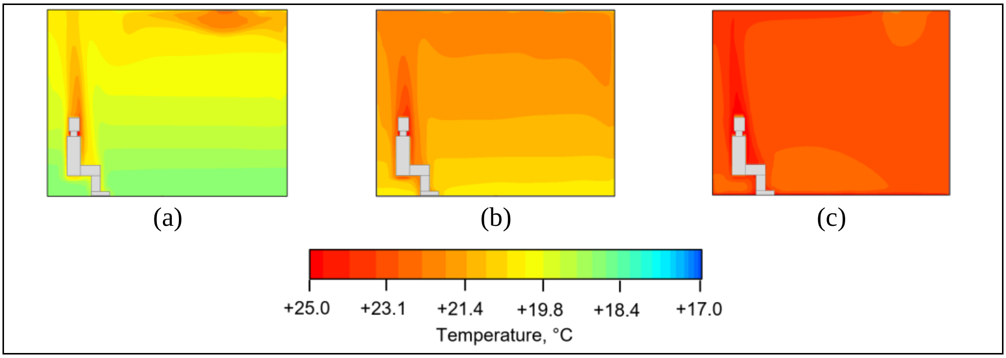


Figure 30. Temperature distribution for the cases with heated dummy in position C and in-ceiling four-way air supply: (a) warm air heating; (b) radiator heating; (c) underfloor heating

Table 3. Experimental results of pollutant removal effectiveness and personal exposure indices in the test chamber

Case number	Air distribution scheme [a)]	Location of the heated dummy	Heating system [b)]	Vertical air temperature gradient °*C/m*	Ventilation effectiveness ε^c	Personal exposure index (exhaust to inhaled) ε^c_{exp}	Personal exposure index (inhaled to ambient) ε^*_{exp}
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1			AH	1.07	1.32	0.81	1.63
2	GR	A	RH	0.72	0.94	0.73	1.29
3			FH	0.06	1.20	1.22	0.98
4			AH	0.94	0.98	0.78	1.26
5	GR	B	RH	0.75	0.96	0.85	1.13
6			FH	0.06	0.94	0.93	1.01
7			AH	0.91	1.13	0.96	1.18
8	GR	C	RH	0.81	1.35	0.89	1.51
9			FH	0.12	1.12	1.04	1.08
10			AH	0.98	1.01	0.83	1.21
11	M4	A	RH	0.52	1.10	0.87	1.23
12			FH	0.04	0.94	1.03	0.91
13			AH	0.75	1.17	0.77	1.52
14	M4	B	RH	0.81	1.20	0.86	1.39
15			FH	0.04	1.14	1.22	0.93
16			AH	0.94	1.05	0.95	1.10
17	M4	C	RH	0.63	1.07	0.96	1.11
18			FH	0.08	1.25	1.23	1.01

a) GR – high-level wall grille; M4 – in-ceiling four-way diffusers;
b) AH – warm air heating; FH – underfloor heating; RH – radiator heating.

Table 4. Numerical results of pollutant removal effectiveness and personal exposure indices in the test chamber

Case number	Air distribution scheme [a)]	Location of the heated dummy	Heating system [b)]	Vertical air temperature gradient °C/m	Ventilation effectiveness ε^c	Personal exposure index (exhaust to inhaled) ε^c_{exp}	Personal exposure index (inhaled to ambient) ε^*_{exp}
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	GR	A	AH	0.76	0.88	0.93	0.94
2			RH	0.65	0.98	0.97	1.01
3			FH	0.11	0.97	0.96	1.01
4	GR	B	AH	0.91	0.95	0.58	1.63
5			RH	0.62	0.97	0.59	1.63
6			FH	0.13	1.09	1.06	1.02
7	GR	C	AH	0.87	0.86	0.74	1.16
8			RH	0.64	1.01	0.86	1.18
9			FH	0.14	0.86	0.91	0.95
10	M4	A	AH	0.79	0.96	0.68	1.41
11			RH	0.61	1.01	0.88	1.15
12			FH	0.18	1.00	1.00	1.00
13	M4	B	AH	0.86	1.01	0.57	1.75
14			RH	0.65	1.02	0.90	1.13
15			FH	0.22	1.02	0.86	1.19
16	M4	C	AH	0.75	0.93	0.85	1.09
17			RH	0.65	1.13	0.84	1.35
18			FH	0.21	1.02	1.01	1.00

a) GR – high-level wall grille; M4 – in-ceiling four-way diffusers;
b) AH – warm air heating; FH – underfloor heating; RH – radiator heating.

Experimental results revealed the highest relative pollutant concentrations in the exhaust air (C_e) in cases with the underfloor heating (FH) system. The lowest relative C_e values were measured in cases with the warm air heating (AH) system. However, there were some exceptions that can be seen in Figure 20, 21 and 24 were the highest relative C_e values were measured in cases with the radiator heating (RH) system. In terms of air distribution scheme, in cases with high-level wall grille air supply of 4%, lower relative C_e values were measured when AH system was used. In cases with FH and RH systems, this air supply type showed a positive effect and relative C_e values where higher by 5 and 13%, respectively than in cases with in-ceiling four-way air diffusers.

The average relative pollutant concentration in the occupied zone ($C_{i,1.1}$) in cases with RH and FH was 0.73 and 0.76, respectively. In the case with AH, the average relative $C_{i,1.1}$ was equal to 0.65; an exception was noticed in cases with the heated dummy in position C (Figures 23 and 24), where relative $C_{i,1.1}$ values were higher than average. Less than 8% differences between the different distribution types were observed.

Lower or slightly higher relative pollutant concentrations in the occupied zone compared to relative concentrations in exhaust air led to ventilation effectiveness (ε^c) ratios, which were roughly equal to 1.0 (Table 3, column 6). This demonstrates that ventilation in all cases worked effectively. Furthermore, no significant difference was noticed when comparing different heating systems. In terms of air distribution scheme, it was noticed that the ventilation effectiveness was lower than 1.0 in four out of nine cases with high-level wall grille air supply. Ventilation effectiveness was higher than 1.0 in all cases where in-ceiling four-way air supply diffusers were used, with one exception (FH and heated dummy in position A). Ventilation effectiveness calculated from CFD also showed that ventilation worked effectively; ε^c fluctuated around 1.0 (Table 4, column 6). The positive effect of air supply through in-ceiling four-way diffusers was also observed in numerical simulations.

Experimental results revealed the lowest relative pollutant concentrations in the breathing zone (C_{exp}) in all cases with the FH system; average relative C_{exp} was 0.75. A 24% higher relative pollutant concentration in inhaled air were in cases with RH system. The average relative C_{exp} in cases with AH was higher by 12 percent than in cases with the FH system. In terms of air distribution scheme 3 – 4% differences were noticed. In terms of the heated dummy position, no systemic differences were found.

The highest personal exposure index, ε^c_{exp}, (Table 3, column 7) was in cases with the FH system, it was equal to 1.11 on average. The high value of personal exposure index shows that air quality experienced by the occupant is higher. The high index value is the result of low relative pollutant concentrations registered in the inhaled air, as well as high relative pollutant concentrations in exhaust air. The average personal exposure index in cases with AH and RH was 0.85 and 0.86, respectively. ε^c_{exp} was approx. 30% lower in these cases compared to FH cases. The personal exposure index was higher by 9% when four-way in-ceiling diffusers were used for air supply, except in cases with AH where no significant effect of the air distribution scheme was noticed. The personal exposure index, ε^c_{exp}, calculated from numerical models showed a similar trend with few exceptions (Table 4, column 7). ε^c_{exp} was almost identical with all heating types in cases with the air supply through the high-level wall grille and the thermal dummy in position A. In the case with air supply through in-ceiling diffusers, thermal dummy in position B and RH; ε^{c}_{exp} was the highest.

The lowest personal exposure index (inhaled to ambient), ε^{*}_{exp}, (Table 3, column 8) was calculated for cases with FH; ε^{*}_{exp} was 0.99 on average for these cases. Approx. 30% higher ε^{*}_{exp} values were calculated for AH and RH cases; ε^{*}_{exp} was 1.32 and 1.28, respectively. Lower values of ε^{*}_{exp} demonstrate that air quality experienced by the occupant was higher. A positive effect of wall grille air supply was noticed on the personal exposure (inhaled to ambient) index; it was higher by 5-7%. A similar trend was noticed in results predicted by CFD with few exceptions, similar to the previous personal exposure index (Table 4, column 8).

Personal exposure indices showed that air quality experienced by the occupant was different from the mean air quality in the test chamber as indicated by the index of ventilation effectiveness. It was observed that personal exposure indices depended more on the type of heating system than on the air distribution scheme or the position of the heated dummy. However, differences between experimental and numerical results for these indices were noticed, which will be discussed in the subsection 3.1.3.

Vertical air temperature gradient (Table 3, column 5) obtained from experimental data in the cases with the AH system was around 0.9 °C/m, with the RH system around 0.7 °C/m and 0.1 °C/m with the FH system. CFD predictions showed similar results (Table 4, column 5). The vertical air temperature gradient in AH, RH and FH were around 0.8, 0.6 and 0.2 °C/m, respectively. In addition, temperature distribution can be seen in Figures 25-30. The vertical air temperature gradient was slightly different in cases with air supply through high-level wall grille and four-way in-ceiling diffusers. It was lower by approx. 0.1 °C/m when the latter air supply was used.

Summarizing all cases, it was observed that relative concentrations in the occupant breathing zone were lower than in the occupied zone, but only in cases with underfloor heating combined with both air distribution schemes. The opposite effect occurred in cases with warm air and radiator heating. This effect can be explained by comparing the temperature differences between the occupant surface and surrounding air ($\Delta t_{o\text{-}a}$), as this difference affects the occupant convective boundary layer behaviour [102, 105, 113]. The higher this difference, the more intense the heat transfer from the occupant to the surrounding air, higher air velocity in CBL and the more intense pollutant entrainment into CBL. Figure 31 shows the vertical temperature gradients for rooms calculated according to the results of experiments of this research. As can be seen in the graphs, at near-floor level $\Delta t_{o\text{-}a}$ is different for cases with different heating systems. Assuming that the occupant surface temperature is +34 °C, in warm air and radiator heating; $\Delta t_{o\text{-}a}$ is approx. 15 °C, in underfloor heating – 14 °C. Higher $\Delta t_{o\text{-}a}$ at near-floor level results in pollutant entrainment from near-floor level into occupant CBL. CBL has the ability to elevate pollutants to the breathing zone [113]. Higher concentrations of pollutants entrained into CBL result in lower air quality in the breathing zone. It is important to emphasize, that pollutant concentrations in the breathing zone and occupied zone were very similar in cases with underfloor heating, which indicates that pollutant distribution is quite uniform in a room and close to ideal in the mixing ventilation case [86].

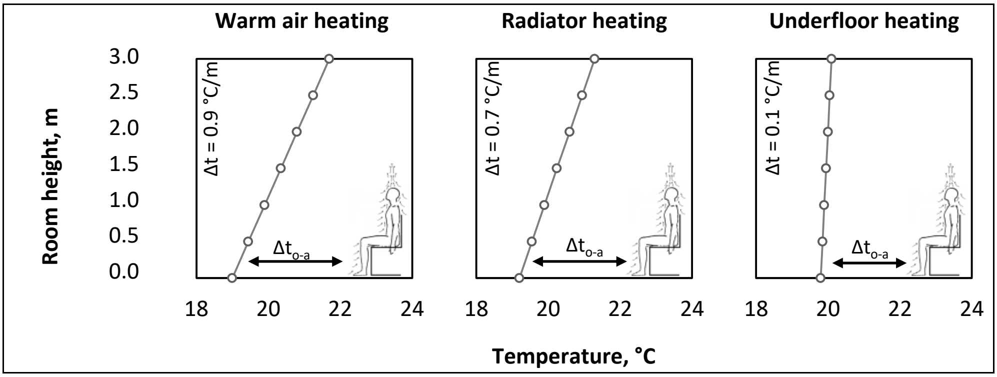


Figure 31. Vertical temperature gradient in mixing ventilation combined different heating systems. Δt – vertical temperature gradient, °C/m, $\Delta t_{o\text{-}a}$ – temperature between occupant surface and surrounding air, °C

Results also revealed that the air distribution type has a minor effect on pollutant distribution compared with heating type. Despite the fact that two different air supply patterns (through in-ceiling four-way diffusers and high-level wall grille) were used, the trend of air distribution in the chamber stayed the same, because both air supply patterns ensure mixing ventilation. Additionally, similar results were obtained by using the same in-ceiling diffusers in one-way mode and using two exhaust air diffusers [148]. However, air supply through the high-level wall grille performed slightly better in some of the cases. The reason for this is the higher supply air momentum through the grille, as well as higher velocities ensured in the occupied zone. In addition, during the experiments, different positions of the thermal dummy in relation to air supply diffusers and wall grille were used. Although differences were noticed between cases with different air supply terminals and their position in relation to the thermal dummy, they were only around 10% and their effect was not as systemic an effect as the heating type. It is likely that, in the presence of different diffusers, or grilles, or other types of diffusers for mixing ventilation, as well as their positions, air distribution will be similar, and hence the distribution trend of pollutants.

The effects of a cold surface as well as a radiator (warm surface) should be mentioned. Cold surfaces induce downward air movement [88], and this effect was observed in the results of numerical simulations (Figures 19a-25a). The effect of a cold wall can be seen in all cases. Therefore, pollutants from the middle of the chamber were transported in the opposite direction from the cold wall. However, the effect of the heated dummy CBL was strong enough to entrain the pollutants and transport them to the higher level in all cases, with only a minor effect of the heated dummy position. In addition, numerical simulations revealed that in cases with radiator heating, the effect of a radiator as a warm surface appears. In buildings heated by radiator systems (especially with higher capacities), they can be the major sources of convection flows that can entrain pollutant from near-floor level pollution sources.

3.2. Results of statistical analysis of experimental data

The results of descriptive statistics for the relative VOC concentrations are presented in Tables 5, 6 and 7. For cases with warm air heating, the results are provided in Table 5, with radiator heating in Table 6 and underfloor heating in Table 7.

Mean and median parameters in the tables below present central tendency measures of relative concentrations. Standard deviation (SD) shows how relative concentrations are spread around the mean relative concentration value calculated for each parameter ($C_{1.1}$, C_{exp}, C_e), while min and max relative concentrations identifies lowest and highest relative concentrations in the data set. The range presents the interval that contains all relative concentrations. Skewness and kurtosis provide information about data normality. In addition, the main parameters (median, min, max) can be seen in the Figures 19b-24b.

Table 5. Results of descriptive statistics analysis for cases with warm air heating

Case [a)]	AH-GR-A			AH-GR-B			AH-GR-C		
Case number	1			4			7		
Relative concentration [b)]	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e
Mean (-)	0.49	0.80	0.65	0.68	0.86	0.67	0.77	0.91	0.87
SD (-)	0.02	0.07	0.02	0.03	0.04	0.02	0.02	0.03	0.04
Median (-)	0.48	0.79	0.65	0.68	0.86	0.67	0.77	0.90	0.88
Min (-)	0.46	0.64	0.59	0.61	0.71	0.63	0.72	0.83	0.78
Max (-)	0.56	1.00	0.71	0.79	1.00	0.72	0.82	1.00	0.95
Range (-)	0.10	0.36	0.12	0.18	0.29	0.09	0.10	0.17	0.17
Skewness	1.55	0.31	-0.04	0.10	0.12	-0.03	0.37	0.17	-0.34
Kurtosis	2.45	-0.32	-0.34	-0.07	0.68	-0.41	0.29	-0.04	-0.93
Case [a)]	AH-M4-A			AH-M4-B			AH-M4-C		
Case number	10			13			16		
Relative concentration [b)]	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e
Mean (-)	0.73	0.88	0.73	0.52	0.80	0.61	0.71	0.79	0.75
SD (-)	0.02	0.05	0.05	0.05	0.08	0.06	0.02	0.08	0.07
Median (-)	0.73	0.89	0.73	0.53	0.81	0.62	0.71	0.77	0.73
Min (-)	0.68	0.73	0.65	0.39	0.57	0.47	0.66	0.66	0.66
Max (-)	0.79	1.00	0.87	0.69	1.00	0.73	0.76	1.00	0.99
Range (-)	0.11	0.27	0.22	0.30	0.43	0.26	0.10	0.34	0.33
Skewness	-0.24	-0.65	0.30	-0.57	-0.67	-0.53	-0.34	0.52	1.27
Kurtosis	-0.64	-0.03	-1.06	0.65	0.43	-0.26	0.06	-0.48	1.06

a) AH – warm air heating; RH – radiator heating; FH – underfloor heating; GR – high-level wall grille; M4 – in-ceiling four-way diffuser; A, B, C – location of the heated dummy;

b) $C_{1.1}$ – relative concentration in occupied zone, C_{exp} – relative concentration in breathing zone, C_e – relative concentration in exhaust air.

In Table 5 it can be seen, that the mean in cases with GR for relative concentrations $C_{i,1.1}$ varies from 0.49 to 0.77, for C_{exp} from 0.80 to 0.91 and for C_e from 0.65 to 0.87. In cases with M4 mean relative concentrations, $C_{i,1.1}$ varies from 0.52 to 0.73, C_{exp} from 0.79 to 0.88 and C_e from 0.61 to 0.75. The standard deviation (SD) in all cases has quite low values and varies from 0.02 to 0.08. Medians of relative concentrations show similar results to mean. The range varies from 0.09 to 0.36 for the cases with GR and from 0.10 to 0.43 for the cases with M4. Less dispersion in the relative concentration is indicated by the range parameter. Skewness and kurtosis shows a tendency towards not normal distributed data.

Table 6. Results of descriptive statistics analysis for cases with radiator heating

Case [a]	RH-GR-A			RH-GR-B			RH-GR-C		
Case number	2			5			8		
Relative concentration [b]	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e
Mean (-)	0.72	0.94	0.68	0.81	0.91	0.78	0.59	0.89	0.79
SD (-)	0.02	0.06	0.04	0.03	0.04	0.03	0.04	0.08	0.07
Median (-)	0.72	0.96	0.69	0.80	0.91	0.78	0.59	0.91	0.81
Min (-)	0.68	0.78	0.58	0.76	0.82	0.70	0.53	0.68	0.63
Max (-)	0.77	1.00	0.74	0.88	1.00	0.83	0.65	1.00	0.89
Range (-)	0.09	0.22	0.15	0.12	0.18	0.13	0.12	0.32	0.26
Skewness	0.35	-1.26	-0.75	0.32	-0.25	-0.58	-0.08	-1.23	-1.01
Kurtosis	-0.86	0.42	-0.70	-0.80	-0.30	-0.44	-1.43	1.05	0.24
Case [a]	RH-M4-A			RH -M4-B			RH-M4-C		
Case number	11			14			17		
Relative concentration [b]	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e
Mean (-)	0.77	0.95	0.85	0.66	0.92	0.80	0.85	0.95	0.91
SD (-)	0.02	0.02	0.03	0.04	0.04	0.04	0.02	0.04	0.03
Median (-)	0.78	0.95	0.86	0.67	0.93	0.81	0.86	0.95	0.92
Min (-)	0.70	0.90	0.76	0.58	0.81	0.68	0.81	0.84	0.83
Max (-)	0.80	1.00	0.89	0.73	1.00	0.86	0.89	1.00	0.98
Range (-)	0.10	0.10	0.13	0.15	0.19	0.18	0.08	0.16	0.15
Skewness	-0.98	0.11	-1.01	-0.36	-0.80	-1.16	-0.33	-0.78	-0.23
Kurtosis	-0.23	-0.67	0.11	-1.22	0.07	1.01	-1.18	-0.19	-1.07

a) b) – similar to Table 5.

In Table 6 it can be seen, that the mean in cases with GR for relative concentrations $C_{i,1.1}$ varies from 0.59 to 0.81, for C_{exp} from 0.89 to 0.94 and for C_e from 0.68 to 0.79. In cases with M4, mean relative concentrations for $C_{i,1.1}$ varies from 0.66 to 0.85, C_{exp} from 0.92 to 0.95 and C_e from 0.80 to 0.91. The standard deviation (SD) in all cases have quite low values and varies from 0.02 to 0.08; as for the cases with warm air heating. Medians of relative concentrations show similar results. The range varies from 0.09 to 0.32 for the cases with GR and from 0.08 to 0.19 for the cases with M4. Less dispersion in the relative concentration is indicated by the range parameter, as well as for the cases with warm air heating. Skewness and kurtosis shows a tendency towards not normal distributed data.

Table 7. Results of descriptive statistics analysis for cases with underfloor heating

Case [a)]	FH-GR-A			FH-GR-B			FH-GR-C		
Case number	3			6			9		
Relative concentration [b)]	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e
Mean (-)	0.72	0.71	0.86	0.82	0.82	0.76	0.71	0.77	0.80
SD (-)	0.05	0.06	0.09	0.08	0.05	0.05	0.04	0.07	0.06
Median (-)	0.74	0.72	0.89	0.85	0.82	0.77	0.72	0.76	0.81
Min (-)	0.59	0.59	0.59	0.64	0.66	0.64	0.62	0.62	0.62
Max (-)	0.81	0.84	1.00	0.99	1.00	0.94	0.80	1.00	0.91
Range (-)	0.22	0.25	0.41	0.35	0.34	0.29	0.18	0.38	0.30
Skewness	-0.71	-0.25	-1.69	-0.84	-0.18	-0.51	-0.41	0.19	-1.49
Kurtosis	-0.73	-0.79	2.00	-0.51	0.85	0.73	-0.77	-0.26	1.94
Case [a)]	FH-M4-A			FH-M4-B			FH-M4-C		
Case number	12			15			18		
Relative concentration [b)]	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e	$C_{i,1.1}$	C_{exp}	C_e
Mean (-)	0.87	0.78	0.81	0.75	0.70	0.86	0.70	0.71	0.88
SD (-)	0.07	0.06	0.06	0.05	0.04	0.07	0.03	0.05	0.04
Median (-)	0.88	0.78	0.80	0.75	0.69	0.86	0.71	0.72	0.88
Min (-)	0.66	0.68	0.66	0.64	0.63	0.64	0.59	0.59	0.64
Max (-)	1.00	0.97	0.96	0.86	0.90	1.00	0.77	0.80	1.00
Range (-)	0.34	0.29	0.29	0.22	0.27	0.36	0.18	0.21	0.36
Skewness	-1.11	0.43	0.16	-0.20	1.06	-0.79	-1.07	-0.62	-1.40
Kurtosis	0.71	-0.20	-1.02	-0.58	1.22	1.29	0.58	-0.28	5.35

a) b) – similar to Table 5.

In Table 7 it can be seen that the mean in cases with GR for relative concentrations $C_{i,1.1}$ varies from 0.71 to 0.82, for C_{exp} from 0.71 to 0.82 and for C_e from 0.76 to 0.86. In cases with M4, mean relative concentrations for $C_{i,1.1}$ varies from 0.70 to 0.87, C_{exp} from 0.70 to 0.78 and C_e from 0.81 to 0.88. The standard deviation (SD) in all cases has quite low values and varies from 0.03 to 0.09, as for the cases with warm air heating and radiator heating. Medians of relative concentrations show similar results. The range varies from 0.18 to 0.38 for the cases with GR and from 0.18 to 0.36 for the cases with M4. Less dispersion in the relative concentration is indicated by the range parameter, as well as for the cases with warm air heating and radiator heating. Skewness and kurtosis shows a tendency towards not normal distributed data.

As it was mentioned in the methods section, the normality of relative concentrations distribution was tested additionally with the Shapiro-Wilk test. The Shapiro-Wilk null hypothesis was rejected in all cases; therefore, the alternative hypothesis was chosen, which identified that the measured values are not normally distributed (p-value < 0.001). A small p-value obtained from the Shapiro-Wilk test indicated that there is strong evidence against the null hypothesis.

The Kruskal-Wallis test was used to compare the relative concentration groups between themselves. For example, mean relative concentrations C_{exp} from the case with underfloor heating, thermal dummy in position A and air supply through high-level wall grille was compared with mean relative concentrations (C_e, $C_{i,1.1}$) from the same experiment, as well as with all parameters from other experiments. By performing this test, it was expected to find out whether the relative concentration in the occupant breathing zone (C_{exp}) differs statistically in cases with different heating systems and air supply patterns. This was done by rejecting the null hypothesis (H_0) formulated for the Kruskal-Wallis test and accepting the alternative hypothesis (H_A) which stated that there is a difference between the mean relative concentrations from different experiments. The analysis showed that there is a significant difference between concentrations in the occupant breathing zone (C_{exp}) with different heating systems and air supply patterns (p-value > 0.05). Significantly, similar concentrations were only found in a few cases comparing mean relative concentrations in exhaust air (C_e) and occupied zone ($C_{i,1.1}$) (p-value < 0.05). However, relative concentrations C_e, $C_{i,1.1}$ were not a target in this comparison.

3.3. Validation of CFD models

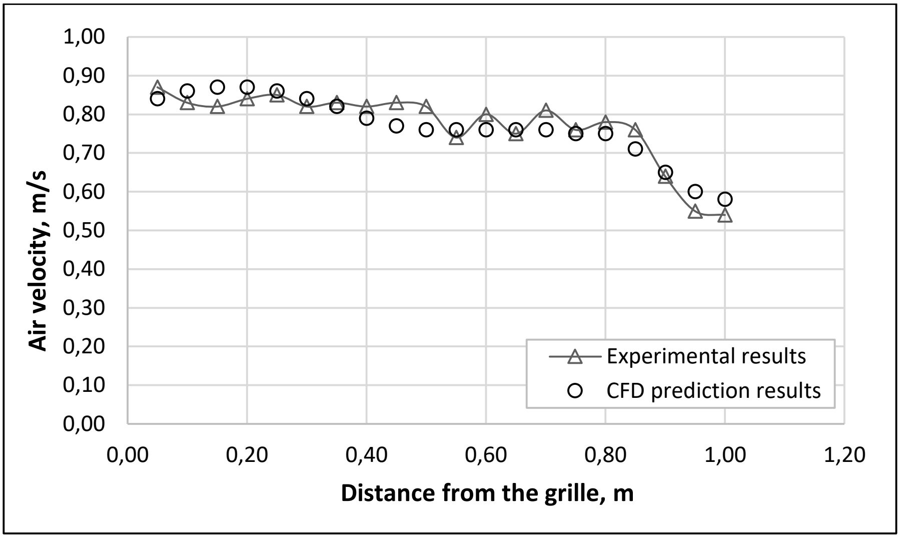
This chapter presents the comparison of experimental and numerical results to validate the CFD models of different cases. Numerical results are presented as values from steady-state simulations while experimental results are average values.

3.1.1. Airflow patterns

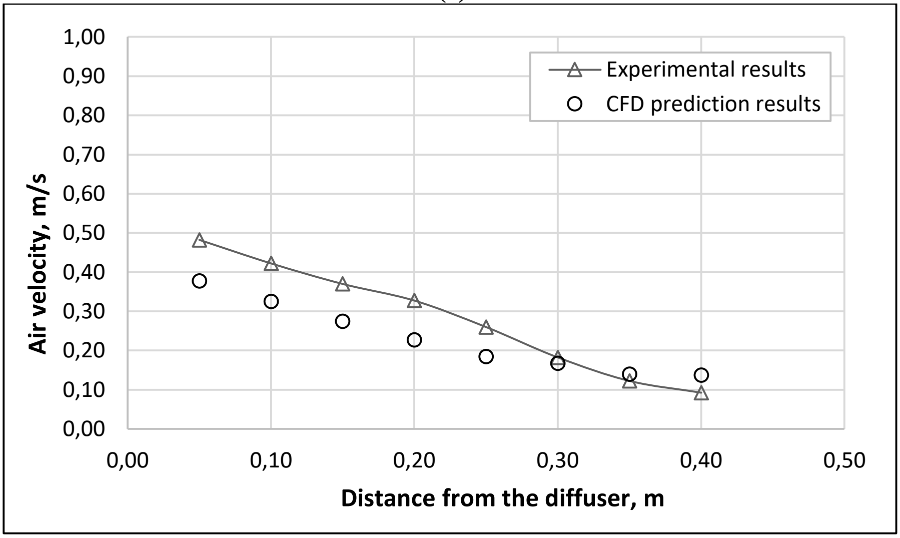
Air velocities in the supply air jet obtained in experiments and numerical predictions were compared for the cases with radiator heating and thermal dummy in position B. The results of this comparison are presented in Figure 32. Results from experiments are presented as mean values obtained within 15 seconds of measurement; while numerical results are values from steady-state simulations.

Figure 32a shows velocity values from experiments and numerical simulations along with a horizontal line at 2.66m from the floor at the centre of the grille. The velocity decreased from 0.86m/s to 0.55m/s on average at the distance of one meter from the grille. The results from numerical simulations were in good agreement with the velocity values obtained from the experiment; the maximum difference was 0.06m/s. The relative percentage error did not exceed ±10%, which is similar to the confidence interval selected by Zhang and Chen [144]. The relative percentage error was in a range from 1.18 to 9.09%. The average relative percentage error was 4.24%.

Figure 32b shows the average velocity values from the in-ceiling diffuser along with a horizontal line at 0.01m from the ceiling at the centre of each side of the diffuser. The velocity decreased from 0.43m/s to 0.12m/s on average at the distance of 0.4m from the diffuser. The average relative percentage error was 25.13%. There are many boundary conditions that can affect this discrepancy, e.g. changing direction of air velocity, measurement at the exact same point, accuracy of “Box method used to create diffusers in CFD model etc. Similar differences were reported by Villafruella et al. [143]; in the experiment with a four-way multi-cone diffuser, the difference of 30% was obtained between experimental and numerical results.



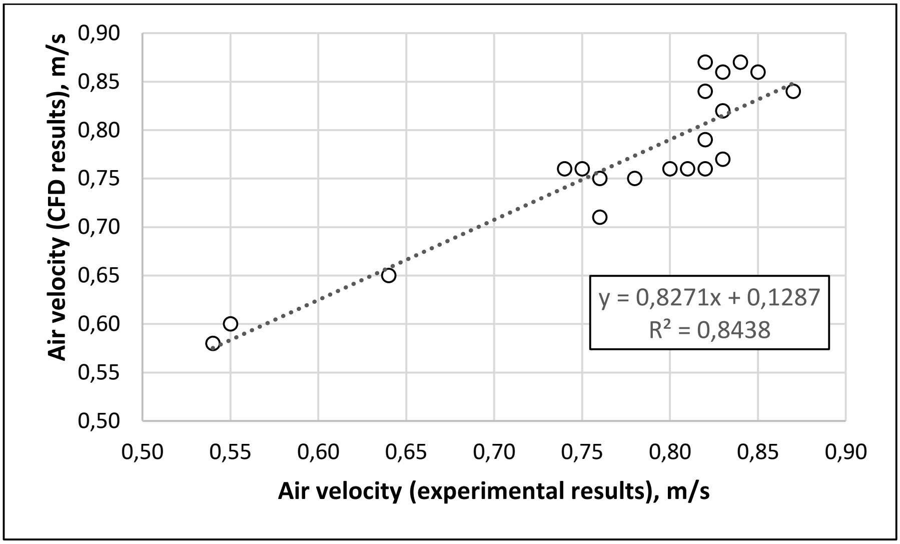
(a)



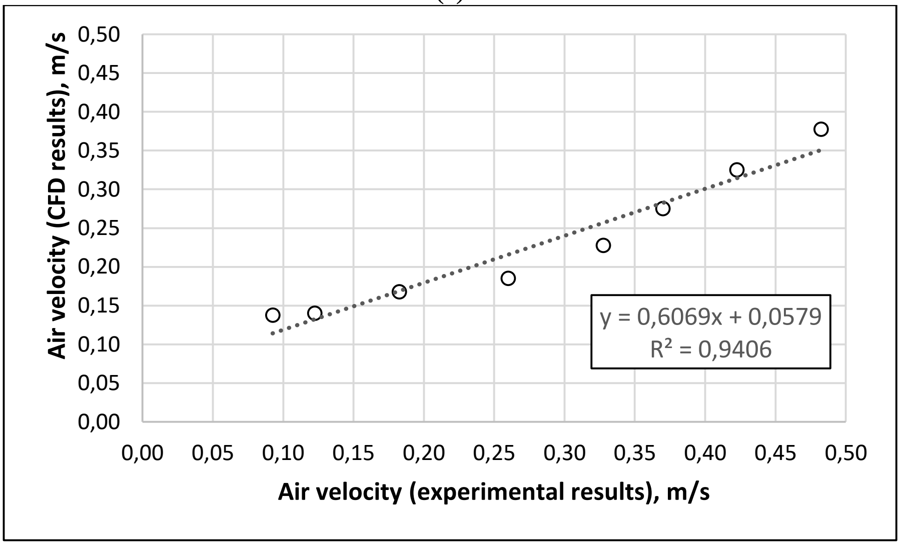
(b)

Figure 32. Experimental and numerical air velocity values in cases with radiator heating and thermal dummy in position B generated by: (a) wall grille along a horizontal line at 2.66m from the floor at the centre of the grille; (b) four-way in-ceiling diffuser along a horizontal line at 0.01m from the ceiling at the centre of each side of diffuser

The results of linear regression analysis are presented in Figure 33. The correlation coefficient (R^2) and the scatter plots presented in Figure 33 indicate a strong (positive) linear relationship between results obtained in the experiment and CFD simulations ($R^2 > 0.8$).



(a)



(b)

Figure 33. Linear regression model for air velocities in cases with radiator heating and thermal dummy in position B generated by: (a) wall grille; (b) four-way in-ceiling diffuser

3.1.2. Temperature gradients in the chamber

The vertical air temperature distribution obtained in experiments and numerical predictions were compared for the cases with high-level wall grille air supply, heated dummy in position C and different heating types (AH, RH, FH). The results of this comparison are presented in Figure 34. Results from experiments are presented as mean values within 20 minutes of measurement, while numerical results are values from steady-state simulations.

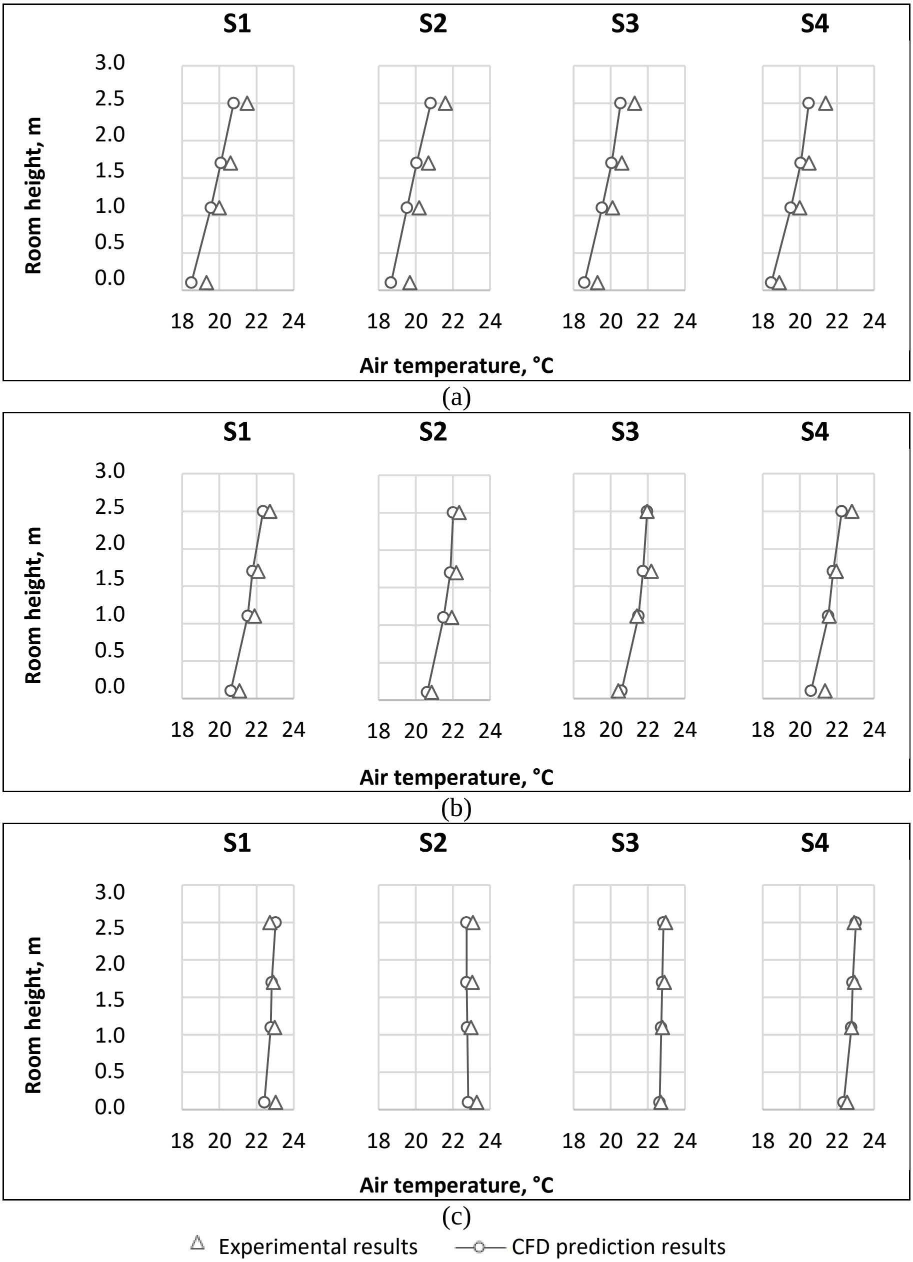


Figure 34. Comparison between measured and simulated air temperatures in four locations at four heights (0.1, 1.1, 1.7 and 2.5m above the floor) for the cases with high-level air supply grille, thermal dummy in position C and warm air heating (a), radiator heating (b), underfloor heating (c)

The vertical air temperature gradient for the case with warm air heating (Figure 34a) was 0.91 °C/m on average, which is typical for warm air heating systems [90]. The results from numerical simulations were in good agreement with the temperature values obtained from the experiment; the average difference was 0.66 °C for the case presented in Figure 34a. For other cases, the difference was in the range of 0.07 and 1.18 °C. Relative percentage error for the case presented in Figure 34a was 3.22% on average, for other cases it varied from 0.37 to 6.09%.

The vertical air temperature gradient for the case with radiator heating (Figure 25b) was 0.64 °C/m. The average difference between the measured and simulated temperatures for this case was 0.28 °C. For other cases with radiator heating, it varied from 0.25 to 0.59 °C. Relative percentage error for the case presented in Figure 34b was 1.29 % on average, for other cases it was in the range between 1.17 and 2.66%.

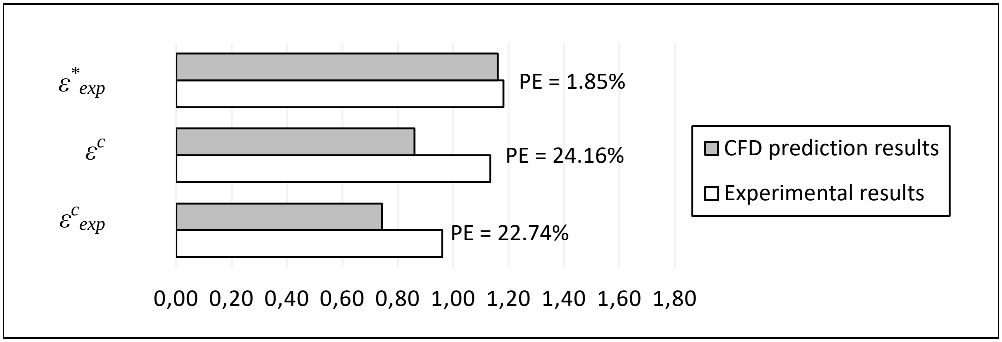
For the case of underfloor heating (Figure 34c), temperature distribution along room height was uniform, vertical air temperature gradient was 0.12 °C/m on average. The results from numerical simulations and experiments were in good agreement; the average difference was 0.16 °C. For other cases with underfloor heating, the average difference between the measured and simulated values was in the range from 0.15 to 0.71 °C. Relative percentage error for the case presented in Figure 34c was 0.70%, for other cases it varied from 0.67 to 3.15%.

It can be concluded that simulated temperature values agreed well with measured values, the relative percentage error did not exceed 6%. Similar differences were obtained by Zhang and Chen [144] and He et al. [145], although the authors did not report the exact values, the figures presented in their publication show a similar level of agreement.

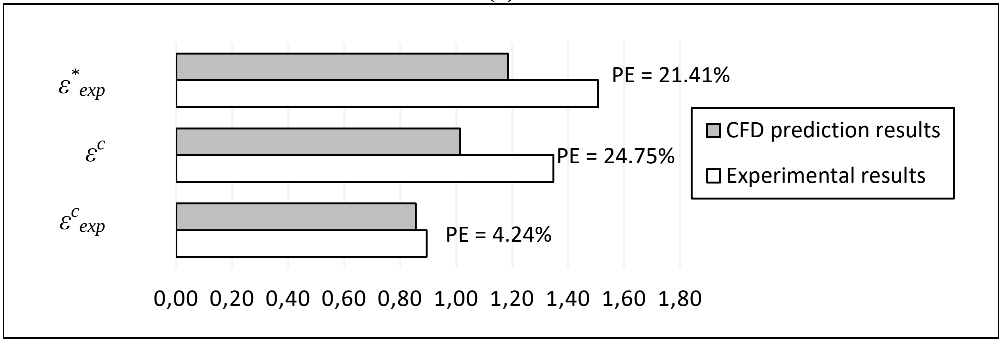
3.1.3. Ventilation effectiveness and personal exposure indices

Comparisons between indices calculated by using concentrations from experimental and numerical results are presented in Figure 35. The relative percentage error can also be seen in the figures. It was selected to present the comparison between cases with different heating types but with the same air supply pattern and thermal dummy position. Ventilation effectiveness and two personal exposure indices were calculated by using VOC concentration values obtained from experiments (mean values within 20 minutes of measurement) and numerical simulations (steady-state conditions).

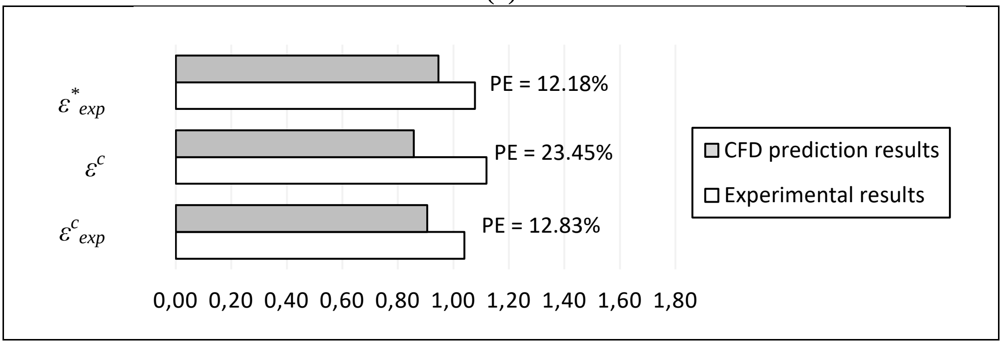
The relative percentage error of ventilation effectiveness for all cases with warm air heating varied from 3.01 to 33.68%, for cases with radiator heating from 0.47 to 24.75% and for cases with underfloor heating from 6.90 to 23.45%. Personal exposure index ε^{c}_{exp} differed from 10.82 to 25.07% in cases with warm air heating, from 0.97 to 32.46% in cases with radiator heating and from 2.78 to 29.68% in cases with underfloor heating. The relative percentage error of the second personal exposure index ε^{*}_{exp} was in the range between 1.42 and 42.45% in cases with warm air heating, between 9.13 and 44.43% in the case of radiator heating and between 1.10 and 27.86% in cases with underfloor heating.



(a)



(b)



(c)

Figure 35. Comparison between measured and simulated ventilation effectiveness and personal exposure indices for the cases with high-level air supply grilles, thermal dummy in position C and warm air heating (a), radiator heating (b), underfloor heating (c). PE – relative percentage error, %

3.4. Analysis of factors affecting air quality experienced by occupant

Since the accuracy of the CFD model appeared acceptable (relative percentage error < 30%) [147], this method was further used to analyse the impacts of several factors on air quality experienced by the occupant.

Three factors that might have an impact on pollutant transportation to an occupant breathing level were studied by means of CFD. The effects of air change rate, chamber height and size of air quality experienced by the occupant were evaluated. When evaluating the effect of each factor, only the factor value was changed in CFD models. All other boundary conditions were kept the same. Since the effect of pollutant transportation by CBL into the breathing level was present in almost all cases, the models with only one location of the heated dummy (location B) were selected for analysis of factors. Both air distribution schemes, as well as all heating systems, were included in the analysis. The ventilation effectiveness, ε^c, and personal exposure indices, ε^c_{exp}, ε^*_{exp}, were calculated for all analysed cases. The effect of each factor will be discussed in the following subsections.

3.4.1. Effect of air change rate

Evaluating the effect of air change rate, supplied and exhaust airflow rates were increased gradually from 72 to 126m³/h, ensuring that air change rates were from 2.0 to 3.5h^{-1}. Higher airflow rates resulted in higher supplied air velocity and momentum, as well as higher air velocities in the occupied zone and more intense air mixing in the chamber.

Table 8 shows that ventilation effectiveness (ε^c) ratios varied within a small range and were roughly equal to 1.0 in all cases. It was observed that the trend of higher ventilation effectiveness when in-ceiling four-way air supply diffusers were used stays when increasing air change rate in the chamber.

Table 8. Ventilation effectiveness index for the cases with different air change rate and with the heated dummy in position B

Air distribution scheme [a)]	Heating system [b)]	Air change rate, h^{-1}			
		2.0 [c)]	2.5	3.0	3.5
GR	AH	0.95	1.00	1.00	0.97
	RH	0.97	0.98	0.98	0.96
	FH	1.09	0.92	0.97	1.08
M4	AH	1.01	0.99	0.99	0.97
	RH	1.02	1.02	1.02	1.01
	FH	1.02	1.03	1.10	1.05

a) GR – high-level wall grille; M4 – in-ceiling four-way diffusers;
b) AH – warm air heating; FH – underfloor heating; RH – radiator heating;
c) 2.0 h^{-1} – initial air change rate.

Personal exposure indices for the cases with different air change rates are presented in Table 9. In the case of warm air heating and high-level wall grille air supply, personal exposure index ε^c_{exp} increased from 0.58 to 1.00, while personal exposure index ε^*_{exp} decreased from 1.63 to 0.98. This means that air quality experienced by the occupant, in this case, was higher when more air was supplied, and higher velocities in the occupied zone were ensured. In other cases, personal exposure indices varied in a small range.

Table 9. Personal exposure indices for the cases with different air change rate and with the heated dummy in position B

Air distribution scheme [a)]	Heating system [b)]	Air change rate, h^{-1}							
		Personal exposure index (exhaust to inhaled) ε^{c}_{exp}				Personal exposure index (inhaled to ambient) ε^{*}_{exp}			
		2.0 [c)]	2.5	3.0	3.5	2.0 [c)]	2.5	3.0	3.5
GR	AH	0.58	0.85	1.00	1.00	1.63	1.18	1.00	0.98
	RH	0.59	0.59	0.76	0.75	1.63	1.67	1.29	1.28
	FH	1.06	0.91	0.92	1.08	1.02	1.01	1.05	1.01
M4	AH	0.57	0.58	0.57	0.55	1.75	1.71	1.72	1.76
	RH	0.90	0.83	0.80	0.78	1.13	1.22	1.27	1.29
	FH	0.86	0.84	0.93	1.01	1.19	1.23	1.18	1.04

a) b) c) – similar to Table 8.

3.4.2. Effect of chamber height

Evaluating the effect of chamber height, the ceiling of the test chamber together with air supply and exhaust terminals were raised in CFD models. Three height steps of 0.4m were tested. By raising the ceiling, the volume of the chamber increased. Therefore, the airflow rates of supply and exhaust units were increased to have the same air change rate of $2.0h^{-1}$. The height of the chamber affects the vertical temperature gradient, and this effect might have an impact on pollutant distribution.

The ratio of ventilation effectiveness fluctuated around 1.0 in all cases (Table 10) and was higher in cases with in-ceiling four-way air supply diffusers.

Table 10. Ventilation effectiveness index for the cases with different chamber heights and with the heated dummy in position B

Air distribution scheme [a)]	Heating system [b)]	Chamber height, m			
		2.8 [d)]	3.2	3.6	4.0
GR	AH	0.95	0.94	0.93	0.94
	RH	0.97	0.97	0.98	0.95
	FH	1.09	1.07	1.12	1.12
M4	AH	1.01	0.97	0.96	0.93
	RH	1.02	1.01	1.00	1.01
	FH	1.02	1.03	1.07	1.06

a) b) – similar to Table 8;
a) 2.8m – initial height of the chamber.

Personal exposure indices for the cases with different chamber heights are presented in Table 11. It was observed that chamber height affected occupant exposure to pollutants in cases with warm air heating. Personal exposure index ε^{c}_{exp} decreased from 0.58 to 0.47 with the increased chamber height, while ε^{*}_{exp} increased from 1.63 to 1.98 in cases with wall grille air supply. The same trend was observed in cases with in-ceiling four-way diffusers. This reduction in air quality experienced by the occupant might be affected by a vertical temperature gradient, which was higher in cases with a higher ceiling. Personal exposure indices in cases with radiator heating varied fractionally; however, air quality experienced by the occupant was higher with in-ceiling four-way diffusers. The opposite effect was noticed in cases with underfloor heating; lower pollutant concentrations were found in the breathing zone in cases with wall grille air supply. Therefore, higher personal ε^{c}_{exp} values were calculated.

Table 11. Personal exposure indices for the cases with different chamber heights and with the heated dummy in position B

Air distribution scheme [a)]	Heating system [b)]	Chamber height, m							
		Personal exposure index (exhaust to inhaled) ε^{c}_{exp}				Personal exposure index (inhaled to ambient) ε^{*}_{exp}			
		2.8 [d)]	3.2	3.6	4.0	2.8 [d)]	3.2	3.6	4.0
GR	AH	0.58	0.53	0.49	0.47	1.63	1.79	1.92	1.98
	RH	0.59	0.59	0.58	0.62	1.63	1.64	1.68	1.54
	FH	1.09	1.07	1.12	1.12	1.02	1.01	1.01	1.01
M4	AH	0.57	0.56	0.52	0.45	1.75	1.74	1.83	2.06
	RH	0.90	0.85	0.95	0.83	1.13	1.19	1.05	1.21
	FH	0.86	0.84	0.67	0.72	1.19	1.22	1.59	1.47

a) b) d) – similar to Table 10.

3.4.3. Effect of chamber size

To evaluate the effect of chamber size to pollutants concentration in the breathing zone, chamber dimensions were changed gradually in CFD models. Five different sizes of chamber were simulated. By changing the size of the chamber, the volume of the chamber increased. Therefore, the airflow rates of supply and exhaust units were increased to have the same air change rate of 2.0h^{-1}. Furthermore, increasing the test chamber size equally to all sides in relation to pollutant location, resulted in the increase of the distance between a pollution source and heated dummy. The effect on the heated dummy decreases, as supply and exhaust airflows increase proportionally to the chamber volume, while convective airflow of the dummy stays the same.

The ventilation effectiveness ratios calculated for all analysed cases are presented in Table 12. As for all previous cases, the ratio of ventilation effectiveness fluctuated around 1.0 in all cases and was slightly higher in cases with in-ceiling four-way air supply diffusers.

Personal exposure indices (ε^{c}_{exp}) and (ε^{*}_{exp}) are presented in Table 13 and 14, respectively. The results of chamber size impact on pollutant distribution show that increasing the size of the chamber, personal exposure index (ε^{c}_{exp}) values impend to 1.00 with one exception; the case of warm air heating and air supply through in-ceiling four-way diffusers. The values of personal exposure index (ε^{*}_{exp}) presented in Table

14, show a similar trend of impending to 1.00. This trend means that the effect of pollutant transportation to the breathing level by occupant CBL disappears.

Table 12. Ventilation effectiveness index for the cases with different chamber sizes and with the heated dummy in position B

Air distribution scheme a)	Heating system b)	Chamber size e), %					
		-25	0	+25	+50	+75	+100
GR	AH	0.96	0.95	0.94	0.93	0.96	0.97
	RH	0.98	0.97	0.90	1.02	1.04	1.02
	FH	1.15	1.09	0.97	1.01	0.99	0.99
M4	AH	1.09	1.01	1.02	0.93	0.99	0.95
	RH	1.09	1.02	1.00	0.98	0.94	1.00
	FH	1.05	1.02	1.05	1.04	1.11	1.07

a) b) – similar to Table 8;

e) Percentage shows how much dimensions of the chamber were changed from the initial dimensions. 0% - refers to the chamber with initial dimensions.

Table 13. Personal exposure index (εcexp) for the cases with different chamber sizes and with the heated dummy in position B

Air distribution scheme a)	Heating system b)	Chamber size e), %					
		-25	0	+25	+50	+75	+100
GR	AH	0.72	0.58	0.96	0.97	1.00	0.99
	RH	0.76	0.59	0.89	1.01	1.05	1.02
	FH	0.85	1.06	1.02	1.02	0.99	1.00
M4	AH	0.71	0.57	0.71	0.67	0.63	0.98
	RH	0.93	0.90	0.95	0.99	0.94	1.00
	FH	0.79	0.86	0.69	0.98	1.00	1.09

a) b) e) – similar to Table 12.

Table 14. Personal exposure index (ε*exp) for the cases with different chamber sizes and with the heated dummy in position B

Air distribution scheme a)	Heating system b)	Chamber size e), %					
		-25	0	+25	+50	+75	+100
GR	AH	1.34	1.63	0.98	0.96	0.96	0.98
	RH	1.29	1.63	1.02	1.01	0.99	1.01
	FH	1.36	1.02	0.95	1.00	0.99	0.99
M4	AH	1.55	1.75	1.45	1.38	1.57	0.97
	RH	1.17	1.13	1.04	0.99	1.00	1.00
	FH	1.32	1.19	1.53	1.06	1.11	0.98

a) b) e) – similar to Table 12.

Additionally, the results from numerical simulations are presented in Figures 36 and 37. Figures provide the sections of the CFD models at the height of 0.1m above the floor. Figure 36 presents results for the cases with wall grille air supply, while Figure 37 presents results for the cases with in-ceiling four-way diffusers. From the results presented in the figures, as well as in the tables, it can be seen that in cases with wall grille air supply the effect of pollutant transportation to the breathing level by occupant CBL disappears when the distance is shorter (the size of the chamber is approx. 50% larger) compared with cases with in-ceiling four-way air supply diffusers.

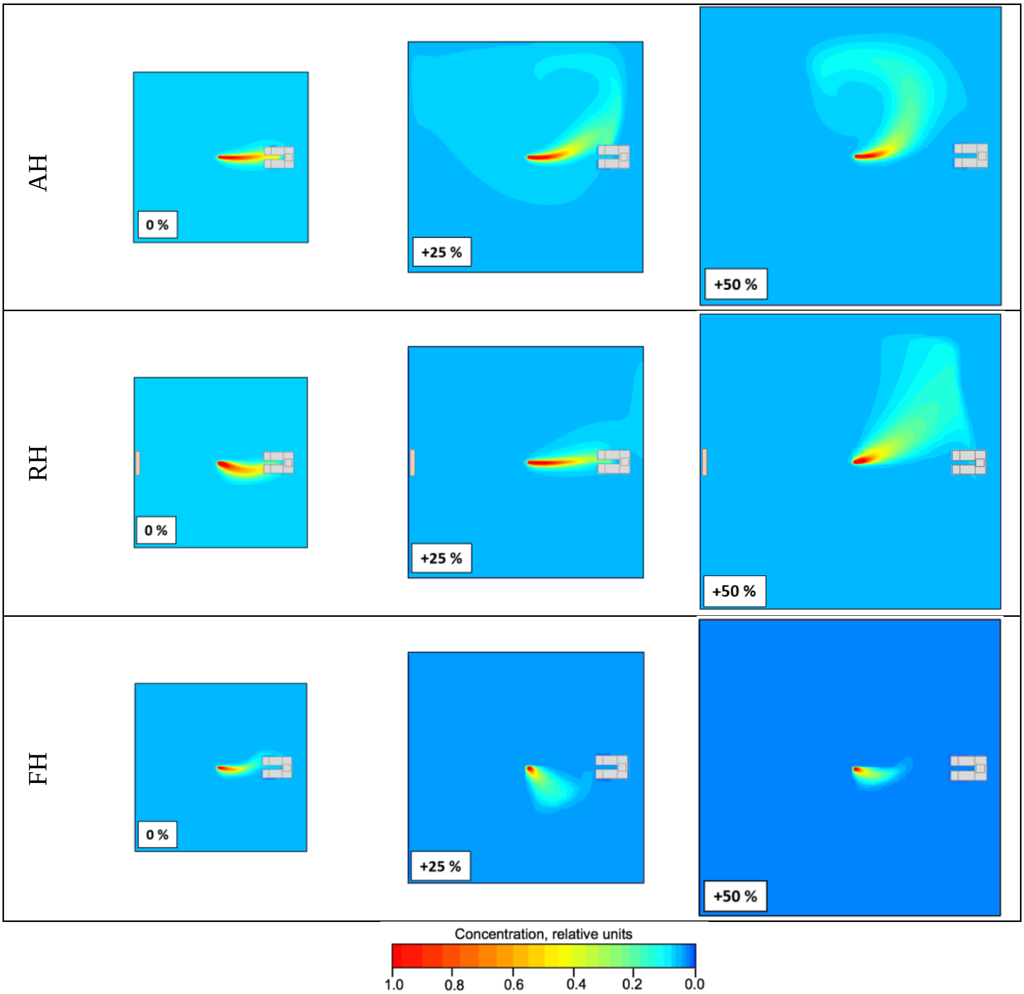


Figure 36. Personal exposure indices for the cases with high-level wall grille air supply, thermal dummy in position B, different heating systems and different sizes of the chamber

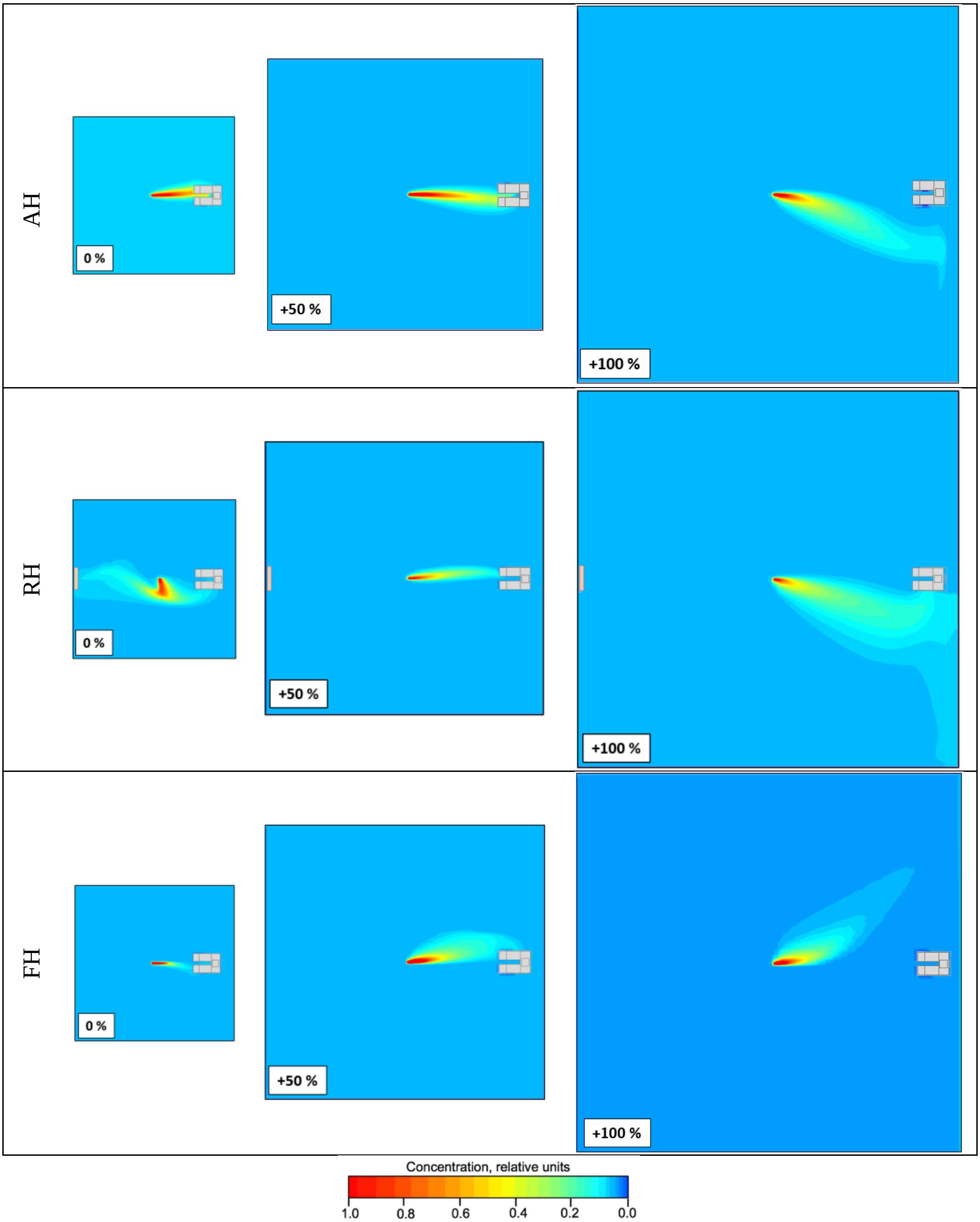


Figure 37. Personal exposure indices for the cases with in-ceiling four-way air supply diffusers, thermal dummy in position B, different heating systems and different sizes of the chamber

4. CONCLUSIONS

Dispersion of volatile organic compounds released at near-floor level in an indoor environment chamber under different combinations of heating systems and air distribution schemes was investigated in this research. Experiments in a full-scale chamber, as well as numerical simulations by means of computational fluid dynamics, were performed. The effects of three heating systems (warm air heating, radiator heating, underfloor heating) and two air distribution schemes (air supply through high-level wall grille and in-ceiling four-way diffusers) were studied. Air quality experienced by the occupant was evaluated, calculating personal exposure indices: ε^{c}_{exp} (exhaust to inhaled) and ε^{*}_{exp} (inhaled to ambient). The results of this research revealed the following:

1. Experiments under laboratory conditions have shown that pollutant entrainment into the human convective boundary layer depends on the heating system type and air distribution scheme. At air change rate $2h^{-1}$, this phenomenon appears to be significantly weaker with underfloor heating ($P < 0.05$). Relative pollutant concentrations in the occupant breathing zone are lower with underfloor heating by 12% and 24% compared to warm air heating and radiator heating, respectively.
2. CFD analysis has shown that pollutants are transported in an opposite direction from the cooled wall. Nevertheless, their path drifts towards the dummy with a minor influence of the heated dummy position.
3. With the accuracy of the numerical model at an acceptable level (relative percentage error < 30%) it can be concluded that the increase in air change rate has a minor influence on air quality in the breathing zone, while increased chamber volume and distance between pollutant and occupant decreases the effect of the human convective boundary layer; resulting in higher air quality in the breathing zone.
4. It was determined that a combination of heating and air distribution schemes should be carefully considered in cases where sedentary activities are carried out in buildings and the presence of near-floor level emitted pollutants cannot be avoided. The focus should be on the heating system type, as the effect of air distribution is comparatively minor. Entrainment of such pollutants into the convective boundary layer is less intense with underfloor heating compared to warm air and radiator heating, especially if the distance between the source and the occupant increases.

5. FUTURE WORK

This research focused on finding the possible dispersion paths of pollutants emitted at near-floor level only on mixing ventilation combined with different types of heating. Displacement ventilation was not analysed because it is not suitable for air heating. Furthermore, displacement ventilation ensures a higher pollutant removal effectiveness in cases when warm air pollution sources are present (e.g. occupants that produce products of metabolism as pollution) [105]. However, dispersion of pollutants emitted at near-floor level under displacement ventilation combined with heating or radiator heating could be a future direction in continuing this research.

It should be emphasized that ventilation of the chamber was ensured by both air supply and exhaust air terminals. This is usually the case in office buildings, where supply and exhaust air terminals are designed on the same premise. In addition, air change rate selected for experiments was $2h^{-1}$. Although it was found (by means of CFD simulations and in previous study experimentally [148]) that the increase of air change rate has a minor effect on pollutant dispersion, an air change rate of $2h^{-1}$ is more related with an office environment. In residential buildings, cross ventilation with lower air change rates is commonly used; where air is delivered to less polluted rooms, such as living rooms or bedrooms and exhausted from more polluted rooms (kitchens, toilets, pantries etc.). Therefore, further studies might investigate the applicability of results for cases with lower air change rates and air supply and exhaust terminals in different rooms.

Finally, experiments were performed without furniture. It is recommended to study effects of furniture in the future, as this affects flows in rooms and the convective boundary layer around the occupant [102, 104]. Additionally, furniture is one of the major sources of volatile organic compounds [24].

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LIST OF PUBLICATIONS

This dissertation was compiled partly based on the data presented in the following peer-reviewed journal articles:

I. Jurelionis, Andrius; **Stasiuliene, Laura**; Prasauskas, Tadas; Martuzevicius, Dainius. Dispersion of indoor air pollutants emitted at near-floor levels in rooms with floor heating and mixing ventilation // Indoor and built environment. London: Sage Publications. ISSN 1420-326X. 2017, vol. 26, iss. 00, p. [1-14]. [Science Citation Index Expanded (Web of Science); Scopus; Environment Complete; Academic OneFile]. [IF: 0,943; AIF: 2,733; IF/AIF: 0,345; Q3; 2015 Journal Citation Reports® Science Edition (Thomson Reuters, 2017)].

II. Jurelionis, Andrius; **Gagyte, Laura**; Šeduikytė, Lina; Prasauskas, Tadas; Čiužas, Darius; Martuzevicius, Dainius. Combined air heating and ventilation increases risk of personal exposure to airborne pollutants released at the floor level // Energy and buildings. Lausanne: Elsevier. ISSN 0378-7788. 2016, vol. 116, p. 263-273. [Science Citation Index Expanded (Web of Science); Science Direct; Academic Search Complete; Academic Search Elite; Academic Search Premier; Academic Search Research & Development; Environment Complete]. [IF: 2,973; AIF: 2,666; IF/AIF: 1,115; Q1; 2015 Journal Citation Reports® Science Edition (Thomson Reuters, 2017)].

And on the following peer-reviewed conference publications:

III. **Gagytė, Laura**; Jurelionis, Andrius; Martuzevičius, Dainius; Prasauskas, Tadas. Experimental study of personal exposure to pollutants released at floor level: floor heating vs air heating // Indoor Air 2016: the 14th International Conference on Indoor Air Quality and Climate, 3-8 July 2016, Ghent, Belgium. Ghent: ISIAQ, 2016. p. [1-8].

IV. **Stasiuliene, Laura**; Jurelionis, Andrius. Dispersion of pollutants released at floor level under three types of heating systems: A CFD study. // Healthy Buildings Europe 2017: the 2nd International Conference on Healthy Building in Europe, 2-5 July 2017, Lublin, Poland. Lublin: ISIAQ, 2017. P0188.

AUTHOR'S CONTRIBUTION TO THE PUBLICATIONS

Publications I and II were written in cooperation with the co-authors. The author is the main author of publications III and IV. All experiments and analysis of measured data in all publications were carried out by the author of this dissertation. CFD modelling in publication IV was performed by the author. The methods part in all publications was developed by the author of this dissertation and her supervisor.

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