SPARK-DISCHARGE METHOD FOR ACCELERATING MASS TRANSFER IN A SOLID – LIQUID SYSTEM

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This article considers the kinetics of mass transfer (solution) between a solid and a liquid in which a vibration process is excited by spark discharges with different frequencies. The relative increase in the mass-transfer constant is a function of frequency and reaches a maximum when the latter has a certain value.

It has been shown in a number of studies [1-4] that the kinetics of mass transfer are to a substantial extent governed by the relative rate at which a liquid flows by a solid. The mass-transfer constant increases with this rate.

Methods for increasing the relative flow rate by imparting low- or high-frequency (ultrasonic) vibrations to the liquid have proved to be effective.

In addition to these methods, the relative flow rate can be increased by spark discharges in the liquid, since the latter excite pulsed accoustic vibrations [6], and their use to accelerate mass-transfer processes may be very promising. This has been confirmed by a study [5] on the intensification of acid decomposition of an apatite concentrate.

It can be assumed that, in first approximation, the mass-transfer kinetics are described by relationships similar to those obtained in studying mass transfer during low-frequency liquid vibrations. Such relationships have been obtained in a number of studies [8-11].

The kinetics of mass transfer from spherical particles to a liquid over a broad frequency range (10-125 Hz) was investigated by Burdukov and Nakoryakov [10]. They obtained the following equation:

$$\mathrm{Nu} = \frac{Kd}{D} = 0.99\left(\frac{B^2 d}{\sqrt{\omega\nu}\,D}\right)^{\frac{1}{3}}. \quad (1)$$

With constant values of d, D, and ν, it follows from Eq. (1) that

$$K = m\omega^{\frac{1}{2}}A^{\frac{2}{3}}. \quad (2)$$

In order to use Eq. (2) to determine the mass-transfer constant under conditions where the vibrations in the liquid are excited by spark discharges, we must determine the manner in which a change in pulsed frequency affects the amplitude of the liquid vibrations.

It can be assumed [12] that, with the same circuit electrical parameters and medium conditions, each discharge produces liquid vibrations of identical amplitude.

Since a spark discharge is actually accompanied by radiation of a compression wave and subsequent formation of a pulsating gas bubble [13], the term "amplitude" means the total displacement of the liquid during the period for which the bubble exists.

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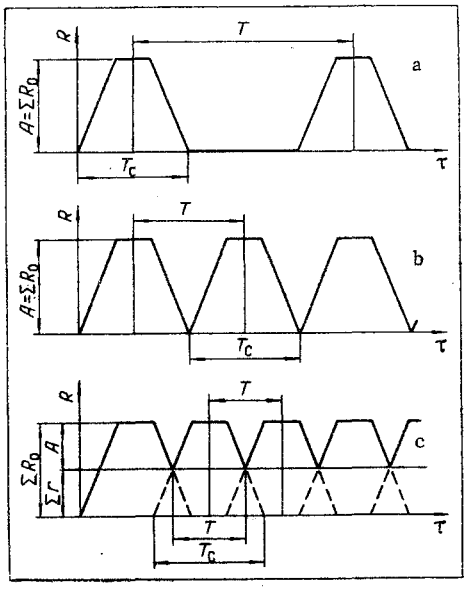

Fig. 1

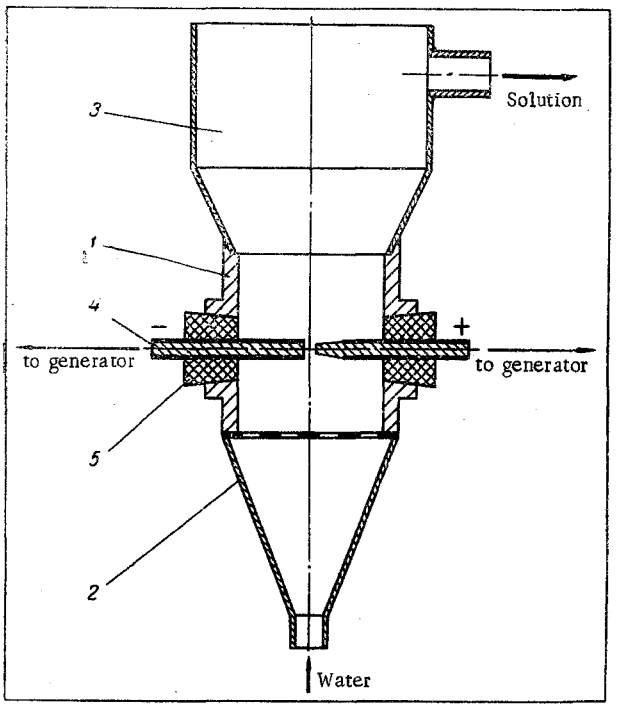

Fig. 2

Fig. 1. Change in displacement amplitude of liquid A with time: a) $T_c < T$, $\omega < \omega_{cr}$, $A = \Sigma R_0$; b) $T_c = T$, $\omega = \omega_{cr}$, $A = \Sigma R_0$; c) $T_c > T$, $\omega > \omega_{cr}$, $A = \Sigma(R_0 - r)$.

Fig. 2. Solution apparatus.

With small discharge gaps, the pulsating gas bubble has the form of a short cylinder [13] and the vibration amplitude of the surrounding liquid is determined by the difference in the cylinder radii during expansion and compression:

$$A = \Sigma (R_0 - r). \tag{3}$$

It can be assumed in first approximation that the change in amplitude with time is similar to the change in pressure at the shock-wave front. The change in amplitude during the period for which the gas bubble exists can then be approximately represented on coordinates indicating the bubble radius versus time, as shown in Fig. 1a, b, and c [14]. It can be seen from Fig. 1 that the amplitude $A = \Sigma R_0 = \text{const}$ remains constant to the discharge frequency at which the discharge period becomes equal to or greater than the time for which the gas bubble exists (Fig. 1a).

This limiting discharge frequency will be called the critical frequency. When the frequency is further increased, the amplitude is reduced (Fig. 1c) and is defined by Eq. (3).

From the conditions that the figures be similar (Fig. 1c) for the postcritical region ($\omega > \omega_{cr}$), it follows that

$$\frac{A}{R_0} = \frac{T}{T_c}. \tag{4}$$

Expressing the discharge period in terms of the frequency, we can write Eq. (4) in the form

$$A = \frac{R_0}{T_c} \frac{1}{\omega}. \tag{5}$$

The quantity R_0/T_c characterizes the rate of discharge-channel expansion [13] and, with all other conditions being equal, is constant for discharges of given energy.

Solving Eqs. (2) and (5) jointly, we find

$$\text{at } \omega \leqslant \omega_{cr} \quad K = m_1 \omega^{0.5}, \tag{6}$$

$$\text{at } \omega > \omega_{cr} \quad K = m_2 \frac{1}{\omega^{0.167}}. \tag{7}$$

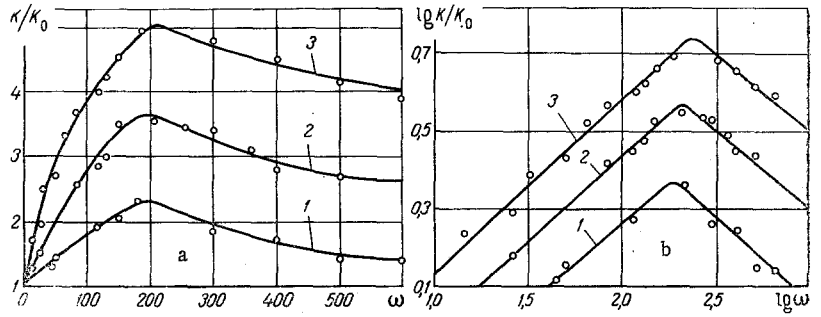

Fig. 3. Relative increase in solution rate as a function of discharge frequency (ω, Hz) (a) and $\log K/K_0$ as a function of $\log \omega$ (b). 1) Gypsum fraction with grain size of 1-1.5 mm, U = 2 kV; 2, 3) cylindrical KNO_3 specimens, d = h = 8 mm; 2) U = 1.5 kV; 3) U = 2 kV.

The present investigation was an attempt at experimental verification of the above theories and of Eqs. (6) and (7), for which purpose we conducted an experimental investigation of the solution kinetics of KNO_3 specimens and natural gypsum particles suspended in water under the action of spark discharge with different frequencies.

Our investigation was conducted in a laboratory apparatus consisting of three main units: a device for suspended-layer solution, a short-current pulse generator, and a controlled-temperature chamber for supplying the solvent to the apparatus at the desired temperature.

The solution unit (Fig. 2) consisted of a metal column 1 40 × 40 mm in size, with a screen 2 in its lower portion and an enlarged area 3 in its upper portion, to prevent losses. Steel electrodes 4 were mounted in the lateral walls of the column, with the aid of rubber insulators 5. Both electrodes were insulated, while the positive electrode was tapered, in accordance with the recommendations in [7].

The electrode power supply was from a short-current pulse generator, which consisted of a capacito energy accumulator with a control device, in the form of a thyratron blocking generator. The current-pulse frequency could be varied over the range 10-600 Hz, the discharge voltage over the range 1-3 kV anc the discharged energy over the range 0.5-1.5 J.

The experimental method consisted in the following.

A given portion of gypsum with a grain size of 1-1.5 mm was introduced into the solution apparatus and suspended in flowing distilled water at 18°C. A sample of the solution was first taken at the apparatus outlet and filtered through a layer of fiberglass. The generator was then connected and another solution sample was taken and filtered. Titration was used to determine the gypsum concentration in each sample.

The relative increase in mass-transfer rate was evaluated from the concentration ratio:

$$\frac{K}{K_0} = \frac{C_2 - C_0}{C_1 - C_0}. \tag{8}$$

Cylindrical particles of KNO_3 produced by pressing were dissolved in flowing distilled water at 18°C in the same apparatus.

Previously prepared samples [3] were introduced into the apparatus with the aid of a special holder, located on the axis of the unit at a distance of 15 mm from the discharge-gap axis; solution was conducted for a predetermined time.

The relative increase in the mass-transfer rate was evaluated from the specimen weight loss:

$$\frac{K}{K_0} = \frac{\Delta G}{\Delta G_0}. \tag{9}$$

Each experiment was duplicated five times with specimens of identical size at each frequency.

The experimental results, which are presented in Fig. 3a, show that the critical discharge frequency under the conditions described above was 190-200 Hz. Mass transfer was accelerated by a factor of five for the mounted particles and by a factor of 2.3 for the suspended particles.

Processing of the experimental results in the form of the function $\log K/K_0 = f(\log \omega)$ (Fig. 3b), taking into account the fact that the value of K_0 was constant for both salts under all the experimental conditions, enabled us to obtain the relationships:

$$\text{at } \omega \leqslant \omega_{cr} \quad K = m_1 \omega^{0.467}, \tag{10}$$

$$\text{at } \omega > \omega_{cr} \quad K = m_2 \frac{1}{\omega^{0.3}}. \tag{11}$$

As can be seen, these relationships are in satisfactory agreement with Eqs. (6) and (7). However, the discrepancy between Eqs. (7) and (11) is large for the postcritical region. This can be attributed to the fact that we did not take into account the thermal and cavitation effects, the dispersion, and the electromagnetic radiation of the spark discharges.

It can be assumed in first approximation that the thermal effect and electromagnetic radiation are independent of the discharge frequency.

The mass-transfer constant in the postcritical region should then be greater than that given by Eq. (7), which is based on an inversely proportional dependence on frequency [Eq. (5)].

NOTATION

Nu	is the diffusion Nusselt number;
K, K_0	are the mass-transfer coefficients with liquid pulsations and without;
d	is the diameter of particle;
h	is the height of particle;
D	is the diffusivity;
ω	is the discharge frequency;
ω_{cr}	is the critical discharge frequency;
ν	is the kinematic viscosity;
A	is the amplitude of liquid pulsations;
$B = 4\omega A$	is the amplitude of liquid pulsation velocity;
R_0, r	are the radius of gas bubble cylinder in expansion and contraction;
$T = 1/\omega$	is the discharge period;
T_c	is the life-time of gas bubble;
C_0	is the initial gypsum concentration in water for solution;
C_1, C_2	are gypsum concentration in solution at apparatus entrance for solving with discharges and without them;
ΔG_0, ΔG	are the losses of sample weight in solving with discharges and without;
m, m_1, m_2	are the constants;
U	is the voltage in discharge region.

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