Abstract: The relevance of the research lies in the development of the current question about the influence of microclimate quality on the efficiency of residential units. The aim of the study is to examine how the microclimate parameters affect the efficiency of residential buildings. Findings. The results obtained are essential for the design of energy-efficient and comfortable residential buildings. The scientific novelty and practical importance of research resides in the thorough study of microclimate in low-rise residential buildings. Microclimate deviation charts for residential buildings have been produced. Keywords: energy audit, heat-insulating cladding; heat insulation, energy efficiency, microclimate parameters, residential unit, complex thermal modernization
1. Introduction

The EU has made a commitment to reduce greenhouse gas emissions from 80% to 95% below 1990 levels by 2050 [6]. Residential buildings contribute significantly to greenhouse gas emissions. That's why energy consumption in buildings has become a major concern worldwide and policy makers endorse measures to improve the energy efficiency of buildings in order to promote sustainable use of energy [19].

The microclimate inside buildings is an essential factor for building energy efficiency. In recent years, people have faced several serious pandemic-related restrictions and stayed at home for a long time. Nearly everyone could feel how comfortable or uncomfortable it was to stay in his place. Temperature, humidity and concentration of carbon dioxide are factors that influence human well-being and comfort. Some indicators are very individual, for example, temperature. When 18°C is a fairly comfortable temperature for one person, the other feels warm, while it can be pretty cold for the third. The factors that may influence are human metabolism, clothes, air humidity, air velocity, and pollution. These parameters are connected. Thus, the analysis and monitoring of microclimate are essential and relevant since it directly influences human health.

The above topic is complicated and complex. The literature review demonstrates the relevance of the research subject matter. The research studies were focused on:

- analysis of thermal losses in buildings [3, 4, 9, 14, 18];
- analysis of energy efficiency and flexibility of the air conditioning and heating [1, 15];
- creating and improving calculation methods, algorithms to achieve optimal and effective energy consumption during peak hours [7, 8, 13, 17];
- experimental research using modern materials and studying their impact on increasing energy efficiency of buildings [11, 16];
- developing heat indicators and energy efficiency class limits in buildings [2, 5, 10, 12].

The research papers analyzed point to a lack of studies on the impact of the microclimate of residential buildings on their efficiency.

The aim of the research is to determine how microclimate influences the efficiency of residential buildings.

The subject of the research is the principles of microclimate changes in residential houses.

An object of the research is microclimate parameters and thermal failures of the low-rise residential building.
2. The methodology

Instrumental monitoring of microclimate parameters (temperature, relative humidity, carbon dioxide concentration) in residential buildings was carried out to analyze how microclimate affects the efficiency of houses [25].

Experimental facility - a residential house in Kherson (II climate zone). The building is located far from main roads on the outskirts of the city. Its total area is 69.9 m²; its living space is 37.6 m². At the time of the experiment, the house was occupied by 6 adults and 5 pets.

The building envelope includes rough masonry (main building and extension №1) and shell masonry (extension №2, kitchen and bathroom). The walls of the house are insulated with 50-mm foam panels. The windows are PVC two-chamber double-glazed, one chamber is filled with argon. The floor of the main building is wooden with some crawl space. The floors in the extension buildings are cement. The roof is garret and double-pitched. The attic is not insulated.

Technical equipment. The measurements were taken with CO2HT-501 digital meter (see fig. 1). This measuring device can simultaneously take readings of temperature, relative humidity, and CO₂ concentration level. Necessary software allowed us to analyze the results obtained. The main technical characteristics are given in table 1.

![Digital meter CO2HT-501](image)

**Fig. 1.** Digital meter CO2HT-501
Table 1

Technical characteristics of CO2HT-501 digital meter

| Parameter                  | Value                   |
|----------------------------|-------------------------|
| Type of gas detector       | stationary              |
| Type of display pattern    | digital                 |
| Types of gases             | carbon dioxide (CO₂)    |
| Measurement time           | 1 sec                   |
| CO₂ measurement range      | 0-9999 ppm              |
| Humidity measurement range | 0.1 ~ 99.9% RH          |
| Temperature measurement range | -10.0 ~ + 70.0°C      |
| Operating temperature range | 0-50°C                  |

Measurements were taken in three premises (the living spaces and a kitchen). The meter was installed at 1-1.5m height and 1.5m from windows. The measurements were taken every 8 minutes during two 24-hour periods; total number of measurements is 360. We analyzed the results of microclimate monitoring in the living space, consisting of 2 living rooms without doors (19.4 m²). The living room is for 2 people, at the time of the experiment, one person worked at the computer from 8:00 to 17:45. Over the 24-hour period there were constantly from one to four people in the room, as well as four pets. In addition, a gas heater was used.

Then we analyzed the results of microclimate monitoring in the service (utility) space, consisting of a hallway, a kitchen (no doors between), and a bathroom. The total area was 16,4 m². There was a gas stove in the kitchen. Over 24 hours, there were from one to five people in the premises. A gas heater was also in use. Ventilation ducts in the kitchen and the bathroom were in poor condition, and there was no exhaust ventilation. Hallway doors were mostly closed. There were five flower pots with indoor plants.

Dates of the experiment: Jan 4-5, 2021.
Weather conditions: 04.01.21 t = +1°C, humidity 94%, overcast, no precipitation. 05.01.21 max. t = +4°C, min. t = +1°C, humidity fluctuated from 91% to 97%, overcast, no precipitation.

3. Results

The results of the microclimate monitoring are presented graphically in fig. 2 for living space and in fig. 3 - for a service (utility) space. The analysis of specific time intervals and extreme values are given in table 2 for living space and in table 3 for a service space.

According to Ukrainian standards [20–22], the specified temperature for a residential building is 20°C, an appropriate humidity rate is from 40% to 60% [21]. A recommended level of carbon dioxide is up to 1000 ppm when 1600 ppm is acceptable. To maintain the level of carbon dioxide within 1000 ppm, it is necessary to provide approximately 30 m³ of
fresh air per hour for every person. To keep it within 1600 ppm, it must give around 15 m³ of fresh air per hour for every person [24].

We could observe that the temperature in the living space fluctuated from 18.2°C to 20°C, humidity – from 58.3% to 67.2%, and CO₂ concentration changed within 944 ppm - 2931 ppm (fig. 2).

Fig. 2. Graphic representation of the microclimate monitoring in a living space: blue – temperature (°C), red – humidity (%RH), orange – CO₂ concentration (ppm), green – standard value
Table 2

Microclimate monitoring results (in the living space)

| №  | Time    | ppm | %   | ºС  | Analysis / Conclusions                                                                 |
|----|---------|-----|-----|-----|---------------------------------------------------------------------------------------|
| point 1 | 00:59  | 2891 | 66,4 | 19,9 | Max. value of CO₂ concentration per night.                                               |
| point 2 | 7:23   | 2406 | 67,2 | 19,9 | Min. value of CO₂ concentration per night.                                               |
| point 3 | 9:07   | 1797 | 65,8 | 19,5 | Min. value of CO₂ concentration without people.                                           |
| point 4 | 11:47  | 2301 | 66,5 | 19,6 | Max. value of CO₂ concentration before ventilating. Two people in the room.             |
| point 5 | 12:19  | 944  | 58,3 | 18,2 | The lowest value per day. The time of ventilating.                                      |
| point 6 | 14:11  | 2723 | 67,9 | 19   | Max. value after ventilating, two people in the room.                                   |
| point 7 | 21:15  | 2931 | 69,2 | 19,5 | The highest value of CO₂ concentration and humidity per day. Two people in the room.   |
| point 8 | 21:39  | 1814 | 66,1 | 19,1 | The values obtained at the moment of ventilating. Time was fixed in 9 min after the windows were closed. |
| point 9 | 21:31  | 1949 | 68,3 | 18,5 | Min. temperature value during ventilation.                                              |
| sector 1 | 6 hours 24 min | ↓385 | ↑0,8 | const | Drop in CO₂ concentration due to infiltration at night.                                   |
| sector 2 | 2 hours 15 min | ↓609 | ↓1,4 | ↓0,4 | Drop in CO₂ concentration due to infiltration without people.                           |
| sector 3 | 15 min  | ↓1357 | ↓8,2 | ↓1,4 | Ventilation. Conclusion: 15 min is enough to get standard values of CO₂ concentration and humidity. |
| sector 4 | 1 hour 52 min | ↑1779 | ↑9,6 | 1,2↑ | Increase in CO₂ concentration and humidity. Conclusion: it is appropriate to ventilate the room again at this time. |
| sector 5 | 15 min  | ↓1117 | ↓3,1 | ↓1   | Ventilation. Lower values of CO₂ concentration and humidity at the time of ventilation do not reach the standard ones. In comparison with previous ventilation, the drop in values is almost the same over the same period of time, regardless of two people in the room. Conclusion: it is recommended to ventilate the room without people for 30 min in the evening. |
We could observe that the temperature in the service (utility) space fluctuated from 19.2°C to 24.3°C, humidity – from 66.4% to 71.5%, and CO₂ concentration changed within 1323 ppm – 4087 ppm (fig. 3).

*Fig. 3.* Graphic representation of the microclimate monitoring in a serving (utility) space: blue – temperature (°C), red – humidity (%RH), orange – CO₂ concentration (ppm), green – standard value
### Table 3

**Microclimate monitoring results in the service (utility) space**

| №   | Time      | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|-----|-----------|-----|-----|-----|--------------------------------------------------------------------------------------|
| point 1 | 21:22 | 2741 | 80,1 | 19,9 | The highest values of humidity per day.                                                |
| point 2 | 21:30 | 2764 | 79,4 | 20   | The time when the shower was used.                                                     |
| point 3 | 23:22 | 2013 | 65,4 | 22,2 | No people, open faulty ventilation duct.                                               |
| point 4 | 00:02 | 2636 | 66,2 | 22,6 | The time when the shower was used.                                                     |
| point 5 | 00:58 | 2184 | 62,7 | 22,7 | No people, open faulty ventilation duct.                                               |
| point 6 | 01:22 | 2653 | 65,8 | 22,4 | The time when the shower was used.                                                     |
| point 7 | 05:22 | 1323 | 65,3 | 21,6 | The lowest value of CO\textsubscript{2} concentration. The effect of infiltration.     |
| point 8 | 06:10 | 2879 | 67,6 | 22,6 | Two people, gas stove in operation.                                                    |
| point 9 | 08:50 | 1901 | 71,1 | 19,6 | Drop-in CO\textsubscript{2} concentration and temperature due to open front door.     |
| point 10 | 09:06 | 2135 | 71,1 | 19,3 | The lowest temperature value per day.                                                  |
| point 11 | 09:22 | 3253 | 75,5 | 19,6 | Increase in CO\textsubscript{2} concentration and humidity. Gas stove in operation.   |
| point 12 | 11:38 | 3928 | 80   | 21,4 | Higher values of all three indicators. Gas stove in use, shower in use.                |
| point 13 | 12:18 | 1951 | 62,7 | 21,2 | Drop-in CO\textsubscript{2} concentration and humidity – ventilation.                  |
| point 14 | 13:14 | 2723 | 69,8 | 21,5 | Four people in the premise.                                                           |
| point 15 | 15:38 | 1963 | 64   | 22,1 | No people.                                                                            |
| point 16 | 16:58 | 2594 | 61,4 | 23,2 | Two people, gas stove in use, ventilation.                                             |
| point 17 | 18:10 | 2201 | 58,7 | 23,3 | The lowest humidity value per day.                                                     |
| point 18 | 18:58 | 2018 | 62,6 | 23,1 | No people.                                                                            |
| point 19 | 20:18 | 4087 | 64   | 24,2 | The highest values of temperature and CO\textsubscript{2} concentration.              |

**Sector 1**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 3 hours | 52 min | ↓111 | ↓13,6 | ↑2,4 | Time when the bathroom was used extensively. Decrease in CO\textsubscript{2} concentration and humidity due to the open faulty ventilation duct. |

**Sector 2**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 4 hours | | ↓1330 | ↓0,5 | ↓0,8 | Low values of all three parameters. The effect of infiltration.                       |

**Sector 3**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 32 min | | ↑1352 | ↑4,4 | const | Increase in CO\textsubscript{2} concentration and humidity due to gas stove in use. Conclusion: exhaust fan should be on when the gas stove is used. |

**Sector 4**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 40 min | | ↓1977 | ↓17,3 | ↓0,2 | Low values of all three parameters due to ventilation. They do not reach normal values. Gas stove in use. Conclusion: indoor air should be exhausted [23]. |

**Sector 5**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 2 hours | 24 min | ↓760 | ↓5,8 | ↑0,6 | No people, appliances are switched off—the effect of infiltration.                    |

**Sector 6**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 1 hour | 12 min | ↓393 | ↓2,7 | ↑0,1 | Ventilation. Gas stove in use. Ventilation decreased the values of CO\textsubscript{2} concentration and humidity but not enough. Conclusion: indoor air should be exhausted [23]. |

**Sector 7**

| Time | ppm | %  | °C  | Analysis/Conclusions                                                                 |
|------|-----|-----|-----|-------------------------------------------------------------------------------------|
| 1 hour | 20 min | ↑12069 | ↑1,4 | ↑1,1 | Three values increased due to gas stove in use and no ventilation. Conclusion: indoor air should be exhausted [23]. |
4. Conclusion

Instrumental monitoring of three micro-climatic parameters: temperature, relative humidity, and carbon dioxide concentration in Kherson's residential home was carried out. Based on the results obtained, it was found that only one parameter, which is the temperature of indoor air, meets current standards. On the one hand, the outside walls of the house were insulated, and the windows were replaced with PVC double glazed ones to provide energy efficiency. On the other hand, the tenants of the house have reduced the natural ventilation time in order to save heat energy. All the measures taken contributed to a higher rate of relative humidity - 70-80% (standard values - 40-60%) and CO₂ concentration - 3000 – 4000 ppm (standard value - not more than 1000 ppm). This last parameter gives the house known as "building-related illness" (from 1500 to 5000 ppm), which adversely affects the health of tenants.

The monitoring has shown the importance of a comprehensive approach to the thermal renovation of buildings. A mechanical supply and waste ventilation system with heat recovery is required for the insulation of the building envelope.

5. References

1. Arteconi A., Polonara F.: Assessing the Demand Side Management Potential and the Energy Flexibility of Heat Pumps in Buildings. Energies 11, 7, 1846, 2018.
2. Attia S. et al.: Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. Energy Build. 239, 110869, 2021.
3. Baciu I.-R. et al.: Green roof influence over the characteristics of the linear thermal bridges. 2019, DOI 10.1088/1757-899x/586/1/012007.
4. Borelli D. et al.: A comprehensive study devoted to determine linear thermal bridges transmittance in existing buildings. Energy Build. 224, 110136, 2020.
5. Danilevski L.N., Danilevsky S.L.: The algorithm and accuracy of definition of heattechnical indicators of buildings. Magazine of Civil Engineering, 73, 5, 2017.
6. Directorate-General for Energy (European Commission): Energy roadmap 2050, https://op.europa.eu/en/publication-detail/-/publication/e758bc9e-b2f9-43f7-8149-8a03becf5c61/language-en, 2012, DOI 10.2833/10759.
7. Hafeez G. et al.: Efficient Energy Management of IoT-Enabled Smart Homes Under Price-Based Demand Response Program in Smart Grid. Sensors, 20, 11, 2020, DOI 10.3390/s20113155.
8. Hakimi S.M., Hasankhani A.: Intelligent energy management in off-grid smart buildings with energy interaction. J. Clean. Prod. 244, 118906, 2020.
9. Ilomets S. et al.: Impact of linear thermal bridges on thermal transmittance of renovated apartment buildings. Journal of Civil Engineering and Management, 23, 1, 96–104, 2017.
10. Krajčík M., Šikula O.: Heat storage efficiency and effective thermal output: Indicators of thermal response and output of radiant heating and cooling systems, 2020. DOI 10.1016/j.enbuild.2020.110524.
11. Kumar S. et al.: Effect of phase change material integration in clay hollow brick composite in building envelope for thermal management of energy efficient buildings. J. Building Phys. 43, 4, 351–364, 2020.
12. Kwiatkowski, J., Rucińska, J.: Estimation of energy efficiency class limits for multi-family residential buildings in Poland. Energies. 13, 23, 6234 (2020).
13. Lee S. et al.: Privacy-Preserving Energy Management of a Shared Energy Storage System for Smart Buildings: A Federated Deep Reinforcement Learning Approach. Sensors. 21, 14, 2021, DOI 10.3390/s21144898.
14. Levinskyte A. et al.: The Influence of Thermal Bridges for Buildings Energy Consumption of “ A “Energy Efficiency Class. Journal of Sustainable Architecture and Civil Engineering, 15, 2, 47–58, 2016.
15. Péan T.Q. et al.: Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings. J. Process Control, 74, 35–49, 2019.
16. Shkarovskiy A., Mamedov S.: Improving the Efficiency of Non-Stationary Climate Control in Buildings with a Non-Constant Stay of People by Using Porous Materials. Materials, 14, 9, 2021, DOI 10.3390/ma14092307.
17. Van Cutsem O. et al.: Cooperative energy management of a community of smart-buildings: A Blockchain approach. Int. J. Electr. Power Energy Syst. 117, 105643, 2020.
18. Vunjak D. et al.: The influence of linear thermal transmittance of thermal bridges on the energy performance class of buildings – simplified method, 2016, DOI 10.7251/afts.2016.0814.073v.
19. Wang K. et al.: IEEE Access Special Section Editorial: Energy Management in Buildings. IEEE Access. 8, 1453–1457, 2020.
20. DBN V.2.6-31:2016. Teplova izolyacia budivel. [Thermal insulation of buildings.] // K.: Minregionbud Ukraini, 2017.
21. DSTU B A. 2.2-12:2015 Energetichna efektivnist budivel [ Energy efficiency of buildings. Method of calculating energy consumption for heating, cooling, ventilation, lighting and hot water supply]. – K.: Minregionbud Ukraini, 2015.
22. DSTU-N B V.1.1-27:2010. Budivelnaya klimatologija [Civil Engineering Climatology]. – K.: Minregionbud Ukraini, 2011.
23. EN 13829 Thermal performance of building - Determination of air permeability of buildings - Fan pressurization method (ISO 9972:1996, modified).
24. Energy performance of buildings - Calculation of energy use for space heating and cooling, European Committee for Standardization, 2008.
25. Iurchenko Iev.L.: Development of the energy saving projects in the buildings of budget organizations on the basis of reinvestment. – Manuscript: 05.13.22 / Iurchenko Iev.L. – Dnipropetrovsk 2004.