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Automated air pressure control system in a motorised breathing apparatus

Abstract. The relevance of the study is to develop an effective system for controlling the pressure in the air supply in motorised breathing apparatus to ensure effective protection of employees from dangerous aerosols and improve their health. The goal was to create an automated air pressure control system in a motorised breathing apparatus using a proportional-integral-derivative controller. For this purpose, the simulation method was used. In order to avoid unforeseen situations of deterioration of the level of protection, the structure of the pressure control system of a motorised respirator has been developed with the selection of the appropriate controller based on the obtained dependences of the influence of the parameters of the breathing mode and the amount of pressure in the under-mask space of the respirator, which ensures an appropriate comfortable mode of operation. This allowed developing a simulation model with a PID controller that would provide the appropriate pressure values within the permissible limits (50-370 Pa). It is proved that the proportional-integral-derivative controller maintains the pressure in the respirator mask within certain limits both with an increase and with a decrease in the control signal, preventing excessive fluctuations in the controlling variable, which leads to an extension of the service life of the filter elements and a reduction in electricity consumption for the operation of the fan motor. Based on modelling the operation of the pressure control system in different modes of operation, it is shown that when using a PID controller with defined parameters, the system provides compensation for changes in air

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pressure in the under-mask space of the respirator in different breathing modes of the user. The results can find practical applications in the field of safety and health, in industrial environments where workers are at risk of inhaling dangerous aerosols, such as toxic particles, gases, or other harmful substances

Keywords: identification; simulation model; motorised respirator; controller; setpoint; pressure

INTRODUCTION

The need to ensure effective protection of employees from potentially dangerous aerosols and pathogens that can cause diseases of the pulmonary system makes this problem relevant. The use of motorised respirators is determined by their efficiency, comfort, and performance, depending on the pressure in the air supply system. High pressure reduces the protection efficiency and reduces the operating time, since increasing the resistance on the filters leads to battery power consumption. In this regard, there is a need to develop an automated air pressure control system in motorised respirators. This system allows controlling the period of protective action, which is critical for the safe operation of respirators. Existing models of respirators have limited control systems that do not consider all possible use situations. For example, insufficient pressure can cause untreated air to enter, and lack of respiratory rate control can cause discomfort and disability. Thus, the task of developing an air pressure control system for motorised respirators, which considers the variability of the parameters of the human breathing cycle under variable physical activity, environmental pollution, and climatic conditions, becomes urgent.

Many studies have been devoted to the issue of determining parameters and configuring the control system for various technological processes. S.S. Zhou *et al*. (2018), P. Otrisal *et al*. (2021) proposed a model for simulating breathing based on the user's physical activity. Their development is quite interesting for building simulation models that allow selecting parameters for the pressure control system in motorised respirators. The disadvantages of the proposed model include the lack of a description of the effect on the dynamics of the respiratory rhythm of the interaction of central circuits that generate biomechanics through feedback from peripheral signalling pathways, as indicated by the authors of another study (Brook *et al*., 2017).

An interesting problem was solved by P. Otrisal *et al.* (2020), which consisted in evaluating the performance of a pneumatic installation for transporting various materials. The researchers used a stimulation approach to solve the problem, which they implemented in the Matlab Simulink software suite. The value of the proposed approach is to develop a flexible model for evaluating the effectiveness of moving materials in pneumatic installations, which considers various parameters: changes in the resistance of the system, the weight of materials, the amount of air, and energy costs for moving materials. However, the use of the proposed model for controlling the pressure in the system of a motorised respirator, unfortunately, is only partially possible to determine the cost of electricity due to changes in parameters. Unfortunately, the system does not provide for dynamic fluctuations in the human breathing process and requires appropriate processing.

The study by R. Weiss *et al*. (2021) developed a model for regulating the air supply to the under-mask space of a respirator based on the design of a blower, which can control the centrifugal fan in automatic mode, in accordance with the breathing patterns. The researchers obtained several important conclusions, which were later used in the development of a new simulation model. In particular, they established a relationship between the duty cycle and the fan speed (W410F1) from the respiratory flow. It was noted that the control system, which is based on a single-chip microprocessor (STM32F103VET6), creates prerequisites for delaying the supply of air flow due to a sharp change in load. This disadvantage was proposed to be reduced by the presence of an additional control system, which will reduce the amount of delay.

G. Gheorghe *et al*. (2021) simulated the operation of a motorised respirator on a dummy with three different breathing modes to build an appropriate mathematical model that will allow for the control process of air purification. However, when considering the process of correcting aerosol particles into the under-mask space, the researchers did not consider the dynamics of changes in respiratory modes due to stress in the mathematical model.

N. Al-Naggar (2015) conducted a simulation study of the work of anesthesiologists who used motorised respirators to determine the comfort of their use. Ease of breathing, noise, heat changes, visibility, and speech intelligibility were evaluated. In one of the conclusions of the study, it was noted that the rapid discharge of the battery leaves users defenceless, which requires further improvement of the design, which would ensure the operability of the motorised respirator in a given service life. Similar conclusions regarding the provision of a comfortable feeling when using motorised respirators were obtained by S. Cheberyachko *et al*. (2020) and A. Licina & A. Silvers (2021), where participants in the experiment also addressed the need to ensure the required duration of their work.

The analysis of the conducted studies confirmed a significant interest in the development of motorised respirators that ensure their comfortable use, based on working conditions, physical activity, and breathing patterns. A study of the effectiveness of using such devices by users showed an inappropriate level of electrical charge of batteries, which did not allow them to work out the entire required service life. Analysis of other papers has shown that such a situation can occur when there is no effective pressure control system or other variable parameters.

The purpose of the study was to develop an automated air pressure control system in a motorised breathing apparatus based on a proportional-integral-derivative controller (PID controller).

In order to achieve the research objective, the following tasks need to be completed:

- to develop the structure of the air pressure control system of a motorised respirator with the selection of the appropriate controller and to obtain the dependences of the influence of the parameters of breathing modes on the functioning of the control system, based on the initial conditions;
- to select the characteristics of the controller that ensure the approximation of the air pressure value to rational values based on the analysis of the dependence of the influence of the parameters of breathing modes on the functioning of the control system;
- to compare the simulation results with experimental data on changes in air pressure in the respirator mask under different operating modes.

MATERIALS AND METHODS

An experimental stand with a physical model of a motorised respirator was used for the study (Fig. 1), the design of which was described in the paper by S. Cheberyachko *et al*. (2020).

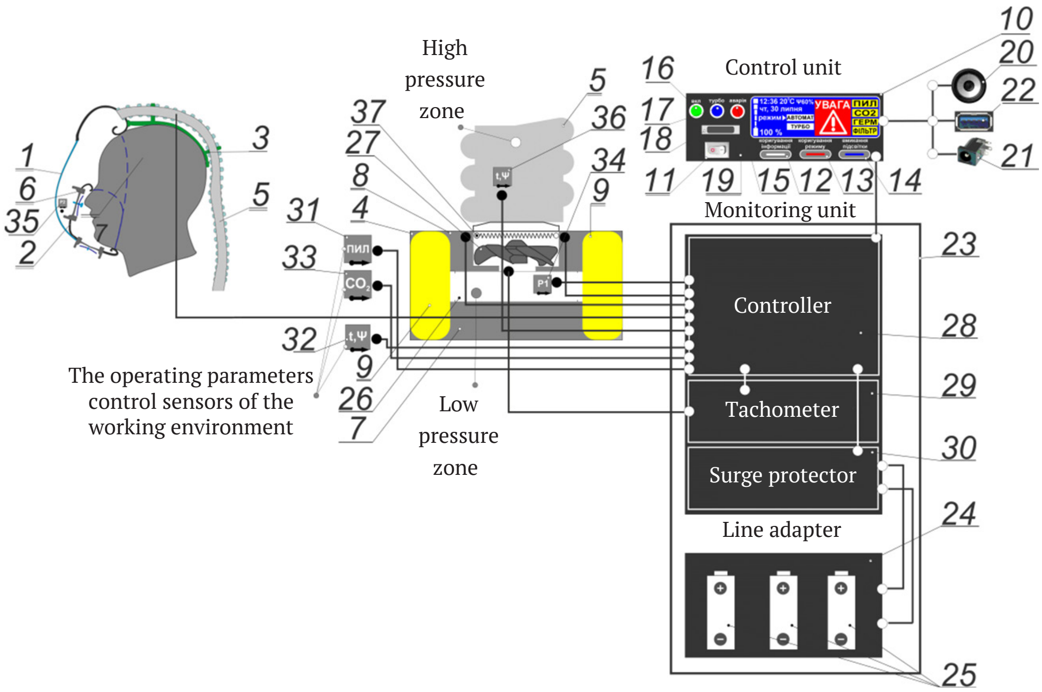

Figure 1. Test stand with a physical model of a motorised respirator

Note: helmet mask (1), gas seal (2), headband straps (3), air purification device (4), flexible corrugated duct (5), inhalation valve (6), exhalation valve (7), air purification device housing (8), filter elements (9), control unit (10), toggle switch "on/off" (11), button No. 1 (12) – "Information adjustment" (time, day of the week, month, ambient temperature, humidity); button No. 2 (13) "Mode adjustment" (automatic mode, turbo mode, emergency mode); button No. 3 (14) – "Display backlight"; light indicators: red indicator light (15) – "Accident", blue indicator light (16) – "Turbo", green indicator light (17), memory card (18), display (19) speaker (20), battery charger (21), USB connector for connecting to a PC for configuring and adjusting the software of the air purification device (22), monitoring unit (23), power supply unit (24) consisting of three batteries (25), channel (26), fan (27), controller (28), tachometer (29), surge protector (30), sensor for monitoring the presence of dust in the atmosphere of the working area (31), sensor for monitoring temperature and humidity in the atmosphere of the working area (32), sensor for monitoring the concentration of carbon dioxide in the atmosphere of the working area (33), pressure monitoring sensor in the low pressure zone (34), pressure monitoring sensors in the high pressure zone (35), temperature and humidity monitoring sensor in the high pressure zone (36), purified air heater (37)

Source: S. Cheberyachko *et al*. (2020)

To create a control system that would qualitatively regulate the selected technological parameters of motorised filtering respirators, it was necessary to obtain detailed information about the dynamic properties and behaviour of the control object: changes in air pressure in the mask of a motorised respirator developed by J. Schumacher *et al.* (2020), which depend on the depth and frequency of human breathing during different work (Fig. 2), characterised by the minimum pressure (during inhalation, p_{min}, Pa); maximum pressure (during exhalation, p_{max}, Pa); inhalation duration (t_{inh}, s); exhalation duration, (t_{exh}, s).

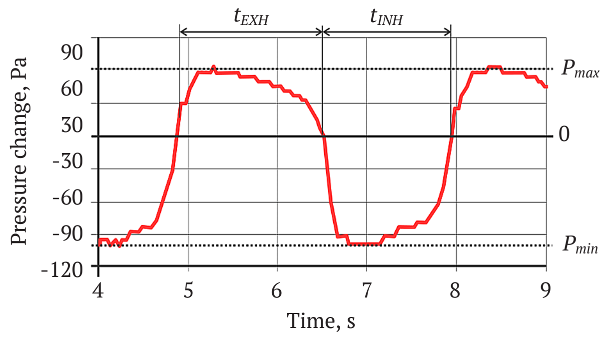

Figure 2. Pressure changes during breathing

Note: the vertical line shows the change in pressure (Pa) in the respirator mask during the process of inhalation and exhalation of air from the lungs: p_{max} – maximum exhalation pressure and p_{min} – maximum rarefaction that is formed during inhalation; the horizontal line shows time interval of exhalation (t_{exh}) and inhale (t_{inh})

Source: I. Dediv (2012), J. Schumacher *et al.* (2020)

To build a simulation model of a motorised filtering respirator, the human breathing process is given in the form of an equation (Cheberyachko *et al.*, 2022):

$$p(t) = A \cdot \sin(2\pi nt/60) - h, \quad (1)$$

where $p(t)$ – pressure created during breathing, Pa; A – respiratory amplitude, Pa; n – respiratory rate, $n = 60/T$, min^{-1}; T – period of the breathing cycle, s; h – signal displacement, which depends on the ratio of respiratory phases (exhalation/inhalation), Pa; t – time, s.

The signal offset was defined as:

$$h = (h_{inh} - h_{exh})/2, \quad (2)$$

where h_{inh} – rarefaction during inhalation, Pa; h_{exh} – exhalation pressure, Pa.

At the same time, h_{inh} and h_{exh} are calculated as the average value of the maximum values of rarefaction and pressure of the respiratory cycle over the selected time interval of experimental data, for example, when performing light physical work (Fig. 3):

$$h_{inh} = \frac{1}{N}\sum_{i=1}^{N} h_{inh} i \text{ and } h_{exh} = \frac{1}{N}\sum_{i=1}^{N} h_{exh} i, \quad (3)$$

where $h_{inh}i$ – maximum inhalation dilution for i-th cycle of breathing, Pa; $h_{exh}i$ – maximum exhalation pressure for i-th cycle of breathing, Pa; N – number of breathing cycles on the selected time interval of experimental data; i – breathing cycle number, $i = 1,2 \ldots N$.

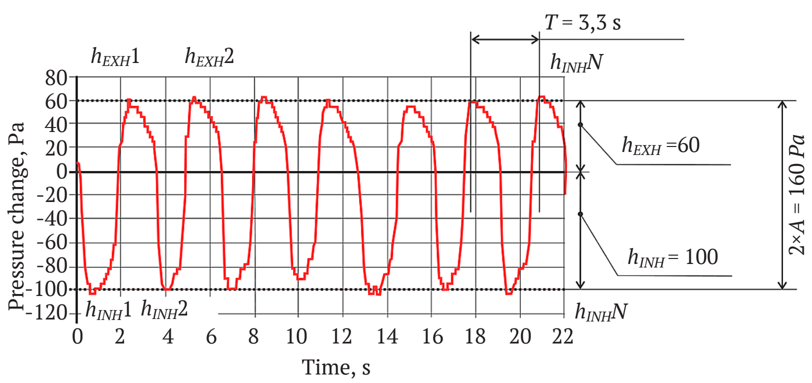

Figure 3. Characteristics of human breathing when performing work of the category "Light physical work 1b"

Note: T – period of the breathing cycle, s; $h_{inh}i$ – maximum inhalation dilution for i-th cycle of breathing, Pa; $h_{exh}i$ – maximum exhalation pressure for i-th cycle of breathing, Pa; N – number of breathing cycles on the selected time interval of experimental data; i – breathing cycle number, $i = 1,2 \ldots N$; experimental data were obtained in the process of human respiration when performing work of the 1b category of severity, which is determined based on the requirements of State Sanitary Standards 3.3.6.042-99 (1999); the period of the inhalation-exhalation process is 3.5 seconds; the change in pressure drop reaches 160 Pa

Source: S.S. Zhou *et al.* (2018), P. Otrisal *et al*. (2021)

Considering the given model of the respiratory signal in accordance with equation (1), a simulation model of a motorised filter respirator was developed (Fig. 4), which shows the relationship between the fan speed (u, rpm) applied to the input of the motorised respirator as a task signal and the pressure that the fan creates (p_{fan}, Pa), and the pressure created by a person during breathing ($p_{breathing}$, Pa), which together allows determining the total pressure in the under-mask space of the respirator (*y*, Pa), which is based on the fact that breathing effort increases by 60% at rest and up to 35% during physical activity. This was due to both the structural elements of the respirator (filter, inhalation/exhalation valves) and the presence of a “dead” space in the respirator mask – the remaining oxygen-depleted air after exhalation.

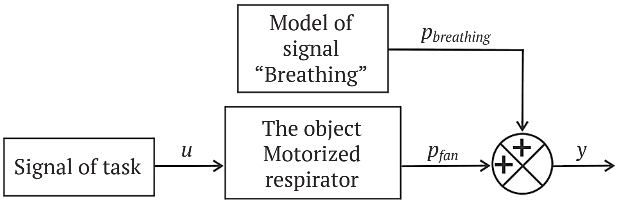

Figure 4. Block diagram of the simulation model

Note: the relationship between the fan speed is shown (*u*), which is applied to the input of the motorised respirator as a task signal, and the pressure p_{fan}, which at the same time creates a fan based on the resistance of filters and channels, and the amount of derivative pressure that the user creates ($p_{breathing}$), which ensures the appropriate mode of operation of the research object

Source: developed by the authors based on P. Otrisal *et al*. (2020), S. Cheberyachko *et al*. (2022)

Since a harmonic signal was used for the simulation, this allows reproducing the breathing mode in a motorised respirator for the category “Light physical work 1b”, with an air flow rate (200 l/min) at the limit of rarefaction with breathing pressure drop amplitude not exceeding 60 Pa. While for the breathing mode for the categories of work “Moderate severity 2a” and “Moderate severity 2b”, characterised by a pressure amplitude of up to 90 Pa, the second level of air flow rate (250 l/min) and for the categories of work “Heavy 3” – the third level: 120 Pa and 320 l/min, respectively (Makaveckas *et al*., 2023; Lee, 2024). With this approach, the user may not always be able to switch the device to the required flow rate in a timely manner, which can cause outside air to enter the mask through leaks when inhaling. This requires the development of a new motorised respirator control system that maintains the required air pressure in the under-mask space by changing the speed of rotation of the fan turbine. To solve this control problem, it is proposed to use two types of controllers: two-position and PID (proportional-integral-derivative).

Quality criteria that the air pressure control system in the respirator mask must meet:

1. Static accuracy (steady-state accuracy):

- established error or mismatch error (ε_{est}) – the maximum permissible deviation of the air pressure in the mask from the set value in the steady-state mode should not exceed 25 Pa.

2. Dynamic accuracy (transition quality):

- transition time (t_{tr}) – time it takes for the motorised respirator to reach the operating mode (the constant value of the corresponding parameter is the pressure in the mask), no more than 0.5 s;
- re-regulation (σ) – maximum permissible pressure deviation in the mask during operation should not exceed 20 Pa.

Approximation of experimental and theoretical data was performed using the normalised root-mean-square error (NRMSE), which was calculated in MATLAB using the “goodnessOfFit” function (Lutska *et al*., 2019).

RESULTS AND DISCUSSION

In general, the system of automatic control of air pressure in the under-mask space of a motorised respirator with feedback is shown in Figure 5.

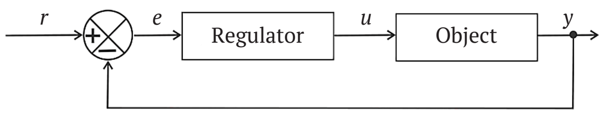

Figure 5. Block diagram of the automatic control system with feedback

Note: the difference between the setpoint (reference, *r*) of the pressure that must be maintained in the under-mask space of the respirator and the current value of the controlled value (*y*) determines the error or mismatch signal (*e*), based on which the output value of the controller or the controlling influence (*u*) is formed on the control object – a motorised respirator

Source: compiled by the authors

To adjust the two-position controller due to the setpoint U_{set} and deviations ΔU. The value of ΔU is selected equal to 0.5-0.7 of the permissible deviation range of the adjustable value. Reduction in ΔU leads to an increase in the frequency of operation of the controller, and the expansion of the zone ΔU may lead to an undesirable deviation of the adjustable value. Value of U_{set} is selected if:

$$U_{set} = U_{avg} + 0.5 \cdot U, \quad (4)$$

where U_{avg} – average value of the regulated value:

$$U_{avg} = (U_{max} + U_{min})/2. \quad (5)$$

That is, with an acceptable pressure fluctuation range of 20 Pa, the deviation will be ±10 Pa. Hence, the first block diagram of the simulation model of the control system of a motorised respirator with a two-position controller is shown in Figure 6. A block diagram of the simulation model of the control system of a motorised respirator with a PID controller is shown in Figure 7.

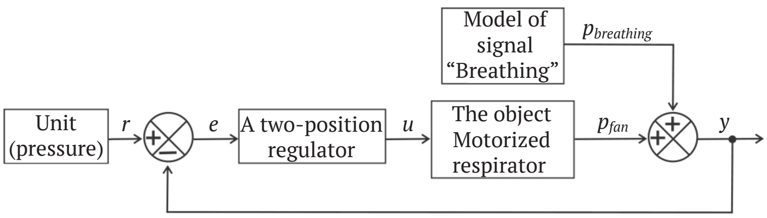

Figure 6. Block diagram of a control system with a two-position controller

Note: based on the pressure setpoint (*r*), which must be maintained in the under-mask space of the respirator, and the current pressure value in the mask (*y*), which is determined by the pressure generated by the fan (p_{vent}) and the user's breathing modes ($p_{breathing}$), the output value of the controlling influence (*u*) from the two-position controller is determined – the fan speedr

Source: compiled by the authors

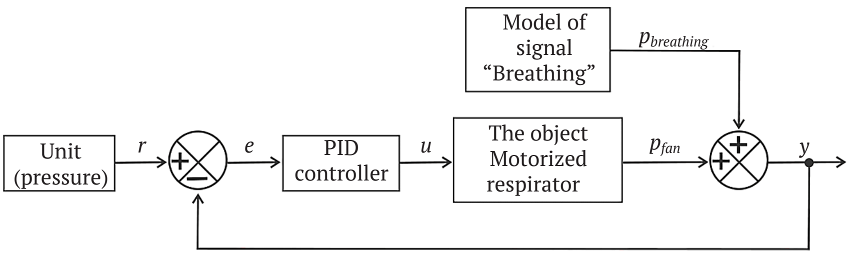

Figure 7. Block diagram of a simulation model of a control system with a PID controller

Note: based on the pressure setpoint (*r*), which must be maintained in the under-mask space of the respirator, and the current pressure value in the mask (*y*), which is determined by the pressure generated by the fan (p_{fan}) and the user's breathing modes ($p_{breathing}$), the initial value of the controlling influence (*u*) from the proportional-integral-derivative (PID) controller is determined

Source: compiled by the authors

The use of a PID controller requires appropriate configuration, which is performed using empirical and heuristic methods. It is proposed to change the controller parameters in the following sequence: first, adjust the gain of the proportional component K_p, when other channels are turned off, the gain of the integral component K_i is adjusted, and the last one determines the gain of the derivative component K_d. The controlling influence u(t), generated at the output of the PID controller, contains proportional and integral components:

$$u(t) = k_p \cdot e(t) + k_i \cdot \int_0^t e(t)dt + k_d \cdot \frac{de(t)}{dt}, \quad (6)$$

where $u(t)$ – controlling influence; $e(t)$ – error (discrepancy between the setpoint and the actual value); k_p – gain of the proportional component; k_i – gain of the integral component; k_d – gain of the derivative component.

This provides the necessary level of control over the air pressure in the respirator mask, based on the user's preset breathing modes. At the first stage, to identify the dependence of the influence of environmental parameters on the functioning of the air pressure control system during the respiration process, the experimental data of pressure changes were compared when performing works of the category "Light physical work 1b", which are published in the study N.M. Lutska *et al*. (2019) with a pressure change curve defined by a mathematical model, which is mapped by equations (1-3). The results of the approximation of experimental and theoretical data shown in Figure 8 are 58.74%, the correlation coefficient is 0.915, and the Fisher statistical criterion is 10273 (Lima *et al*., 2023). This indicates sufficient reliability of the mathematical model, which allows it to be used in further studies of the air pressure control system in motorised personal respiratory protection equipment (PRPE).

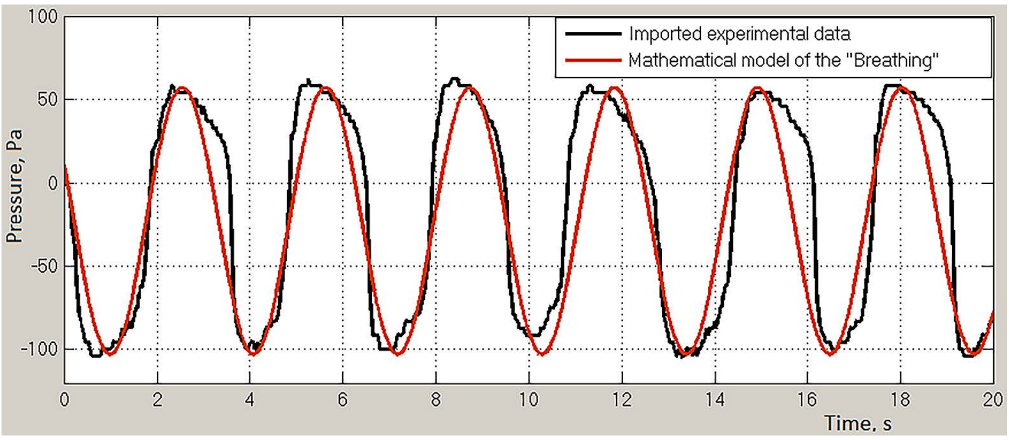

Figure 8. Experimental data for the category of "Light physical work 1b" and data from the mathematical model
Source: compiled by the authors

The next step was to test the operation of the motorised respirator on its simulation model, the block diagram shown in Figure 7, under different air supply modes (Fig. 9).

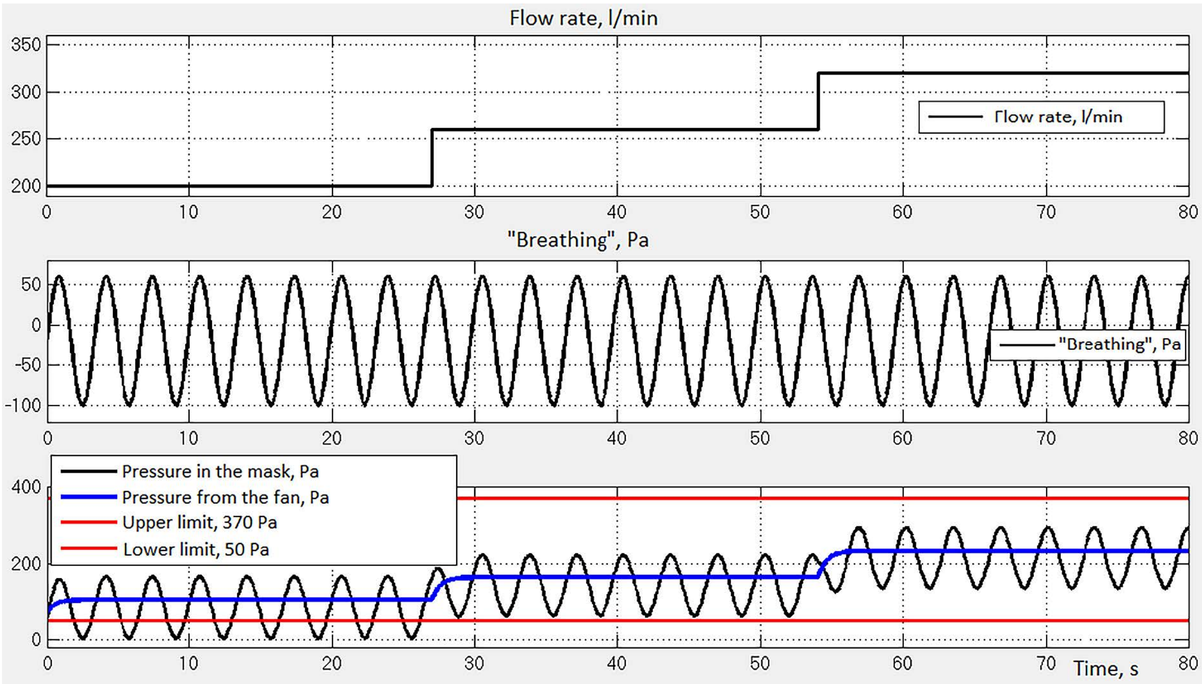

Figure 9. Result of the simulation model when changing the flow rate as a controlling influence under different operating modes
Source: compiled by the authors

Figure 9 shows that the disadvantage of the functioning of the simulation model of a motorised respirator is the drop in air pressure in the mask beyond the lower permissible limit (below 50 Pa), which can cause the suction of external polluted air into the mask, and there is also no compensation for forces during inhalation/exhalation.

Studies of the operation of the control system with a two-position air pressure controller in motorised respirators when performing work of the category "Light physical work 1b" and category "Heavy 3", considering the respiratory rate of 15 cycles per minute at a pressure amplitude of 60 Pa and 30 l/min at an amplitude of 120 Pa, respectively, are shown in Figures 10 and 11. However, the air pressure value was set for light physical work of 120 Pa, with fluctuations in the permissible range of 110-130 Pa, and for heavy physical work – 260 Pa with fluctuations in the range of 250-270 Pa.

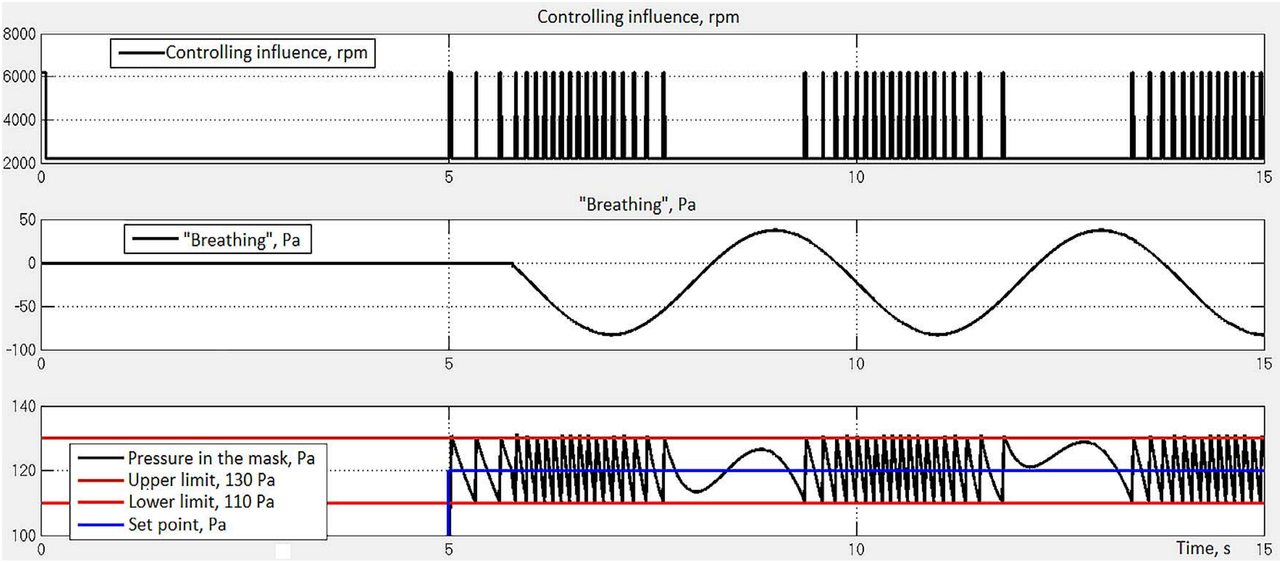

Figure 10. Simulation results at a sinusoid frequency corresponding to respiration of 15 cycles per minute with an amplitude of 60 Pa, a setpoint of 120 Pa

Source: compiled by the authors

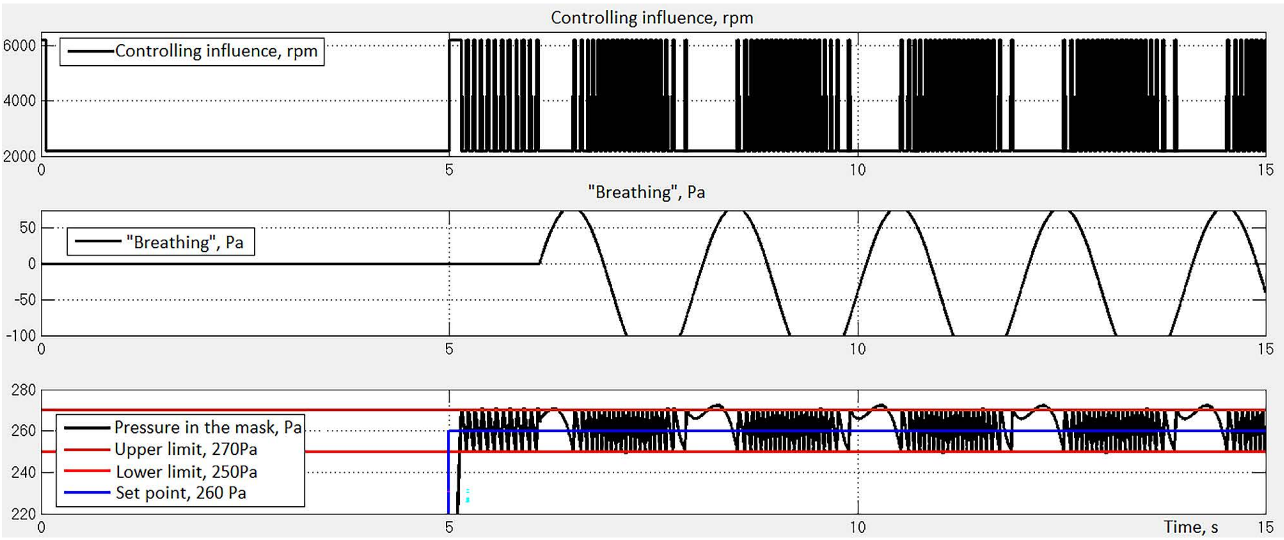

Figure 11. Simulation results at a sinusoid frequency corresponding to respiration of 30 cycles per minute with an amplitude of 120 Pa, a setpoint of 260 Pa

Source: compiled by the authors

Analysis of the results obtained when modelling a control system with a two-position controller showed that during operation there are exceeding the control limits up to 1 Pa during inhalation compensation and up to 2 Pa during exhalation. In addition, the fan is in the mode of constant fluctuations in the speed of rotation (min/max), up to 20 Hz, which can lead to premature exhaustion of the working life and its failure, cause additional noise and vibration.

Studies of the operation of the control system under the air pressure controller in motorised respirators when performing work of the category “Light physical work 1b” and category “Heavy 3” are shown in Figures 12 and 13.

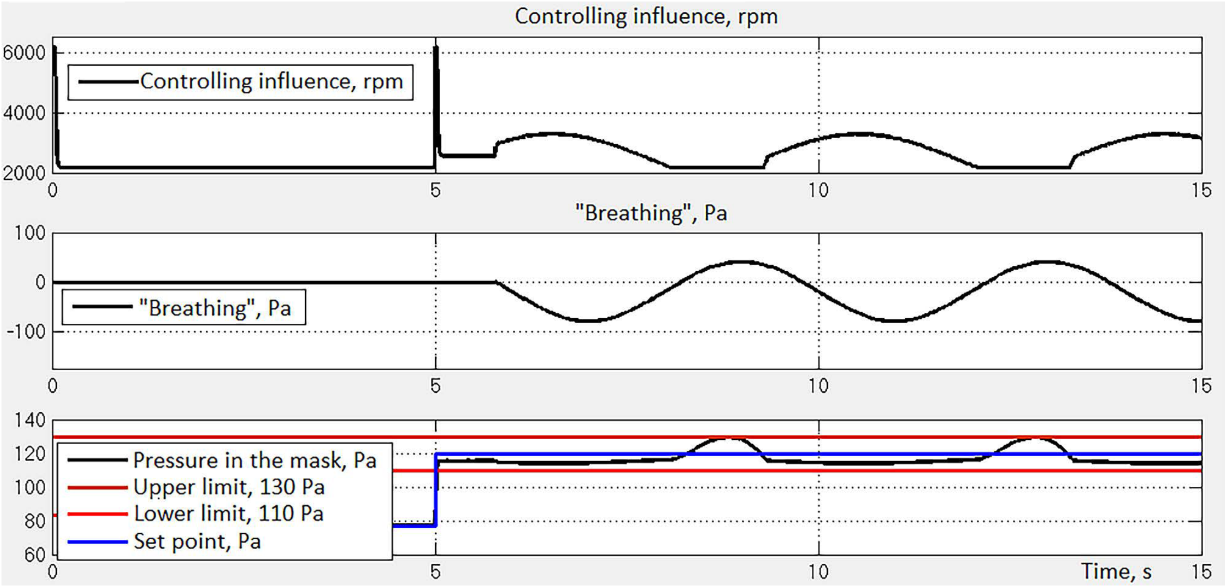

Figure 12. Simulation results at a sinusoid frequency corresponding to respiration of 15 cycles per minute with an amplitude of 60 Pa, a setpoint of 120 Pa

Source: compiled by the authors

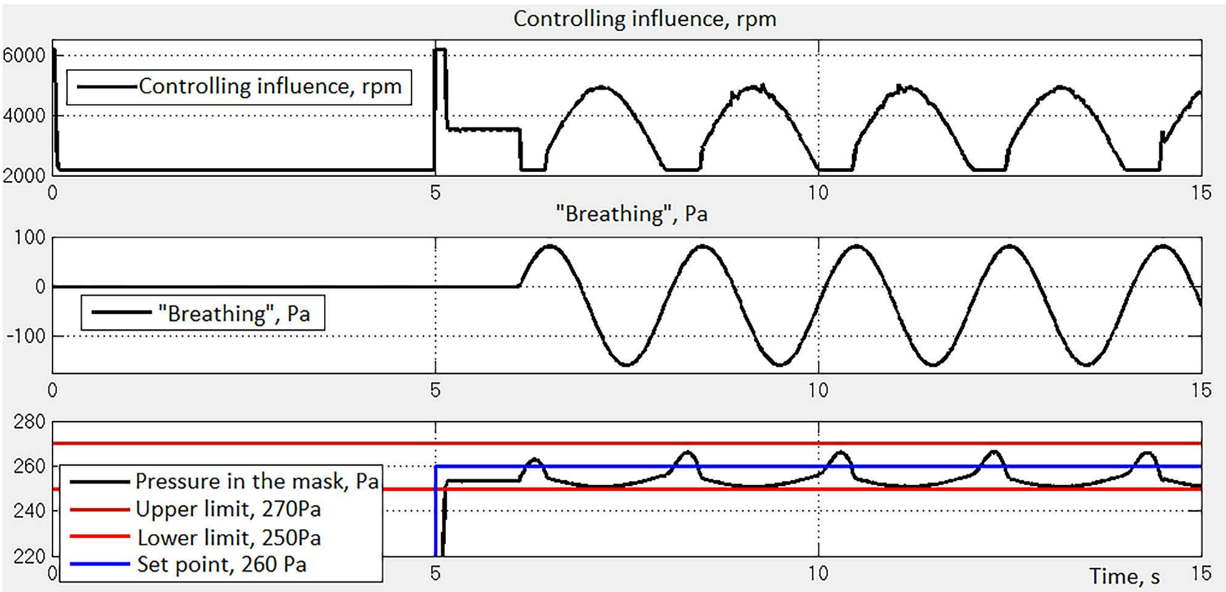

Figure 13. Simulation results at a sinusoid frequency corresponding to respiration of 30 cycles per minute with an amplitude of 120 Pa, a setpoint of 260 Pa

Source: compiled by the authors

Based on the results of modelling the air pressure control system in the mask of a motorised respirator using a PID controller, it was found that:

- gain of the proportional component K_p of the PID controller significantly affects the established error: within the coefficient values *Kp* from 50 to 967, the steady-state error varies from -60 Pa to -1 Pa. When the value is K_p more than 250, there is an appearance of minor fluctuations, which gradually increase until the appearance of system overshoot at K_p above 967;

- the gain of the integrating component in the range of 0.1-10 affects the static accuracy of the system, reducing the established error. An increase in K_i, when changing the setpoint due to an increase/decrease in physical load on the user (changing the amplitude and frequency of breathing), increases the established error;
- when increasing the gain of the derivative component K_d from 0.01 to 5, the established error decreases. A further increase causes fluctuations to appear; while a decrease in K_d allows expanding the boundaries of changes K_p up to 500 without any fluctuations;
- changing the breathing mode causes the need to increase the setpoint to compensate for the exhalation pressure and decrease it to prevent useless operation of the fan at high speeds (saving battery power).

The next step was to compare the results of simulation models of control systems with a two-position and PID controller, respectively, as shown in Figure 14, where the advantage of using a PID controller in air pressure control systems is demonstrated, which eliminates fluctuations in the controlling influence – the fan speed and reduces the deviation of the air pressure in the mask from the set value (air pressure setpoint).

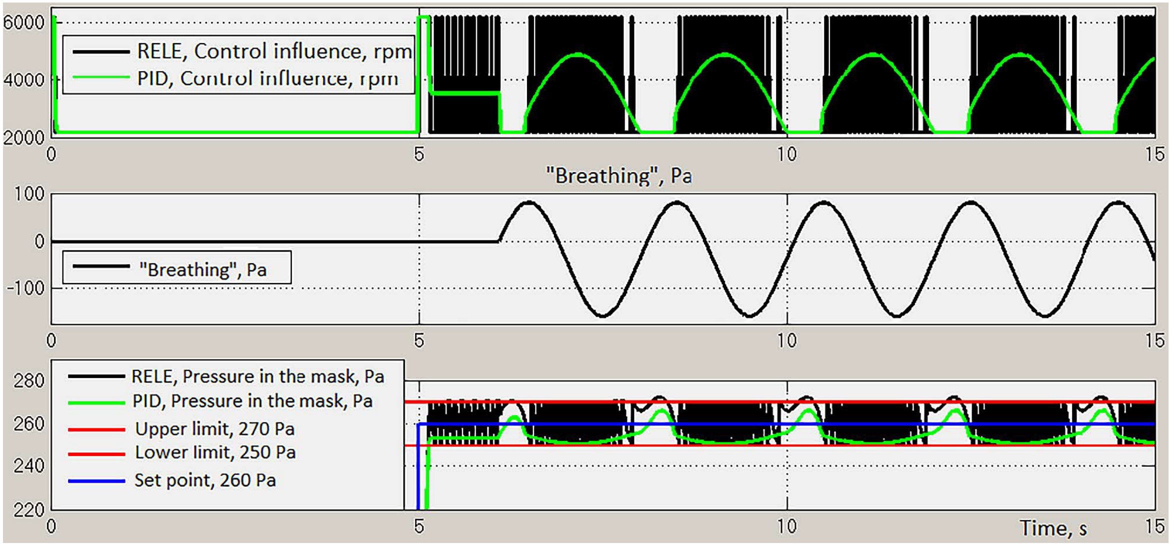

Figure 14. Comparison of the results of simulation models of control systems with a two-position and PID controller
Source: compiled by the authors

At the last stage, the operation of the simulation model of the control system was checked when providing experimental data – the "Breathing" test signal. The test results, shown in Figure 15, showed that when using a PID controller with defined parameters, the control system compensates for changes in air pressure in the under-mask space of the respirator under different respiratory modes of the user (changes in breathing frequency and depth). The air pressure is within certain limits (50-370 Pa).

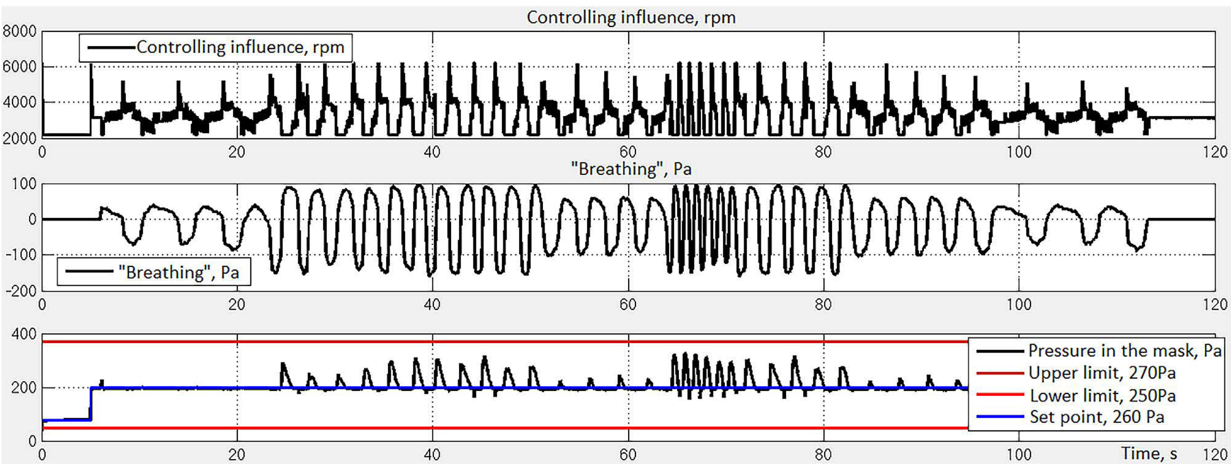

Figure 15. Operation of the control system simulation model when a test signal is sent
Source: compiled by the authors

Studies have shown that the process of human breathing in a motorised respirator can be set by a harmonic signal in the form of a sinusoid with a frequency and amplitude corresponding to different modes of physical activity of the user while working in a motorised respirator. The obtained conclusion does not contradict a number of studies conducted on changing the respiratory mode when the load changes, which indicate the possibility of calculating changes in air pressure according to the harmonic law, considering coefficients that reflect the sinusoid (Vitazkova *et al*., 2024). This allows using the proposed model to test the effectiveness of various simulation models. At the first stage, it was found that the well-known simulation model for controlling air pressure does not allow providing the necessary air flow rates when changing signals to maintain both the required pressure level in the under-mask region and when increasing the filter resistance. Similar results, which showed the presence of problems in the control system of motorised respirators, were obtained by G. Teng *et al*. (2023), who investigated the effect of various artificial ventilation regimens on the effectiveness of nebulised bronchodilators in the treatment of intubated adult patients with obstructive pulmonary disease.

According to M. Bergman *et al*. (2017), the structure and configuration of the respirator blower monitoring system requires refinement and verification in real process conditions. This allows adjusting the parameters based on the appropriate working conditions. S. Xu *et al*. (2019), N.A. Kamaluddin *et al*. (2022) note the need to create systems that will adapt to the individual parameters of the user, and to external influences, such as filter contamination, the presence of moisture, etc.

The paper by L.F. Miles *et al*. (2021) proposed a mathematical model of mechanical air supply for artificial ventilation with various modes of pressure-controlled ventilation (PCV). The model considers the possibility of obtaining dynamic signals to monitor the amount of air that needs to be supplied to the under-mask space. However, the model does not provide for the possibility of increasing the resistance of filters due to dust, which does not allow it to be used to describe the operation of motorised respirators. The study by C. O'Toole *et al.* (2020) included an analysis of a number of key indicators, such as inhalation and exhalation volume, respiratory rate, and analysis of oxygen and carbon dioxide concentrations in the exhaled air. The obtained data help to determine the effectiveness of the respirator in simulating situations associated with possible equipment failure. Analysis of these ventilation parameters under controlled conditions allows understanding how the system responds to stressful scenarios and determines how effectively it provides volunteers with the necessary amount of fresh air and appropriate gas levels during respiration. These results can be useful for further improving the design and functionality of respirators, which will provide optimal protection and comfort for users in various situations.

C. Pintavirooj *et al.* (2022) reviewed an emergency ventilator based on a fan with a sensor and ventilation drive of a new design. They described in detail the emergency ventilator, which uses a new fan with an innovative sensor and ventilation drive. This device is designed for use in emergency situations and is highly efficient and reliable due to the use of advanced technologies in the sensor and ventilation control system. The integration of these innovations into the design of the device ensures a fast and accurate response to the patient's needs, making it an effective tool in emergency medical cases. X. Zhao *et al.* (2024) describe the improvement of power supply systems for electric respirators for air purification, which involves optimising the design parameters of the impeller of a centrifugal fan. This allows increasing the efficiency and productivity of the ventilation system, ensuring an optimal volume of air supply with minimal energy consumption. Optimisation of impeller parameters involves manufacturing elements based on their shape, size and material, which maximises air movement and ensures optimal pressure. This helps to increase productivity and ensure efficient operation of the respirator in air purification from contaminants and particles. This approach to optimising the fan design ensures a reliable and energy-efficient operating process of the respirator power system, which is important in the context of ensuring the safety and comfort of users in situations related to air pollution.

To avoid these shortcomings in this study, it was proposed to develop new simulation models of the control system of a motorised respirator with a two-position controller and a PID controller. As a result of the conducted research, it was found that the simulation model of the air pressure control system in a respirator mask with a configured PID controller fully meets the quality criteria put forward: static error of 0.3 Pa (average value), transition time of 0.135 s, and no system overshoot. However, to determine the parameters of the PID controller, it is not possible to use analytical calculation methods due to the non-linearity and unsteadiness of processes to ensure the necessary compensation by the control system for pressure fluctuations in the mask caused by the user's breathing during various physical exertion, which are responsible for the air supply to motorised respirators, as an object of control. This requires additional research to determine the parameters of the controller that allow maintaining the air pressure in the under-mask space of a motorised respirator within acceptable limits (50-370 Pa), which will ensure the comfort of using a motorised respirator (Teng *et al*., 2023). Preventing excessive fluctuations in the controlling variable also helps to reduce the wear and breakage of system elements, which can occur due to constant loads and instability in operation (Diekman *et al*., 2017; Damiani *et al*., 2023). This can significantly reduce the time and cost of equipment maintenance and repair, and ensure smooth and efficient operation of the system for a long time. This management approach is key to production and helps to conserve resources and energy, which is critical in modern industry.

CONCLUSIONS

The structure of the pressure control system in the middle of a motorised respirator is developed with the selection of the appropriate controller based on the obtained dependencies between the change in the breathing mode and the pressure value in the under-mask space, which allows providing an appropriate comfortable mode of operation for users. It is determined that the simulation model with a PID controller will provide appropriate pressure values within the permissible limits (50-370 Pa), which increases the comfort of using a motorised respirator, providing the necessary compensation by the control system for pressure fluctuations in the mask caused by the user's breathing during various physical exertion, characterised by changes in the pressure drop and the volume of air consumed.

It is proved that the PID controller maintains the pressure in the respirator mask within certain limits, both with an increase and with a decrease in the control signal, preventing excessive fluctuations in the controlling variable, which leads to an extension of the service life of the filter elements and a reduction in electricity consumption for the operation of the fan motor. Based on modelling the operation of the pressure control system in different modes of operation, it is shown that when using a PID controller with defined parameters, the system provides compensation for changes in air pressure in the under-mask space of the respirator in different breathing modes of the user. It was found that the simulation model of the air pressure control system in a respirator mask with a configured PID controller fully meets the quality criteria put forward: static error of 0.3 Pa (average value), transition time of 0.135 s, and no system overshoot.

Future studies may include the evaluation of the effectiveness of the system during different physical activities and in different climatic conditions, to determine the optimal regulation parameters for maximum user comfort and safety. Another possible area for further research is to expand the functionality of the control system, considering the individual characteristics of users and the dynamics of their breathing. The integration of additional sensors and algorithms can further improve the system and expand its capabilities to provide the highest level of comfort and protection for respirator users.

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CONFLICT OF INTEREST

None.

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Автоматизована система керування тиском повітря у моторизованому дихальному апараті

Анотація. Актуальність дослідження полягає в розробці ефективної системи керування тиском в подачі повітря у моторизованих дихальних апаратах для забезпечення ефективного захисту працівників від небезпечних аерозолів та покращення їхнього здоров'я. Метою було створення автоматизованої системи управління тиском повітря в моторизованому дихальному апараті, використовуючи пропорційно-інтегрально-диференціальний регулятор. Для цього було використано метод імітаційного моделювання. Щоб унеможливити непередбачені ситуації з погіршення рівня захисту, розроблено структуру системи керування тиском моторизованого респіратора з обранням відповідного регулятора на основі отриманих залежностей впливу параметрів режиму дихання та величину тиску у підмасковому просторі респіратора, що дозволяє забезпечити відповідний комфортний режим роботи. Це дозволило, розробити імітаційну модель з ПІД-регулятором, яка забезпечить відповідні величини тиску в допустимих межах (50-370 Па). Доведено, що пропорційно-інтегрально-диференціальний регулятор забезпечує підтримку тиску в масці респіратора у визначених межах як при збільшенні так і при зменшенні сигналу керування, запобігаючи зайвим коливанням керуючої величини, що призводить до подовження ресурсу фільтрувальних елементів та зменшення витрат електроенергії на роботу двигуна вентилятора. Показано на основі моделювання роботи системи керування тиском при різних режимах роботи, що при використанні ПІД-регулятора з визначеними параметрами, система забезпечує компенсацію змін тиску повітря в підмасковому просторі респіратора при різних режимах дихання користувача. Отримані результати можуть знайти практичне застосування в сфері безпеки та охорони здоров'я, в промислових умовах, де працівники піддаються ризику вдихання небезпечних аерозолів, таких як токсичні частки, гази чи інші шкідливі речовини

Ключові слова: ідентифікація; імітаційна модель; моторизований респіратор; регулятор; уставка; тиск