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The role of ventilation systems on indoor air quality. Analysis and Solutions for a Healthy Environment

Rolul sistemelor de ventilare asupra calitatii aerului interior. Analiză și soluții pentru un mediu sănătos

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Abstract. This paper presents the relation between indoor air quality (IAQ) and the efficiency of ventilation systems in indoor spaces, given their impact on the health and comfort of occupants. In the context of urbanization and modern construction trends, in which the tightness of buildings has increased significantly, inadequate ventilation can lead to the accumulation of internal pollutants, such as carbon dioxide (CO_2), volatile organic compounds (VOCs), fine particles, and biological agents (molds, bacteria). The paper presents the different types of ventilation systems used in homes (natural, mechanical and hybrid ventilation), analyzing their effectiveness in maintaining a healthy indoor environment. The study highlights that proper ventilation not only prevents the build-up of pollutants, but also helps to improve occupant performance, reducing risks to respiratory and mental health. In conclusion, this paper highlights the need for a balance between energy efficiency and occupant health protection by implementing sustainable and smart ventilation solutions in modern homes.

Key words: indoor air pollution, IAQ, heat recovery technologies (HRV), indoor pollutants, ambiental comfort, ventilation systems, healthy environment, mechanical ventilation, natural ventilation, hybrid ventilation, CO_2 concentrations,

1. Introduction

Indoor air quality (CAI) is a determinant of health and comfort in the residential environment, especially in the context in which individuals spend, on average, more than 90% of their time indoors [1]. The air inside homes can contain a variety of contaminants, both from internal sources (building materials, domestic activities) and external sources (traffic, industry, pollen). In this paper, the main categories of pollutants encountered in the residential environment are analyzed, along with their sources, accumulation mechanisms and effects on human health. Proper ventilation of

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spaces is essential for maintaining good indoor air quality and preventing the build-up of pollutants [2].

2. Content of the paper

Indoor air quality (IAQ) has become a topic of major interest only in recent decades but concerns about home ventilation can be traced back to ancient times. In ancient Rome, architects designed dwellings with open atriums to allow air circulation and the dispersion of smoke from cooking or heating [3]. Until the nineteenth century, most homes benefited from natural ventilation through cracks in buildings, frequently opened windows and the use of chimney stoves. Although uncontrolled and energy-inefficient, this natural ventilation reduced the build-up of pollutants. Since the Industrial Revolution (19th century), urbanization and the intensive use of fossil fuels have led to an increase in pollution, and concerns about home hygiene have increased, but from the perspective of infectious diseases rather than indoor air. A turning point was the energy crisis of the 1970s, when the focus was on sealing homes to reduce heat loss. This measure, although energy-efficient, has led to the emergence of problems with the accumulation of pollutants in the indoor air, especially in residential spaces. In the 1980s and 1990s, the first systematic studies on Sick Building Syndrome (SBS) and the effects of indoor pollution on health began to appear [4]. The World Health Organization (WHO) and ASHRAE have begun to develop standards and recommendations on acceptable levels of indoor pollutants (such as CO_2, VOCs, $PM_{2.5}$, formaldehyde). Since the 2000s, with technological advancement and the digitalization of homes, mechanical ventilation systems with heat recovery (HRV), air quality sensors and smart home solutions have been developed, which allow precise monitoring and control of ventilation [5].

Today, in the context of increasing time spent indoors (over 90% of the day, according to recent studies) and long-term health concerns, indoor air quality in homes is recognized as an essential factor for physical and mental well-being, being increasingly integrated into sustainable design norms and public health policies. [1]. Changes in construction, energy cost, materials and health concerns are shifting ventilation philosophy once again. Buildings are now a source of contamination. Health, economics and aesthetics are becoming more important than comfort in determining the specification for ventilation. Table 1 is described as an extension of the concept presented by Fanger in 1996 and shows the paradigm for ventilation design. [6]. There is expected to be in a transition period over the next 5 to 10 years, because the design industry struggles to incorporate qualitative attributes into prescriptive standards. Performance criteria based on developing indices for quantifying the health hazard of air composed of a mixture of contaminants or subjective rating schemes are likely to emerge. In 1869 Lewis Leeds told to Franklin Institute that “We are thus to conclude that our own breath is our greatest enemy”. [6]

Table 1

Paradigms in the philosophy of ventilation since 1800 [Extension of Fanger -1996]

Years	*Pollution Sources*	*Paradigm*
1800	People	Poison
1900		Contagion
1935		Comfort
1975	People Buildings	Comfort + Health
2000	People Buildings Outside Environment	Comfort + Health + Productivity
2050		Personal aesthetics

Studies show that proper ventilation systems play a crucial role in maintaining indoor air quality. In the absence of adequate ventilation, internal pollutants (such as CO_2, VOCs, fine particles) can reach dangerous concentrations, affecting the health of occupants. Also, the accumulation of moisture, combined with insufficient air exchange, can favor the development of mold and other biological contaminants.

As main pollutants we mention chemical and biological pollutants, particulate matter and radon. Chemical pollutants include gaseous or volatile substances that can affect the respiratory, cardiovascular or nervous systems. Among the most relevant are: carbon dioxide, volatile organic compounds, carbon monoxide and nitrogen oxides. Carbon dioxide (CO_2) is an indirect marker of insufficient ventilation, accumulating especially in bedrooms and poorly ventilated spaces. Although it is not toxic at normal concentrations, values above 1000 ppm can indicate discomfort, decreased cognitive capacity and the feeling of "closed" air [7].

Volatile organic compounds (VOCs) are a large group of substances emitted by common products: adhesives, varnishes, paints, furniture materials, detergents and room fragrances. Among the most common are benzene, toluene and formaldehyde – a chemical agent recognized as a potential carcinogen by the International Agency for Research on Cancer (IARC). Carbon monoxide (CO) and nitrogen oxides (NO_x) occur predominantly in homes where combustion sources are used: gas stoves, stoves, fireplaces without adequate draught. Carbon monoxide, being colorless and odorless, poses an increased risk of poisoning, especially in poorly ventilated spaces. Fine particles, classified according to aerodynamic diameter (PM_{10}, $PM_{2.5}$, $PM_{0.1}$), are transported into the indoor air from both internal (cooking, smoking, cleaning, candles) and external (road traffic, industry) sources. $PM_{2.5}$ particles can penetrate deep into the respiratory tract, favoring the appearance of cardiovascular and respiratory diseases [8]. In conditions of high humidity and poor ventilation, homes can become a favorable environment for the development of biological contaminants, such as: mold spores, allergens, bacteria and airborne viruses. Mold spores (aspergillus, cladosporium) colonize the walls or ceiling in the presence of condensation. Allergens such as dust mites, animal hair, pollen, are associated with allergic reactions, rhinitis or asthma. Airborne bacteria and viruses are found especially in crowded spaces or without efficient air circulation. Radon is a natural radioactive gas, resulting from the decay of uranium in the soil, which can enter homes through cracks in the foundation or through building materials. Depending on the geographical area, concentration can vary significantly. According to the World Health Organization (WHO), prolonged exposure to radon is considered the second leading cause of lung cancer, after smoking [9].

Indoor CO_2 concentrations are used as an indicator of indoor air quality. The rate at which carbon dioxide is generated and oxygen is consumed depends on physical activity. These relationships between these two and breathing rates are shown in Figure 1 to maintain the steady-state CO_2 concentration below a given limit [6], [10].

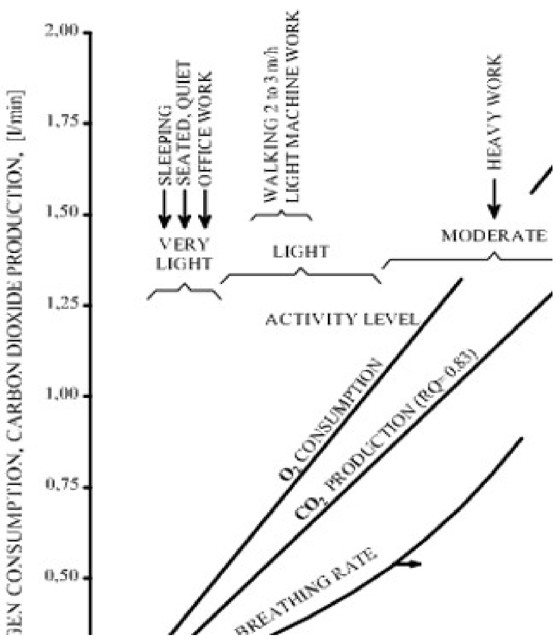

Fig.1 . Metabolic data

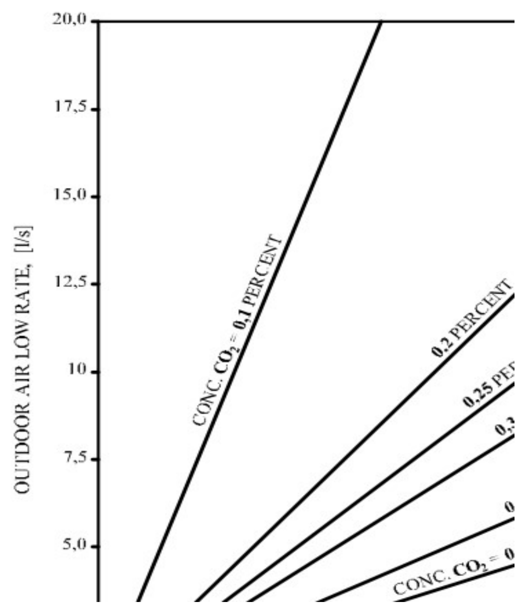

Fig.2. Ventilation requirements

The mass balance equation gives the outdoor air flow rate needed to maintain the steady-state CO_2 concentration below a given limit and Equation 1 presents the outdoor air flow rate per person:

$$V_o = \frac{N}{(C_s - C_o)} \quad (1)$$

Where: V_o= outdoor air flow rate per person; N= CO_2 generation rate per person.

C_s=CO_2 concentration in a specific space; C_o = CO_2 concentration in outdoor air [10],[11]. In Figure 2 the ventilation requirements are presented as a report between the outdoor air flow rate required and physical activity. The required ventilation must be increased if the physical activity level is greater than 1.2 met, in order to have the same carbon dioxide level. In equation 1 the decrease in oxygen content of the room air could be substituted for carbon dioxide concentration [10].

$$C_s - C_o = \frac{N}{V_o} \quad (2)$$

Considering equation 1, CO_2 generation rate per person has a negative value because oxygen is consumed rather than generated.

$$C_s = C_o - \frac{N}{V_o} \quad (3)$$

When the activity level is reached at 1.2 met, the oxygen consumption rate is 0.36 l/min.

Ventilation is essential for maintaining good indoor air quality, but the method of achieving this can vary. Two primary approaches are natural ventilation and mechanical ventilation. Each has its advantages and disadvantages, and the choice between them often depends on the specific needs of a building and its occupants. Natural ventilation is the process by which fresh air enters the home through hardware openings, window hardware or cracks in construction, and is eliminated through air vents (either through exhaust hardware or chimneys) [5]. It was the main way of ventilating homes before the industrial revolution, but also in regions where the climate allowed the frequent opening of hardware stores. The main advantage it has is that it allows a natural air exchange, based on temperature and pressure differences. Another advantage is that it is an inexpensive and simple to implement ventilation system, which does not require additional equipment. As a disadvantage, natural ventilation can lead to significant losses of thermal energy, especially in the cold period of the year. The efficiency of natural ventilation depends on external weather conditions (wind, temperature), which makes the system inefficient in extreme weather conditions or in thermally insulated buildings. Mechanical ventilation uses electrical equipment, such as fans, to control the flow of air inside the home. It is divided into two main types: mechanical ventilation with extraction and mechanical ventilation with air intake. Mechanical extraction ventilation involves extracting stale air from rooms, and fresh air enters through passive openings or non-airtight hardware. It is often used in bathrooms, kitchens and other spaces with high humidity or pollutant emissions. Mechanical air intake ventilation (VMA) involves supplying fresh air from the outside, constantly, while stale air is exhausted. VMA systems can include heat exchangers (HRVs – Heat Recovery Ventilators) to recover heat from the exhaust air and transfer it to fresh air, thus reducing heat energy losses. Mechanical ventilation systems, especially those with heat recovery, have demonstrated superior efficiency in reducing pollutant concentrations and improving thermal comfort. These systems not only improve air quality, but also contribute to reducing energy consumption, which is essential in the context of energy efficiency requirements in modern construction. They have higher efficiency in removing pollutants, especially in modern buildings with high tightness. As a disadvantage is the possibility of accumulation of pollutants in ventilation systems if they are not properly maintained. Hybrid ventilation combines the advantages of natural and mechanical ventilation, using both passive airflow and mechanical equipment to ensure optimal air exchange. In favorable weather conditions, natural ventilation can be used, and when conditions do not allow this, the system switches to mechanical ventilation [5], [6], [12].

3. Conclusions

Ventilation is more than just a building requirement; it's a critical component that affects the health and comfort of building occupants. Poor ventilation can have a range of negative consequences, from minor discomforts to severe health risk. In the absence of an efficient air exchange, the pollutants emitted inside accumulate. Ventilation has the role of diluting internal pollutants, achieved through the intake of clean air, but also that of evacuating contaminated air, especially through mechanical systems or natural ventilation. The more efficient the ventilation is, the lower the concentration of pollutants substances.

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