Due to the breathing physiology the carbon dioxide poisoning starts when its amount in the inhaled air reaches 1.5%. Normally, a person exhales air with a 4% amount of the carbon dioxide, i.e. the condition for the critical CO_2 breakthrough is

$$\omega(\eta, \tau_{кр}) = 1,5/4 = 0,375\,. \tag{11}$$

It means that if $\tau \le \tau_{кр}$ then the adjustments to $\omega_0(\tau)$ (see (8)) appearing during the iterative procedure can be evenly estimated by the members of a descending geometric sequence with the denominator $q = 0.375$ which converges if $q<1$.

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EVALUATION OF THE RESOURCE USAGE EFFICIENCY INCREASE OF THE FIXED OXYGEN BREATHING APPARATUS

EVGENIY POTAPENKO, STEPAN EKHILEVSKIY, OKSANA GOLUBEVA
Polotsk State University, Belarus

The research shows that the CO_2 critical breakthrough time when using a heterogeneously fitted regenerative cartridge connected via the open scheme provides an understated breathing apparatus protection increase evaluation. It is better to employ the average oxygen-containing product usage along the full length of the cartridge by the time of the CO_2 critical breakthrough, because the breakthrough decrease due to the dependence of the product granules diameter on the granules occurrence depth evolves in time by itself. It is shown that the suggested evaluation in terms of quantity equals the one determined by the protection term for the circular airway scheme where the CO_2 breakthrough returns during breath.

The current fixed oxygen breathing apparatus have a substantial reserve for protection resource usage efficiency increase of the regenerative cartridge. For instance, a 2-litre cylinder for P12 respirator designed for a 4-year protection term is filled with 550g of compressed oxygen. The PX-4 apparatus is designed for the same term. Its regenerative cartridge contains 3.7kg of oxygen-containing product 90% of which is potassium superoxide. Taking into account the formula KO_2 of the chemical compound and the molecular weight of its elements we get 0,9.3,7.32/71=1,5kg of oxygen. If we apply the stoichiometry of the reaction

$$4KO2 + 2CO2= 2K2CO3 + 3O2 + 360\ \text{kJ}\,, \tag{1}$$

$1.5 \cdot 3/4 = 1.13$ kg is produced in free form which is more than twice the amount in the cylinder. It means that by the end of the apparatus protection term only half of the cartridge resource is used. The performance of the apparatus with a shorter protection term is even worse.

The main reasons for the inefficient resource usage is a dead layer of the sorbent which is not used by the CO_2 critical breakthrough time and granule sintering of the oxygen-containing product affected by unevenly distributed exothermal heat sources [1].

When the dynamic sorption activity is mathematically modeled, dimensionless variables related to time t and coordinate x as

$$\tau = \beta\gamma t \in \left[0, \tau_{kp}\right], \qquad \xi = \beta x / v \in \left[0, \eta\right] \tag{2}$$

where v is the filtration speed, τ_{kp} – the CO_2 critical breakthrough time, η – dimensionless length of the cartridge, β and γ – phenomenological constants that characterize the speed and resource of the reaction (1). The intervals of changing ξ and τ characterize in a general way not only the regenerative cartridge itself, but its operation regime.

Attempts are made to increase the cartridge resource usage efficiency by means of influencing v [2, 3] altering the apparatus structure in order to accelerate the filtered air flow in the frontal layers of the oxygen-containing product, and to slow it down in the closing. It allows to broaden the product working layer i.e. to engage a greater amount of product with a larger heat dissipation surface in the process of heat removal at the beginning of the cartridge. As a result the cartridge temperature conditions soften and the chance of the product sintering lowers. On the other hand the contact time of its reagents increases at the end of the cartridge i.e. the dead layer of the chemisorbent gets thinner. The both factors increase the cartridge dynamic sorption activity i.e. increase the cartridge resource usage efficiency. However, introducing additional elements to the apparatus construction results in additional weight, dimension, physiological cost of wearing and reduces reliability etc.

The alternative way to increase the cartridge efficiency is suggested in [4, 5] and based on controlling the granulometric composition of the oxygen-containing product. The point is that the sorption speed is determined by CO_2 molecule diffusion inside the oxygen-containing product granules and it is inversely proportional to their square diameter [6]. Since it is the β value that is influenced by the granule diameter we will introduce a correction factor α:

$$\beta \to \alpha\beta, \tag{4}$$

which possesses the value of α_1 and α_2 in the first and the second parts of the cartridge respectively.

Now we will evaluate efficiency increase of the regenerative cartridge available resource due to the granule diameter reduction towards the filtration of the exhaled air. In order to do so we will apply the formalism developed in [4].

$$\omega(\xi,\tau) = \omega_1(\xi,\tau)\theta(\zeta-\xi) + \omega_2(\xi-\zeta,\tau)\theta(\xi-\zeta), \tag{3}$$

$$u(\xi,\tau) = u_1(\xi,\tau)\theta(\zeta-\xi) + u_2(\xi-\zeta,\tau)\theta(\xi-\zeta), \tag{4}$$

$$\omega_1(\xi,\tau) = e^{-\alpha_1\xi}\left[1 + \sum_{n=1}^{\infty}\frac{(\alpha_1\xi)^n}{n!}\left(1 - e^{-\alpha_1\tau}\sum_{k=0}^{n-1}\frac{(\alpha_1\tau)^k}{k!}\right)\right], \tag{5}$$

$$u_1(\xi,\tau) = 1 - e^{-\alpha_1\tau}\left(1 - e^{-\alpha_1\xi}\sum_{n=1}^{\infty}\frac{(\alpha_1\xi)^n}{n!}\sum_{k=1}^{n}\frac{(\alpha_1\tau)^k}{k!}\right), \tag{6}$$

$$u_2(\xi,\tau) = e^{-\alpha_2\tau}\alpha_2\int_0^{\tau} e^{\alpha_2\tau}\omega_2(\xi,\tau)\,d\tau, \tag{7}$$

$$\omega_2(\xi,\tau) = e^{-\alpha_2(\xi+\tau)}\sum_{n=0}^{\infty}\frac{f_n(\tau)}{n!}(\alpha_2\xi)^n, \tag{8}$$

$$f_{n+1}(\tau) = \alpha_2\int_0^{\tau} f_n(\tau)\,d\tau, \tag{9}$$

$$f_0(\tau) = e^{\alpha_2\tau}\omega_1(\zeta,\tau), \tag{10}$$

where $\omega(\xi,\tau)$ is a modified CO_2 concentration in the filtered airstream, $u(\xi,\tau)$ is a modified concentration of fixed carbon, ζ is a dimensionless coordinate of the point of the granule diameter leap and $\theta(\xi)$ is the Heaviside function.

The correlations (3), (10) allow any precision of calculation of the breakthrough and determination of the waste product share (see pic. 1, 2 curves 2) in the cartridge with granule diameter leap. The calculations are done for $\eta = 4,426$, $\zeta = 0,91$, $\alpha_1 = 0,64$, $\alpha_1 = 1,78$

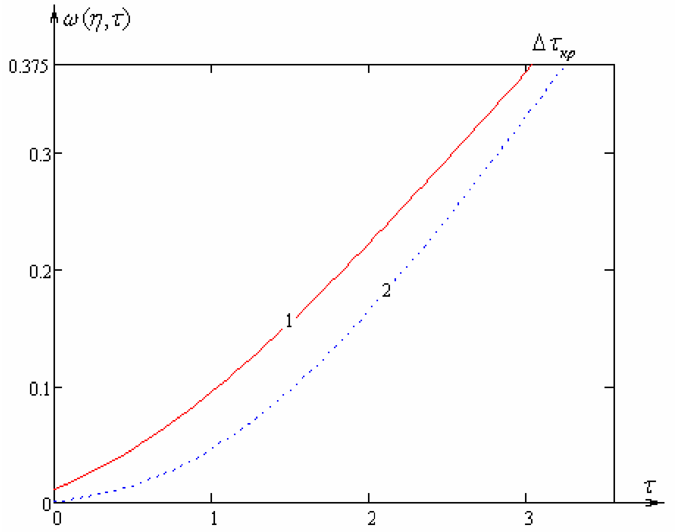

Fig. 1. CO_2 break through the regenerative cartridge:1 – homogeneously fitted; 2 – with a granule diameter leap

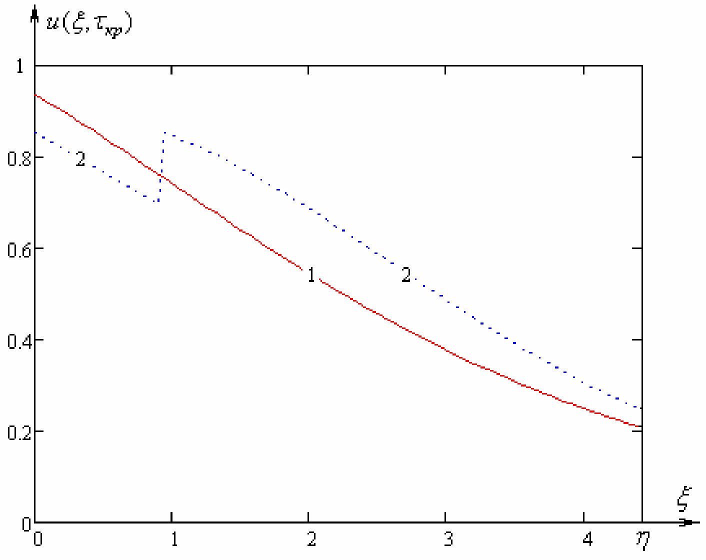

Fig. 2. Oxygen-containing product wear: 1 – in a homogeneously fitted cartridge; 2 – with a granule diameter leap

The curves 1 introduced for comparison in both figures correspond to a homogeneous cartridge are constructed with the help of formulas (5) and (6) respectively with $\alpha_1 = 1$

$$\omega_o(\xi,\tau) = e^{-\xi}\left[1+\sum_{n=1}^{\infty}\frac{\xi^n}{n!}\left(1-e^{-\tau}\sum_{k=0}^{n-1}\frac{\tau^k}{k!}\right)\right], \tag{11}$$

$$u_o(\xi,\tau) = 1-e^{-\tau}\left(1-e^{-\xi}\sum_{n=1}^{\infty}\frac{\xi^n}{n!}\sum_{k=1}^{n}\frac{\tau^k}{k!}\right), \tag{12}$$

The CO_2 critical breakthrough time was established on condition that

$$\omega(\eta, \tau_{кр}) = 0.375\,. \tag{13}$$

It increased by 6.9% in a heterogeneously fitted cartridge (fig. 1). The fixed carbon distribution (as well as the exothermal heat sources) has become more even and the average regenerative cartridge performance increased by 12.9%

Now we will find out which of the last two values we should use to evaluate the breathing apparatus protection resource usage efficiency increase. We must take into account that the apparatus is insulating i.e. the breakthrough remains inside the airway. It mixes with the air that comes for a breath inside the breathing bag. This leads to the increase of the CO_2 amount exhaled. It means that the boundary condition for the sorption dynamics problem stops being stationary. Such situation is simulated in [7] for a homogeneous cartridge. Using the iterative method, breakthrough addition to the constant constituent (conditioned by the apparatus operation regime) shows the substantial reduction of the protection term. The effect must be less noticeable in an apparatus with a chemisorbent granule diameter leap because of a slower breakthrough growth (see fig.1). In order to perform a quantitative assessment expression (5) must be neglected when describing the breakthrough in the first part of the cartridge and formulas (8) and (9) must be applied having substituted α_2 for α_1:

$$\omega_{11}(\xi, \tau) = e^{-\alpha_1(\xi+\tau)} \sum_{n=0}^{\infty} \frac{f_n(\tau)}{n!} (\alpha_1 \xi)^n \,, \tag{14}$$

$$f_{n+1}(\tau) = \alpha_1 \int_0^{\tau} f_n(\tau)\, d\tau\,. \tag{15}$$

The first index in the left part of (14) numbers the regenerative cartridge part under study and the second one – the steps of the iterative procedure (for more details see [7]). According to the mentioned above for $f_0(\tau)$ instead of (10) we should write

$$f_0(\tau) = e^{\alpha_1 \tau}(1 + \omega(\eta, \tau))\,, \tag{16}$$

where $\omega(\eta, \tau)$ must be calculated using (3), (8) – (10). The resulting function $\omega_{11}(\zeta, \tau)$ must be substituted into (10) as a modified boundary condition in order to get (using (8) and (9)) the breakthrough in the second part of the cartridge $\omega_{21}(\eta, \tau)$:

$$\omega_{21}(\xi, \tau) = e^{-\alpha_2(\xi+\tau)} \sum_{n=0}^{\infty} \frac{f_n(\tau)}{n!} (\alpha_2 \xi)^n \,, \tag{17}$$

$$f_{n+1}(\tau) = \alpha_2 \int_0^{\tau} f_n(\tau)\, d\tau\,, \tag{18}$$

$$f_0(\tau) = e^{\alpha_2 \tau} \omega_{11}(\zeta, \tau)\,, \tag{19}$$

Remember that the first index of the reduced concentration ω numbers the parts of the regenerative cartridge and the second one – the steps of the iterative procedure. By combining the functions (14) and (17) in the first approximation we determine the evolution of the CO_2 modified concentration of the regenerated airstream in a heterogeneous cartridge of an apparatus with a circular scheme of the airway

$$\omega^{(1)}(\xi, \tau) = \omega_{11}(\xi, \tau)\theta(\zeta - \xi) + \omega_{21}(\xi - \zeta, \tau)\theta(\xi - \zeta)\,, \tag{20}$$

As the null approximation we should use expression (3) that describes the CO_2 break through a heterogeneously fitted cartridge connected via the open scheme $\omega^{(0)}(\xi, \tau) = \omega(\xi, \tau)$. The results of the calculations done with the MathCAD package are illustrated in fig.3

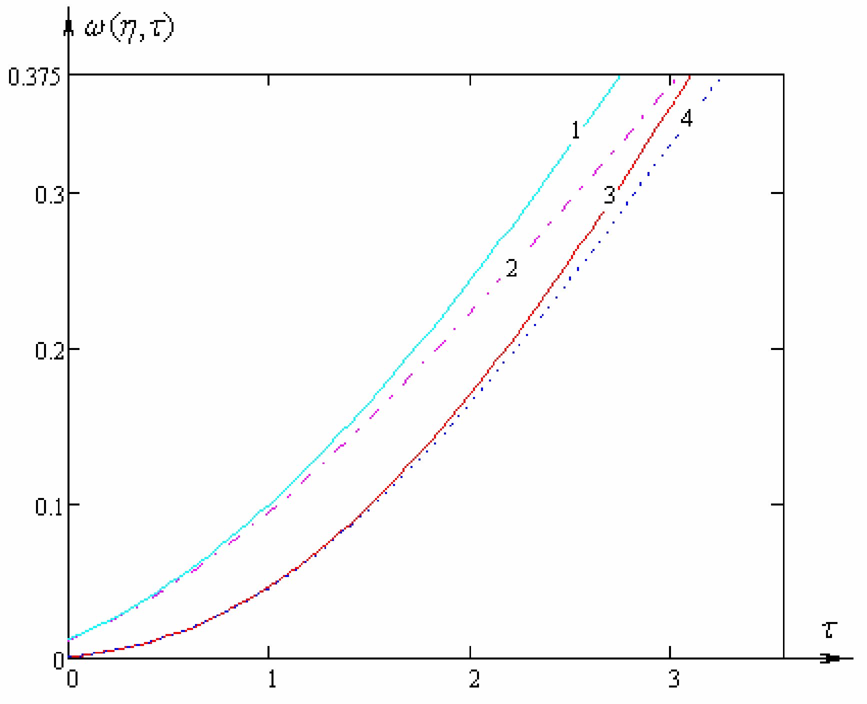

Fig. 3. CO_2 break through the regenerative cartridge: homogeneously fitted with the circular (1) and open (2) connection schemes; with a granule diameter leap in the circular (3) and open (4) schemes

The curves 2, 3 and 4 are built using formulas (11), (20) and (3) respectively. And the curve 1 – with the procedure described in [7]. Apparently, the influence of the closed character of the airway is less evident in a cartridge with a granule diameter leap. It increases the critical breakthrough time growth from 6.9% to 12.9% which equals the value calculated on the average pollution of the cartridge connected via the open scheme by the time of the CO_2 critical breakthrough time. This is probably not a random coincidence and it is a result of the carbon dioxide molecules conservation law. Indeed, with a specified filtration speed the CO_2 critical breakthrough time is determined by the number of molecules that went into the filter which equals the number produced in the process of human's vital activity minus those absorbed by the cartridge.

Thus there is no need to build the circular airway scheme in order to evaluate the protection increase of a heterogeneously fitted apparatus. One is only to calculate the average pollution growth of the cartridge with an open connection scheme.

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