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Reducing the Concentration of Carbon Dioxide in Indoor Air Using Absorption-Based Capture

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ABSTRACT

Preservation of the quality of the environment and the safety of human life depend on a multitude of factors. Recently, one of the most significant of these factors has been increasing carbon dioxide content in the Earth's atmosphere and the air in industrial facilities and residential and public buildings. Capturing CO_2 to lower its content in the air is among the most topical issues in current scientific studies. The presented study demonstrates the adverse effects of CO_2 on human health and climate change. The authors conduct a patent search and an analysis of literary sources on methods of CO_2 removal and systematize and substantiate the expediency of further experimental studies on improving sorption-based removal. The study presents a specially developed toolkit, including an experimental setup for testing various substances and reagent solutions for efficiency of CO_2 capturing in indoor spaces, a program methodology of respective experiments, and a dedicated software program "Processing of the results of experimental studies of the properties of CO_2 absorbers". The research findings indicate that all the examined solutions can be used to reduce CO_2 concentration in the air in indoor spaces, although the most efficient of these is a solution of caustic soda. The obtained results are of undoubted interest for the development of technologies and methods of capturing CO_2 to reduce its concentration in the air in residential, public, and industrial buildings, in emergency shelters, and in the atmosphere.

1. INTRODUCTION

1.1 Urgency of the problem of reducing carbon dioxide concentration in the air

Human safety is defined by a variety of factors, which are formed both in daily life (including production activities) [1] and in natural and anthropogenic emergencies [2]. One of the negative factors affecting both humans and the environment is the increasing content of carbon dioxide in the air in residential, public, and industrial buildings and the Earth's atmosphere [3].

For example, inefficient ventilation of residential and public buildings results in a significant elevation of CO_2 concentration due to people breathing, which reduces air quality [4]. Experimental data show that in one hour, the content of CO_2 in a 215 m^3 room with eleven people in it almost doubles (from 903 to 1,735 ppm) [5, 6]. Established standards regulating the content of CO_2 in indoor rooms prescribe the optimal content equal to 800 ppm, which corresponds to high air quality. An allowable concentration of CO_2 falls within 1,000-1,400 ppm. CO_2 content above these values indicates that the air in the room is of low quality and can have a negative influence on the human body. Low-quality air can cause reduced attention span and drowsiness, and even higher CO_2 concentrations may lead to a decrease in mental and nervous activity, deterioration of hearing and vision, migraines, and more [5, 7]. The risk of CO_2 accumulation in such rooms further increases if they have combustion-based energy sources (fireplaces, furnaces, stoves, etc.) [8]. CO_2 can increase the body's resistance to bacterial and viral infections and plays a part in the exchange of biologically active substances. During physical activity, CO_2 supports balance in the body, and yet elevated CO_2 content in the air causes malaise. Furthermore, increased CO_2 content leads to a higher risk of infections [9]. For example, American researchers S.N. Rudnick and D.K. Milton conducted a study on the risk of contracting flu in the classroom. In their experiment, 30 people, one of whom had the flu, were kept in the same room for four hours. With a CO_2 concentration at 1,000 ppm, the number of persons who got infected was five, at 2,000 ppm it reached 12 people, and at 3,000 ppm 15 people got sick [10].

CO_2 can negatively affect people engaged in production activities, which is particularly problematic in industrial facilities where CO_2 is used as part of production technologies [11]. This applies to special machinery producing dry ice and fog, the production of carbonated beverages in the food industry, the use of CO_2 for mushroom cultivation, the production of fire extinguishers, etc. [12]. Studies have found elevated CO_2 concentrations at workplaces in underground spaces [13] and in premises designed to protect the public in emergencies [14].

The leading concern of modern researchers is the negative impact of CO_2 emissions on the environment [15-17]. The primary consequence of atmospheric CO_2 emissions is the increase of the greenhouse gas effect, which contributes to global warming, the melting of glaciers, the rise of the sea level, changes in the salinity and temperature of seawater, changes in weather conditions, etc. Ecologists estimate that in technologically developed countries, CO_2 is the greatest contributor to greenhouse gas emissions (86%) [18]. In October 2022, an international group of scholars announced that the concentration of CO_2 in the Earth's atmosphere had reached 418 ppm, which is the highest global monthly concentration ever registered [19]. Furthermore, concern about increasing CO_2 emissions is explained by the fact that global warming can have an adverse impact on natural ecosystems and humanity as a whole [20-23]. The urgency of this problem is reflected in official documents by the European Commission and the United Nations [24-26]. By 2025, many countries are planning to make their economies carbon-neutral, thereby lowering their greenhouse gas emissions. A critical step to reducing CO_2 concentrations and preventing global warming is to develop CO_2 capture and recycling technologies [27]. Thus, decreasing the concentration of CO_2 in the air both in the environment and in residential, public, and industrial buildings is highly relevant.

Our literature analysis shows that research on reducing the concentration of CO_2 in the atmosphere is carried out primarily on two fronts:

- reducing CO_2 emissions from its sources [28-30];
- removing CO_2 from the atmosphere [31, 32].

2. LITERATURE REVIEW

2.1 Different CO_2 Capture Methods

At present, the leading methods of CO_2 capture are well-defined and can be systematically grouped into distinct categories, each with its unique mechanisms and applications.

2.1.1 Absorption

The process of the sorbate (CO_2) penetrating throughout the volume of the sorbent (amines, ammonia, alkali, ion fluids).

In the process of absorption-based CO_2 capture, the gas passes through the liquid, which absorbs CO_2, forming a solution. This solution is then separated, and CO_2 is reused or stored in a secure place.

A diagram of CO_2 absorption is shown in Figure 1.

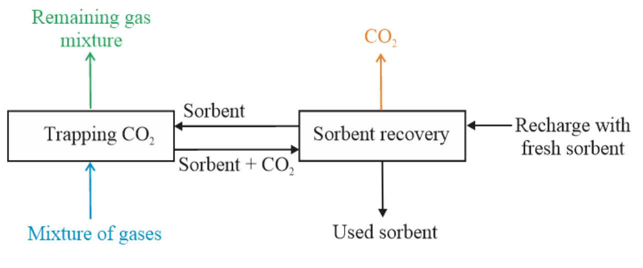

Figure 1. Diagram of CO_2 absorption

There are several types of liquids used to absorb CO_2. The most common option is an amine solution, which is made up of water-soluble amines. Amine solutions have a high capacity to absorb CO_2 and can be used in various types of industrial plants including power plants and oil and gas refineries [31].

One of the leading advantages of absorption is its capability to efficiently capture CO_2 while requiring relatively low costs. Furthermore, this method is characterized by high productivity and the simplicity and convenience of application.

Nevertheless, the absorption method is not devoid of limitations. Specifically, it can only be effective if the concentration of CO_2 in the air is high enough.

2.1.2 Adsorption

The process of absorption of molecules, atoms, or gas ions on the surface of solid matter (zeolites, metal-organic compounds, metal oxides, applied amines), where they can bind to the solid surface or create weak intermolecular forces.

Adsorbents can be metal, ceramic, or polymeric materials with certain chemical properties. In the development of effective sorbents, preference is given to porous materials with a high specific surface area and CO_2 adsorption capacity [33]. One of the most popular adsorbents is a chemical lime-based absorber used in breathing apparatuses and protective constructions, including protection against adverse factors and emissions in fires [34].

The process of CO_2 adsorption can be improved by changing the temperature, pressure, and composition of the gas mixture. Another option is to use various adsorbent regeneration methods that restore adsorption capacity.

The methods commonly used in CO_2 adsorption include:

- adsorption with temperature fluctuations;
- adsorption with regeneration pressure fluctuations;
- adsorption with electrical current oscillations.

Of importance are also the renewal and recirculation of adsorbent materials in the process of adsorption. Importantly, an adsorbent with high adsorption capacity and good selectivity consumes a lot of energy during regeneration.

2.1.3 Membrane separation

Membranes used for separation are specially manufactured materials that are selectively permeable to gases. The membrane's selectivity to different gases is closely connected with the nature of the material, as the flow of gas through the membrane is usually determined by the pressure difference on this membrane. For this reason, high-pressure gas flows are generally preferred for membrane separation [35].

In the process of membrane separation of CO_2, the gas mixture is supplied to the membrane, where CO_2 passes through, while the other components remain on the other side of the membrane. Thus, CO_2 can be extracted from the gas mixture and disposed of or recycled. An important parameter in membrane separation is the gas separation coefficient, which is determined by differences in the size of gas molecules in the mixture. The larger the molecule, the lower the probability of it passing through the membrane.

Membrane CO_2 separation technologies have several advantages over other methods, including lower service and exploitation costs, as well as the possibility of applying them under low temperatures and pressure. Furthermore, this method achieves a higher degree of purification of gas flows from CO_2.

2.1.4 Cryogenic separation

This process consists in cooling the gas to an extremely low temperature and liquefying the concentrated CO_2 in the gas stream to the point of CO_2 eventually changing phases and separating.

The principle of cryogenic CO_2 separation relies on utilizing the different boiling points of gas mixture components. CO_2 has higher boiling and condensation temperatures than other components in the gas mixture, such as nitrogen, oxygen, and argon. Therefore, when the mixture is cooled down to cryogenic temperatures, CO_2 can be separated from other components. The mixture is ultimately supplied to a distillation column, where the gases are more fully separated based on their boiling and condensation temperatures. Cryogenic separation is used in the production of highly purified CO_2 required for many industrial and medical purposes [36].

2.2 Research problem

Current studies reflected in patents are indicative of research attention to adsorption and absorption methods. Russian Federation patent No. 2600348 "Method for capturing carbon dioxide in power station flue gas and device therefor" describes a method of capturing CO_2 from the flue gas of a power plant and the installation for its realization. The method is marked by a high efficiency of capturing, low energy costs, and a simple technological scheme. This CO_2 capture method relies on the use of an adsorbent, which is applied in two consecutive stages. The invention proposes to use spherical adsorbent granules, which raise the efficiency of CO_2 capture. Furthermore, efficiency is increased by a multistage system of adsorbent regeneration.

The installation implementing this method includes absorbers for primary CO_2 absorption, regenerators for the separation of CO_2 from the adsorbent, and process control and monitoring systems [37].

The RF patent No. 2732647 "Mechanical system for capturing and transforming pollutant gases and air purification method" describes a mechanical complex for the purification of polluted air from harmful substances, such as CO_2 and NO_x and solid particles, in industrial systems. This system consists of metal components installed in a specific order, including a particle trap module and a molecular conversion module, which function as sorbents. The device works only with solid components, does not use solvents, and does not require an external energy source to capture gases or separate products, making it more environmentally friendly. The proposed invention consists of a material matrix, a porous and chemically active matrix arranged in a specific sequence, and filters, which need to be replaced at certain time intervals depending on the degree of outgassing in the industrial system.

The system has a wide range of applications and can be utilized for air purification in a variety of circumstances [38].

The purpose of RF patent No. 2540613 "Process gas purification system" is to improve the efficiency of CO_2 absorption by an ammonia solution. The system is designed to remove CO_2 from a gas stream by bringing the stream into contact with a circulating stream of an ammoniated solution so that CO_2 is removed from the gas by the flow of the ammoniated solution. This method involves the separation of the injected solution into the gas phase enriched with ammonia and the liquid phase containing non-volatile compounds, followed by the reintroduction of the gas phase back into the circulating ammonia solution flow. This prevents the negative impact of non-volatile compounds on the extraction process, as well as the corrosion activity of the ammonia solution. The gas-liquid separation device allows adding an alkaline additive to the solution. This process gas purification system can reduce harmful emissions into the environment and improve the efficiency of industrial processes [39].

Currently published results of research on CO_2 absorption processes and the reduction of CO_2 concentration, including through gas absorption by various reagents [40-42], demonstrate their effectiveness and the need for continued research on the selection of reagents. CO_2 capture technologies are actively developed, and their application becomes increasingly relevant for resolving contemporary environmental problems [43-45]. This entails the relevance of practical experiments aimed at reducing CO_2 content in the air of various interior spaces by capture methods. In turn, the reduction of CO_2 content in indoor air will lower CO_2 emissions into the environment and contribute to solving the problem of greenhouse gas emissions.

2.3 Research objectives

The goal of the present study was to assess the extraction of CO_2 from the air of indoor spaces for various purposes through different sorption methods. Accordingly, the following research objectives were established:

- to systematize CO_2 capture methods;
- to choose the direction for further improvement of CO_2 capture technology for indoor air;
- to conduct an experiment to evaluate different methods of reducing the concentration of CO_2 in the air in indoor spaces.

3. METHODS

The theoretical and methodological foundation of our research is comprised of research and popular science sources. Additionally, a patent search was conducted on the topic of CO_2 capture from the air. The study employed the methods of analysis and synthesis, generalization and systematization, mathematical statistics, formalization, and a full-scale experiment.

3.1 Systematization of CO_2 capture methods and the choice of direction to improve the technology of indoor CO_2 capture

To choose the direction of CO_2 capture technology for the study, we conducted an analysis and systematization of literary information sources and patents.

Various methods of CO_2 extraction and capture from a gas stream were analyzed and systematized. As a result, the advantages and disadvantages of existing methods and their strengths and weaknesses were identified.

Ultimately, the improvement of absorption-based methods of CO_2 capture in various indoor spaces was chosen as the direction for further research given the advantages of this group of methods.

3.2 Experimental testing of ways to deduce CO_2 concentration in indoor air by the method of absorption-based capture

To assess the efficiency of CO_2 capture by various substances under meteorological conditions close to normal, a series of experimental tests were carried out. Current regulations in the Russian Federation establish optimal and allowable CO_2 concentrations in indoor spaces. A high quality of indoor air is achieved with a CO_2 concentration not exceeding 400 ppm (cm^3/m^3). Medium air quality implies around 400-600 ppm of CO_2. At the level of 600-1,000 cm^3 of CO_2/m^3, air quality is considered acceptable. Finally, low-quality air contains more than 1,000 ppm of CO_2.

The tests carried out as part of this study were performed using an experimental setup whose structural diagram is provided in Figure 2.

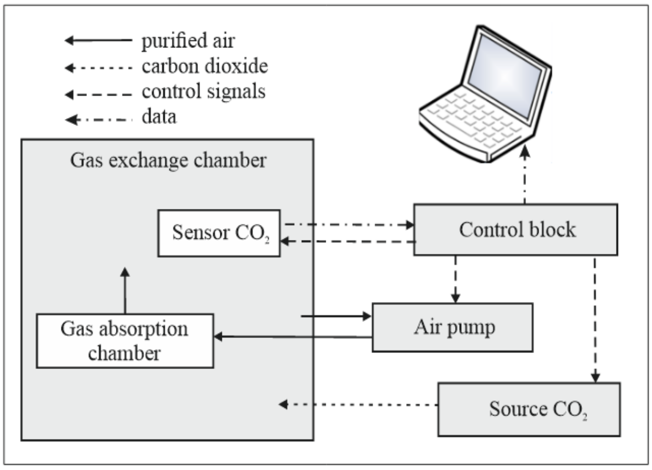

Figure 2. Structural diagram of the experimental setup

The experimental setup (laboratory) included the following elements:

1. Gas exchange chamber: An artificial environment where most of the experiment on absorption with various reagents was conducted. The chamber is shaped like a parallelepiped, with dimensions of 50 cm × 40 cm × 50 cm, and a volume of 100 liters (0.1 m^3). It is made of clear organic glass to allow visual monitoring of the experiment.
2. A computer recording data as grapes and files in the .xlsx format.
3. Control block based on a microcontroller. The control block was comprised of the microcontroller itself, a commutation block, a supply unit, a power relay, and switching devices.
4. The source of CO_2 (a gas cylinder with the necessary shut-off equipment).
5. Air pump supplying air for purification.
6. Gas absorption chamber with a diffusor.
7. Sorbent.
8. CO_2 detector with a range of measurable concentrations from 0 to 3,000 ppm.
9. Connecting tubes.
10. Connection, control, and data lines.

3.3 Research objects

The objects under study were substances and reagent solutions capable of capturing CO_2:

1. Distilled water complying with TU 2638-007-52600040-2005. Chosen as a control substance due to its purity and lack of additional reactive components. It serves to illustrate the baseline CO^2 absorption capacity of water without impurities;
2. Tap water. Selected to understand the impact of common water impurities (such as nitrites, nitrates, fluorides, and chlorides) on CO_2 absorption. This provides a practical comparison to distilled water;
3. Soda ash (sodium carbonate – Na_2CO_3): used in a 5% solution due to its well-documented ability to react with CO_2 to form bicarbonate, thereby absorbing CO_2 from the air. Sodium carbonate is also a widely available and cost-effective reagent;
4. Caustic soda (sodium hydroxide – NaOH): used in a 5% solution, it is known for its high reactivity with CO2, forming carbonate and water. Sodium hydroxide is an effective and strong alkali, making it a potent absorber for CO_2.

Per the developed research program, tests were carried out in two stages:

1. Stage 1 – preparatory, which included preparing the room for the experiment and assembling and setting up the experimental installation.
2. Stage 2 – the primary stage, which involved:

a) conducting the experiment, specifically:
- preparing reagent solutions of specified concentrations;
- measuring the pH of the solution;
- pouring the reagent solution into the absorption chamber;
- recording initial temperature readings and CO_2 content in the gas exchange chamber;
- injecting CO_2 into the gas exchange chamber;
- pumping air through the sorbent solution for 90 minutes while measuring temperature in the gas exchange chamber and recording the results in a dedicated file;
- measuring the pH of the solution;
- resetting the experimental setup;

b) processing the results of experimental studies. Data processing was performed using specialized software both on the side of the control unit and on the side of the PC. For this purpose, a software program “Processing of the results of experimental studies of the properties of carbon dioxide absorbers” was created and registered [46].

4. RESULTS

4.1 Experimental study of CO_2 absorption

Proceeding from the results of the experiment and the processing of experimental data, we created graphs of the dependence of changes in average CO_2 concentrations during air purification using different substances.

A) Distilled water

Figure 3 reflects the dynamics of average CO_2 concentration throughout air purification using distilled water. In this and subsequent graphs, red, yellow, and green lines stand for the concentrations of CO_2 corresponding to low, medium, and high air quality, respectively.

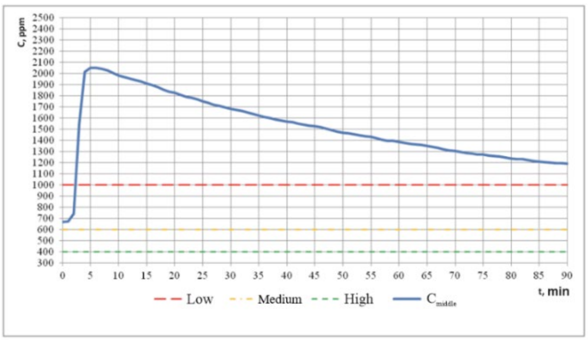

Figure 3. Dynamics of average CO_2 concentration during air purification using distilled water

The obtained data show that pH lowered from 7 to 6 and the concentration of CO_2 in the air decreased by 1.72 times. This indicates that distilled water can decrease CO_2 content in the air. The reduction in CO_2 concentration is primarily due to the dissolution of CO_2 in water and less so through the formation of carbonic acid. The limited effectiveness of distilled water as a CO_2 absorber is likely due to its neutral pH and lack of reactive components that can bind with CO_2 more effectively.

B) Tap water

Figure 4 displays the dynamics of average CO_2 concentration during air purification with tap water.

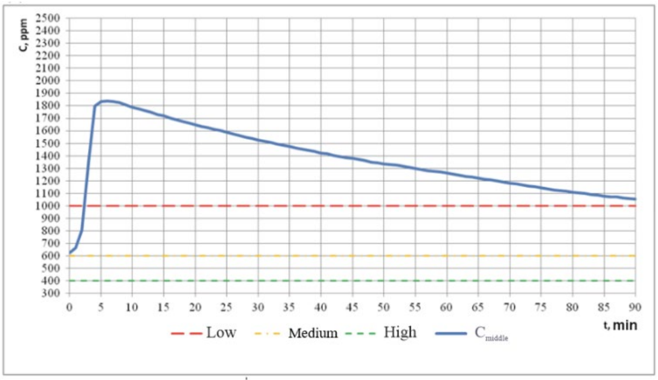

Figure 4. Dynamics of average CO_2 concentration during air purification using tap water

The obtained results indicate that pH reduced from 7 to 6, while CO_2 content lowered by 1.74 times, which is a little more than what was achieved with distilled water. Same as distilled water, tap water can only minorly reduce the concentration of CO_2 in the air. This effect is provided more by the dissolution of CO_2 and less by the formation of carbonic acid. Therefore, water cannot hold dissolved CO_2 for a long time and eventually releases it back into the air. Given that chemical analysis was not conducted as part of our experiments, we can draw a theoretical conclusion that the impurities contained in water do not have a significant effect on CO_2 absorption.

C) Soda ash

Figure 5 demonstrates the dynamics of average CO_2 concentration during air purification with a soda ash solution.

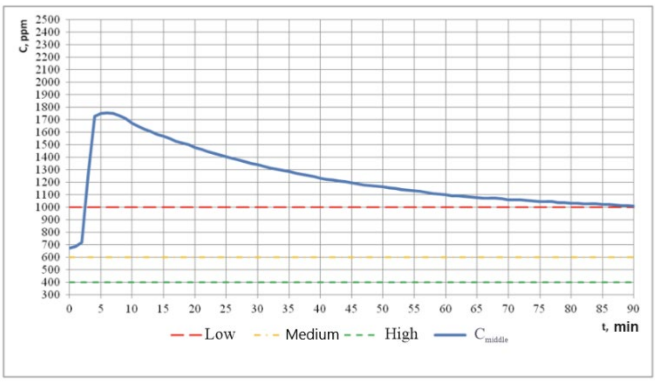

Figure 5. Dynamics of average CO_2 concentration during air purification using a soda ash solution

The obtained results show that pH lowered from 13 to 12 and CO_2 concentration dropped 1.75 times. Caustic soda is thus more efficient at absorbing CO_2 than distilled and regular tap water. This effect is provided by the following chemical reaction of CO_2 sequesting:

$$Na_2CO_3+H_2O+CO_2 \leftrightarrow 2NaHCO_3 \quad (1)$$

This indicates that sodium carbonate reacts with CO_2 to form sodium bicarbonate, effectively sequestering CO_2 from the air. The higher pH of the solution enhances its ability to capture CO_2, making it a more viable option for CO_2 absorption.

D) Caustic soda

Changes in the average concentration of CO_2 in the process of air purification using caustic soda are presented in Figure 6.

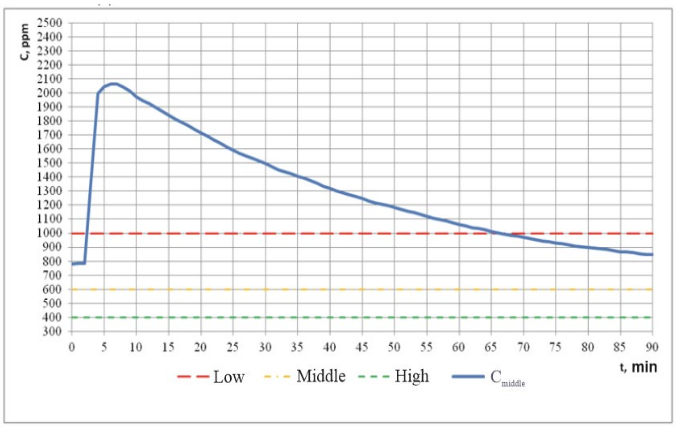

Figure 6. Dynamics of average CO_2 concentration during air purification using a caustic soda solution

Analysis of the obtained data shows that pH reduced from 14 to 13 and air CO_2 content lowered by 2.44 times. Caustic soda thus proves to be the most efficient of the considered substances by its ability to sequester CO_2.

This effect is achieved through the following chemical reaction of CO_2 sequesting:

$$2NaOH+CO_2 \rightarrow Na_2CO_3+H_2O+Q \quad (2)$$

The chemical reaction illustrates the strong alkaline nature of caustic soda, which facilitates a greater degree of CO_2 absorption compared to other substances. The substantial pH drops from 14 to 13 highlights the active conversion of CO_2, indicating that caustic soda can effectively reduce CO_2 concentrations in the air.

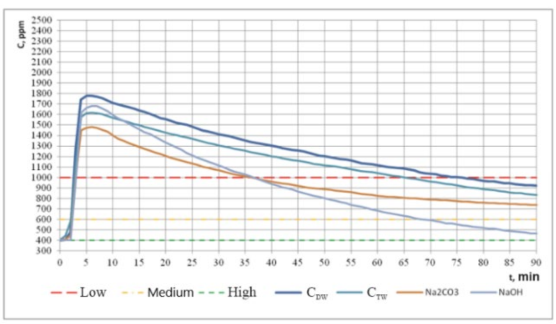

Figure 7. Dynamics of CO_2 concentration depending of the substance used in air purification

In Figure 7 we provide a comparative graph of changes in the average concentration of CO_2 in the process of air purification by different substances. The values of CO_2 concentration were brought to the same background value of 400 ppm.

5. DISCUSSION

5.1 Systematization of CO_2 capture methods

The conducted study has established that CO_2 capture methods can be presented in the following classification:

- absorption;
- adsorption;
- membrane gas separation in the flow;
- cryogenic gas separation.

Improvement of absorption-based CO_2 capture methods is chosen as the direction for further research given the following advantages of absorption:

- efficient CO_2 capture;
- comparatively low cost of sorbents based on aqueous alkali solutions;
- the possibility of using waste solutions as a detergent or disinfectant.

Further studies focus on developing a program of an experiment to determine the efficiency of CO_2 capture depending on the composition of the solution and the concentration of alkaline reagents in it.

5.2 Discussion of the results of the experiment to choose sorbents for CO_2 absorption

The conducted experiment established that all considered substances can be used to capture CO_2 and reduce its concentration in the air in indoor spaces. However, caustic soda was found to be the most efficient CO_2 sorbent. In the conducted experiments, pH was reduced by 1, showing an increase in the acidity of solutions due to the absorption of CO_2. Water can be used to reduce CO_2 concentration in the air under the condition that it is removed from the serviced room.

The efficiency of purification is not only contingent on the features of the sorbent solution but also increases with longer capture time.

6. CONCLUSIONS

The problem of the negative impact of CO_2 on the environment and the human body is acute. From this follows the relevance of the line of research on the improvement of CO_2-capturing methods. The significance of this study lies in its focus on capturing CO_2 from the air of indoor spaces for various purposes. We believe that the obtained findings are of undoubted interest for the development of technologies and methods to reduce the concentration of CO_2 in atmospheric air. The conducted experiment on CO_2 absorption by various substances is an important research step in the search for effective technologies and methods to reduce CO_2 concentration and improve the quality of air in the interior spaces of residential, public, and industrial buildings. Lower CO_2 content and better air quality will improve the quality of citizens' lives and reduce the probability of adverse situations. The reduction of CO_2 concentrations in interior rooms will also contribute to the reduction of CO_2 emissions into the environment, as well as the resolution of problems associated with greenhouse gases.

The proposed CO_2 capture methods have significant environmental and economic implications. Environmentally, reducing CO_2 concentration in indoor air can improve air quality, leading to better health outcomes for occupants by mitigating issues such as reduced attention span, drowsiness, and other health problems associated with high CO_2 levels. On a larger scale, implementing effective CO_2 capture in buildings could contribute to overall reductions in greenhouse gas emissions, helping to combat climate change.

In residential settings, small-scale CO_2 capture devices could be integrated into HVAC systems to continuously purify indoor air. For commercial and industrial settings, larger-scale installations could be designed to handle higher volumes of air and CO_2 concentrations.

Improved air quality can enhance productivity and reduce healthcare costs associated with poor indoor air quality. The use of relatively inexpensive sorbents like caustic soda and soda ash makes the implementation of these methods cost-effective. Additionally, the potential to use waste solutions as detergents or disinfectants can provide added value and reduce waste disposal costs.

7. LIMITATIONS AND FUTURE SCOPE

This study has several limitations. The experiments were conducted in a controlled laboratory setting, which may not fully replicate real-world indoor environments where variations in temperature, humidity, and air flow could impact the effectiveness of CO_2 capture methods.

To build on these findings, future research should include real-world testing in varied indoor environments to validate the laboratory results and assess practical applicability. Investigating a broader range of potential CO_2 absorbing substances, including novel reagents, could identify more effective solutions.

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