Trends in Pollutant Accumulations in Energy-Efficient Residential Buildings

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Improving the energy efficiency of buildings is a major target in developed countries toward decreasing their energy consumption and CO2 emissions. To meet this target, a large number of countries have established energy codes that require buildings to be airtight. While such a retrofitting approach has improved health outcomes in areas with heavy traffic, it has worsened the health outcomes in Nordic countries and increased the risk of lung cancer in areas with high levels of radon emissions. The implementation of mechanical ventilation in new energy-efficient buildings has solved some of these problems; however, for others, a decrease in the level of outdoor pollutants was still required in order to achieve a good indoor air quality. A good balance between the air exchange rate and the air humidity level (adapted to the location) is key to ensuring that exposure to the various pollutants that accumulate inside energy-efficient buildings is low enough to avoid affecting inhabitants′ health. Evidence of the protective effect of mechanical ventilation should be sought in dwellings where natural ventilation allows pollutants to accumulate to threatening levels.

indoor air quality | natural ventilation | mechanical ventilation | energy-efficient homes

1. Pollutants Studied in Residential Energy-Efficient Buildings after 2010

$PM_{2.5}$ was the most frequently monitored pollutant, with a wide geographical distribution—four studies were run in the USA, two in South Korea, four in different European countries (France, Italy, Finland, and Lithuania). Radon was monitored in eight studies—seven in different European countries and one in the USA. The VOCs were quantified in eight studies—five in European countries (France, Austria, and Switzerland), two in the USA, and one in South Korea. Formaldehyde was monitored in the largest number of countries: the USA (3 studies), the United Arab Emirates (1 study), South Korea (1 study), China (1 study), Austria (1 study), and France (1 study). NO_2 levels in indoor air were monitored in only four studies—two in the USA and two European (one in a French building stock, and one in Finnish and Lithuanian stocks). Ozone was quantified in indoor air in only one study that compared a Finnish and a Lithuanian stock of dwellings. Concentrations of fungal spores were reported in five studies, all European (Austria, France, and Switzerland). The relative humidity of the air was also studied in two Asiatic countries (Bahrain and South Korea).

2. Efficiency of Energy-Efficient Buildings to Limit Outdoor Pollutant Infiltration

In indoor environments, concentrations of pollutants originating from outdoor air are influenced by their outdoor spatiotemporal patterns of concentration and by the proximity of the building to outdoor sources (e.g., roads with heavy traffic). While indoor pollution concentrations depend on the amount of air pollution penetrating from outdoors, they also depend on the efficiency of the ventilation and, for gaseous air pollutants, on the reaction rates with indoor surfaces. Thus, air pollutants with a lower penetration factor such as $PM_{2.5}$ remain suspended indoors longer than gases such as O_3, which has a high reaction rate with indoor surfaces [1]. While the role of these different factors has been compared between conventional, retrofitted, and new energy-efficient buildings in different countries on different continents [2][3][4][5][6], the health issues related to modulating the concentration of some of these pollutants has rarely been addressed.

2.1. Efficiency of Energy-Efficient Buildings to Limit Radon Accumulation Indoors

Radon is a radioactive gas naturally emitted by soils at variable concentrations depending upon the topography and soil structure. For example, Germany, Poland, the Netherlands, most French regions, and the UK have lower levels of radon emissions, on average, than Austria, Finland, Sweden, Switzerland, or the Czech Republic. This pollutant infiltrates indoors and can accumulate to life-threatening concentrations when the ventilation is poor. Due to the carcinogenic effects of radon, its concentration in indoor air is recommended to be lower than 100 Bq/m^3 if possible [7]. Nevertheless, the action level for reduction is frequently set between 200 Bq/m^3 and 400 Bq/m^3. At the same time, all new buildings are expected to have concentrations below 100 Bq/m^3. These expectations were confirmed in a French stock of dwellings [2] and an Austrian stock [4] for energy-efficient dwellings built after 2010. The radon level was within the same range in both studies (17–31 Bq/m^3 and 24–29 Bq/m^3, respectively), and rarely exceeded the WHO reference level of 100 Bq/m^3 [7][8]. In areas that have a low risk of radon emissions, the modern characteristics of dwellings built after 2010—even without mechanical ventilation—seem sufficient to avoid radon accumulate to life-threatening concentrations. In contrast, in areas that have a high risk of radon emissions, the implementation of mechanical ventilation with heat recovery had a better performance in radon reduction. Relative to naturally ventilated residences, Austrian and Swiss dwellings with mechanical ventilation systems have been found to present a significantly lower radon concentration [4][9]. This was particularly true for dwellings located in areas with a very high risk of radon emission, in which mechanical ventilation increased the difference in radon concentrations between mechanically and naturally ventilated houses (geo-mean: 96 vs. 251 Bq/m^3, $p < 0.001$) [9]. Nevertheless, the Swiss dwellings accumulate slightly more radon than Austrian ones, in both mechanically and naturally ventilated dwellings (geo-mean: 58 and 105 Bq/m^3, respectively) [9]. At the same time, thermal retrofitting without the implementation of mechanical ventilation in the houses located in areas with such a high risk must be avoided. Airtightness of buildings has been negatively linked to indoor radon levels [9]. However, while centralized and decentralized mechanical supply and exhaust ventilation with heat recovery yielded a good efficiency in radon reduction, the best performance was confirmed to be based on subslab depressurization (SSD) [10]. The inconvenience of implementing SSD systems in inhabited houses is related to the cost and the disruption of daily household activities. These findings highlight the importance of adapting a retrofitting strategy to local radon emission levels in order to protect residents′ health.

2.2. Efficiency of Energy-Efficient Buildings to Limit $PM_{2.5}$ Infiltration

Another pollutant with recognized short- and long-term impacts on human health is particulate matter (PM) with an aerodynamic diameter smaller than 10 microns. PM emissions are associated with windblown desert dust and anthropogenic activities such as road traffic, but also with cigarette smoke, and solid fuel or wood heating (reviewed in [11]). While both PM_{10} and $PM_{2.5}$ were recognized to impact human health, data in energy-efficient residential dwellings were reported only on $PM_{2.5.}$ Ambient $PM_{2.5}$ concentrations are known to vary substantially between and within regions of the world, and evolve with time. While they decreased in the WHO European Region, the WHO Region of the Americas, and the WHO Western Pacific Region in the recent years, they increased elsewhere in the world. This was partially due to a difference in the $PM_{2.5}$ sources. Therefore, to control the level of this pollutant in indoor air, it is necessary to adapt an intervention in response to the $PM_{2.5}$ sources. In dwellings located in urban areas with heavy traffic, the infiltration of $PM_{2.5}$ from outdoors must be reduced [12][13]. In dwellings where people are using solid fuel, wood heating, or continuing to smoke inside, the users' habits must be changed. Indeed, a high air exchange rate in areas of heavy traffic was associated with adverse respiratory outcomes [13][14]. The airtightness of the last generation of energy-efficient dwellings (European standard) is an efficient tool for limiting $PM_{2.5}$ infiltration indoors [15]. Even more so, the implementation of mechanical ventilation reduced the $PM_{2.5}$ accumulation indoors in both recent and retrofitted energy-efficient dwellings, in particular during the heating period [2][14][15]. Nevertheless, the difference in the $PM_{2.5}$ level between mechanically and naturally ventilated energy-efficient dwellings is generally small. The $PM_{2.5}$ median indoor levels was below the WHO guideline (5 µg/m^3) only in a Finnish stock of dwellings (4.3 µg/m^3), while it was below 10 µg/m^3 of annual exposure in a Lithuanian stock of dwellings [14] and in an American one [16], but was above this target in French or Italian stock with similar characteristics (13 µg/m^3 and 15 µg m^{-3}, respectively, during the winter) [2][17]. Interestingly, the mechanical ventilation was reported to decrease $PM_{2.5}$ median indoor levels to 7.5 in comparison to 13.4. The health issues related to modulating the concentration of outdoor $PM_{2.5}$ in indoor air was addressed in a Korean energy-efficient stock of buildings with similar energetic standards [15]. The $PM_{2.5}$ level was lowered enough by the mechanical ventilation versus the natural ventilation (6.0 ± 6.9 µg/m^3 vs. 8.7 ± 8.6 µg/m^3, respectively [15]) to observe a decrease in allergic rhinitis incidence in adults. However, this decrease was insufficient to prevent the incidence of allergic rhinitis and atopic dermatitis in children. Complementary measures must be taken to keep the $PM_{2.5}$ low enough to avoid detrimental effects on health. One approach is to decrease outdoor pollution by increasing the density of energy-efficient buildings [18], while another involves directly substituting for coal in its use for power in industry and households [19].

3. Efficiency of Energy-Efficient Buildings to Limit Indoor Pollutant Accumulations

While the airtightness of retrofitted energy-efficient buildings might limit the infiltration of outdoor pollutants, the resulting reduced ventilation can have unwanted repercussions on indoor air quality (IAQ) [20] and adverse effects on respiratory health [21][22][23]. When the household air changes per hour (ACH) fall below the European standard of 0.5 ACH [24], this results in the accumulation of most indoor pollutants—including bacteria that are closely related to human pathogens [25]—and an increase in the relative humidity of the ambient air, which favors the development of molds [23][26]. Indoor air temperature also matters, as it regulates the relative humidity content and can promote the release of pollutants from building materials.

3.1. Efficiency of Energy-Efficient Buildings to Exhaust Humidity

Exposure to molds was associated with increased incidence of asthma and allergic symptoms [27][28][29]. In addition to its negative effects on health, dampness affects the durability of materials and favors interstitial condensation. Taken together, all of these negative effects have prompted the implementation of ventilation requirements—whether natural or mechanical—in building energy standards [30]. The more efficient the ventilation system, the larger the decrease in the relative humidity of the ambient air. However, the implementation of mechanical ventilation does not guarantee an efficient air exchange rate, not only due to technical deficiencies (such as unbalanced ventilation systems), but also due to human interaction with the systems (reviewed in [31]). In parallel, natural ventilation has been shown to offer sufficient air exchange in green buildings (that were conceived with this orientation in mind) in areas with mild summers [32]. Therefore, small or nonexistent differences in the air relative humidity (varying between 45% and 50%) might be observed between mechanically and naturally ventilated energy-efficient dwellings [4][15]. However, even a slight decrease in the air humidity level in mechanically vs. naturally ventilated dwellings may be sufficient to prevent the development of certain fungal species on building surfaces, such as the species indicative of water damage, *Ulocladium* and *Stachybotrys*, or pathogenic species of the *Aspergillus* complex [33]. In addition, mechanical ventilation is also efficient in lowering the concentration of airborne fungal spores [4][5][33][34]. Consequently, any increase in the ventilation rate is expected to reduce both the prevalence of respiratory symptoms (e.g., asthma, allergic rhinitis, and sinusitis) and the incidence of severe respiratory infections that are caused by *Aspergillus* (reviewed in [35]). Nevertheless, to have a healthy house, no mold development should occur during the construction process. Such an event is favored by the lack of ventilation and the airtightness of the latest generation of energy-efficient buildings [36]. If this occurs, it could persist during the whole life of building. When molds develop on surfaces, extensive environmental remediation and replacement of the infected materials is recommended for their removal. The use of a chemical treatment reduces exposure to molds and their byproducts (the mycotoxins), although it does not eradicate them [37]. The effectiveness of each remediation approach in improving health outcomes must be supported by epidemiological studies, and almost all data on the effectiveness of extensive remediation methods were evaluated here [38]. However, it must be ensured that the air relative humidity is not excessively lowered, as skin dryness and eye fatigue were regularly reported in such cases [15][39].

3.2. Efficiency of Energy-Efficient Buildings to Limit VOCs Accumulation

Mechanical ventilation of buildings not only results in decreased concentrations of fungal and bacterial colony-forming units, but also decreases in the indoor levels of other pollutants, such as volatile organic compounds (VOCs), in particular formaldehyde. However, while this decrease has been systematically reported in recent years [4][17][40][41], very few studies examined the associations between respiratory health and exposure to VOC accumulations in residential indoor air, in particular in energy-efficient dwellings [15][39][41].

Formaldehyde was classified as a Group 1 human carcinogen by the International Agency for Research on Cancer in 2004. To protect against both acute and chronic sensory and airway irritation in the general population, the WHO issued an air-quality formaldehyde guideline threshold of 100 μg/m^3. In an indoor environment, the emission rate of formaldehyde greatly depends on the building and furniture materials. Nevertheless, an efficient ventilation can limit its accumulation. The formaldehyde levels in residential energy-efficient-dwellings greatly differed between the established cities and regions with a rapid urbanization process. Thus, the formaldehyde levels reported in the USA, Canada, and different European countries were generally lower than the WHO AGL (100 μg/m^3) or even the Canadian AGL (50 μg/m^3) [16][39][41], while those reported in Asian countries were generally higher than the AGL [42][43]. Nevertheless, none of the epidemiological studies conducted on energy-efficient dwellings were done in these at-risk populations. The few existing ones were conducted in dwellings with low levels of formaldehyde. These studies showed that, while formaldehyde and, more generally, total VOC concentrations, were lower in dwellings with mechanical ventilation systems than in those with only window ventilation, both remained generally in the range of the air-quality guidance levels. Therefore, when a weak but statistically significant correlation between the frequency of symptoms (dizziness, nausea, and headaches in adults [39]; emotional distress in the elderly [41]) and the concentration of formaldehyde was reported, this correlation was independent of the type of ventilation systems [39]. Therefore, health effects will benefit from being monitored in Asian or African countries with a rapid urbanization process, where very high levels of formaldehyde have been reported indoors. The only existing Asian epidemiological study, conducted in South Korea, did not specifically monitor formaldehyde, but total VOC. Total VOC concentrations in dwellings with mechanical ventilation systems were lower than in the properties with only window ventilation [15]. Nevertheless, they both remained generally in the range of the air-quality guidance levels (total VOC: 0.2–0.6 mg/m^3 (FISIAQ)). The researchers detected a significant contribution of the level of exposure to total VOC in the development of an allergic rhinitis in adults, but not specifically associated with the presence of mechanical ventilation [15]. Consequently, evidence of the protective effect of mechanical ventilation should be sought in dwellings where natural ventilation allows pollutants to accumulate to threatening levels.

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