11. Soundproofing materials and acoustic Solutions. URL: http://www.keepitquiet.co.uk/
12. Kiseleva E. G. Raschet zvukoizolyatsii ograzhdayuschih konstruktsiy zhilyh i obschestvennyh zdaniy. Moscow, 2011. 52 p.
13. Mistakidis E. S., Stavroulakis G. E. Nonconvex Optimization in Mechanics: Algorithms, Heuristics and Engineering Applications by the F.E.M. New York: Springer, 2013.
14. Gurskiy D., Turbina E. Vychisleniya v MATHCAD 12. Sankt-Peterburg: Piter, 2006. 544 p.
15. Rybalko O. M. Vyshcha matematyka (spetsialni rozdili). Osnovy teoriyi imovirnostei z elementamy matematychnoi statystyky. Kharkiv, 2014. 359 p.

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# ASSESSMENT AND PREVENTION OF THE PROPAGATION OF CARBON MONOXIDE OVER A WORKING AREA AT ARC WELDING

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***Проведено дослідження повітряного середовища у виробничих приміщеннях, де відбуваються зварювальні процеси, особливу увагу звернено на утворення монооксиду вуглецю (CO) в робочому середовищі в процесі ручного електродугового зварювання. Наведено класифікацію основних шкідливих речовин, які утворюютьсяпри зварюванні і споріднених процесах за характером негативного впливу на організм зварювальника. Побудовано математичну модель динаміки зміни концентрації чадного газу в повітрі робочої зони, виходячи зкількості шкідливої речовини (т) в повітрі приміщення у момент часу, інтенсивності виділення її у повітря та кратності повітрообміну. Дана математична модель включає розповсюдження чадного газу в повітрі, враховуючи повітрообмін між загальним об'ємом приміщення і локальними об'ємами робочої зони.***

***Досліджень щодо утворення монооксиду вуглецю у процесах електрозварювання обмаль, тому необхідність дослідження цього є пріоритетним.***

***Експериментальними дослідженнями було підтверджене, що концентрація чадного газу за межами локальних об'ємів пристроїв місцевої вентиляції, тобто в повітрі робочих зон, залишається постійною (до 0,01 мг/м$^3$) і не перевищує ГДК (20 мг/м$^3$). Відмова або відсутність загально-обмінної вентиляції, призводить до швидкого зростання концентрації газу моноксиду вуглецю (CO) в експоненційній залежності (від 150 до 200 мг/м$^3$ за 0,5–0,6 години) у малому замкнутому робочому просторі (1 м$^3$), а далі може розповсюджуватись по усьому приміщенню.***

***Але відмова загально-обмінної вентиляції, призводить до швидкого зростання концентрації газу монооксиду вуглецю (CO) в експоненційній залежності. Це свідчить про те, що загально-обмінна вентиляція має важливе значення, але вона не є гарантом забезпечення безпеки зварювальників та інших працівників щодо отруєння газом. Тому повинно бути передбачено застосування місцевої вентиляції та захист органів дихання усіх, хто є присутнім при проведенні процесів електрозварювання. Отримані математичні моделі дозволяють виконати оцінку ризиків праці зварювальників, врахувати емісії CO при розрахунках систем вентиляції у робочій зоні, скорегувати систему менеджменту ризиками та охороною праці***

***Ключові слова: електродугове зварювання, монооксид вуглецю, шкідливі емісії, робочий простір, отруєння газом***

## 1. Introduction

Arc welding processes are widely used in many industries for making non-detachable joints when assembling separate elements of articles and structures [1]. Given the large number of enterprises where these types of processes are common, as well as a possibility to apply them at small workshops and everyday life, there is an issue related to improving their

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management. First of all, this concerns safety and respiratory protection from a rapid penetration of carbon monoxide if protective means and measures are not used. The processes of arc welding employ a large number of different types of electrodes, which are the direct sources of CO gas. One can reduce the amount of emissions by choosing the type of electrodes. However, it must be taken into consideration that almost all welding processes are accompanied by emissions of harmful substances into the environment [2].

One of the ways to manage emissions of harmful and hazardous gases into the workspace of a welder is to constantly improve welding techniques and welded materials. However, no matter how hard one tries to improve the welding process, as long as it is associated with an extremely high temperature, emissions of gases and substances that penetrate the environment with humans (welders), this issue cannot be resolved. A catalyst of the problem is the presence of human factor that explains why some employees do not use, or use partially, protection means and do not turn on ventilation when carrying out welding operations. That is why the conditions for electric welders' work remain harmful, which negatively affects their health and working capacity [3].

It is noted that the recent trend has involved deaths and poisoning of workers by emissions that accompany various industrial processes, as well as in everyday life, where there are sources for the formation of carbon monoxide. Most often, these negative phenomena occur in closed spaces, at mines, etc.

To date, there are no statistics on the amount of CO, which penetrates the body of a welder during operation, which is why it is a relevant task to study the effect of a manual arc welding (AW) technology on the formation of carbon monoxide in a working area and in the environment.

## 2. Literature review and problem statement

Using different welding technologies produces harmful substances in the form of gaseous particles, specifically carbon oxide; nitric oxide; nitrogen dioxide; ozone. Paper [4] emphasizes that carbon monoxide forms in critical concentrations during welding operations MAG in a protective atmosphere of carbon dioxide or at welding operations MAG in a protective atmosphere of the mixed gas with a high percentage of carbon dioxide. However, CO forms and is present in almost all welding technologies where a metal is heated to high temperatures, and therefore there is a need for the further research that would pay more attention to risks of carbon monoxide poisoning.

Study [5] examined a model for the formation of a solid constituent of welding aerosol (SCWA) and a gas component of welding aerosol (GCWA) in the air at industrial premises. The authors indicate that this is associated with the kind and type of welding materials, welding modes, conditions of labor, the existence and efficiency of work of inflow-exhaust ventilation, etc. When using coated electrodes during fabrication of structures for vessels, the concentration of SCWA in the zone of welders' breathing ranges from 10...30 to 200...280 mg/m$^3$ and larger; in the production of machine building and construction structures the average level of SCWA in a breathing zone is 2...4 times lower; at mechanized welding in $CO_2$ gas, when using a powdered wire and a wire of continuous cross-section, the concentration of SCWA in a breathing zone is between 15...30 to 80...120 mg/m$^3$. Paper [5] considered the mechanism of SCWA formation during arc welding of steel in carbon dioxide, but failed to mention the model of GCWA (gas component of welding aerosol). Investigating GCWA and constructing its model is an important scientific task.

The research into electrodes coated with the base, rutile-base, and rutile-silicate types shows that the minimum level of the release of welding aerosols and the most toxic compounds of hexavalent chromium is achieved when using welding electrodes with the rutile-silicate type of coating. Paper [6] noted that it is expedient when welding high-alloyed steels in order to minimize the emission of hexavalent chromium compounds in the composition of a welding aerosol (WA) and to reduce their toxicity: in formulations for a coating of the base type one must ensure the ratio $CaCO_3/CaF_2>1$; for electrodes with the rutile-base type of coating, in order to deoxidize the electrode metal, one must use manganese or a manganese mixture with silicon; in electrodes with the rutile-silicate type of coating one must implement the ratio $TiO_2/SiO_2>3$. The paper does not report reducing carbon monoxide in WA when using rutile-silicate coatings, but a possibility to define such an influence follows from the paper, as well as the need to examine it.

Paper [7] noted that the emission volumes of AW depend on the physical-chemical properties of a coating, the acidity of slags, characteristics of the electric arc and an electrode, the welding modes; however, not enough attention was paid to gas emissions. In other words, by analyzing studies [6, 7] one can conclude that changing the above indicators could help find a more or less safe mode of operations, but it would not ensure complete safety without the use of protection means and measures for welders. Special attention should be given to the welding processes that occur within localized spaces with no ventilation. At the same time, the very process of searching for this optimal variant is rather difficult given the large assortment of welding materials and production tasks.

Article [8] reports a study during which none of the concentrations of metal components in WA exceeded the maximum permissible limit of influence (PEL) for enterprises. However, statistical analysis showed significant average differences in lung function between welders and non-welders. The effect of a dose and risk in this study follows the model of dose-risk for inhalation toxicity, as shown by formula:

$$\text{Subindex} = \text{dosage rating} \times \sum \text{health hazard rating}. \qquad (1)$$

The paper noted that there is some impact exerted by WA on the health of welders, but did not specify the gases that influence, so one can make an assumption on that being CO, which can exert this kind of impact, and therefore there is a need to explore its dosing indicators to determine the risk of exposure to it.

Study [9] consider a possibility to improve the environmental friendliness of arc welding processes. It is shown that the minimum mass of harmful substances is released at arc welding under flux, but the technological features of a given technique dramatically limit the scope of its application. The maximum amount of harmful substances is released when welding using a powder wire and at manual arc welding. It is very important that improving the environmental friendliness of welding processes is facilitated by the application of materials with a lowered content of harmful substances. However, in this case the gain is very small because the mechanical properties of welded joints are typically endured by doping the metal of welding joints. That, in turn, is provided by appropriate doping of welding consumables – electrodes and electrode wires, so it is almost impossible to substantially reduce the content of a series of alloying elements that are responsible for the quality and properties of welding joints and for the content of harmful substances in the area of welding. Therefore, at present, the main area for improving the environmental friendliness of welding is to purify ventilation emissions from harmful substances.

Paper [10] provides an overview of welding fumes, their effect on health, and measures to protect welders against welding fumes. In the industrially developed countries, about 2 % of the workforce are employed in welding. These employees are exposed to smoke and toxic substances that pose a danger to their health. Most small and medium-sized enterprises (SMEs) do not invest in providing comfortable working conditions, which is not positive to the safety and health of the worker. Most welders who work in construction, at factories, in mining industry, metallurgy, railroad, petrochemical and metallurgical enterprises, shipbuilding or the steel making industries are exposed to respiratory or pulmonary infections. The result of welding MAG is the formation of carbon monoxide when spraying carbon dioxide to a protective gas. Carbon monoxide affects the ability of the blood to absorb oxygen. The work does not consider the process of formation and the ways of CO penetration to lungs of welders, but it only indicates the importance of this issue. Therefore, one should pay attention to the processes of formation of carbon monoxide and the ways it penetrates the body of a welder.

Paper [11] reports results of research into the influence of stability of transfer of metals and the composition of a protective gas on the emissions of CO and $CO_2$ at short-circuit welding MIG/MAG. It was found that the richer the composition of a protective gas in $CO_2$, the more the amount of CO and $CO_2$ generated by arc. $CO_2$ can be reduced and transformed into CO. It is common knowledge that $CO_2$ reduces to CO at high temperatures, both in the electric arc and at the surface of a molten metal, so it is chemically more stable. CO is a deadly poison; people exposed to it may be affected without prior notice, because it is colorless, odorless, tasteless, and not irritating. A direct correlation between the emissions of CO and a welding current has been established. Using a gas mixture (18 % $CO_2$) significantly reduced the emissions of CO compared with 100 % $CO_2$ (protective gas), especially at higher currents. The high concentration of $CO_2$ is typically a problem only in limited spaces. The work does not give a specific figure regarding the indicators of emissions reduction that is a disadvantage. However, it is the formation of gases and work in confined spaces that require additional research into CO and the conditions for its impact on employees. By analyzing the procedure applied in work [11] for the selection of gases by detectors one can note that it is not perfect, because the gas that forms is measured out of the process at the same level, and therefore its greater part is not registered because it quickly rises avoiding the measurement region. It is necessary to improve the procedure for selecting CO considering its high volatility.

Paper [12] reported a study into life indicators for welders in terms of compliance to HRQL. The authors used a multivariant power regression, employing eight SF-36 sizes as dependent variables, and risk factors as independent variables. The level of statistical incorporation of independent variables was set at 0.05, and the level of exclusion was set at 0.10 in a stepwise process. The results from a multivariant step regression indicate that a welder's year of service, the type of welding, the use of protective personal equipment (PPE), as well as social factors, affect a welder's operation. The disadvantage of the research is that the authors did not consider WA (including gas) and other factors that affect a worker on a daily basis. It is necessary to supplement these studies by determining the dose of effect from a gas component in WA emissions.

Medical studies indicate that emission at welding are one of the main reasons for the development of occupational diseases such as pneumoconiosis of a welder, as well as a series of other dangerous damage to the body that negatively affect life expectancy [13, 14]. In terms of industrial safety, the maximum permissible concentration (MPC) of hazardous substances that are formed in the air of the working area of welding operations is regulated for each element or carbon oxide [15]. The disadvantage of these studies is that it is very difficult to take into consideration the impact of CO without undertaking a specialized research. And it is even harder to determine the chronic effect of this gas on workers. Thus, one needs to advance these studies regarding the effect of exposure to WA, given their importance.

The issues of environmental protection, specifically, the localization and neutralization of harmful substances at welding, were in detail examined in papers [15–17]. Article [15] examined the dangers that lead to industrial injuries at electric and gas welding of non-ferrous metals and alloys. The authors highlight the possibility of poisoning the body with harmful gases, dust and fumes released when welding. Particularly harmful substances affect workers when welding and cutting non-ferrous metals. Their maximum permissible concentrations (MPC) are often far exceeded in practice (Table 1). This table was updated by giving information on welding in $CO_2$, where there is the presence of dioxide of nitrogen, and on welding in protective gases where carbon monoxide is present. Study [16] proposed theoretical substantiation of the air pool quality management based on environmental management. The disadvantage of earlier work was the lack of analysis of the influence of WA and CO emissions on the environment. The study reported makes it possible, at the mathematical level, to systemize and formalize all the variables involved in the management of the quality of air pool in the ecosystem. The welding technologies proposed in the study were developed taking into consideration the Kyoto agreement, in a closed system of filtration with minimal risk. However, first of all, it is necessary to take into consideration that a large number of welding operations, which are impossible to calculate, take place in the open space with WA directly penetrating the environment (repair and tubing, welding of metal structures, car repairs, etc.). When performing welding operations outdoors, one should consider emissions of pollutants into the atmosphere of residential areas [17]. Given data from [11] regarding the possible conversion of CO into $CO_2$ and vice versa, under certain conditions, it is necessary to pay attention to the possible ecological impact of WA on ecosystems.

Paper [18] highlights the environmental issue, which considers smoke that is produced at welding and consists of a mixture of finely dispersed particles and gases. Most of the smoke components that are emitted at welding can be extremely toxic. These include: chromium, nickel, arsenic, asbestos, manganese, silicon, beryllium, cadmium, oxides of nitrogen, carbon oxychloride, acrolein, compounds of fluorine, carbon oxide, cobalt, copper, lead, ozone, selenium, and zinc. A welding aerosol is mainly composed of iron and its oxides, but it can include such substances and compounds as manganese, chromium, nickel, aluminum, copper, zinc, fluoride, silicon, nitrogen, and many others [19]. Thus, ventilation systems must be used to ensure safety from the above-mentioned additives; it is necessary to take into consideration the presence of CO in all these processes. The ventilation systems must be fitted with filters that include elements with adsorbing properties. In this case, it is necessary to take into consideration that the toxicity of emission in a welding process increases with the application of welding electrodes whose concentration of carcinogenic hexavalent chromium and nickel increases, which is specified in paper [20].

Article [15] gives the permissible norms of harmful substances in the air when welding metals and alloys – aluminum, copper and its oxides, oxides of manganese, silicon, nickel, zinc, nitrogen, beryllium bronze, lead, and compounds of hydrogen. MPC of harmful substances in the air of a working area when welding metals are given in Table 1, with added dioxide of nitrogen and carbon monoxide [21].

Table 1

MPC of harmful substances in the air when welding metals

| Welded metals, alloys, and gas compounds | Substances | MPC, mg/m$^3$ |
|---|---|---|
| Aluminum and alloys based on it | Aluminum | 2 |
| Copper and alloys based on it | Copper (metal and its oxides) | 1 |
| | manganese oxide | 0.3 |
| | silicon oxide | 1 |
| | nickel oxide | 0.5 |
| | lead oxide | 5 |
| | nitrogen oxide | 5 |
| | ozone | 0.1 |
| Beryllium bronze | Beryllium and its compounds | 0.01 |
| Lead | Lead and its inorganic compounds | 0.01 |
| Oxygen compounds | Fluoric oxygen | 0.05 |
| Welding in $CO_2$ | Carbon dioxide | 2 |
| Welding in protective gases | Carbon monoxide | 20 |

Paper [22] gives the characteristic of carbon monoxide for toxicity. It is indicated that this is a gas that has no color, smell and taste, moreover, its poisonous effect is based on the ability to create, with the hemoglobin of the blood, a strong complex compound – carboxyhemoglobin, which exceeds by more than 200 times the ability of hemoglobin to attach oxygen. That is why 0.1 % of CO in the air of a working area binds the same amount of hemoglobin (50 %) as oxygen. The presence of CO causes the oxygen hunger of the body, which, at significant concentrations of CO in the air and over a long time, may cause serious illness or lethal consequence [23]. Very important in this case are the detectors or instruments for determining the presence of CO in the air and for timely notification about it. The work does not specify it. It is necessary to specify modern devices for determining the dose thresholds of CO at a working premise.

Paper [24] reports the formation of CO at gas-pressed welding and when welding using a metal electrode in the environment of an inert gas (MIG). CO forms at arc welding when using a metal electrode in a gas environment (GMAC) and when welding using a tungsten electrode in an inert gas (TIG). Less common are the welding processes used in manufacturing, namely: arc welding with a tungsten electrode in a gas environment (GTAW); arc welding in the environment of helium, plasma welding (PAW) and plasma spraying; arc cutting using a tungsten electrode, welding using a tubular electrode (FCAW). CO also forms in arc welding using a molten electrode in the environment of active gas (MAG) and air-arc cutting. To date, dozens of welding techniques have been developed. The most common types are MIG, MAG, TIG, and MMA welding. Ukraine is a leading country in terms of state-owned enterprises – more than 3,000 [25]. If we take into consideration the fact that each of them has a workshop or area where welding operations are performed, with 1–2 welders employed, then, accordingly, about 3,000–6,000 workers are exposed every day to the danger of being affected by carbon monoxide. Based on this, it is necessary to explore the dynamics in the formation of CO in a working area, the possible ways for WA to penetrate a worker's breathing zone, to define the dosage risks of poisoning and to provide recommendations for prevention and protection of welders against the effects of gas emissions considering the exposure to a negative impact.

Based on our analysis of data from the scientific literature, there is a need to undertake an additional study to assess the propagation of carbon monoxide in the working zone of a welder, to select the necessary means of protection, as well as ventilation systems.

## 3. The aim and objectives of the study

The aim of this study is to assess the character of the formation and propagation of carbon monoxide in a welding aerosol depending on the condition of ventilation systems considering the exposure to welding processes. That would make it possible to calculate the risks of poisoning with carbon monoxide, to compile recommendations on the application of systems of ventilation and gas analyzers-signaling detectors in the working zone of welders and thus reduce the probability of poisoning with carbon monoxide to a minimum.

To accomplish the aim, the following tasks have been set:

– to improve the procedure for analysis of gas CO under industrial conditions, to suggest a way for preventing the propagation of carbon monoxide in the environment, and to estimate effectiveness of application of a gas analyzer-signaling detector of the type Dozor-S-M in order to prevent the effect of carbon monoxide to welders under industrial conditions;

– to evaluate the hazards of welding processes at localized spaces where there is no ventilation and an increased risk for poisoning welders with carbon monoxide;

– to assess the measures and means for protecting workers and the environment from the impact of carbon monoxide and possible ways in which carbon monoxide penetrates the body of a welder during his work.

## 4. Procedure for studying the propagation of carbon monoxide in a welding aerosol throughout the space of a welder's working zone

The experiment was conducted at the laboratory of welding, at Department of Welding of the National Technical University «Kharkiv Polytechnic Institute» (Ukraine). The laboratory is an isolated facility with an area of 240 (15×16) m$^2$, a height of the room is 6 m. A ventilation system is designed for a facility. The study aims to define the best approaches to the location of welders' workplaces, to design general-exchange ventilation, and reduce the risk of a negative impact of carbon monoxide on welders.

Before welding began, we specified the location of a welder at one of 5 designed welding posts.

The elements to weld were samples of a metal made from steel VST3SP, a thickness of 8 mm. The welding employed the electrodes UONI-13-55 with a basic coating, the electrode's diameter is 3 mm. The power of an electric welding current (welding I) was 110 A. The choice of the welding mode and a power source characteristic for supplying electric current indicate the formation of a welding aerosol, as well as its negative impact on workers at the laboratory. We estimated WA emissions for presence, and measured the concentrations of carbon monoxide, under two modes at manual arc welding: first – in the area of welding within a closed volume; second – in the area of welding under an exhaust umbrella (artificial ventilation is not enabled). The derived measurement results are given in Tables 2–4.

In the course of the research we took into consideration that carbon monoxide released during welding processes is extremely dangerous because it is difficult to detect it in a working zone and it has grave consequences for the health of a worker.

Determining the level of CO concentrations was carried out using the multicomponent individual signaling detector-gas analyzer «DOZOR-S-M» [26].

Characteristic of the measuring device: signaling detector-analyzer «DOZOR-S-M», manufactured by the scientific and production enterprise «ORION», Kharkiv, Ukraine (Fig. 1). The signaling detector is designed to measure the concentrations of components in a gas mixture of flue gases (emitted gases). The signaling detector can be used to control the gas contamination of air at industrial sites.

Measurement ranges and limits of standard permissible error: values for the concentration of gases are expressed: in mg/m$^3$ when measuring ammonia, nitrogen dioxide, sulfur dioxide, nitrogen oxide, carbon monoxide, hydrogen sulfide and chlorine; in % NKPR (volume fractions, % vol.) when measuring combustible gases and vapors; in volume fractions, % vol. when measuring the dioxide of carbon and oxygen. The unit price of the smallest category: 0.1 % NKPR (0.01 % vol.) when measuring combustible gases and vapors; 0.1 mg/m$^3$ when measuring ammonia, nitrogen dioxide, sulfur dioxide, nitrogen oxide, carbon monoxide and hydrogen sulfide.

We took samples of the analyzed gas mixture using a gas assembling probe. A gas assembling probe is designed to ensure the reliability of measuring the concentration of components in flue gases, to take samples of flue gases from a chimney, as well as to protect equipment from the abrasive wear by the products of combustion of solid fuel. The sensing element, to carbon oxide (CO), nitrogen oxide (NO), dioxide oxide ($NO_2$), dioxide of sulphur ($SO_2$) and hydrogen sulfide ($H_2S$), is a three-electrode electrochemical cell, which, in case a gas mixture contains a component to be defined, triggers an electrical signal directly proportional to its concentration. The research was carried out according to the manual for the signaling detector-gas analyzer DOZOR-S-M [26], Fig. 1.

The acquired measurements results were stored in the form of an archive of research results that registered the time and date of measurements at the device and for displaying at a PC through the USB port and an Ir adapter.

Fig. 1. Measuring CO at the laboratory of welding using the signaling detector-gas analyzer DOZOR-S-M

## 5. Assessment of the character of formation and propagation of carbon monoxide in a welding aerosol

### 5. 1. Examining the danger of welding processes at localized spaces and the risk of poisoning welders with carbon monoxide

The laboratory, where the research was performed, had 5 workplaces for manual arc welding. The measurements were carried out at a single workplace. We measured and analyzed the concentration of carbon monoxide at the workplace; based on the acquired experimental data, we conducted a mathematical modeling of the content of carbon monoxide in the air of the working area considering 5 workplaces.

When gas formation is calculated in any process, the estimation of a hazard effect always employs the variant according to which all workplaces are in operation, that is, the maximum load is considered. Exposure time of gas evolution was determined based on triggering the signal POROG-1 (20 mg/m$^3$), POROG-2 (50 mg/m$^3$) and POROG-3 (100 mg/m$^3$) at the gas analyzer.

Given the considerable complexity of determining CO in an open premise when using devices of the type DOZOR, considering its volatility, it was proposed to use an additional dome-like canopy (internal volume of 1 m$^3$) over the area of welding. This canopy helps retain gas and concentrate it within a certain area. Failure to use such a canopy makes it almost impossible to determine the dynamics of carbon monoxide formation in the area of welding. The research results are given in Tables 2–4.

Experimental data given in Table 2 showed no expediency to study $SO_2$, so hereafter it was excluded from the research.

Data from Tables 2–4 of show that the gas quickly concentrates within a confined space and then disappears, dissolved in the air of a working area. Under the umbrella of exhaust ventilation, the CO gas, albeit slowly, but reduces its concentration due to its release through the ventilation system where there is an exit in the direction of the outside premise.

Table 2

Concentration of CO and $SO_2$ in a welding zone within a closed volume at manual arc welding

| Gases | Gas evolution (welding process) in three experiments, mg/m$^3$ | | | | Error of measurement, mg/m$^3$ | | | |
|---|---|---|---|---|---|---|---|---|
| | in 10 s | | | | | | | |
| | 1 | 2 | 3 | Mean value, % | 1 | 2 | 3 | Mean value, % |
| CO | 127 | 124 | 126 | 125.7 | 1.3 | 1.7 | 0.3 | 3.3 |
| $SO_2$ | 0.1 | 0 | 0.1 | 0.067 | 0.033 | 0.067 | 0.033 | 3.4 |

Table 3

Decrease in the concentration of CO in a welding zone within a closed volume at manual arc welding

| Concentration of gas in a working area in *t*, s upon completing a welding process, mg/m$^3$ | | | | | | | |
|---|---|---|---|---|---|---|---|
| 20 s | | | | 30 s | | | |
| 1 | 2 | 3 | Cp | 1 | 2 | 3 | Cp |
| 183 | 190 | 185 | 186 | 41 | 48 | 45 | 44.6 |
| 40 s | | | | 50 s | | | |
| 1 | 2 | 3 | Cp | 1 | 2 | 3 | Cp |
| 17 | 14 | 16 | 15.7 | 11 | 13 | 13 | 12.3 |

Table 4

Concentration of CO in a welding zone under an exhaust umbrella (artificial ventilation is not enabled) at manual arc welding

| Concentration, mg/m$^3$ | Gas evolution (welding process) in three experiments (averages), mg/m$^3$ | | | Gas residue upon completing a welding process in three experiments (averages), mg/m$^3$ | | |
|---|---|---|---|---|---|---|
| | 10 s | 20 s | 30 s | 10 s | 20 s | 30 s |
| CO | 6.2 | 14.4 | 14.7 | 15.0 | 5.5 | 3.2 |

To assess the risk of poisoning welders with carbon monoxide, we use a Fine-Kinney method [27]:

$$R = P \cdot E \cdot D, \tag{2}$$

where *P* is the probability of hazards (Table 1 [27]); *E* is the seriousness of consequences (Table 2 [27]); *D* is the probability of damage (Table 3 [27]).

*P* is once per hour – 6. *E*, the seriousness of consequences, can be defined based on two variants: first – poisoning (injury) with a disability for 1 day – 1, respectively; fatality – 50. The likelihood of poisoning *D* (damage) – possible under circumstances (ventilation is disabled) – 1. According to expression (2), the risk is determined based on two variants for *E*. For the first variant, *R*=6, and according to [27], professional risk is not great. For the second variant, *R*=300, which indicates a high level of risk and the need to take immediate action.

**5. 2. Mathematical model of the gas component in a welding aerosol (GCWA) for carbon monoxide**

The content of carbon monoxide in the air of working areas at a production facility is determined by two factors: release and removal. If removal is performed through a general-exchange ventilation that implies complete mixing of air at the premises, the rate of change in the content of the substance in the air is calculated from formula:

$$\frac{dm}{dt} = J - Km, \tag{3}$$

where *m* is the amount of a harmful substance in the air at premises at time point *t*, h; *J* is the intensity of release, mg/h; *K* is the multiplicity of air exchange, 1/h;

$$K = \frac{L}{V}, \tag{4}$$

*L* is the performance of a ventilation system, m$^3$/h; *V* is the volume of premises, m$^3$.

The general solution to differential equation (3) is expression [28]:

$$m = m_0 \exp\left(K\left(t_0 - t\right)\right) + \frac{J}{K}\left[1 - \exp\left(K\left(t_0 - t\right)\right)\right], \tag{5}$$

where $m_0$ is the initial quantity (g) of a harmful substance in the air of premises at time point *t* (h), where $t_0$ is the initial time point.

To calculate the concentration, one must divide the left and right sides of equation (3) into *V*. By dividing the mass *m* of a substance that is found in the air of the premises, into the volume of premises *V*, we obtain the concentration of substance *C*. This statement applies to both the left and the right sides of equation (3).

By dividing the left and right sides of equation (3) into *V* we obtain the corresponding expression for the concentration of a harmful substance *C*:

$$\frac{dC}{dt} = \frac{J}{V} - \frac{L}{V} C. \tag{6}$$

When a harmful substance is released in the premises and there is a simultaneous air exchange, the concentration of the harmful substance in the air of working areas grows in line with an exponential law (Fig. 2, curve 1). The charts are the numerical solution to equation (6) acquired in the Mathcad environment.

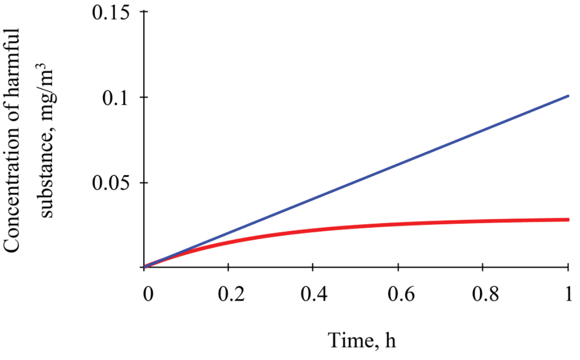


Fig. 2. Increase in the concentration of carbon monoxide in the air inside premises (Mathcad; $V$=100 m$^3$; $L$=350 m$^3$/h; $J$=10 mg/h)

Curve 1 is the solution to equation (6) and represents a change in the concentration of a harmful substance in the air of working areas in the presence of a source of the harmful substance and air exchange. Curve 2 is the solution to equation (6) in the absence of air exchange.

At $J=0$, the substance is not released, and its decrease in the air of working areas is subject to an exponential law (Fig. 3).

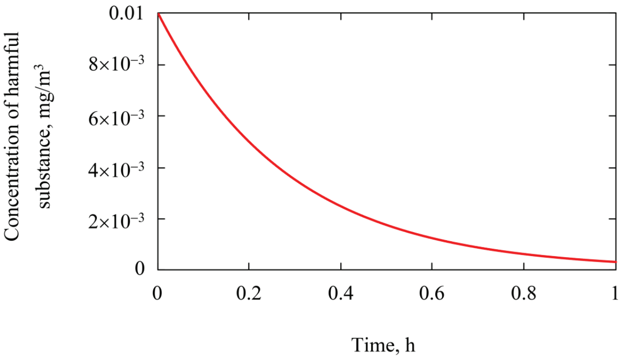


Fig. 3. Decrease in carbon monoxide in the air inside premises (Mathcad; $V=100$ m$^3$; $L=350$ m$^3$/h; $J=0$ mg/h)

Equation (5) describes the dynamics (a rate of change) of mass of the substance in the air in the presence of a source of release and a general-exchange ventilation. Equation (7) describes a special case when polluted premises are ventilated; it corresponds to the dynamics in the concentration of a substance.

$$C=C_0\exp\left(K\left(t_0-t\right)\right). \tag{7}$$

Important is the *kinetic characteristic* of the process of change in the concentration of a substance, which relates to the rate of a saturation process. It is observed at $K=0$. Simple substitution of this value in expression (5) would yield the uncertainty of type «0/0». Thus, to find an analytical solution, it is necessary to find the boundary of function at $K\to 0$ by using a L'Hospital's rule:

$$m=\lim_{K\to 0}(m_0\exp(K(t_0-t)))+$$
$$+\frac{J}{K}\left[1-\exp\left(K\left(t_0-t\right)\right)\right]=m_0+Jt. \tag{8}$$

Proceeding from the mass to the concentration of a substance in the air, we obtain the kinetic description of the process (Fig. 2, curve 2):

$$C=C_0+\frac{J}{V}t. \tag{9}$$

Often, in practical tasks, on must consider a change in the mode of operation (enabling/disabling) of air pollution source or ventilation. To this end, it is proposed to use the mathematical function sign ($t$) as a factor in the corresponding terms in equations (3) and (6). Its value is equal to 0 if $t$ is equal to 0. If $t$ is greater than 0, it is equal to 1. Otherwise, sign (t) is equal to – 1 [29]. For example, when a ventilation system is disabled or malfunctions, equation (7) will be written in the following way (Fig. 4):

$$\frac{dC}{dt}=\frac{J}{V}-\frac{L\cdot C\cdot v(t)}{V}. \tag{10}$$

Where $v(t)$ is the function that determines the mode of operation (workability) of ventilation system (Fig. 4):

$$v(t)=\frac{sign(0.6-t)+1}{2}. \tag{11}$$

Equation (11) is a special case of workability of the ventilation system. The value «0.6» in this case defined the moment it is disabled (malfunctions) over 1 hour.

The dynamics of the concentration of carbon monoxide in the air inside premises, taking into consideration the efficiency of a ventilation system, are shown in Fig. 4.

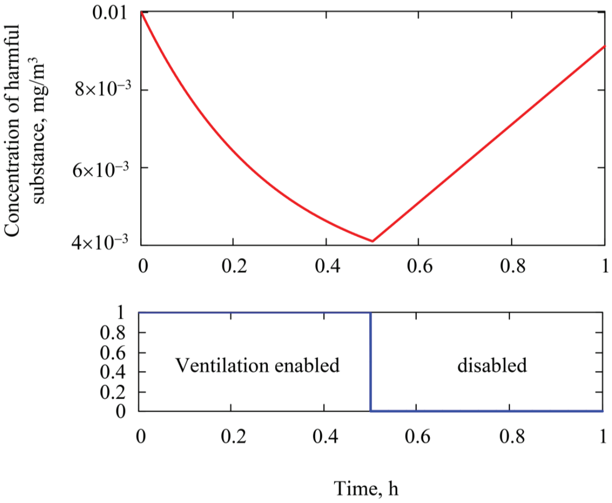


Fig. 4. Dynamics of the concentration of carbon monoxide in the air inside premises taking into consideration workability of a ventilation system (Mathcad; $V=100$ m$^3$; $L=350$ m$^3$/h; $J=1$ mg/h)

These numeric values represent a separate case. They are applied because they match common (typical) operational conditions and demonstrate the efficiency of the model in general.

In the course of experimental study, we have established the dependence of concentration of carbon monoxide on the operation duration of a welding machine within a confined space (Fig. 5) and under an exhaust umbrella (Fig. 6).

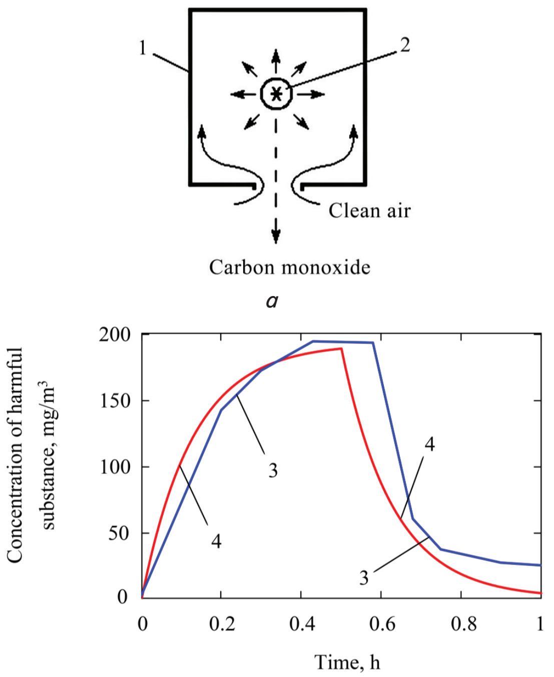
The experiment shown in Fig. 5 modeled an event in a closed space at limited working areas (cabins, wells, mines, etc.). The exchange of air ($L$) here is carried out through the vent hole. In order to derive a mathematical model of gas contamination of the air of a working area with carbon monoxide, we used a directly proportional dependence of the inflow of fresh air on the intensity of the CO gas release:

$$L=J\cdot 0.0052. \tag{12}$$

The coefficient of proportionality 0.0052, obtained from processing experimental data, matches the special case. When changing the volume and area of the vent hole, its value would also change. Important is not the value itself, but the possibility of using a linear model.

Broken line 3 is the mean statistical result of experimental measurements [30, 31]; it reflects a change in the concentration of carbon monoxide depending on time within the constructed mathematical model derived using a method of least squares [32]. In this experiment, we modeled an event in a closed space at limited working areas (cabins, wells, mines, etc.).

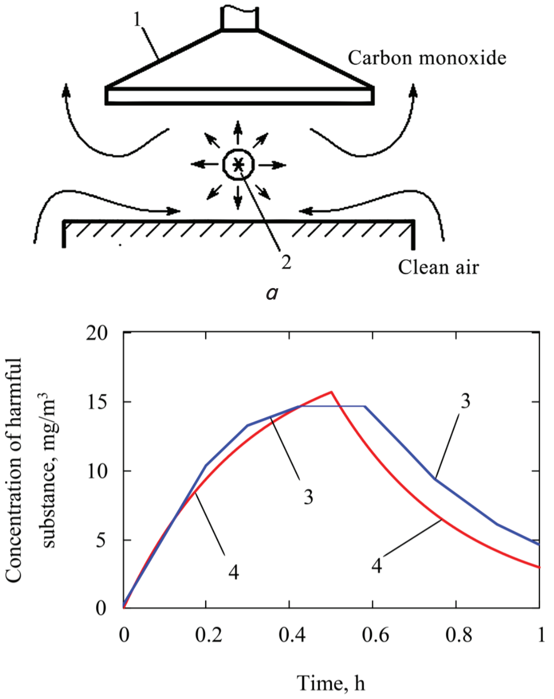
Similarly derived is the mathematical model of gas contamination of air in the working area at the border of the external contour of the exhaust umbrella (Fig. 6). We have also used a directly proportional dependence of the inflow of fresh air on the intensity of release of carbon monoxide in form (12).



*a*

*b*

Fig. 5. Dynamics of dependence of the concentration of carbon monoxide on time within a quasi-homogeneous local volume (*J*=4.5; *V*=0.003): *a* — the source of CO in a local volume (1 — limited volume; 2 — the source of CO); *b* — dynamics of the carbon monoxide concentration dependence on time in a local volume (3 — experimental data; 4 — mathematical model)



*a*

*b*

Fig. 6. Dynamics of concentration of carbon monoxide under an exhaust umbrella when ventilation is disabled (*J*=4.5; *V*=0.07): *a* — the source of CO under an exhaust umbrella (1 — exhaust umbrella; 2 — the source of CO); *b* — dynamics of concentrations of carbon monoxide under an exhaust umbrella (3 — experimental data; 4 — simulation results)

### 5. 3. Application of a mathematical model for calculating the content of carbon monoxide in the air of working areas in case a ventilation system fails

Under actual industrial conditions carbon monoxide is removed from a working area by using devices of local ventilation. Typically, these devices have a limited internal volume, inside which the intensive stirring of a gas-air mixture occurs. We shall hereafter consider them as local volumes of a quasi-homogeneous gas-air mixture. It is obvious that premises at an actual plant or laboratory may host several such devices ($n$). Typically, their number is equal to the number of workplaces.

Of particular interest in terms of ensuring the safety of industrial processes where carbon monoxide is released are the events related to the failure of a ventilation system. We shall next consider an industrial facility, equipped with a system of combined ventilation. Five workplaces are equipped with devices from a local general-exchange ventilation, connected to a common airduct and a fan. The premises have a general inflow ventilation. To calculate the content of carbon monoxide in the air of working areas in case the ventilation system fails, we propose the following model, based on a system of differential equations (13), (14).

$$\frac{dm_1(t)}{dt}=J_1+K_1(m-m_1); \tag{13}$$

$$\frac{dm_n(t)}{dt}=J_n+K_n(m-m_n); \tag{14}$$

$$\frac{dm(t)}{dt}=K_1\cdot m_1+\dots+K_n\cdot m_n-Km\cdot v(t), \tag{15}$$

where $m_I...m_n$ are the amounts of carbon monoxide in the air of premises at time point $t$, h; $J_I..J_n$ are the intensities of carbon monoxide release in respective local volumes, mg/h; $K_I...K_n$ are the multiplicities of local air exchange volumes, calculated from formula (4), 1/h. Air inflow is calculated from formula (12); $n$ is number of local volumes; $v(t)$ is a function that defined the mode of operation (failure) of general ventilation, – equation (11).

Equations (13) to (15) reflect the dynamics of carbon monoxide content within a respective local volume at a simultaneous failure of local ventilation at $n$ workplaces. This situation can occur when depressurizing or clogging the general air duct, as well as when a fan fails. The right sides of the equations represent the simultaneous inflow and removal of carbon monoxide.

In this case, an inflow to each local volume is carried out in two ways:

- from a corresponding internal source $J_I...J_n$;
- from the air coming from the premises (components $K_Im...K_nm$).

Equation (17) reflects the dynamics of carbon monoxide content in the volume of the premises outside local areas. The last term reflects the removal of carbon monoxide using a general ventilation. The preceding components reflect its inflow to premises from local areas.

Fig. 7 shows dependences of the concentration of carbon monoxide inside five local volumes (Curves 1–5).

Fig. 8 shows the dynamics of concentration of carbon monoxide in the air of the premises. Calculations were performed by a numerical method in the environment Mathcad. The source data, approximate to actual, are given in Table 5.

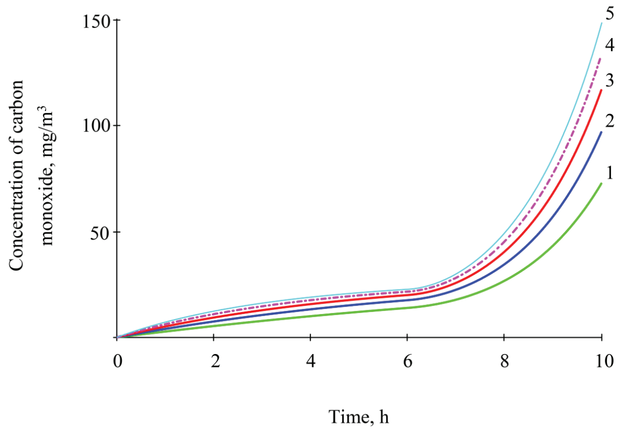


Fig. 7. Dynamics of concentration of carbon monoxide in the air of local volumes. The source data and equations for the calculation of Curves 1–5 are shown in Table 4, the values for local volumes are equal to, respectively, *V*0–*V*4 (m$^3$)

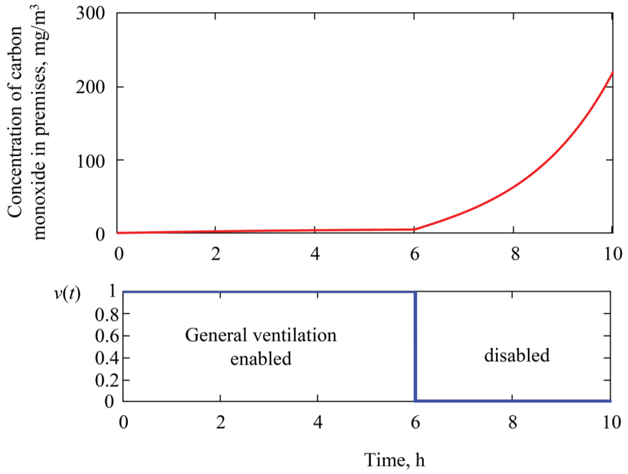


Fig. 8. Dynamics of concentration of carbon monoxide in the air of premises

Table 5

Source data for calculations (Mathcad, to Fig. 7, 8)

| | | | |
|---|---|---|---|
| $J0:=2$ | $V0:=0.7$ | $L0:=0.052\cdot J0$ | $K0:=\dfrac{L0}{V0}$ |
| $J1:=3$ | $V1:=0.7$ | $L1:=0.052\cdot J1$ | $K1:=\dfrac{L1}{V1}$ |
| $J2:=4$ | $V2:=0.7$ | $L2:=0.052\cdot J2$ | $K2:=\dfrac{L2}{V2}$ |
| $J3:=5$ | $V3:=0.7$ | $L3:=0.052\cdot J3$ | $K3:=\dfrac{L3}{V3}$ |
| $J4:=6$ | $V4:=0.7$ | $L4:=0.052\cdot J4$ | $K4:=\dfrac{L4}{V4}$ |
| $\nu(t):=\dfrac{sign(6-t)+1}{2}$ | $V5:=100$ | $L5:=450$ | $K5:=\dfrac{L5}{V5}$ |
| $M(t,m):=\begin{bmatrix} J0+K0(m_5-m_0) \\ J1+K1(m_5-m_1) \\ J2+K2(m_5-m_2) \\ J3+K3(m_5-m_3) \\ J4+K4(m_5-m_4) \\ K0\cdot m_0+K1\cdot m_1+K3\cdot m_3+K4\cdot m_4-K5\cdot m_5\cdot v(t) \end{bmatrix} \quad m=\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ | | | |
| $r1:=rkfixed(m,0,10.1000,M)$ | | | |

Fig. 8 shows that the concentration of carbon monoxide outside local volumes of devices from local ventilation, that is in the air of working areas, remains constant and does not exceed MPC (20 mg/m$^3$), in accordance with Hygienic norm GN 3.3.5-8-6.6.1 2002 [21]. This indicates that a general exchange ventilation under considered conditions acts as a «hot» reserve for the local ventilation, sufficient to provide safety in terms of carbon monoxide in the air of working areas. In case a general-exchange ventilation fails, the concentration of carbon monoxide increases in line with an exponential dependence, which leads to the compromised safety. It is obvious that providing for it requires adopting additional measures (alarm, evacuation, use of means for individual protection, etc.).

## 6. Discussion of results of studying the formation of carbon monoxide in the processes of arc welding

The set goal – to minimize the risks of poisoning welders with carbon monoxide – can be achieved by addressing all tasks comprehensively. That is, to solve the issues related to approaches for assessing the danger of welding processes, to pay special attention to work at localized spaces where there is no ventilation and a high risk of poisoning welders with carbon monoxide. To apply the derived dependences to other production places, it was necessary to construct a mathematical model of the gas component of a welding aerosol (GCWA) for carbon monoxide. It was necessary to evaluate the measures and means of protection of workers and the environment from effects of carbon monoxide and to elucidate the penetration of carbon monoxide to the body of a welder during his work.

The main aspect of our study was the use of the signaling detector-gas analyzer of the type DOZOR-S-M, which has made it possible to perform measurements at workplaces of welders, taking into consideration the threshold values of parameters. In addition, the application of this device enabled the automated acquisition of recordings for the indicators of concentrations that change over time, depending on different conditions in the environment and changes in the modes of ventilation operation.

Gas analyzer-signaling device DOZOR-S-M, which is portable and easy to use. By using a gas assembling probe from the device, which is of a sufficient length and is made from metal, that is not afraid of high temperatures, we performed measurements directly in the area of welding and at industrial premises in hardly reachable places. The device DOZOR-S-M is set for certain threshold concentrations reaching which triggers a signal on achieving a respective concentration, which makes it possible to recommend it as a necessary gear for welders who work in areas with no ventilation.

When assessing professional risk, by applying a Fine-Kinney method, it was found that depending on the conditions that may form at a welding laboratory, the risk may be of high category (*R*=300), and so one should constantly pay attention to the condition of systems that protect welders, personal protection means, and the operational state of ventilation. To identify risks, one can use other methods, but it is necessary to consider the probabilistic character and changeability of a welding process.

We have constructed a mathematical model of the gas component of a welding aerosol (GCWA) relating to a dynamic time-dependent change in the concentration of carbon monoxide inside local volumes and beyond them inside the premises. In the course of research at the workplace of a welder it was established that it is necessary to take into consideration the physical-chemical properties of carbon monoxide and the specificity of its diagnosing. In the course of the study, we paid attention to CO being a light gas that is hard to observe in a work space until it concentrates in a certain volume. Therefore, the measurements had to be performed using a special suspended panel; owing to this only, we managed to obtain credible results. Thus, when installing detectors for analysis of gas formation, not carbon monoxide only, it is necessary to use concentrators in certain areas, which would help determine at greater probability the dangerous concentrations in the air of a working area.

The result of research into the formation of carbon monoxide in the processes of welding and its effect on s welder in a production environment (operational process) is the established fact that CO penetrates the zone of respiration of a welder; this issue has not been studied by researchers in detail, therefore it can be assumed that this has some impact on the development of occupational diseases of employees. It is known that many welders neglect protection means or use ineffective ones that cannot ensure the proper respiratory protection. The issues on welders' work in closed spaces at premises have been insufficiently examined, and there are sources of carbon monoxide formation, which leads to poisoning and death of people. Thus, resolving this task is addressed by most studies.

We have experimentally studied the concentration of carbon monoxide inside a local volume and outside it inside the premises. The results of our experiment demonstrate (Table 3, Fig. 2, 3) that the concentration of carbon monoxide outside the local volumes of devices from local ventilation, that is in the air of working areas, remains constant within (0.1–0.3 mg/m$^3$) and does not exceed MPC (20 mg/m$^3$). However, the study reported here has proven that the absence of a general-exchange ventilation leads to a rapid growth in carbon monoxide concentration in line with an exponential dependence (Fig. 2, 6). Also shown is the importance of using local ventilation only in combination with general-exchange ventilation.

The research results could be recommended for risk assessment of welders' work at manual arc welding, as well as for determining different emissions and CO in calculations of ventilation systems for industrial premises.

It is expedient to conduct a study aimed at developing methods of adsorption and absorption of emissions at welding in order to design local ventilation systems for closed workspaces where AW is performed. It is possible to install water fountains or partitions that would implement the above-mentioned processes of air purification.

The study may be further advanced to study the extent of CO formation in technologies with open flame and high-temperature heating systems, to adjust the systems that manage risk and labor safety, etc.

The disadvantages of the current study include the limited types of electrodes that were used for the analysis of concentrations of carbon monoxide formed in a working zone. We consider it necessary to continue the study, focusing on the technologies of welding and the impact of ergonomic and social issues on health and on minimizing the risk of poisoning welders. The environmental issues related to the formation of carbon monoxide and its transformation into carbon dioxide also need more attention. One should pay attention to economic issues to ensure the safety of welders, specifically to search for signaling detectors, which would be effective and less costly. The current research has not considered an overall risk management system at an enterprise, as well as making a map of risks at a workplace. We believe that this task also requires a separate research.

## 7. Conclusions

1. It was established that the means of individual protection, which must be applied at workplaces of welders, are almost not used, or do not match the level of protection required in the formation of carbon monoxide. Thus, the basic means of protection is air ventilation in a welding zone. It is necessary to take into consideration the specificity of carrying out welding operations outside the fixed workplaces, especially in closed spaces, where, according to the obtained calculations, the concentration of carbon monoxide increase in line with an exponential dependence. Based on the derived dynamic indicators for a growth in the concentrations of carbon monoxide, one must check every hour the concentration of carbon monoxide when working at premises equipped with ventilation, and its absence – every 0.5 hour. That would make it possible to avoid acute poisoning of welders with carbon monoxide. To control the concentration of carbon monoxide, one can effectively use signaling detectors-gas analyzers of the type DOZOR-S-M.

We have determined the efficiency of applying the gas analyzer DOZOR-S-M regarding the prevention of risk of poisoning welders with carbon monoxide when carrying out operation in areas with no ventilation and in the absence of appropriate respiratory PPE. A gas assembling rod must be placed so that a gas sample is taken a little above a welder's head. When the level «POROG-1» (20 mg/m$^3$) is reached, the device signals the necessity of work termination and taking measures regarding the ventilation of the space where the welding is performed. That would prevent accidents related to poisoning welders.

2. The formation of carbon monoxide at manual AW leads to events when the risk is unacceptably high (exceeding $R=300$ by a Fine-Kinney method), which indicates a critical threat to the life and health of welders. Therefore, welders should constantly monitor the presence and concentration of carbon monoxide at premises where the welding process takes place, and control operation of ventilation systems in order to reduce the risk to a minimum indicator ($R\leq 10$).

3. Evaluation of the derived mathematical models of the process of formation and propagation of carbon monoxide in a workspace of a welder has proven that the process of accumulation of gas at premises may take both an exponential dependence and linear and logarithmic. Each of these variants depends on the condition of ventilation at premises where the welding process is performed, its dimensions, the type of the electrode used and the exposure duration of the welding process. In the presence, and at proper work, of ventilation the process of carbon monoxide evolution proceeds in line with a logarithmic form, in its absence – linearly, which is very dangerous.

## References

1. Markiv B. Umovy pratsi zvarnykiv. Vplyv shkidlyvykh vyrobnychykh faktoriv. URL: http://te.dsp.gov.ua/umovy-pratsi-zvarnykiv-vplyv-shkidlyvyh-vyrobnychyh-faktoriv/

2. Welding fume hazards. Safety+Health. URL: https://www.safetyandhealthmagazine.com/articles/14291-welding-fume-hazards&prev=search
3. Horbokon A. V. Zvariuvalnyi aerozol ta zasoby zmenshennia yoho shkidlyvoho vplyvu // Unyversytetskaia nauka – 2017: materialy mezhdunar. nauk.-tekhn. konf. Vol. 1. Mariupol, 2017. P. 293–294.
4. Shkidlyvi rechovyny pry zvariuvanni i navishcho potribno filtroventyliatsiine obladnannia. URL: http://sammit.dp.ua/articles/svarka_vred.htm
5. Grishagin V. M., Lugovtsova N. Yu. Svarochnyy aerozol' kak osnovnaya ekologicheskaya problema sovremennogo svarochnogo proizvodstva v mashinostroenii // Vestnik nauki Sibiri. 2011. Issue 1. P. 726–728.
6. Levchenko O. H., Bulat A. V., Bezushko O. M. Vplyv vydu elektrodnoho pokryttia na hihienichni kharakterystyky aerozoliv, shcho utvoriuiutsia pry zvariuvanni vysokolehovanykh stalei // Visnyk NTU «KPI». Seriya «Hirnytstvo». 2010. Issue 19. P. 171–177.
7. Development of Welding Fumes Health Index (WFHI) for Welding Workplace's Safety and Health Assessment / Hariri A., Paiman N. A., Leman A. M., Yusof M. Z. Md. // Iran J Public Health. 2014. Vol. 43, Issue 8. P. 1045–1059. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4411901/
8. Savytskyi O. M., Mandryk O. M. Ekolohichna skladova duhovoho zvariuvannia ta napriamok yii pidvyshchennia // Naukovyi visnyk IFNTUNH. 2014. Issue 1 (36). P. 66–73. URL: http://elar.nung.edu.ua/bitstream/123456789/2544/1/3450p.pdf
9. Mistry P. K. J. Impact of Welding Processes on Environment and Health // International Journal of Advanced Research in Mechanical Engineering & Technology (IJARMET). 2015. Vol. 1, Issue 1. P. 17–20. URL: http://ijarmet.com/wp-content/themes/felicity/issues/vol1issue1/pankaj1.pdf
10. Meneses V. A. de, Leal V. S., Scotti A. Influence of Metal Transfer Stability and Shielding Gas Composition on CO and $CO_2$ Emissions during Short-circuiting MIG/MAG Welding // Soldagem & Inspeção. 2016. Vol. 21, Issue 3. P. 253–268. doi: https://doi.org/10.1590/0104-9224/si2103.02
11. Health Related Quality of Life and Influencing Factors among Welders / Qin J., Liu W., Zhu J., Weng W., Xu J., Ai Z. // PLoS ONE. 2014. Vol. 9, Issue 7. P. e101982. doi: https://doi.org/10.1371/journal.pone.0101982
12. Otsenka rasprostraneniya chastits svarochnogo aerozolya v prostranstve rabochey zony svarschika v zavisimosti ot vremeni / Kirichenko K. Yu., Rogulin R. S., Drozd V. A., Gridasov A. V., Holodov A. S., Il'yaschenko D. P. et. al. // Ekologicheskaya bezopasnost' stroitel'stva i gorodskogo hozyaystva. 2018. Issue 2. P. 42–51. doi: http://doi.org/10.24411/1816-1863-2018-12042
13. Ignatova A. M., Ignatov M. N. Otsenka morfologii, dispersnosti, struktury i himicheskogo sostava tverdoy sostavlyayuschey svarochnyh aerozoley posredstvom sovremennyh metodov issledovaniy // Nauchno-tekhnicheskiy vestnik Povolzh'ya. 2012. Issue 3. P. 133–138.
14. Issledovanie fiziko-himicheskih harakteristik tverdoy sostavlyayuschey svarochnyh aerozoley / Kuznetsov D. A., Simonovich A. L., Naumov S. V., Ignatova A. M. // Aerozoli Sibiri: sb. tez. dokl. XIX Rab. gruppy konf. Tomsk, 2012. P. 78.
15. Bykovskyi O. H., Lazutkin M. I. Okhorona pratsi pry vyrobnytstvi konstruktsiy z kolorovykh metaliv i splaviv // Visnyk Nats. tekhn. un-tu «KhPI». 2012. Issue 1. P. 128–136.
16. Demchina M. Vpliv komponentiv zvaryuval'nogo aerozolyu na zdorov'ya lyudini. 2016. URL: https://city-adm.lviv.ua/news/society/emergency/233003-vplyv-komponentiv-zvariuvalnoho-aerozoliu-na-zdorovia-liudyny
17. Logvinov Y. V. Ecological management, and decision of a concrete question of welding aerosol localization and neutralization at surfacing // Visnyk Pryazovskoho derzhavnoho tekhnichnoho universytetu. Seriya: Tekhnichni nauky. 2016. Issue 33. P. 193–197.
18. Hranychno dopustymi kontsentratsiyi \HDK\ ta orientovni bezpechni rivni diyannia \OBRD\ zabrudniuiuchykh rechovyn v atmosfernomu povitri naselenykh mists. URL: http://www.mcl.kiev.ua/wp-content/uploads/2017/10/OBRV-2017.pdf
19. A Cross-Sectional Study of the Cardiovascular Effects of Welding Fumes / Li H., Hedmer M., Kåredal M., Björk J., Stockfelt L., Tinnerberg H. // PLOS ONE. 2015. Vol. 10, Issue 7. P. e0131648. doi: https://doi.org/10.1371/journal.pone.0131648
20. Levchenko O. G., Demetska O. V., Lukyanenko A. O. Cytotoxicity of welding fumes generated in welding with covered electrodes // Ukrainskyi zhurnal z problem medytsyny pratsi. 2016. Issue 3. P. 30–35.
21. Hihienichna klasyfikatsiya pratsi za pokaznykamy shkidlyvosti ta nebezpechnosti faktoriv vyrobnychoho seredovyshcha, vazhkosti ta napruzhenosti trudovoho protsesu. Hihienichni normatyvy HN 3.3.5-8-6.6.1 2002 r. Kyiv, 2001. 46 p.
22. Opara N. M., Dudar N. I. Chadnyi haz: vplyv na orhanizm liudyny, sposoby indyvidualnoho zakhystu i bezpechnoi povedinky. URL: http://dspace.pdaa.edu.ua:8080/bitstream/123456789/798/1/Чадний%20газ%20%20вплив%20на%20організм%20людини%2C%20способи%20індивідульного%20захисту%20і%20безпечної%20поведінки.pdf
23. Okys vuhletsiu (chadnyi haz). URL: https://empendium.com/ua/chapter/B27.II.20.10
24. Entsiklopediya po ohrane i bezopasnosti truda. URL: http://base.safework.ru/iloenc
25. Ukraina lidyruie za kilkistiu pidpryiemstv derzhavnoi formy vlasnosti. 2017. URL: https://konkurent.in.ua/publication/14844/ukrayina-lidiruye-za-kilkistyu-pidpriyemstv-derzhavnoyi-formi-vlasnosti-/
26. Dozor S M Signalizator-analizator gazov mnogokomponentniy individual'nyy. Rukovodstvo po ekspluatatsii AGAT RE. URL: https://docplayer.ru/53460271-Dozor-s-m-signalizator-analizator-gazov-mnogokomponentnyy-individualnyy-rukovodstvo-po-ekspluatacii-agat-re.html
27. Dangerous and harmful factors of production processes in snack food establishment / Pachurin G. V., Shevchenko S. M., Galka N. V., Galka A. G. // Fundamental research. 2016. Issue 11. P. 69–73. URL: https://www.fundamental-research.ru/ru/article/view?id=40929
28. Zaets Yu. L., Belyaeva V. V. Raschet obrazovaniya vzryvoopasnoy kontsentratsii v pomeschenii pri avariynoy utechke gaza // Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana. 2008. Issue 20. P. 91–93. URL: http://nbuv.gov.ua/UJRN/vdnuzt_2008_20_21

29. Tolstyh V. K. Programmirovanie v srede Mathcad. Donetsk: DonNU, 2010. 128 p.
30. Rybalko O. M. Vyshcha matematyka (spetsialni rozdili). Osnovy teoriyi ymovirnostei z elementamy matematychnoi statystyky. Kharkiv: Kolehium, 2014. 359 p.
31. Kir'yanov D. V. Mathcad 15/MathcadPrime 1.0. Sankt-Peterburg: BHV-Peterburg, 2012. 432 p.
32. Makarov E. G. Inzhenernye raschety v Mathcad 15. Uchebniy kurs. Sankt-Peterburg: BGTU-Voenmekh, 2011. 345 p.

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# DEVELOPMENT OF A HIGHLY EFFICIENT COMBINED APPARATUS (A COMBINATION OF VORTEX CHAMBERS WITH A BIN) FOR DRY DEDUSTING OF GASES

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***Розглянуто застосування пиловловлювачів нового типу, які поєднують принцип дії відцентрових і жалюзійних-вихрових апаратів. Розглянуто застосування гетерогенного реактора для систем газ-тверде з двома потоками, що знаходяться в циклоні, прямотангеційного циклону з камерою попереднього зіткнення газопилових потоків, а також вдосконалені конструкції вихрових камер.***

***Комбінований пиловловлювач представляється у вигляді вихровий труби Ранка в поєднанні з бункером, в якому встановлені жалюзійні-вихрові пристрої. Комбінований досліджуваний пиловловлювач забезпечує організовану подачу газодисперсної системи з регульованим гідродинамічним режимом в очисну споруду (апарат), в якості якого використовуються жалюзійні-вихрові пристрої. При цьому передбачається, що в вихровий трубі будуть проходити процеси коагуляції частинок при відповідних гідродинамічних умовах, а також частково деструкція шкідливих газових домішок в суцільній фазі. Таким чином розглянуто: створення для заданих початкових умов обґрунтованої фізичної моделі (конструкцій) комбінованого пиловловлювача; на основі теоретичних і експериментальних положень обґрунтована працездатність конструкції.***

***Встановлено, що найбільш перспективним напрямком для підвищення ступеня очищення газодисперсного потоку є створення гідродинамічних умов в відцентрових апаратах і в трубопроводах. Ці умови повинні забезпечувати подачу газодисперсної системи в відцентровий апарат, що забезпечують агломерацію дрібних частинок.***

***Таким чином, конструкції пилоочисного апарата, в якому передбачається інтенсивне зіштовхування частинок пилу в спеціальній камері і їх агломерація, а потім сепарація в камері, яка представляє собою фактично циклон, є доцільним і ефективним рішенням. Воно забезпечує ступінь очищення газопилового потоку, незалежно від розміру частинок, на рівні 98–99 %***

***Ключові слова: вихрова труба, гідродинамічні умови, ефективність очищення, пиловловлювання, комбінований пристрій, пиловий потік***

## 1. Introduction

Significant amounts of dusty gases are formed in various industries because of imperfection of manufacturing methods of processing raw materials into target products as well as imperfections of manufacturing and auxiliary cleaning equipment. Industrial emissions cause product losses and reduce product quality. In many cases, emissions cause significant heat losses because of lack of utilizing heat of the gases emitted into atmosphere that dramatically worsens ecological situation.

Various methods and apparatuses are used for gas dedusting including apparatuses for dry cleaning of gas-dispersed systems: cyclones, vortex chambers, vortex tubes. These devices

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