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PHYSICAL AND CHEMICAL PRINCIPLES OF BENEFICIATION

INTENSIFICATION OF AERATION IN TREATING NATURAL WATER AND MINE WATER

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Operations of the coal industry, in particular the open-pit and underground mines in the Kuzbass and the Moscow Basin, have an acute need for pure water to meet the requirements for potable and domestic water. The main sources of water for underground and open-pit mines and the supporting infrastructure are subsurface waters that usually do not meet elementary quality characteristics in terms of their contents of suspended matter, iron, manganese, hydrogen sulfide, and so on. For example, subsurface water sources in the underground and open-pit mines of the Yuzhnyi and Belovskii districts of the Kuzbass and in most underground mines of the Moscow Basin contain large amounts of iron and manganese, as much as ten times the amounts permitted by standards; also, these waters do not meet the standard limits on contents of hydrogen sulfide, organic matter, carbon dioxide, or bacterial contamination. Data reported by hydrogeological services indicate that this undesirable trend persists in the subsurface water sources in the area of the new and promising Erunakovskii deposit of the Kuzbass.

Apart from problems in supplying potable water for coal mining regions, other problems exist – and are becoming more acute – in protection of the environment against pollution by domestic and mine waters, where the most urgent task is biological treatment and disinfection of wastewater to eliminate organic and bacterial contaminants. The principal method of disinfection is chlorination, which has well-known adverse effects on the human organism. Hence there is a great demand for the replacement of chlorinating agents by the less toxic and more effective ozonation method; however, the practical application of ozone treatment is limited by its relatively high cost and the unavailability of commercial-scale ozonators.

An analysis of the current problems in water treatment in coal mining regions of the country shows that the typical schemes used today to treat natural and mine waters are very ineffective and unwieldy; also, in most cases they do not meet the required treating standards.

Any progress in solving these problems can be expected only on the basis of fundamental advances in understanding the mechanism of the processes on which water-system treating technology is based.

In this article we are presenting results from research on intensification of aeration processes of water treatment, based on new concepts of the mechanism of mass transfer in water–air systems. It is known that the aeration process, which serves basically to saturate the water with oxygen, is accomplished through contact between the water and air phases in which the decisive factor is the state of the surfaces of the interacting phases.

In water treating practice here and in other countries, water aeration is performed in specially designed units of the bubble, spray, cascade, or blade type.

Sparged (bubbled) aerators operate on the principle of feeding air into the volume of the water through perforated tubes, porous plates, or diffusers [1].

In spray aerators, the water is broken up by nozzles into fine drops in the atmosphere, thus increasing the area of contact between the water surface and the air [2].

In cascade-type aerators, the water flows successively, either as jets or as a sheet flow, across a series of weirs positioned one above the other, so that the water comes into contact with the atmosphere at each overflow. A typical example of this method of aeration is a cooling tower with shelves located at different heights [3].

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Other aeration methods, differing mainly in the design of the aeration device, are less widely used. Examples may be found in surface aeration using various types of impellers, blade or brush devices, and so on.

All of these aeration methods have certain common shortcomings in three areas: a) the low efficiency of oxygen dissolution, even with large inputs of air (up to tens of cubic meters per cubic meter of water), owing to the small unit surface of interacting phases and the absence of any complete contact between the entire volume of the water and the air bubbles; b) excessive requirements on the area of the facility site, capital investment, and operating costs; c) the large amounts of metal required for construction, and the complexity of the treating units.

The technology we have developed is based on the principle of homogenizing a water–air medium in specially designed dispersing devices, with the formation of a highly developed contact surface between the water and air. Let us examine the mechanism of air bubble breakup and mass transfer under conditions of turbulent flow. An air bubble in a turbulent flow of liquid is subjected to the continuous action of such destabilizing factors as fluctuations of the flow velocity and pressure fields in the carrier phase. Under the influence of these factors, the bubble is deformed and executes oscillating motions of two types: radially symmetric and surface oscillations. In a two-dimensional system of coordinates, the bubble surface can be described by the equation

$$R = R(t) + \sum_{n=0}^{\infty} a_n(t) Y_n, \tag{1}$$

where R(t) is the instantaneous radius of the bubble; $a_n(t)$ is the amplitude of deviation of the surface from a spherical shape; Y_n is the surface spherical harmonic, of degree n. With a sufficiently strong action, the bubble will be broken up into smaller parts. Let us assume that in a turbulent flow, as a result of an encounter of two turbulent formations, there has been a local increase of the liquid pressure around the bubble. Under the influence of forces arising through the sudden application of the pressure field, the bubble will be compressed. Assuming that the change of gas pressure in the bubble is uniform throughout its volume and that the pressure change is described by an adiabatic law with a constant ratio of heat capacities, i.e., that $P = P_0(R_0/R)^{3\gamma}$, the radial motion of the bubble wall in an unbounded (infinite) incompressible liquid can be written in the form [4]

$$R\frac{d^2R}{dt^2} + \frac{3}{2}\left(\frac{dR}{dt}\right)^2 = \frac{1}{\rho_f}\left[P_\infty - P\left(\frac{R_0}{R}\right)^{3\gamma}\right], \tag{2}$$

where P_∞ is the pressure in the liquid; R_0 is the initial radius of the bubble; ρ_f is the density of the liquid; t is the time; γ is the adiabatic exponent (ratio of specific heat); P is the gas pressure in the bubble; R is the instantaneous radius of the bubble.

Simultaneously, upon encounter of a turbulent formation with a bubble surface, initial velocities of radial perturbed motion will be communicated to the bubble. For the case of a plane front of the turbulent formation, the distribution of initial velocities will be taken in the form

$$V_0 = v_0 \cos\Theta. \tag{3}$$

Here, V_0 is the velocity of the turbulent formation; Θ is the angle in a spherical coordinate system with the origin at the center of the bubble. The equation for the amplitude of deviation from a spherical shape, according to [5], is

$$\ddot{a}_n(t) + 3\frac{\dot{R}}{R}\dot{a}_n(t) - L_n a_n(t) = 0, \tag{4}$$

where $L_n = [(n - 1)\ddot{R}]/R - (n - 1)(n + 1)(n + 2)(\sigma/\rho_f R^3)$ when $\rho_f >> \rho_g$ (ρ_g is the density of the gas of the bubble atmosphere).

We will seek a solution of the outer problem for the Laplace equation in the case of axial symmetry, in the form

$$\varphi(r,t) = -\frac{R^2\dot{R}}{r} + \sum_{n=0}^{\infty} \frac{A_n(t)P_n(\cos\Theta)}{r^{n+1}},$$

where $P_n(\cos\Theta)$ is an n-degree Legendre function.

Imposition of the boundary condition (3) leads to the equality

$$V_0\cos\Theta = -\sum_{n=0}^{\infty} P_n(\cos\Theta)\,\frac{(n+1)A_n(t)}{r^{n+2}}.$$

Owing to the linear independence of Legendre polynomials, $A_n(t) = 0$ when $n \neq 1$. Consequently, compression of a bubble with an initial perturbation of the surface due to an asymmetric perturbation of liquid velocity will be expanded only in the first Legendre polynomial with an initial amplitude of the expansion $a_1(t)\cos\Theta = 0$ with $t = 0$. Then, considering (1), we find that the free surface of the bubble will behave in accordance with the equation

$$R(t,\Theta) = R(t) + a_1(t)\cos\Theta.$$

From Eq. (4) with $n = 1$, it follows that the amplitude of deviation of the surface from spherical will vary with the passage of time in accordance with the law

$$a_1(t) = -V_0\cos\Theta\int_0^t \left(\frac{R_0}{R}\right)^3 dt. \tag{5}$$

A relationship between the time differential and the cube of the relative radius of the bubble was found in [6]:

$$dt = R_0\left(\frac{\rho_l}{6P_\infty}\right)^{1/2} x^{-1/6}(1 - x)^{-1/2}dx,$$

where $x = (R/R_0)^3$. Substituting this relationship into (5), we will have

$$a_1(t) = -V_0\cos\Theta\cdot R_0\sqrt{\frac{\rho_l}{6P_\infty}}\int_0^x x^{-1/6}(1 - x)^{-1/2}dx.$$

Appearing in this expression is an incomplete beta function with a negative numerical parameter. Using the substitution $x^p = x^{p-1} - x^{p-1}(1 - x)$ and expressing the incomplete beta function in terms of a hypergeometric function, we finally obtain

$$a_1 = -V_0R_0\cos\Theta\sqrt{\frac{\rho_l}{6P_\infty}}\left\{\frac{12}{5}\left(\frac{R}{R_0}\right)^{5/2}F\left[\frac{5}{6},\frac{1}{2},\frac{11}{6},\left(\frac{R}{R_0}\right)^3\right] + 6\left(\frac{R_0}{R}\right)^{1/2}\left(1 - \frac{R^3}{R_0^3}\right)^{1/2}\right\}. \tag{6}$$

The ratio R/R_0 is determined from the expression

$$[(\alpha - 1)A + 1]\left(\frac{R}{R_0}\right)^3 - A(\alpha - 1) = \left(\frac{R_0}{R}\right)^{3\gamma},$$

where $A = P_0/P_\infty$.

If we understand breakup of a bubble to mean the emergence of a small perturbation into the field of finite perturbations, then, upon reaching a value $\delta = a_1/R_0 = 0.25$ to 0.3, a bubble of this particular size will be broken up.

We now find the energy consumption in dispersing the gas phase in a pneumohydraulic disperser, assuming that the local structure of the turbulent flow is the predominant factor influencing the maximum dimension of bubbles that are resistant to breakup. In the inertial interval of the region of universal statistical equilibrium, determined by the relationship $\lambda_0 < 2R_0 < L$, the relationship $\bar{V}_0^2 = 2.0(2\varepsilon R_0)^{2/3}$ is valid [6]. Here, λ_0 and L are the microscale and macroscale of turbulence; ε is the rate of energy dissipation in the liquid. Substituting this value of the velocity V_0 of the turbulent formation into (6), we find the rate of energy dissipation in the pneumohydraulic disperser. At the same time, the work of formation of a spherical bubble with diameter $2R_0$ is equal to $4\pi R_0^2\sigma$. As shown by calculations, the efficiencies of pneumohydraulic dispersers are no greater than 5-8%. The time of residence of unit volume of liquid in the zone of active breakup is taken as approximately 1 sec.

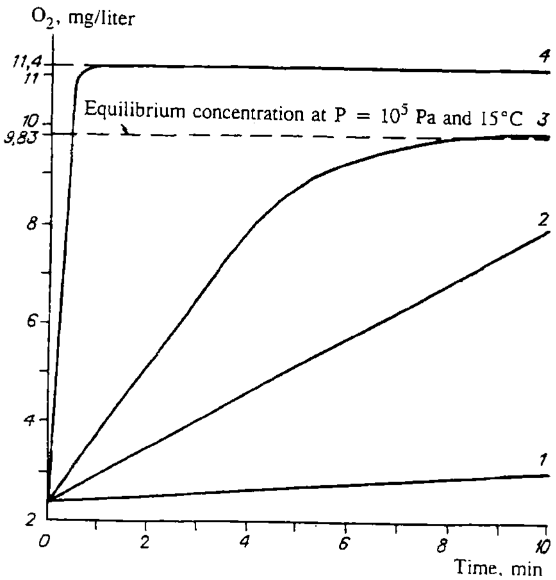

Fig. 1. Kinetics of water saturation by oxygen. 1) Simplest aeration (with flow of the water over a system of baffle plates); 2) bubbling of air into the water; 3) forced aeration (spouting the water and air together); 4) intensive aeration.

In order to increase the gas–liquid interfacial surface, in accordance with Eqs. (6) and (7) it is necessary to increase the rate of energy dissipation ε in the zone of active breakup in the pneumohydraulic disperser. This can be done, for example, by means of a sharp change of the velocity profile of the averaged flow. The rate of turbulent formations with a scale of $2R_0$ may have the same order of magnitude as the averaged flow velocity.

Transport of atmospheric oxygen from the bubble atmosphere to the water is accomplished by molecular and turbulent diffusion mechanisms. As a result of the developed turbulent motion of liquid in the disperser and following the disperser, the takeoff of gas from the bubble surface into distant volumes of water is accomplished for the most part in this aeration method through the turbulent diffusion mechanism. The more intense the turbulent motion, the higher will be the rate of liquid pulsations and hence the higher the rate of takeoff of oxygen into the liquid volume. The coefficient of turbulent diffusion for water is at least 10^{-1} m^2/sec; i.e., it is defined in values many order of magnitude (10^8) greater than the coefficient of molecular diffusion. Actually, in turbulent flow around bubble surfaces, the zone of significant change in mass concentration is concentrated in a small layer close to the bubble surface. Intense turbulent motion of the liquid distorts the spherical shape of the bubble and produces bubble pulsations – radially symmetric and surface pulsations. Pulsations of the bubble break-down the ordered structure of water around the bubbles and tend to increase the rate of molecular diffusion of oxygen. Simultaneously, along with the bubble pulsations, microconvective flows are set up, mixing the volume of water at the bubble surface and increasing the rate of oxygen takeoff close to the surface.

In the presently known methods of aeration by bubbling, spraying, or the use of a cascade, mass transport is also accomplished mainly through the turbulent diffusion mechanism. In these methods, however, the rate is considerably lower, since there is a lower velocity of liquid pulsations with a scale close to or smaller than the bubble dimensions. With these methods of aeration, the zone around the bubbles in which the oxygen concentration changes significantly is much wider. The velocity head of the liquid pulsations is insufficient to produce any significant deformation of small bubbles, and there is no mixing of the liquid in the immediate vicinity of the surface. The change in solvency of water close to the hydrophobic surface can be neglected, since the length of orientational ordering of water molecules in the boundary layer is about 1 nm.

In the proposed dispersion method, the head developed by the pump, apart from communicating kinetic energy to the liquid to break-up the air bubbles in the disperse, is also used to increase the rate of oxygen dissolution in the water. In this situation, the concentration of oxygen dissolved in the water reaches a level considerably higher than the equilibrium concentration at atmospheric pressure. Non-use of the pressure factor to increase the rate of the mass transfer process and increase the oxygen concentration in the water is also an undoubted advantage of the proposed technology.

In Fig. 1 we present comparative data on the kinetics of water saturation by oxygen when using the different techniques of aeration. It can be seen that the technology of intensive aeration has indisputable advantages over the other techniques; the efficiency of oxygen dissolution is increased severalfold when the comparison is made at the same air input.

The intensive aeration technology consists of the following: The water is pumped into a pipeline, and air is fed into the line simultaneously; the resulting water – air mixture passes into a pneumohydraulic disperser that is installed in the same line. The disperser operates on the jet impact principle, with the jets colliding with an obstacle and with oppositely directed jets; this ensures full-volume contact of the interacting phases. The homogenization process goes forward under a certain pressure, which in turn favors the dissolution of oxygen in water to a concentration above the equilibrium concentration.

As an example of application of this technology, let us examine experimental data on the treatment of subsurface water from the well that supplies the domestic and potable water system of the Sibirginskii open-pit mine (Southern Kuzbass). The principal undesirable components in the water are as follows: iron 3.3 mg/liter, manganese 0.61 mg/liter, hydrogen sulfide rating 2, turbidity 10 mg/liter. This water was treated by intensive aeration followed by filtration through a granular filter bed, producing water with the following indexes: iron 0.05 mg/liter, manganese 0.13 mg/liter, no hydrogen sulfide, turbidity 0.3 mg/liter. These results served as the design basis of a water treating station for the mine.

From the results of experimental and semicommercial studies on actual subsurface water from a number of coal industry operations (the Raspadskaya underground mine and the Sibirginskii open-pit mine) and on certain facilities in Yakutia and elsewhere, it is concluded that the primary spheres of application of the intensive aeration technology may be the following: a) treatment of subsurface artesian water intended for drinking, to remove iron, manganese, hydrogen sulfide, and organic impurities; b) intensification of the ozonation process in disinfection of potable water and wastewater (the possibility of increasing the efficiency of ozone dissolution in water by a factor of 4-5 opens up the possibility of commercial realization of ozonation in existing ozonator capacity); c) intensification of processes for biological treatment of domestic sewage, where aeration processes are a necessary condition for viability and activity of microorganisms.

The use of the intense aeration technology and equipment in these fields of application will permit a sharp reduction of capital investment in construction and a significant reduction of the requirements for metal and energy carriers; and, most importantly, it can provide a higher quality of treatment of natural water and wastewater.

REFERENCES

1. L. A. Kul'skii, Theoretical Principles and Technology of Water Conditioning [in Russian], Naukova Dumka, Kiev (1980).
2. Degremont, Water Treatment Handbook, 5th ed., Halstead Press, New York (1979).
3. V. A. Klyachko and I. É Angel'tsin, Treatment of Natural Waters [in Russian], Stroiizdat, Moscow (1971).
4. V. K. Kedrinskii and R. I. Soloukhin, "Compression of a spherical gas cavity in water by a shock wave," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1961).
5. M. S. Plesset, "On the stability of fluid flows with spherical symmetry," J. Appl. Phys., **25**, No. 1 (1954).
6. A. N. Kolmogorov, "On the breakup of drops in a turbulent flow," Dokl. Akad. Nauk SSSR, **66**, No. 5 (1949).