INDUSTRIAL USAGE OF HYDRODYNAMIC CAVITATION DEVICE

Tatiana Vitenko[1], Paweł Droździel[2], Anna Rudawska[2]

[1] Faculty of Engineering of Machines, Structures and Technologies, Ternopil Ivan Puluj National Technical University, Ruska str., 56, Ternopil, Ukraine, e-mail: vitenko@tntu.edu.ua

[2] Lublin University of Technology, Faculty of Mechanical Engineering, Nadbystrzycka Street 36, 20-618 Lublin, Poland, e-mail: p.drozdziel@pollub.pl, a.rudawska@pollub.pl

ABSTRACT

In the paper the results of research on the use of cavitation effects in certain technologiesare presented. Intensification of mass transfer processes in the system 'solid phase - liquid' is reviewed taking into account solid phase cavitation crashing, turbulization of boundary diffusion layer of fluid by cavitation bubbles, the emergence of non-stationary aspects of mass transfer, changes in physical and chemical properties of the liquid phase. Prospects of practical use of cavitation equipment in industryare also described.

Keywords: hydrodynamic cavitationdevice, mass transfer processes, cavitation bubbles, system 'solid phase - liquid'.

INTRODUCTION

The experience in the use of cavitation devices in industry shows that among the known hydro-mechanical methods of influence on technical processes that can significantly increase their intensity, cavitation is quite effective. Modern theorists consider hydrodynamic cavitation intensification as a complex problem, whosesuccessful solution depends on a large number of constituent aspects. The works [7, 6, 9, 14] are devoted to hydrodynamic cavitation, in detail they describe models of cavitation flow, mechanism of dynamics, emergence, growth and implosion of vapour-gas cavities, they present the results on physical and chemical phenomena accompanying cavitation and causing severe destructive effect or intensification of action, regardless of the variety of mechanisms and forms of expression.

Numerous scientific publications devoted to the use of cavitation as a method of processes intensification in chemical, chemical-pharmaceutical and food industries, [5, 6, 7, 13, 14] explain the mechanism of impact of cavitation fields on technological environment based on cumulative hypothesis according to which in the final stage the implosion of cavitation bubbles emerge micro-streams oh high energy potential. They affect the surface of phase distribution, i.e. destroy its borders forming an emulsion [1, 2, 8, 9, 10]. In scientific monographs [8, 11] intensification is explained by the emergence of a number of effects, namely, pulsating pressures (approximately 10^3-10^4 atmospheres) and compression-dilatation waves under steam bubbles pulsation; emergence of cumulative streams; phase transitions that occur on the surface of bubbles; temperature pulsation; formation of turbulent areas; chemical transformations. Along with this, experimental studies and theoretical generalizations regarding the mechanism of intensification of hydrodynamic cavitation on mass transfer system "solid phase - liquid" today are scarce.

The basis of this article is the author's research, which examines the effects of cavitation in terms of their use in certain processes that usually set limits for production. Their objective analysis allows to assess the advantages and

disadvantages of this method of influence on the technological environment and determine the prospects for further research in this area. The above mentioned fully applies to the dissolution processes that have diffusion and kinetic nature of dissolution and are often used in industry

ANALYSIS OF RESEARCHES

Analysis of abstract theorems that define complex hydrodynamics of cavitation mode that causes the intensification of processes, reveals the mechanisms of its influence on technological environment. Cavitational hydrodynamics is accompanied by a large number of effects that determine and explain its difference from the turbulent mode. In works that aim to study this question, are presented in detail physical and mathematical models that reveal and describe the mechanism of cavitation [2÷4, 9, 16]. The effectiveness of the impact on technical environment is explained by pressure gradient (approximately 10^2-10^3 MPa), compression-dilatation waves under steam bubbles pulsation, effect of cumulative streams, phase transitions that occur on bubbles surface, pulsation of local temperatures, formation of turbulent areas [6, 10]. Such an approach provides discrete energy distribution in the work volume, which is possible due to creation of conditions for generating multiple vapour or vapour-gas bubbles.

Under hydrodynamic cavitation boiling of liquid occurs due to the rapid decrease in external pressure that can be achieved in the devices, which are widely used in chemical engineering, in particular, mechanical mixers, Venturi tubes. Let us consider the physical interpretation of influence mechanism of hydrodynamic cavitation on diffusion and kinetically controlled processes in the system "solid phase - liquid". During fluctuations, growth and implosion of cavitation bubbles in the liquid within cavitation area unsteady flowsare formed, which intensify convective mass transfer and implement a dynamic effect on solid particles.

It should be noted that cavitation bubbles - that form continuously, pulse and implode - can perform a dual effect. On the one hand, they turbulize and destroy diffusion boundary layer thickness of which is related to the mass transfer by the ratio $\beta = D/\delta$ and crash solid fraction. After implosion bubbles start forming diffusion boundary layer on the surface of mass transfer. Under such conditions initially $\delta \rightarrow 0$ and $\beta \rightarrow \infty$

. Over time, its thickness increases and decreases, and tends to a constant value. Then the process repeats. It creates the conditions of unsteady mass transfer, which is characterized by high values of coefficients of mass transfer and is important for outer-diffusion processes. Formed vapour-gas inclusions exist 10^{-6} – 10^{-5} s. They quickly implode due to significant pressure drop, unlike the gas phase, which can be formed, for example, as a result of reactions when these processes are much slower. On the other hand, partial isolation of particle surface by vapour-gas bubbles from the access of fresh solventoccurs. First of all, it is especially true of fine fractions. These assumptions require experimental verification and synthesis.

In [6, 8] it is stated that treatment of liquid in cavitation devices leads to the reduction of its viscosity, increases its conductivity, changes pH in alkaline side, increases the limit of solids solubility. Such changes may affect the kinetically controlled processes. Therefore, prior cavitation activation (processing) of solvent, which maintains its properties over time, may be appropriate. Let us consider the mechanism of cavitation activation of liquid phase. For example, let us consider water, which is often used as extractant or solvent. According to theoretical propositions about the structure of the molecule via an asymmetric distribution of positive and negative charges within the molecule of water their power centers do not coincide. This leads to the formation of molecules with two oppositely charged poles - dipole. Bipole force is expressed through a dipole moment. Water dipole moment is electric stat. units.

Cavitation treated water is enriched with a sufficient amount of monomer molecules, free radicals - atoms and groups of atoms with unpaired electrons. Such active particles, due to their unpaired electrons, are attracted to the positive pole of water dipole, increasing its dipole moment on the value of the electron charge (electric stat. units). This leads to the increase of activity of the dipole with a subsequent breach of the so-called hydrogen bonds (the latter arising between opposite poles of adjacent dipoles and thus are formed the association of water molecules, they seem to be "sewn" one to another). Thus cavitation treated water loses its spatial structure, its dipoles activated by free radicals become free and actively hydrate ions in lattice points of salt. Due to the increased dipole moment, they "stretch" them faster, which speeds up the transfer to the liquid phase. Thus, the acceleration of dissolution processoccurs.

EXPERIMENTAL PROCEDURE AND STANDS

Based on the comprehensive analysis of chemical-engineering processes and features of cavitation effects on the environment, the following processes under study were selected: mass transfer processes of solids dissolution, characterized by diffusion and kinetic mechanisms; physical and chemical transformations of liquid initiated by cavitation effects, including: vapour-gas emergence, activation of water molecules, complex interrelated chemical transformations, which together are determined by hydrodynamic situation in a liquid environment and cause the intensification effect on the studied processes;

The study was performed using hydrodynamic stands of dynamic and static types. For analysis were used standard research methods, including spectroscopy (determining the content of phenolic compounds, hydrogen peroxide, iodine), pH metry (measuring the pH of water and solutions), conductometry (determination of electrical conduction of solutions and concentrations of target components), titrimetry (determination of concentrations of target components) etc.

PRESENTATION OF RESULTS

In previous studies [14] were experimentally studied the mass transfer laws during dissolution of solids in terms of hydrodynamic cavitation. The obtained results also demonstrate the feasibility of using cavitation devices for intensification of the processes of substances dissolution (substances with diffuse nature of dissolution).

More detailed examination reveals a definite dependence of cavitation intensification degree from particles size in the range of diameters 1 mm $< \bar{d}_p <$4mm, and vice versa, limiting effect for $\bar{d}_p$ <1 mm. Features of dependencies are shown in
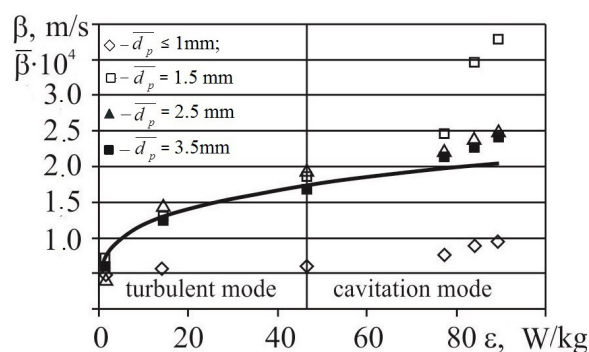

Fig. 1. Mass transfer coefficient dependence of NaCl from the energy dissipation ε, solid curve - theoretical dependence calculated by the equation (1), points - experimental values

Figure 1, they can be explained in terms of impact of vapour-gas phase on the mass transfer by comparing particles size of the solid phase and the size of vapour-gas bubbles.

It is known that cavitation bubbles continuously form, pulse and implode, have a dual effect. On the one hand, they turbulize and destroy diffusion boundary layer thickness of which is related to the mass transfer coefficient. After bubble implosion on the surface starts to form the boundary diffusion layer, and primarily $\delta \to 0$ and $\beta \to \infty$. Over time its thickness increases and β decreases, and tends to a constant value. It reminds unsteady mass transfer scheme. On the other hand, occurs a partial insulation of particles surface with vapour-gas bubbles from the access of fresh solvent. The comparison of the size of solids and formed cavitation bubbles confirm that the particle diameter $\bar{d}_p = 0.5$ mm is lesser than the diameter of vapour-gas phase (see Figure 2) in all energy ranges under study.

Thus, it can be assumed that particles $\bar{d}_p < 0.5$ mm are fully absorbed by vapour-gas bubbles. Due to a formed vapour-gas film the solvent does not diffuse for some time and mass transfer oc-
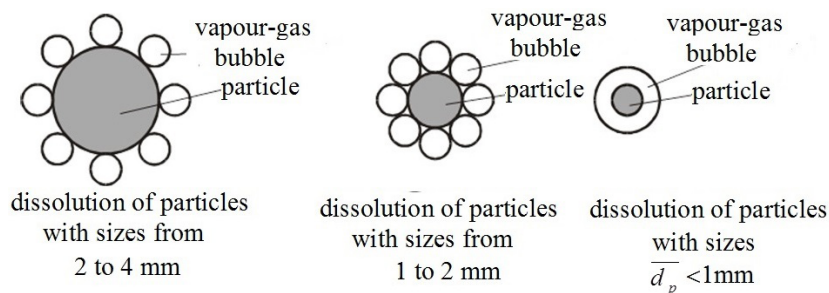

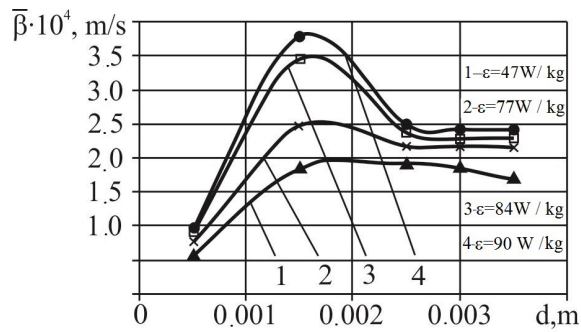**Fig. 2.** Scheme for mass transfer under cavitation

Fig. 3. Dependence of mass transfer coefficient from the size of solids during their dissolution under cavitation

Fig. 4. Dependence of $\overline{\beta}/\beta$ from dissipationenergy ε

curs only after bubbles implosion. Therefore, $\overline{\beta}$ for $\overline{d}_p < 1$ mm is smaller than for larger particles.

Let us consider the dependence of the mass transfer coefficients from particles size (Figure 3). Dissolution of particles with size $\overline{d}_p > 1.0$ mm is the most intense and reminds bubble boiling regime, and the bigger the diameter of the bubble - the broader the diameter of its curve, and the area of contact between these particles and bubbles decreases. This facilitates rapid implosion of bubbles (see Figure 2). The largest radius of curvature is observed for particles $\overline{d}_p = 1.5$ mm, and for factions with size $\overline{d}_p = 2.5 - 3.5$ mm the number of bubbles that form and correspond to the surface unit will be smaller and therefore $\overline{\beta}$ will have lowervalues. In order to assess the intensification effect of cavitation was performed the analysis of dependencies $\overline{\beta}/\beta = f(\varepsilon)$ for different sizes of solid fractions NaCl, shown in Figure 4.

The processing of experimental data in the range $47\text{W/kg} \leq \varepsilon \leq 100\text{W/kg}$ gave the opportunity to receive analytical dependences $\overline{\beta} = f(\beta, \varepsilon)$
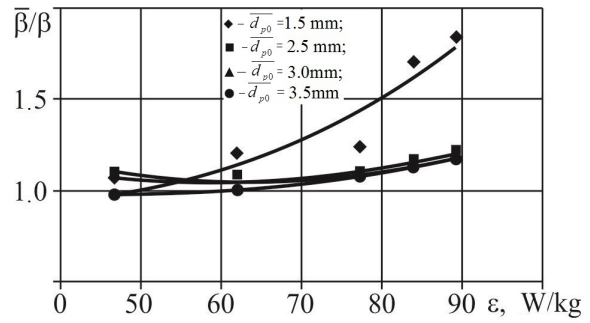
for each averaged diameter of the solid phase particle. It occurred that between $\overline{\beta}/\beta$ and dissipation energy a quadratic dependenceexists, which can be presented as a polynome of a second degree:

$$\frac{\overline{\beta}}{\beta} = a \cdot \varepsilon^2 - b \cdot \varepsilon + c \qquad (1)$$

where a, b, c - coefficients;
β - mass transfer coefficient calculated by the equation:

$$\beta = 0.267 \cdot (\varepsilon \cdot \nu)^{1/4} \cdot Sc^{-3/4} \qquad (2)$$

Table 1 shows the coefficients a, b, and c in the test range of diameters (standard deviation is less than 10%).

During the second series of experimental studies natural gypsumwas used (low-soluble substance). It was found that the value of the mass transfer coefficients changes over time (see. Table 2).

The change of mass transfer coefficients may be explained by the fact that in the working volume a partial mechanical destruction of the solid

Table 1. The estimated coefficients of mass transfer

№	$\overline{d}_{0p}$, mm	Value of the coefficient			Equation of the dependence
		a	b	c	$\overline{\beta} = \beta \cdot f(\varepsilon)$
1	1.5	0.0003	0.0235	1.4	$\overline{\beta} = \beta(0.0003\varepsilon^2 - 0.0235\varepsilon + 1.4)$
2	2.5	0.0002	0.0252	1.92	$\overline{\beta} = \beta(0.0002\varepsilon^2 - 0.0228\varepsilon + 1.92)$
3	3.0	0.00019	0.0188	1.59	$\overline{\beta} = \beta(0.0002\varepsilon^2 - 0.0188\varepsilon + 1.59)$
4	3.5	0.0001	0.0087	1.16	$\overline{\beta} = \beta(0.0001\varepsilon^2 - 0.0087\varepsilon + 1.16)$

Table 2. The change of the mass transfer coefficients over time

n, s^{-1}	16.6	33.3	50	66.6	83.3	100
ε, W/kg	16	22	47	77	84	90
Change of β over time	$5.69 \cdot 10^{-5} - 3.86 \cdot 10^{-5}$	$8.9 \cdot 10^{-5} - 8.25 \cdot 10^{-5}$	$1.84 \cdot 10^{-4} - 1.65 \cdot 10^{-4}$	$1.93 \cdot 10^{-4} - 1.9 \cdot 10^{-4}$	$2.27 \cdot 10^{-4} - 1.99 \cdot 10^{-4}$	$2.97 \cdot 10^{-4} - 2.9 \cdot 10^{-4}$

phase occurs with the emergence of particles of different sizes (1 - 3 mm), complete dissolution of some particles of smaller diameter and uneven reduction of their sizes in the process of dissolution. The reduction of coefficients is better observed under developed cavitation modes. Therefore, in order to compare, analyse and generalize experimental results the average coefficient of mass transfer $\overline{\beta}$ over the period of time $\tau = \sum \Delta \tau_i$ was determined according to the equation:

$$\overline{\beta} = \frac{V \cdot (C_k - C_0)}{F_{ev} \cdot (C_s - \overline{C}) \cdot \tau} \qquad (3)$$

where $C_к$, $\overline{C}$, C_0 - final, average and primary concentration of gypsum, kg/m³; V - volume of the liquid phase, m³; F_{ev} - average surface area of particles m².

The average surface area of dissolution was calculated with the help of graphic dependence

$$F_{ev} = \frac{\int\limits_0^\tau F(\tau) d\tau}{\tau} \qquad (4)$$

The surface F at various intervals was determined on the basis of the material balance equation, where the mass of the solid phase was expressed through its volume. With the help of the average value of the surface area the average concentration value $\overline{C}$ was found, corresponding to the value τ_{ev}. The obtained results are shown in Figure 5 as the dependence of the mass transfer average coefficient changes $\overline{\beta}$ from the speed of rotation of the special profile impeller. The results showed that with increasing Reynolds rate the coefficient of the mass transfer also increases, which confirms the diffuse nature of the dissolution of natural gypsum.

Graphic dependence, reflects the change of mass transfer coefficient according to the impeller speed of rotation, can be divided into two sections: I - up to 50s⁻¹, where values increase slowly, and II - from 50s⁻¹ up to 100s⁻¹, where more significant growth of values can be observed. The analysis of the obtained coefficients of mass transfer (Fig. 5, 6) and their comparison with published data confirmed that in the range of cavitation mode coefficients are higher than described in the literature [6]. Let us compare the obtained value $\overline{\beta}$ with the valuescalculated according to the equation (2). In Figure 6 solid curve corresponds to the theoretical dependence (2), which is valid in terms of intensive mixing and turbulent fluctuations.
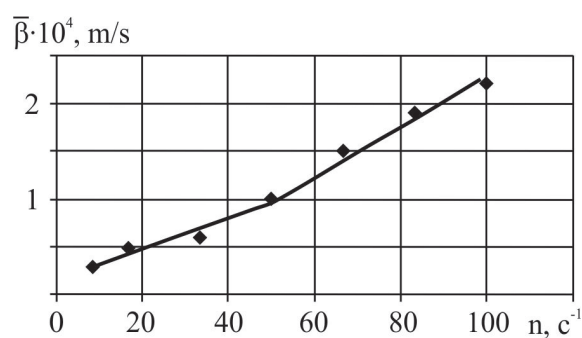

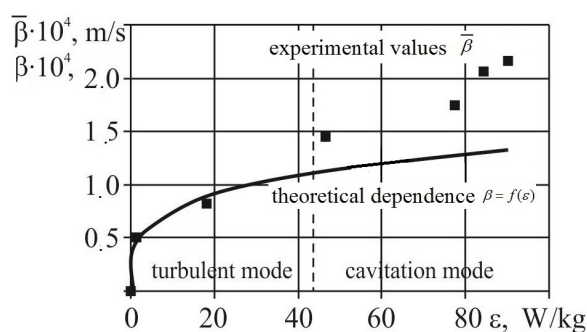**Fig. 5.** Dependence of the mass transfer coefficient from the speed of impeller rotation

Fig. 6. Dependence of mass transfer coefficients β and $\overline{\beta}$ from the value of energy dissipation ε during the dissolution of gypsum

Points - calculated values of the average mass transfer coefficients that correspond the conditions of gypsum particles dissolution in the range of cavitation and turbulent mixing. Position of experimental points above the theoretical curve ranging, starting from 50s⁻¹ (corresponds to the dissipation energy 47W/kg), confirms the assumption that cavitation is the additional intensification mean. The additional action of cavitation is based on the effects related to the physical and chemical properties of the liquid. There occur transient aspects of mass transfer, which have high values of mass transfer coefficients [6].

On the other hand, high velocity fluid flows are formed near particle surface due to bubbles implosion, which are formed on the basis of vapour-gas inclusions or cracks that are on the surface of particles. All these factors create significant shear force on the surface of the solid particles, which reduces the size of the boundary diffusion layer, increasing its mobility, providing concentrations renovation. Thus, it is clear that intensification of dissolution occurs due to concentrations renovation and reduction of the dif-
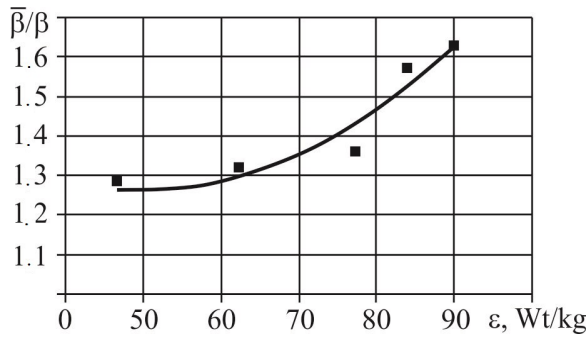
Fig. 7. Graphical dependence $\overline{\beta}/\beta = f(\varepsilon)$

Fig. 8. The dependence of the average diameter of the solid phase particles from processing time (no dissolution)

fusion layer thickness. Increase of mass transfer coefficients can be estimated by the change in ratio $\overline{\beta}/\beta$, that depends on the energy dissipation ε. With the help of the graphical dependence $\overline{\beta}/\beta = f(\varepsilon)$ (Fig. 7), we get equations to determine coefficients of mass transfer under cavitation mixing

$$\frac{\overline{\beta}}{\beta} = 1.8 + 0.0002\varepsilon^2 - 0.0217\varepsilon \qquad (5)$$

where β is calculated by equation (2).

Test for adequate of the equation (5) showed that the deviation of calculated values of mass transfer coefficients from experimental values is less than 10% ($R^2 = 0.9$).

In order to study the effect only of a vapour-gas phase on the intensity of dissolution and elimination of the impact of the gas phase entering the water as a result of air capture under intense mixing, conducted the study in terms of liquid free surface isolation. The results of studies on the dis-
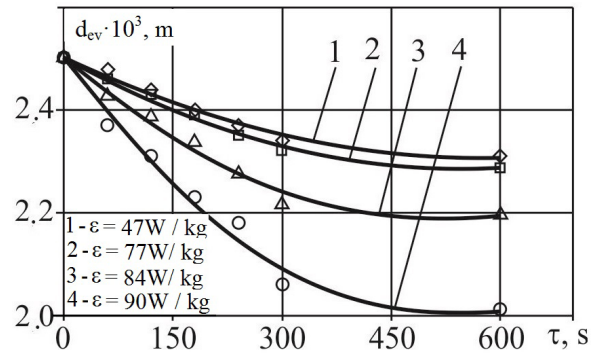
solution of solid particles of gypsum and sodium chloride under different conditions are presented in Table 3. Averaged values of mass transfer coefficients were determined by the standard method. It should be noted that certain deviations of separate values from the average value does not exceed 12%. Analysis of these data shows that the main influence on the intensity of dissolution has vapour-gas phase generated by cavitation.

These studies refer to monodisperse fractions that are not used in the production. Therefore, in the following experiments polydisperse mixture of sodium chloride with particle sizes from 0 to 4 mmwas selected. Table 4 presents the average values of mass transfer coefficients $\overline{\beta}$ for the ensemble of NaCl particles during dissolution in water at different values of energy dissipation.

Table 3. The estimated coefficients of mass transfer

	$CaSO_4 \cdot 2H_2O$ ($\overline{d} = 3mm$)		$NaCl$ ($\overline{d} = 3mm$)	
ε, W/kg	Dissolution under conditions of the contact of the liquid phase with air	Dissolution under conditions of the isolation of the liquid phase from air access	Dissolution under conditions of the contact of the liquid phase with air	Dissolution under conditions of the isolation of the liquid phase from air access
	$\overline{\beta}$, m/s		$\overline{\beta}$, m/s	
47	$1.45 \cdot 10^{-4}$	$1.49 \cdot 10^{-4}$	$1.86 \cdot 10^{-4}$	$1.923 \cdot 10^{-4}$
77	$1.74 \cdot 10^{-4}$	$1.77 \cdot 10^{-4}$	$2.17 \cdot 10^{-4}$	$2.231 \cdot 10^{-4}$
84	$2.05 \cdot 10^{-4}$	$2.16 \cdot 10^{-4}$	$2.29 \cdot 10^{-4}$	$2.359 \cdot 10^{-4}$
90	$2.16 \cdot 10^{-4}$	$2.18 \cdot 10^{-4}$	$2.44 \cdot 10^{-4}$	$2.455 \cdot 10^{-4}$

Table 4. The value of the average mass transfer coefficients

ε, W/kg	Turbulent mode		Cavitation mode			
	16	22	47	77	84	90
Re	$1 \cdot 10^5$	$1.6 \cdot 10^5$	$2.4 \cdot 10^5$	$3.2 \cdot 10^5$	$4 \cdot 10^5$	$5 \cdot 10^5$
$\overline{\beta}$, m/s	$3.47 \cdot 10^{-5}$	$4.24 \cdot 10^{-5}$	$1.051 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$	$2.291 \cdot 10^{-4}$	$2.47 \cdot 10^{-4}$

According to the analysis of the data presented in the table, it becomes clear that in case of dissolution of monodisperse fractions mass transfer coefficient increases under cavitation mode in the installation. Under all modes of dissolution the increase of coefficients $\overline{\beta}$ with the increase of vapour-gas phase volumecan be observed. For polydisperse composition in the range of low values of φ the averaged coefficients of mass transfer $\overline{\beta}$ are low, and with increasing energy and therefore vapour-gas content occurs an increase of $\overline{\beta}$, which occupies an intermediate position between the values valid for particles with size $2.5 \le \overline{d}_p \le 3.5$ mm. Small values of coefficients $\overline{\beta}$ for the ensemble of polydisperse composition for the values of φ = 24% (corresponding to the initial cavitation mode) can be explained by lower content of vapour-gas phase and therefore lesser transiency caused by cavitation.

It is important and necessary to consider the features of dissolution of the solid phase under conditions of cavitation taking into account the impact of crashing. According to the research results, the average particle size of the solid phase decreases over time, and the surface area of mass transfer increases. Figure 8 shows a change in the average diameter defined by the equation

$$\overline{d}_i = d_{1i} \cdot F(m_1) + d_{2i} \cdot F(m_2) + d_{3i} \cdot F(m_3) + d_{3i} \cdot F(m_4) \qquad (6)$$

where d_i - the average particle diameter of each of the fractions, m; $F(m_i)$ - mass content of individual fractions of polydisperse mixture.

Figure 9 shows that the largest impact of crashing for the substance occurs under cavitation mode, characterized by Reynolds number $Re_{cav} > 4 \cdot 10^5$ and cavitation number $\sigma \le 0.6$ ($\varepsilon \ge 84$W/kg). During calculating the coefficients of mass transfer under such conditions you should take into account the increasing surface area ofthe solid phase. This process will depend on the nature of the substance, including material hardness and cavitation flow characteristics.

Figure 9 shows graphic representation of the distribution by the obtained equations. Generalized dependencies, describing the change of distribution of solids according to size *f(d)* over time for different values of energy parameters:

$$f(d) = \frac{1}{0.0014\tau + 0.62} e^{-\frac{(d-[2.5-0.0003\tau])^2}{0.1+0.0009\tau}} \qquad \text{under the condition that } \varepsilon = 47\text{W} / \text{kg} \ (\sigma = 1.6)$$

$$f(d) = \frac{1}{0.0014\tau + 0.68} e^{-\frac{(d-[2.5-0.0003\tau])^2}{0.168+0.0014\tau}} \qquad \text{under the condition that} \varepsilon = 77\text{W} / \text{kg} \ (\sigma = 0.9)$$

$$f(d) = \frac{1}{0.0014\tau + 0.86} e^{-\frac{(d-[2.5-0.0004\tau])^2}{0.23+0.0011\tau}} \qquad \text{under the condition that} \varepsilon = 84\text{W} / \text{kg} \ (\sigma = 0.6) \qquad (7)$$

$$f(d) = \frac{1}{0.0016\tau + 1.08} e^{-\frac{(d-[2.5-0.0007\tau])^2}{0.35+0.0015\tau}} \qquad \text{under the condition that} \varepsilon = 90\text{W} / \text{kg} \ (\sigma = 0.4)$$

Similar results were obtained during dissolution of natural gypsum and milk protein powder.Along with the analysis of the processes intensity in dynamic and static type devices it is important to compare cavitation influence with other methods, including mechanical mixing, ultrasound, electrolysis, vacuuming, etc.
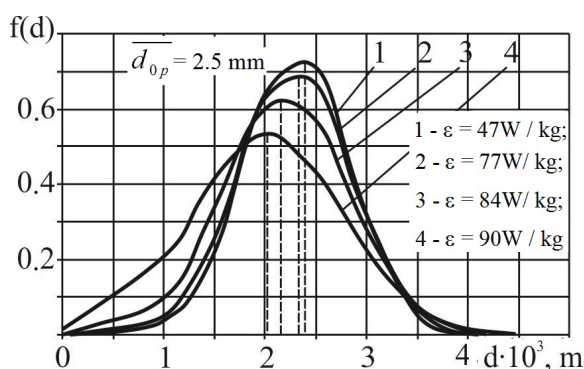

Fig. 9. The distribution of solid phase particles CaSO$_4$ · 2H$_2$O according to the size over 600s of treatmentunder energy values
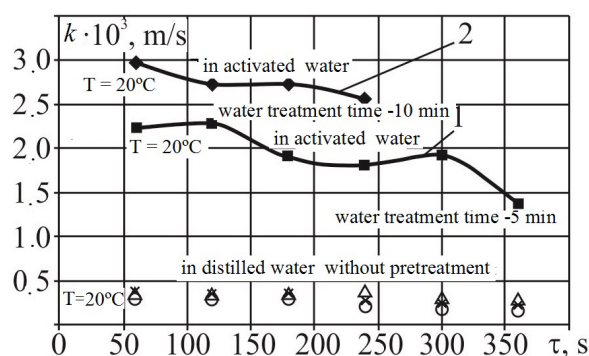

Fig. 10. Change of the langbeinite dissolution coefficients

Table 5. Comparison of mass transfer coefficients and consumed energy during the dissolution of NaCl

β, m/s	Intensification method		
	Cavitation (author`s data)	Vacuuming [14]	Mechanical mixing (turbulent mode) [15]
	$(1.7 - 3.8) \cdot 10^{-4}$	$(1 - 3) \cdot 10^{-4}$	$(0.9 - 1.8) \cdot 10^{-4}$
Energy E, MJ	40 – 60	48 – 64	60 – 80

Table 5 shows the comparison of mass transfer coefficients and consumed energy to obtain saturated solution of NaCl, which is dissolved according to diffusion mechanism. Analysis of the submitted data shows that within comparable values of specific energy consumption the mass transfer coefficients under the condition of cavitation mode or vacuum system approximately corresponds and significantly differs from calculated data for turbulent mode. It is important that the consumption of energy for a saturated solution under turbulent mode increases by 20% compared to vacuuming and cavitation mode. However, the choice of the method of intensification, including cavitation or vacuuming will depend on the particular production.

As noted above, the effects that occur during cavitation bubbles implosion lead to changes in physical and chemical properties of water. Such treatment can be effective for kinetically-controlled dissolution processes. The object of the research was langbeinite, which is known to have a kinetic nature of dissolution. Dissolution was performed in the apparatus with a mechanical mixer. Activation of water was performed in cavitation device of dynamic type. Water was subjected to cavitation impact within two minutes at the temperature T = +20ºC and Reynolds numbers in the range from $2.4 \cdot 10^5$ up to $4.5 \cdot 10^5$. As langbeinite belongs to kinetically-soluble salts, it means that the process of dissolution in water is governed by physical and chemical factors. During hydro-cavitational processing water increases its reactivity, leading to increased dissolution rate of langbeinite, and this is confirmed by the experimental data (Figure 10).

On the basis of the research was proposed to use cavitation devices for potash fertilizer production, including activation of carnallite solution to intensify conversion of low-soluble minerals with the formation of soluble kainite. The research was conducted for langbeinite particles with the size of $d_{ev} = 3$mm. Figure 11 illustrates the langbeinite conversion degree change over time at different temperatures of the process.

Let us compare the rate of change in the degree of conversion of activated and non-activated processes. Analysis of the results shows that the degree of conversion of langbeinite into kainite at 35ºC (inactivated process) on the first day is 3.96%, over five days increases up to 29.73%, and over 10 days up to 54.17%. Over 20 days the degree of conversion of langbeinite into kainite increases up to 78.48%. Comparing these data with the results in activated process confirms its intensification. Thus, over the first five days the degree of conversion is 34.5%, over 10 days - 68.58%, and over 20 days it increases up to 93.6%. At temperature 45ºC a similar patterncan be observed. During the first day - 5.4%, over five days increases up to 38.6%, and over 10 days is 62.3%. Over 20 days the degree of conversion of langbeinite into kainite increases up to 89.4%

Under the condition of prior activation of carnallite solution over the first five days the degree of conversion is 44.3%, over 10 days - 68.0%, and over 20 days increases up to 95.5%. According to the results of core technology such values were obtained at t = 50ºC. With further increase of the temperature up to 55ºC the decrease of the process speedcan be observed. Under normal conditions over the first day the degree of conversion is 4.2%, over five days increases up to 36.4%, and over 10 days is 56.4%. After 20 days the degree of conversion
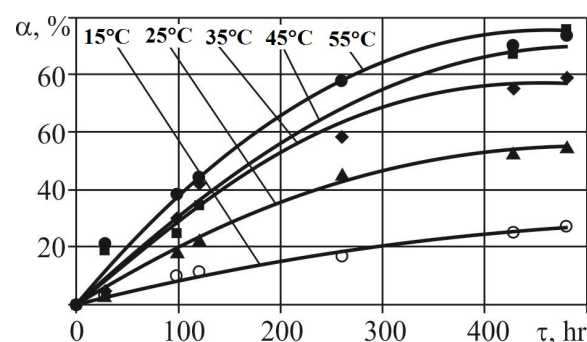

Fig. 11. The dependence of thelangbeinite conversion degree (α) from the time under the condition of using activated carnallitesolution and temperature of the process

Table 6. Calculation of the results of the fertilizer output depend on the degree of conversion of langbeinite into kainite at different temperatures

№	T, ºC	Inactivated process		Activated process	
		Degree of conversion %	Output of fertilizer %	Degree of conversion %	Output of fertilizer %
1.	15	21.8	17.01	27.2	21.15
2.	25	44.8	56.93	55.1	64.94
3.	35	78.5	83.10	93.6	95.06
4.	45	89.4	91.95	95.5	96.55
5.	55	77.8	77.01	81.4	85.40

of langbeinite into kainite increases up to 77.8%. In activated process over the first five days the degree of conversion is 38.3%, over 10 days - 58.4%, and over 20 days increases up to 78.8%. The reduction of speed in this case occurs due to increased field of crystallization of langbeinite, which is a stable phase in the system K^+, $Mg_2^+ \| Cl^-$, SO_4^{2-} (H_2O). Under these conditions, the overall speed of reaction slows down. Thus, the basic processing technology of polymineral potash ore with the previous conversion of low-soluble minerals into kainite can be improved by additional installation of cavitation circulation circuit for pre-processing of carnallite solution before passing it through for the conversion.

Under different temperature conditions fertilizer output increases (Table 6).

CONCLUSIONS

On the basis of experimental studies the mechanism of intensification of hydrodynamic cavitation in the system "liquid-solid phase" was revealed, proven by dynamic action of vapour-gas phase, crashing of dispersed particles, change in physical and chemical characteristics of the liquid phase and the formation of monomer molecules and chemically active compounds. It was found that in terms of cavitation the coefficients of mass transfer increase from 5 up to 30%, compared to the coefficients calculated for conditions with intensive turbulent flow. The degree of influence of vapour-gas phase on the coefficient of mass transfer is 3-20% depending on the mode of the process conduction and the crashing effect 2-10%. The analysis of change in disperse composition of the solid phase and the coefficients of mass transfer over time showed that the reduction of β occurs due to an increase in the mass fraction of fines in the mixture. Summarizing the obtained graphic dependencies for the change of the average particle diameter of the solid phase and setting changes in the composition of solids over time we obtained equations that can be used to calculate the average

coefficient of mass transfer and predict the size of the solid phase during dissolution under conditions of cavitation mixing.

Under study was the intensification effect of cavitation on the kinetically- soluble substances (langbeinite) that can be explained due to a change in the structure and chemical reactivity of water, also it was proposed to use cavitation devices in production of potash fertilizers.

REFERENCES

1. Balasundaram B., A.Pandit. Selective relese of invertase by hydrodynamic cavitation. Biochemical Eng. Jornal, 8, 2001, 251 – 256.
2. Brandner P.A, G.J.Walkler. Hydrodynamic performance of a vortex generator. Experimental Thermal and Fluid Science, 27, 2003, 573 – 582.
3. CAV-OX Cavitation Oxidation Process. Application Analysis Report, Mag num Water Technology, Inc., Risk Reduction Eng. Laboratory, Office of Research and Development, U.S.E.P.A., Cincinnati, Ohio 45268, 1994.
4. Chervyakov. V.M., Yudaev. V.F. Cavitational phenomena in the "gas-liquid" environment. Problems of engineering and automation, 4, 2004, 73 - 77.
5. Couppis E.S., Klinzing G.E. Effect cavitation of the reactive systems AIChE Journal, 20(3), 1974, 485-491.
6. Fedotkin. I.M., Hulyi. I.S. Cavitation, cavitation technics and technologies, their use in industry, Polygraphic book, 1997.
7. Gogate P. R., Pandit A. B. A review and assessment of hydrodynamic cavitation as a technology for the future. Ultrason. Sonochem., 12, 2005, 21 – 27.
8. Hammitt F.G. Cavitation and multiphase flow phenomena. McGraw-Hill Book Co., 1980, 250-270.
9. Hanson I., V. Kedrinskii. Morch On the dynamics of cavity cluster. J. Appl. Phys., 39, 1981, 1725 – 1734.
10. Neppiras E.A. Acoustic cavitation. Phys. Repts. 61 (3), 1980, 159 – 251.
11. Promtov M.A. Pulsation Apparatus of rotor type: Theory and Practice. Engineering - 1, 2001.

12. Promtov M.A. V.M.Chervyakov. Kinetics of NaCl dissolution in water under the treatment in a rotary-pulse apparatus. Chemistry and chemical technology. 43(6), 2000, 133-135.

13. Vichare N. P, Goate P.R., Pandit A.B. Optimisation of hydrodynamic cavitation using a model reaction. Chem.Eng. Tecn., 2(4), 2000, 683.

14. Viten'ko T.N., Gumnitskii. Ya.M. Mass Transfer during Dissolution of Solids Using Hydro-dynamic Cavitation Devices. Theoretical Foundations of Chemical Engineering, 40, (6), 2006, 598–603.

15. Vitenko T.M.,Kalinichenko I. Kinetics of Reactions with Participation of Iodide and Iodine under Conditions of Hydrodynamic Cavitation. Journal of water chemistry and technology, 33(5), 2012, 301-306.

16. Yu Po-wen, C. Steven. The collapse of a cavitation bubble in the shear flows a numerical study Physics of Fluids, 7,(11), 1995, 2608 – 2616.

17. Yudaev V.F. Hydromechanical processes in rotor apparatus with modulation of the open flow area of treated environment. Theoretical Fundamentals of Chemical Technologies. 28(6), 1994, 581 - 590.