Control of indoor air quality by demand controlled ventilation

ALEXANDER L. NAUMOV
Central Scientific Research Institute for Industrial Buildings and Structures TSNIIPROMZDANII, Moscow, Russia

IURI A. TABUNSHCHIKOV
Moscow Architectural Institute (State Academy), Moscow, Russia

DMITRY V. KAPKO
Central Scientific Research Institute for Industrial Buildings and Structures TSNIIPROMZDANII, Moscow, Russia

MARIANNA M. BRODACH
Moscow Architectural Institute (State Academy), Moscow, Russia

This article discusses the advantages of using carbon dioxide concentration as a measure of indoor air quality and the possibility of improving it by choosing the optimal air distribution scheme and reducing energy consumption by indoor ventilation systems, which also reduces the emission of carbon dioxide into the atmosphere

Keywords: Air quality, health, carbon dioxide, ventilation, air exchange, energy efficiency, energy saving.

Highlights

- The human health depends on the indoor air quality.
- The carbon dioxide concentration is an indicator of the indoor air pollution.
- The indoor air quality was considered with different schemes of the air distribution.
- DCV systems – optimal indoor air quality and low power consumption.

Environmentalists, physicians and diagnosticians as well as engineers and designers of ventilation and air conditioning systems all pay special attention to the influence of indoor air quality on human well-being. A person's physical condition depends on air quality; where it is unsatisfactory, people feel unwell, lose concentration, develop diseases, etc.

All kinds of pollutants may be released into indoor air and affect its quality (carbon dioxide released by humans; phenol/formaldehyde, acetone, ammonia and other components released by furniture and decoration materials). Both Russian and international experts have done a lot of studies [1, 2, 3, 4] that led to the adoption of carbon dioxide concentration as an indicator of indoor air pollution. In 2011, Russian standard GOST 30494 was amended to include this [5].

Air quality is a key component of a healthy microclimate at the workplace.

The human breathing process under normal conditions mainly alters the concentration of two air components, oxygen and carbon dioxide. The metabolic processes in the human body reduce oxygen content in exhaled air from 20.9% to 16.3%, while increasing carbon dioxide concentration from 0.03% to 4% [6]. It should be noted that carbon dioxide concentration increases more than a hundred times. Both Russian and international experts have done a lot of studies [1, 2, 3, 4] that led to the adoption of carbon dioxide concentration as an indicator of indoor air pollution. Other hazardous gas emissions into the air of residential and public buildings (phenol/formaldehyde, acetone, ammonia and other components released from furniture and decoration materials) are converted into carbon dioxide equivalents [7].

General

GOST 30494-2011 'Residential and Public Buildings. Microclimate Parameters for Indoor Enclosures' [5], developed with the participation of the authors of this article, includes four indoor air quality classes depending on the concentration of carbon dioxide:

- Class 1 (optimal microclimate, high quality) – carbon dioxide level not higher than 400 ppm;
- Class 2 (optimal microclimate, medium quality) – carbon dioxide level between 401 and 600 ppm;
- Class 3 (acceptable microclimate, acceptable quality) – carbon dioxide level between 601 and 1000 ppm;
- Class 4 (unacceptably high carbon dioxide level, low air quality) – more than 1000 ppm.

The advantages of this approach to assessing air quality and the air exchange requirement over the traditional one (based on the relative blowing rate or air exchange rate) are as follows:

- air exchange calculations can take into account outdoor air pollution;
- higher ventilation efficiency is promoted: fresh air supply into the breathing area, no fresh air streams blowing across 'dirty' zones on the premises, etc.;
- the fresh air in the room can be taken into account before the room is filled by people;
- 'background' air exchange for removing hazardous emissions of furniture and decoration materials at non-working hours can be determined correctly;
- control of air quality becomes more adequate and accurate due to measuring carbon dioxide concentration directly in the room area serviced.

Information on carbon dioxide concentration in outdoor air is provided by weather observation stations. For reference: according to [5], approximate average annual values of carbon dioxide concentrations are:

- in the countryside, 350 ppm;
- in small towns, 375 ppm;
- the polluted center of a big city, 400 ppm.

The air exchange rate for the most widespread 'mixing' ventilation system is calculated from the formula:

$$L = 55 \cdot 10^4 \frac{G}{g_{out} - g_n} \quad \text{m}^3/\text{h} \qquad (1)$$

where G is the amount of carbon dioxide entering the enclosure, g/h;
g_n and g_{out} are the normative and outdoor carbon dioxide concentrations, respectively, ppm.

Mixing ventilation is supposed to spread air evenly across the room, and the concentration of pollutants, including carbon dioxide, is expected to be the same everywhere (**Figure 1, A**). Mixing ventilation usually features a high air exchange rate, at least 3 1/h.

Mixing ventilation systems include air recycling systems and those combined with fan terminals of air conditioning systems (split systems and fancoils).

In many public and office buildings, false ceilings are used to house both air supply and exhaust devices. In traditional solutions, air exchange rates usually do not exceed 1 – 1.5 1/h. In some cases of isothermal ventilation or slightly overheated incoming air, a large share of fresh air is drawn into the exhaust grids, forming what is called 'short circuit' circulation (**Figure 1, B**). This is an example of inefficient organization of ventilation.

An example of efficient ventilation is 'displacement' ventilation [8, 9]. Fresh incoming area is supplied into the serviced area at a small velocity through air diffusers with a large surface area to effectively 'flood' it. Polluted air, lifted by convective flows from occupants and office and other equipment, will be displaced into the upper tier and then exhausted (**Figure 1, C**). In this case, concentration of carbon dioxide in the serviced area may be lower than in the air removed.

Formally, in all the three cases (**Figure 1**) the same air exchange rate may be adopted under the traditional design approach, but the resultant air quality will differ widely.

The air volume required for ventilating the premises should be calculated according to [5] taking into account the air distribution efficiency factor:

$$L = \eta \cdot L_b \quad \text{m}^3/\text{h} \qquad (2)$$

where L_b is the base amount of external air according to the current Russian norms, m³/h.

The value of the air distribution efficiency factor is shown in **Table 1**.

Thus, if the statutory concentration of carbon dioxide is 800 ppm, and in the outdoor air its content is 400 ppm, for a workplace in an office building where a person exhales 45 g of carbon dioxide per hour (a quantity adopted according to [10] for adult brainworkers), the flow of external air in the ventilation system can be calculated from the formula (1):

$$L = 55 \cdot 10^4 \cdot \frac{45 \cdot 10^{-3}}{800 - 400} = 61.875 \text{ m}^3\text{/h} \approx 60 \text{ m}^3\text{/h}$$

This is the exact volume of air per workplace that the mixing ventilation system must supply to the premises. A 'short circuit' system will need more, 66 to 78 m^3/h in the light of **Table 1**, while 'displacement' ventilation will permit a lower air exchange rate, 36 to 48 m^3/h, and personal ventilation, 18 to 30 m^3/h.

In other words, with air quality being the same, the air exchange rate and, consequently, energy consumption (on air transportation through ducts and heating/cooling) may differ 1.5 to 2 times.

The distribution of carbon dioxide concentration fields across the volume of premises can be calculated accurately enough. Still, in most cases the air and heat regime modeling effort is made for unique facilities only [11]. **Figure 2** shows approximate carbon dioxide distribution patterns for displacement ventilation (A) and in the vicinity of a fresh air stream (B) based on the calculation assumptions [17].

The efficiency of ventilation systems can also be characterized by the lifetime of fresh air – the time that air flowing from the air distributor takes to reach the breathing area. In personal ventilation system it takes less than a second; in 'displacement' systems, 20 to

Table 1. Air Distribution Efficiency Factors.

S/N	Ventilation Systems	Air Distribution Efficiency Factor
1.	Mixing ventilation systems with air exchange rates higher than 2.5 1/h, including those using recycling, split systems and fancoils	1.0
2.	Isothermic ventilation systems or those combined with air heating that have a 'top to top' air distribution system and air exchange rates not exceeding 1.5 1/h	1.1 – 1.3
3.	Displacement ventilation systems	0.6 – 0.8
4.	Personal ventilation systems supplying fresh air into the breathing area	0.3 – 0.5

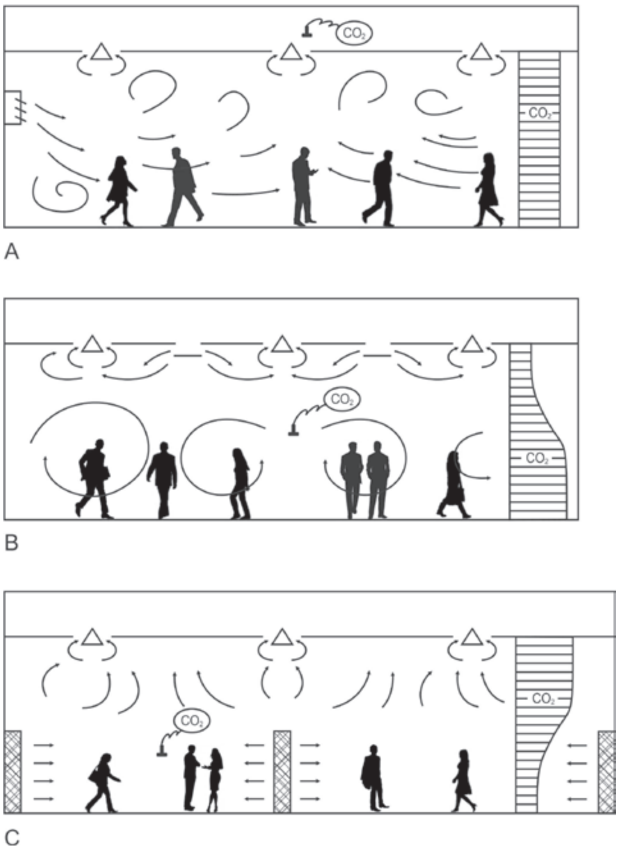

Figure 1. Carbon Dioxide Distribution Pattern with Mixing (A), Short-Circuit (B) and Displacement (C) Ventilation Installed.

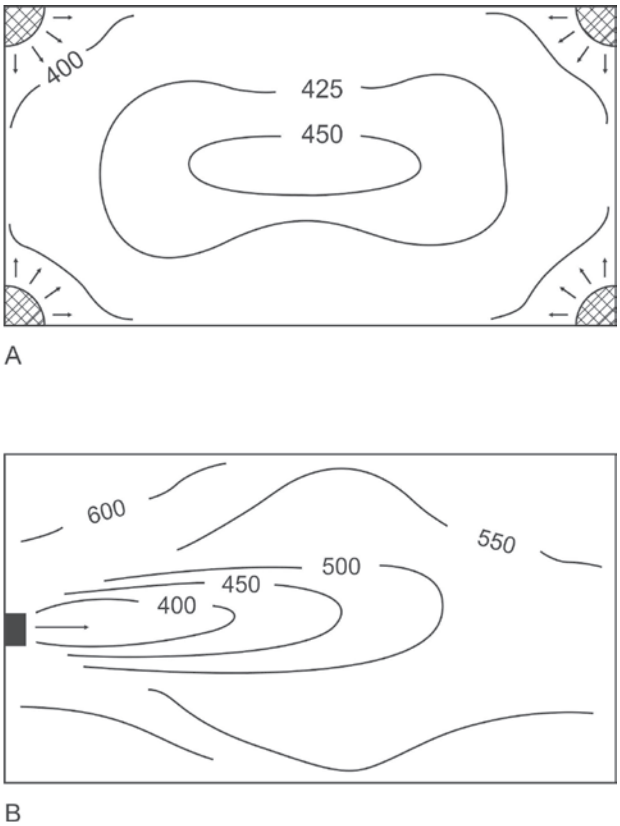

Figure 2. Lines of Equal Carbon Dioxide Concentrations on a Room Plan with Displacement Ventilation Installed (A) and in a Stream of Incoming Fresh Air (B).

30 seconds, and in 'short circuit' systems, up to ten minutes.

The efficiency retention of the air distribution system can thus be considered the criteria of the adaptability of ventilation systems (DCV systems). Demand Controlled Ventilation (DCV) stands for a special type of variable air velocity (VAV) ventilation systems that permit wide-range control of air exchange in individual areas and at different times depending on the actual occupancy of the premises [12, 13, 14, 15,16].

Another adaptability criterion should be the correspondence between the amount of the pollutants released (in this case, carbon dioxide) and the air exchange rate.

Traditional ventilation systems are designed for the rated occupancy of the premises and cannot adjust air exchange.

E.g., if the standard staff number in an office is 1,000 persons, the system will keep supplying and exhausting 60,000 m³ of air per hour. On the other hand, if holidays, sick leaves and business trips are taken into account, the actual number of personnel in the office will be just 70% of the rated figure, or fewer. Moreover, even if the business has fixed office hours, the first employees will come an hour or two earlier, and the last ones will leave three or four hours later than required to.

A traditional ventilation system will thus operate in its design mode since the first employees arrive and until the last leave.

Plotted in **Figure 3** are the working cycles of a traditional ventilation system with a constant air exchange rate and of demand-controlled ventilation depending on the number of personnel present at the office. The hatched area on the plot represents the power and air saving in the demand-controlled ventilation system than can reach 40 to 50%.

Air exchange control in a demand-controlled ventilation system can be governed by carbon dioxide levels measured by a special sensor. Following the sensor's signal, regulated gates will adjust the flow of air entering the premises. The signal is then forwarded to the

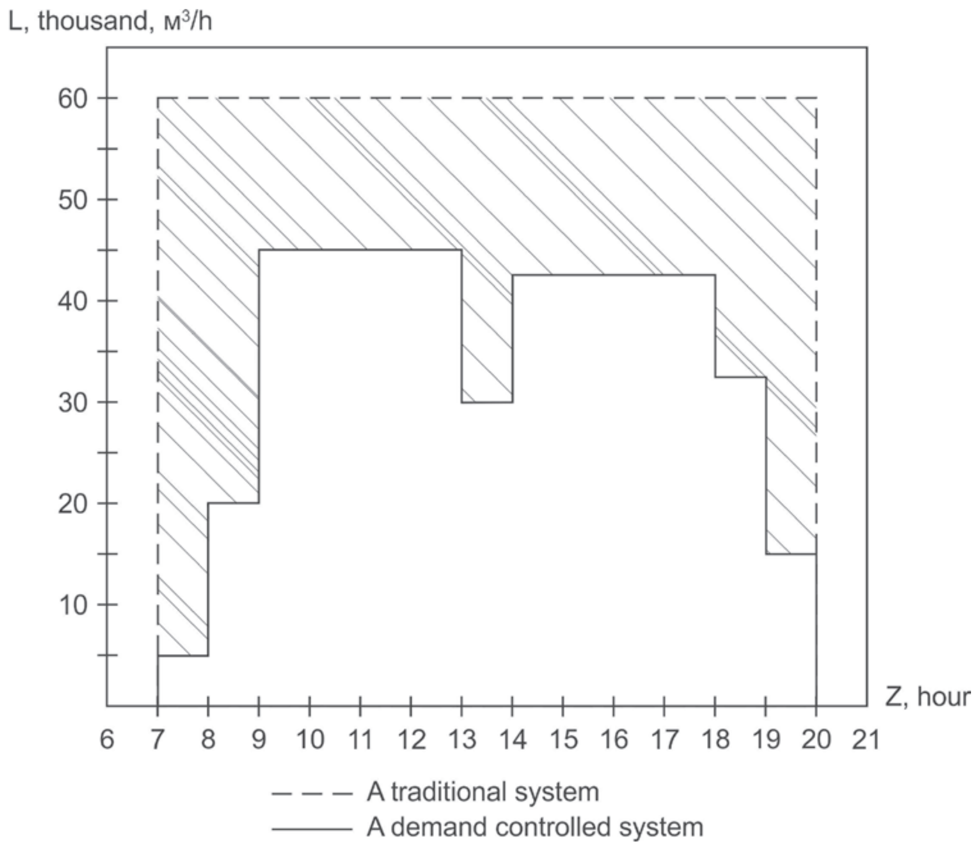

Figure 3. A Ventilation System Operation Schedule.

air-supply unit and the exhaust unit equipped with variable-frequency drives for adjusting fan delivery.

The place where the carbon dioxide level sensor is installed is important. In a mixing ventilation system, the sensor may be installed in the exhaust air manifold, and in other cases, in the serviced area or breathing area (**Figure 1**).

Acknowledgements

This research was performed under the federal target program "Research and Development on Directions Areas of the Research and Technological Complex of Russia in the Years 2014-2020" (Grand Agreement No. 14.576.21.0009 dated 17 June 2014, Unique Identifier RFMEFI57614X0009).

Conclusions

1. The concentration of carbon dioxide can serve as an indicator of air quality in residential and public buildings.
2. The efficiency retention of air distribution is an important adaptability criterion to be used in selecting ventilation systems. The target should be for fresh air to reach the breathing area by a short trajectory, without crossing 'dirty' zones where hazardous substances are released.
3. It is important to make the fresh air inflow match the number of people on the premises. While a high air quality is maintained in buildings with variable numbers of personnel or visitors (such as railway stations, airports, trade centers, sports or recreational facilities, offices), demand controlled ventilation can save 40 to 50% of energy as compared to traditional ventilation systems. ■

References

[1] Gurina I.V. Safe level of carbon dioxide requires a revision. Environmental Bulletin of Russia #10, 2008.

[2] Shilkrot E.O., Gubernskij I.D. How much air needs to a person for comfort? ABOK #4, 2008.

[3] Gładyszewska-Fiedoruk K. Correlations of air humidity and carbon dioxide concentration in the kindergarten. Energy and Buildings,Volume 62, July 2013, Pages 45–50.

[4] Almeida R. M. S. F., Freitas V. P. Indoor environmental quality of classrooms in Southern European climate. Energy and Buildings, Volume 81, October 2014, Pages 127–140.

[5] GOST 30494-2011 "Residential and public buildings. Microclimate parameters for indoor enclosures".

[6] West J. Physiology of respiration. Basics. M., 1988. – 202 pages.

[7] EN 13779:2007. Ventilation for non-residental buildings – Performance requirements for ventilation and room-conditioning systems.

[8] W. Chakroun, N. Ghaddar, K. Ghali. Chilled ceiling and displacement ventilation aided with personalized evaporative cooler. Energy and Buildings, Volume 43, Issue 11, November 2011, Pages 3250–3257

[9] Taki A.H., Jali L. I, Loveday D.L. Experimental and computational investigation into suppressing natural convection in chilled ceiling/displacement ventilationenvironments. Energy and Buildings, Volume 43, Issue 11, November 2011, Pages 3082–3089

[10] Heating and ventilation. Textbook for institutes. In 2 parts. Part 2. Ventilation. Redaction by V.N. Bogoslovskij. M., Stroyizdat, 1976. 439 pages. Authors.: V.N. Bogoslovskij, V.I. Novozhilov, B. D. Simakov, V. P. Titov.

[11] Gorbunov V. A. Modeling of heat transfer in the finite element package Femlab. Ivanovo. 2008. – 216 pages.

[12] Demand controlled ventilation systems. ABOK #7, 2011.

[13] Yunqing Fan, Keiji Kameishi, Shigeki Onishi, Kazuhide Ito. Field-based study on the energy-saving effects of CO2 demand controlled ventilation in an office with application of Energy recovery ventilators. Energy and Buildings, Volume 68, Part A, January 2014, Pages 412–422

[14] Bei Zhang, Yunhua Li, Josephine Lau, Mingsheng Liu. Demand control ventilation: Influence of terminal box minimum airflow setting on system energy use. Energy and Buildings, Volume 79, August 2014, Pages 173–183.

[15] Toke Rammer Nielsena, Christian Drivsholmb. Energy efficient demand controlled ventilation in single family houses. Energy and Buildings. Volume 42, Issue 11, November 2010, Pages 1995–1998.

[16] Zhongwei Sun, Shengwei Wang, Zhenjun Ma. In-situ implementation and validation of a CO_2-based adaptive demand-controlled ventilation strategy in a multi-zone office building. Building and Environment. Volume 46, Issue 1, January 2011, Pages 124–133.

[17] Shepelev I. A. Aerodynamics of indoor air flows. M., Stroyizdat, 1978. 144 pages.