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USE OF THE PRINCIPLE OF DISCRETE PULSED INTRODUCTION OF ENERGY FOR DEVELOPMENT OF EFFICIENT ENERGY-CONSERVING TECHNOLOGIES

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We discuss basic aspects of the principle of discrete pulsed introduction of energy as a general approach to intensification of heat and mass transfer and hydromechanic processes in disperse media. The principle is based on spatial and temporal localization of the energy introduced, which provides high power values in discrete zones of the system. The intensification results from the dynamic action of an ensemble of growing or collapsing bubbles upon rapid change in the external pressure. Intensification mechanisms and basic criteria for their efficiency are analyzed. Examples of practical implementation of the principle as applied to development of energy-conserving technologies are considered.

Introduction. The solution to the pressing global problem of energy conservation and the search for new energy sources are presently related to development and introduction of modern efficient technologies in the most energy-consuming branches of production in metallurgical, chemical, food, and other industries. According to data from the Energy Center of the Unified Electric Power System, the possible energy saving due to adoption of new efficient technologies can be as large as 10 to 25%, although, according to the same data, in a number of cases it is possibility to make this value as high as 80%.

In recent years, a tendency toward application of nontraditional methods of intensification of technological processes utilizing powerful physical actions is notable, which makes it possible to achieve results impossible for traditional technologies, at comparable costs. A number of these physical phenomena were studied earlier primarily in connection with the need to prevent or diminish their destructive action. For example, a number of works are devoted to investigation of phenomena in high-temperature rapidly boiling flows in the context of the problem of predicting emergency situations caused by depressurization of high-pressure loops of intense-cooling systems of thermal and atomic power stations. An abrupt drop in the pressure as a result of damage to a pipeline shell leads to explosion-like boiling of the liquid, which is accompanied by rapid transformation of the heat accumulated in the liquid into mechanical energy and release of a pressure pulse with a large destructive force in a local volume.

The adverse consequences of erosive damage of blades of ship propellers, water turbines, pumps, and other hydraulic installations that take place as a result of collapse of cavitation bubbles formed due to a local pressure drop in the liquid are well known.

Destructive phenomena of this type that are connected with cavitation or explosion-like boiling of an overheated liquid can be used successfully in technological operations that require strong actions, e.g., in crushing solid or liquid dispersions in grinding, emulsification, and homogenization processes, as well as for intensification of heat and mass transfer processes.

The above-mentioned physical phenomena, in spite of differences in their initiation mechanisms and forms of manifestation, have a common regularity. They take place in liquid media upon rapid change in the external pressure and are accompanied by intense growth or collapse of bubbles being formed, which ultimately determines the dynamic action on solid surfaces or dispersions. Spatio-temporal energy localization is considered to be a distinctive feature of these processes, which makes it possible to create directed high-power pulses at a comparably low energy level.

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In what follows, we consider basic concepts of the principle of discrete pulsed introduction of energy, which suggests new approaches to intensification of technological processes in disperse systems. The operation of apparatuses and installations that implement this principle is analyzed.

Basic Assumptions. Stimulation of hydromechanical and heat and mass transfer processes in disperse systems usually involves high energy consumption. The latter is dictated by the need to satisfy the following requirements: grinding a dispersion in order to increase the specific contact surface of the phases, activating the hydrodynamic environment in the vicinity of a phase interface and increasing the transfer coefficients by this means, macromixing a carrier phase in order to maintain a substantial transfer potential. Optimum satisfaction of these requirements determines the level of intensification in each particular case.

Traditional intensification methods are largely connected with maximum turbulization of the liquid medium either by using rotating mixers or by achieving high flow rates in channels. In both cases, a substantial portion of the energy being introduced is spent for work against viscous forces and friction. For example, operation of such traditional emulsifiers as mixers and propeller agitators involves energy losses for macromixing the entire volume of the liquid in the apparatus just in order to provide adequate conditions for crushing dispersions in a small local zone in the vicinity of the propeller blades. This leads to a substantial decrease in the efficiency of the apparatus.

We propose a fundamentally different approach to intensification of heat and mass transfer and hydromechanical processes in disperse media [1, 2]. Known as the principle of discrete pulsed introduction of energy (DPIE), it is based on useful utilization of the above-mentioned and other physical phenomena in vapor–liquid systems upon rapid change in the external pressure. Realization of the principle implies existence or creation of a substantial number of bubbles distributed uniformly over the liquid phase. Upon a sharp increase in the pressure in the system, each bubble first shrinks and then collapses, releasing a high-pressure pulse in the form of a spherical shock wave or, when located in the vicinity of a solid surface, it forms a cumulative microjet directed toward the surface. When collapsing, the bubble can experience high-frequency vibrations and emit acoustic energy in the ultrasound region into the surrounding liquid. Upon a rapid drop in the external pressure, phenomena of explosion-like boiling accompanied by emission of a high-amplitude pressure pulse and turbulization of adjacent layers of the liquid are observed. As a result, intense microflows with high instantaneous values of local velocity, acceleration, and pressure arise in the interbubble space.

A set of dynamically evolving bubbles can be considered as a kind of microtransformers that transform the potential energy accumulated in the system into kinetic energy of the liquid that is discretely distributed in both space and time.

When implementing DPIE methods, the well-known principle of the shock action used that forms the basis of, for example, operation of an optical laser or the action of a directed explosion: slow accumulation of a relatively small amount of energy and its release in a short time interval in a small spatial region. Thus, a high value of the specific power is reached in the treatment zone as a result of the simultaneous decrease in the spatial and temporal region of energy localization.

DPIE Efficiency Criteria. Despite the wide variety of problems of intensification of heat and mass transfer and hydromechanical processes in disperse media and all the differences in the methods used for their implementation, just a single simple general principle forms the basis for the intensification. To provide crushing of a disperse particle or to increase the coefficient of heat or mass transfer through a phase interface, one should provide that the liquid have a high relative velocity of motion. With constancy of the carrier phase flow, the velocities of motion of both phases equalize rapidly, the relative streamlining velocity approaches zero, and the external action on the particle vanishes. In order to maintain a certain difference in the phase velocities, one should provide accelerated motion of the liquid in the vicinity of the dispersion. Therefore, attaining the greatest possible amplitude values of the velocity and maximum values of the acceleration of the microscale flow created by the growing or shrinking bubbles is one of the important conditions for efficiency of DPIE mechanisms.

Simultaneous fulfillment of the requirements of high values of the velocity and acceleration of the liquid in the vicinity of the dispersion is reduced to the condition of the most rapid change in the kinetic energy at a particular point of the liquid [2]. The rate of change of the kinetic-energy density at a particular point located a distance r

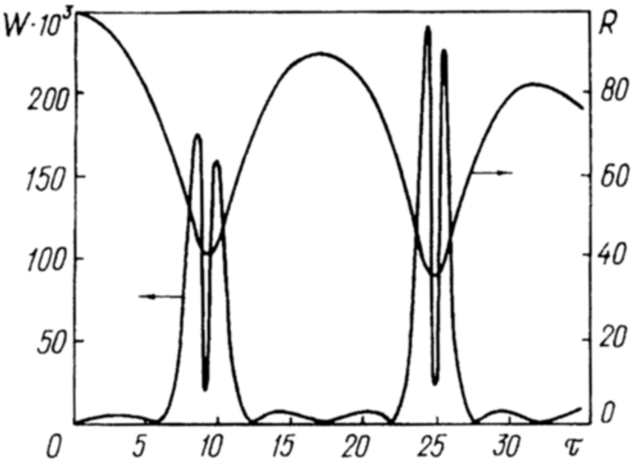

Fig. 1. Time dependence of the specific power W_R in the liquid at the bubble boundary and the bubble radius R in the first two oscillation periods of a collapsing bubble. Initial radius of the equilibrium bubble $R_0 = 100$ μm, temperature of the liquid $T_{liq} = 363$ K ($p_{liq0} = 70$ kPa); final pressure in the liquid $p_{liq} = 200$ kPa; pressure rise time $\Delta\tau = 0$. W, MW/m^3; R, μm; τ, μsec.

from the center of the bubble, which determines the specific power W at this point, is related to the velocity w_R and acceleration $dw_R/d\tau$ of the liquid at the boundary of the bubble by the formula

$$\frac{d\varepsilon_k}{\partial\tau} = W(r, \tau) = \frac{\rho_{liq}R^3}{r^4}\left(Rw_R\frac{dw_R}{d\tau} + 2w_R^3\right). \tag{1}$$

This means that the rate of change of the kinetic energy of the radial pressure of the liquid at the boundary of the bubble is the parameter that determines the degree of the dynamic action of the bubble and, consequently, the level of intensification. Within the framework of the energy conservation law, the requirement of the maximum rate of change of the kinetic energy of the radial pressure of the liquid is equivalent to the requirement of the most rapid change in the potential energy accumulated by the system.

To initiate DPIE mechanisms, one should displace the system from thermodynamic equilibrium as rapidly as possible by creating a pressure difference in the vapor and liquid phases. Inasmuch as the pressure in each phase is precisely the specific potential energy of that phase, a high initial pressure difference provides a store of accumulated potential energy that transforms into kinetic energy of radial motion of the liquid in the vicinity of an individual bubble in the process of relaxation of the system to the stationary state. Upon reaching the maximum value, the kinetic energy transforms into potential energy of the compressed gas within the bubble and partially into potential energy of the compressed liquid, which appears in the form of a narrow high-pressure zone in the vicinity of the bubble and then propagates in the liquid with the velocity of sound as an acoustic wave. During collapse and oscillation of the bubble these transformations of mechanical energy take place repeatedly.

Figure 1 shows how the specific power in the vicinity of an individual bubble that is calculated by Eq. (1) changes over several oscillation periods of the bubble during its collapse. Four power pulses are observed in one oscillation period, and it should be noted that in the final compression stage and the initial expansion stage the amplitudes of the pulses are especially large. These transformations of mechanical energy are repeated to the point of collapse.

In considering intensification mechanisms, it is desirable to establish criteria for estimation of the extent to which the requirement of the most rapid energy transformation is satisfied in each particular case.

Each of the energy transformation stages is characterized by its own transformation time $\Delta\tau_{tr}$. The lower the value of $\Delta\tau_{tr}$, the higher the rate of change of the kinetic energy and the larger the amplitude of the power pulse $W = \Delta\varepsilon_k/\Delta\tau_{tr}$. At the same time, the amplitude of the pulse is also determined by the amount of the specific energy $\Delta\varepsilon_k$ being transformed. The latter depends on the amount of potential energy accumulated by the system

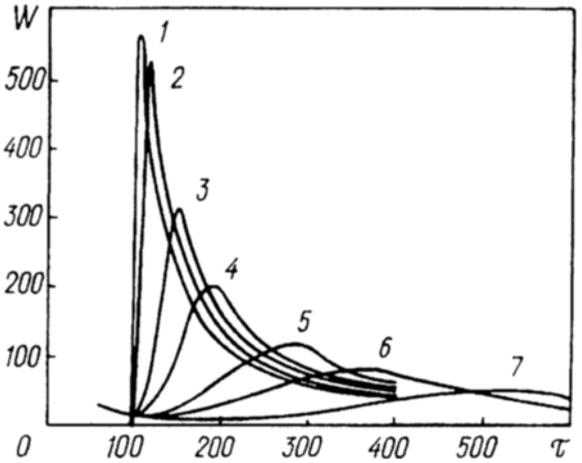

Fig. 2. Effect of the duration of a pressure drop from 50 to 20 kPa on the specific power W_R in a pulse in the process of continuous growth of a vapor bubbles: 1) 0 μsec, 2) 10, 3) 50, 4) 100, 5) 200, 6) 300, 7) 500 μsec. T_{liq} = 363 K. At the instant of the pressure drop R = 104 μm.

prior to its transformation into kinetic energy or, in other words, on how large a pressure difference between phases $\Delta p = p_{\text{liq}} - p_g$ is created before completion the transformation stage. It is evident that if the required effect in the system can be achieved by accumulation of a certain store of specific potential energy $\Delta\varepsilon_p = \Delta p$, the accumulation time $\Delta\tau_{\text{ac}}$ during which the external pressure changes by the quantity Δp should be substantially less than the energy transformation time $\Delta\tau_{\text{tr}}$.

Irrespective of the means of practical implementation of the DPIE principle one should be guided by the following criteria in seeking the optimum solution.

1. The rate of accumulation of potential energy in the system should exceed the rate of its subsequent transformation ($\Delta p/\Delta\tau_{\text{ac}} \to \max$, $\Delta\tau_{\text{ac}} << \Delta\tau_{\text{tr}}$).

2. The energy transformation should be extremely fast, since the useful power released in the form of a pulse is inversely proportional to the transformation time and directly proportional to the energy accumulated in this time ($\Delta\varepsilon_k/\Delta\tau_{\text{tr}} \to \max$; $\Delta\tau_{\text{tr}} \to \min$).

3. The energy in the form of a pulse should be released simultaneously in a number of small local zones uniformly distributed over the entire working volume of the apparatus.

In solving specific practical problems, these conditions play the part of necessary criteria that should be used as guidelines for the choice of the most efficient and rational DPIE method.

The two first conditions impose strict constraints on the rate of change of the external pressure or on the rate of introduction of energy, which should be as high as possible. The duration of the change in pressure in the system is determined by the technological and structural possibilities of the equipment used, whereas the duration of the energy transformation depends on the properties of the system itself: thermophysical characteristics of the components, regime parameters, and the concentration of bubbles.

Physical and mathematical models that describe the dynamics of a single bubble [2] and the dynamics of a two-phase bubble system [3] upon a change in the external pressure have been developed at the Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine for conducting a numerical analysis and choosing the optimum mechanism. The behavior of bubble systems upon initiation of various mechanisms and their potentiality to intensify technological processes in disperse systems can be predicted with sufficient accuracy within the framework of these models.

With these models, in particular, one can demonstrate with concrete examples how substantially the energy accumulation rate affects the value of the specific power realized in the liquid in the vicinity of growing and collapsing bubbles. Figure 2 shows how the amplitude of the pulse of specific power released by a growing vapor

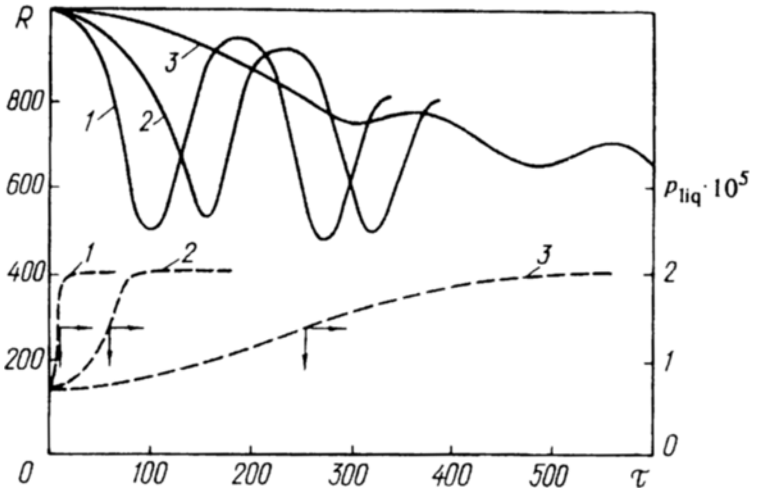

Fig. 3. Effect of the external-pressure rise time (dashed lines) on the character of radius variations of a collapsing bubble (solid lines): 1) $\Delta\tau = 10\ \mu$sec, 2) 100, 3) 500; $R_0 = 100\ \mu$m; $T_{\text{liq}} = 363$ K ($p_{\text{liq}0} = 70$ kPa); final pressure in the liquid $p_{\text{liq}} = 200$ kPa. p_{liq}, Pa.

bubble changes for various values of the duration of a pressure drop $\Delta\tau_{\text{ac}}$. The effect of the duration of an increase in the external pressure on the dynamics of a collapsing bubble is presented in Fig. 3.

Basic DPIE Mechanisms. The general principle of intensification of hydrodynamic and heat and mass transfer processes in disperse media consists in the dynamic action of intensely growing or collapsing bubbles on the surrounding liquid. However, the mechanisms of this action and the methods of their initiation can differ fundamentally. We will distinguish conventionally between rigorous and mild DPIE mechanisms without marking a sharp border between them. The former should be used for stimulating hydromechanical processes related to destruction of solid and liquid dispersions when the result has a stepwise character: either the required dispersion level is achieved immediately, or it cannot be achieved even in prolonged processing without applying more powerful action. Mild mechanisms are used primarily for intensification of processes of heat and mass transfer between the disperse and continuous phases when the level of intensification can be varied continuously within certain limits.

In what follows, we analyze briefly basic DPIE mechanisms and specify fields of their preferential application.

1. Cavitation Phenomena. For certain technological operations in liquid media such as homogenization, emulsification, dissolution, and liquid extraction, grinding of liquid or solid inclusions is essential. In solving problems of this kind it is advisable to use rigorous cavitation mechanisms. To implement these mechanisms one should first initiate generation of vapor bubbles in the liquid by dropping the pressure and then elevate sharply the external pressure. This leads to collapse of bubbles and release of a powerful pulse in the form of a spherical shock wave.

The cavitation mechanism can be initiated by acoustic irradiation of the liquid or by creating optimum hydrodynamic conditions in the flow. Cavitation and accompanying dynamic phenomena are also observed in bubbling overheated vapor into a cool liquid. In this case high flow rates are unnecessary and no special devices for rapid change of the pressure in the flow are required.

2. Cumulative Microjets. When a bubble collapses in the vicinity of solid surfaces or solid dispersions, the energy of the radial motion of the liquid is transformed into the kinetic energy of a cumulative liquid microjet escaping toward the solid surface at a very high velocity. The thickness of the jet does not exceed several micrometers, whereas its velocity reaches several hundred meters per second, and the time of action of the microjet on the solid surface comprises fractions of a microsecond.

The cumulative mechanism is responsible, in particular, for grinding of particles when a solid or high-boiling liquid material heated to a very high temperature is dispersed into a cold liquid with a low boiling temperature. Cavitation bubbles form, grow, and collapse immediately on the surface of overheated dispersions.

The cumulative mechanism reflects precisely the basic principle of the discrete pulsed introduction of energy: energy localization within very short temporal and very small spatial regions and directed shock action of the concentrated energy in the form of a pulse.

3. Explosion-Like Boiling of a Liquid. If a liquid is heated to a temperature exceeding substantially its boiling temperature and is kept at the same time under high pressure, an abrupt drop in the pressure in this system leads to explosion-like boiling of the liquid accompanied by intense growth of the vapor bubbles. At the initial stage of their growth, the bubbles emit pressure pulses of the same intensity as collapsing cavitation bubbles. Application of this mechanism is efficient in producing stable emulsions when a volatile liquid is the disperse phase and a liquid with a high boiling temperature is the continuous phase. Explosion-like boiling of droplets of the volatile liquid leads to their breakup and substantial reduction in size. Experimentally measured values of the amplitude of the pressure pulse from an exploding droplet reach 1200 MPa.

4. Oscillation of Bubbles. When the external pressure is elevated rapidly, a vapor bubble in a heated liquid manages to oscillate at a high frequency for a time, before it collapses completely. This is explained by the fact that uncondensed vapor remains in the bubble at the instant of maximum compression, and some of the kinetic energy of the liquid is transformed into potential energy of the compressed vapor.

During oscillation of bubbles, the peak values of acceleration of the liquid in the vicinity of a bubble can be as high as $10^8\ g$, and the peak values of pressure reach hundreds of MPa, and it should be noted that such a pressure jump takes place in a fraction of a microsecond. Each oscillating bubble can be treated as a microgenerator of ultrasound oscillations whose unit characteristics are comparable to those of commercial acoustic generators used for intensification of technological processes.

With regard to the collective action of the remaining pulsing bubbles, a complex rapidly changing interference pattern is observed in the liquid. By choosing appropriate oscillation conditions, one can initiate mild and rigorous intensification mechanisms.

5. Collective Phenomena in an Ensemble of Bubbles. The DPIE concept assumes that a large number of bubbles are present in the liquid. The behavior of any individual bubble in such an ensemble is determined by the action exerted on it by its nearest neighbors, and the dynamic characteristics at a local point of the liquid are considered with regard for the collective action of all bubbles of the ensemble. This leads to the fact that within the ensemble of bubbles a chaotic pattern of velocity and pressure fields that is constantly changing in both time and space is observed, and the microflows in the interbubble space have a vortex character [3].

The ensemble of dynamically evolving bubbles forms pressure and velocity fields resembling by their character the corresponding fields in a strongly turbulized flow of a liquid. The fundamental difference lies in the fact that in this case the high level of turbulence is reached in a system that stays in macrorest, and the need to use hydraulic devices that provide flow turbulization and expend for this a large part of the energy is eliminated.

6. Perturbation of the Phase Interface. During intense expansion, compression, or pulsation of bubbles containing a gas that is soluble in the liquid, mass transfer through the phase interface increases substantially. In this case all three above-mentioned intensification factors operate: an increase in the area of the phase interface as a result of breaking up of bubbles, turbulization and surface renewal, and mixing of the liquid in the interbubble space. In the case under consideration a bubble is simultaneously both the object of the action and a transformer of the energy introduced. It was found that in processes of bubbling aeration, when pulsation of bubbles is initiated, maximum saturation of the liquid is observed if the resonance condition is satisfied [4].

Practical Applications of DPIE Methods. Comprehensive investigation of DPIE mechanisms made it possible to develop and create new types of mass transfer and hydromechanical technological devices in which the principle of transformation of the energy introduced and release of high power in the form of a mechanical pulse at discrete points of the working volume is implemented. The advantage of these devices is manifested most effectively in technological operations in which the presence of a developed phase interface and intensification of heat and mass transfer through this interface dominate. Being highly competitive with traditional installations in capacity, these apparatuses are distinguished by substantially lower specific power consumption, small dimensions, and reliability of operation.

1. Pressure-Drop Fermenter. A graphic example of practical application of DPIE principles is an industrial pressure-drop fermenter. To provide the required rate of biochemical reactions in biosynthesis of pharmaceutical and microbiological preparations, yeast, and other similar products, air oxygen is used. Air is bubbled in the lower part of the apparatus, and oxygen is dissolved in the liquid during floating-up of the bubbles. An optimum O_2-to-CO_2 balance should be maintained in the liquid phase to carry out normal fermentation, and therefore sorption processes at the phase interface should be intensified. When bubbles float up in an organic medium, a protein film is rapidly formed on their surface, which hinders mass transfer, and, for a large part of their stay in the fermenter, bubbles do not deliver oxygen to the liquid. To intensify processes in the fermenter, mechanical mixers are normally used, which distribute dissolved oxygen more or less uniformly over the entire volume. However, they cannot prevent film formation or provide the maximum attainable level of mass transfer intensification at the phase interface. In addition, the presence of a rotary mixer within the fermenter is undesirable from considerations of sterility.

To increase the fermenter efficiency by maximum use of air oxygen and to decrease the number of nonsterile operations, another intensification method is used that excludes the use of mechanical mixers. The casing of the fermenter is sealed hermetically and, due to continuous supply of the gas being bubbled, the pressure in the fermenter rises rapidly. With the use of a special valve the pressure is periodically dropped to atmospheric. The air bubbles expand rapidly, thus turbulizing and mixing adjacent layers of the liquid. In this process, the film is removed from the surface, and the mass transfer coefficient increases. The potential energy of the compressed gas that is accumulated in the bubbles occurs in the form of pulses distributed discretely over the entire fermenter volume, with bubbles being simultaneously the object of the action and an energy transformer. Inasmuch as fermenters have large volumes (up to 50 m^3) and the duration of a single cycle is as long as 3–4 days, the entire decrease in energy consumption can be substantial when this method is used. In addition, this method makes it possible to reduce by 50% the water consumption for cooling and decrease the number of nonsterile operations. Due to comparatively slow evacuation of air from the large-volume fermenter the rate of the pressure drop is not high. Therefore, rather mild regimes are used in this method.

2. Tubular Pulser. The use of tubular pulsers, which implement DPIE mechanisms that are different from those decribed in the previous case, is more efficient for intensification of fermentation processes in low-capacity apparatuses (up to 5 m^3). The principle of operation of this apparatus is as follows. The lower end of the vertical tube of the pulser is submerged in the liquid mixture being processed, which is contained in the fermenter tank. The upper end of the pulser is alternately connected by means of a special quick-operating valve to air tanks maintained at high (3–5 atm) and low (0.3 atm) pressures. During operation, the liquid is periodically (at a frequency of the order of 1 Hz) sucked into or, at a high rate, ejected from the pulser tube. In each cycle a finely disperse air suspension is formed and rapid growth and compression of bubbles take place as a result of pressure variations, i.e., cavitation processes occur, which provide both intense saturation of the liquid with oxygen and microscale mixing in the pulser. Macroscale mixing occurs in the fermenter volume due to the action of the nonstationary pulser jet. The overall mass transfer coefficient with respect to oxygen increases more than fivefold. In this case both mechanical mixing and bubbling devices are excluded. The tubular pulser implements completely the main DPIE principle: transformation of the introduced energy that is accumulated in the high-pressure receiver, and its appearance in the form of pulses at discrete points of the volume. In this modification of the pulser stronger mechanisms are implemented compared to the previous case, inasmuch as the rate of pressure variation is higher by an order of magnitude. These mechanisms are sufficient for intensification of interphase mass transfer and, at the same time, not so rigorous as to exert dangerous dynamic actions on the bacterial medium being processed.

3. Pulser with a Rapidly Varying Volume. When necessary, more rigorous mechanisms that make it possible, for example, to break up solid suspensions and homogenize liquid mixtures and suspensions can be implemented in a pulser. A device of the type is a tubular pulser with a rapidly varying volume, whose main distinction consists in isolation of the liquid being processed from the gas phase [5].

The apparatus consists of a chamber and a vertical connecting channel submerged in the medium being processed. A flexible rubber diaphragm situated within the chamber separates the liquid from the gas. The gas volume of the chamber is alternately connected via a special channel with high- and low-pressure receivers, and

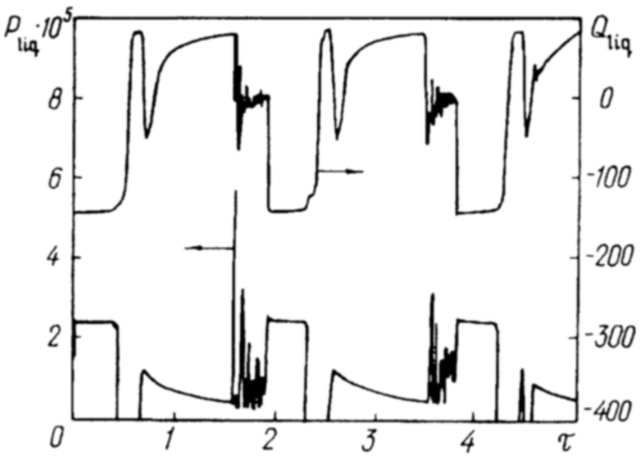

Fig. 4. Variations of the pressure p_{liq} in the liquid in the pulser chamber and the flow rate Q_{liq} of the liquid in the connecting channel of an industrial apparatus with a 4-m^3 capacity in several cycles. In a cycle the chamber is connected to a high-pressure (300-kPa) receiver for 1.5 sec and to a low-pressure (20-kPa) receiver for 0.4 sec. The pressure peaks correspond to hydraulic shocks at the diaphragm. Q_{liq}, kg/sec; τ, sec.

the motion of the diaphragm changes the working volume of the chamber. At the low-pressure stage the liquid fills the chamber at a high rate and a hydraulic shock is initiated when the diaphragm is completely pressed against the wall. The pressure amplitudes in the chamber reach tens of atmospheres, and the frequencies of the pulses generated lie within limits of 0.5 to 1 kHz. At the high-pressure stage the diaphragm pushes the liquid into the connecting channel and, when the diaphragm is completely pressed to the exit opening, conditions of explosion-like boiling and subsequent cavitation of vapor bubbles arise in the channel, and microscale effects of local shock waves and cumulative microjets are formed. Figure 4 presents results of numerical calculations of pressure variations in a pulser chamber and the mass flow rate of the liquid through the connecting channel in several working cycles of an industrial apparatus.

The combination of rigorous mechanisms, including hydraulic shocks in the chamber, provides rather powerful action on disperse media being processed and determines multifunctional utilization of the apparatus in performing various operations. In this apparatus, the rate of pressure variation is three to four orders of magnitude higher than in a diaphragm-free pulser, which makes it possible to achieve extremely rigorous processing regimes.

Pulsers with a rapidly varying volume have been found to be useful in extracting food and pharmaceutical components from vegetative raw materials – berries, grass, fruit, etc. The pre-shredded raw material is loaded into a thermostated tank along with the extracting liquid agent – water or organic liquids. The DPIE mechanisms implemented in the pulser provide an increase in the mass transfer coefficient by a factor of 15–20 compared to existing technologies, which makes it possible to increase the yield of the components to the maximum in a short time. In a number of cases, this extraction method makes it possible to decrease the working temperature in the apparatus and to use water as an extracting agent instead of expensive organic solvents.

This type of pulsers is already being used successfully under field conditions for production of high-quality clay muds that are used extensively in drilling gas, oil, and geothermal wells. Experience in using the pulsers shows their advantage over traditional methods first of all in a substantial (fivefold) reduction in unit production time and a threefold decrease in specific energy consumption and also in the high degree of homogenization and the high rheological parameters of the product.

At present, this technology is being tested in the production of a high-quality clay-based raw material for the china and faience industry and in the production of clay and cement mortars for water-development works in industrial and civil engineering.

Apparatuses of the type were tested successfully in the metallurgical industry as efficient mixing devices in continuous casting of steel and aluminum ingots with a homogeneous structure. Implementation of microscale DPIE mechanisms in cooling liquid metal provides uniformity of temperature and concentration fields during ingot crystallization in the mold, which makes it possible to produce metals with a unique fine-grained structure.

4. Rotary-Pulsed Apparatuses. Another method of initiation of a wide spectrum of DPIE mechanisms is possible with the use of rotary-pulsed apparatuses. As in tubular pulsers, the principle of abrupt acceleration or deceleration of a fluid flow is employed in these apparatuses, which provides for sharp pressure drops in the working volume of the liquid and the appearance of conditions for cavitation.

The main elements of rotary-pulsed devices are an immobile stator with a large number of small holes and a rotor with similar holes that rotates around the stator. When the holes in the rotor and the stator coincide, a fluid flow moves at a high rate along the channel and is decelerated abruptly when the holes are covered. By this means, the liquid within the apparatus performs pulsed motion and each element of the liquid is subjected to the alternating action of compression and rarefaction. The rate of rotation controls the frequency and amplitude of the pressure pulses, which makes it possible to control the intensification level. Although the time interval between pulses can equal hundredths of a second, microscale cavitation phenomena with accompanying effects of shock waves and cumulative jets have enough time to develop fully. Rotary-pulsed apparatuses can be designed in a number of variants: the rotor and the stator can be manufactured in the form of flat disks or as cylindrical surfaces, etc., and the holes can be round, square, or slit-like. However, the principle of initiation of the DPIE mechanisms in these devices and the method of design of these apparatuses are common to all of them.

A number of modifications of rotary-pulsed apparatuses that differ in output, dimensions, and intended purpose have been designed at the Institute of Technical Thermophysics. These devices are intended for production of finely disperse emulsions and homogenized mixtures. A series of efficient energy-conserving technologies is developed based on them for various branches of industry in which, as a rule, rigorous DPIE mechanisms are used.

Thus, based on an ARD-5 rotary-pulsed apparatus, a production line has been developed for producing water-fuel emulsions in which water contaminated with petroleum and oil residues is utilized. This production line can produce up to 10 ton/h of a high-quality fuel mixture at a consumed power of 20 kW.

Based on an RIA-1000 apparatus with a rated output of 1 ton/h and a power of 2.4 kW, lines have been developed for production of homogenized vegetable and fruit pastes and purees for the food-canning industry, milk products, mayonnaises, etc.

5. Rotary Apparatuses for Saturation of a Liquid with a Gas. Rotary-pulsed apparatuses have found wide application in technologies connected with intense saturation of a liquid with a gas, for example, for aeration of fish-breeding reservoirs, saturation of wines and soft drinks, etc. In carrying out these operations, it is desirable to provide a maximum coefficient of mass transfer through the developed contact surface of the phases or, in other words, to create the maximum possible number of extremely small pulsing bubbles in a unit volume of liquid. Rotary apparatuses show good results in solving this problem, provided that in this case the holes shut the flow of gas rather than liquid.

In these apparatuses, compressed gas is dispersed into the aerated liquid through three adjacent disks with a large number of extremely small holes. The outer disks are immobile, and the inner disk, rotating at a controlled velocity, plays the part of a rotor. Periodic shutting off of the gas at a preset frequency of 1 to 6 kHz produces a monodisperse cloud of bubbles and additionally creates high-frequency pulsations in the bulk of the liquid. It was found that in this case a resonance phenomenon occurs: a sharp increase in the mass transfer coefficient within a narrow frequency range. At the same time, it has been shown that the most intense mass transfer takes place in the process of formation of bubbles at the edges of the holes when growth and oscillation of their surface take place. At this stage, about 80% of the total amount of dissolved gas enters the liquid.

Rotary aerators of this type are used in various modifications for aeration of ponds and large reservoirs. Use of these devices makes it possible to oxygenate in a short time reservoirs with an area of 5 to 100 ha, depending on the efficiency of the installation, at a mean oxygen concentration of 22 g/m^3. Operation of these apparatuses has substantiated their profitability.

These devices are now widely used as saturators in the production of sparkling wines and soft drinks based on natural raw materials. Their production technology provides for saturation of a liquid with carbon dioxide that is dispersed under a substantial pressure (3–5 atm) through perforated disks of a rotary pulser into a continuous flow of the liquid.

6. *Adiabatic-Boiling Apparatuses.* As is known, traditional methods of production of stable oil-in-water emulsions with a nonvolatile disperse phase envisage the use of energy-consuming valve homogenizers that provide a high level of dispersion and homogenization. These apparatuses are used worldwide in the production of water-bitumen emulsions for highway and civil engineering and the production of homogenized milk products. However, efficient operation of them requires employing energy-consuming high-pressure (up to 20 MPa) pumps at the inlet, and the velocity of the liquid in the valve gap should be as high as 200 m/sec, which leads to substantial friction losses. Therefore, these devices are characterized by high specific energy consumption and, in addition, are produced from expensive high-strength durable materials.

The use of the principles of discrete pulsed introduction of energy made it possible to develop machinery with the same intended purpose that, at the same level of production capacity and quality of the final product, consumes substantially less energy and excludes the use of energy-consuming methods of energy introduction or expensive parts.

The operating principle of apparatuses that simultaneously employ several DPIE mechanisms is as follows. A mixture of two immiscible liquids, one of which has a substantially lower boiling temperature, is fed via a channel equipped with a special nozzle from a tank under a pressure of about 100 kPa to a working chamber kept at a low pressure of the order of 10–20 kPa with the use of a vacuum pump. The low-boiling component (usually the carrier phase) becomes superheated if the pressure in the evacuated chamber is lower than the pressure of the saturated vapor of the component at the temperature of the mixture. As a result of a sharp pressure drop, the motion of the liquid through the nozzle is accompanied by boiling of the volatile component and intense bubble growth. The collective effect of the growing bubbles leads to strong turbulization of the interbubble space with high values of the spatial and temporal fluctuations of the local pressure and velocity. When the liquid passes through the nozzle, cavitation mechanisms that stimulate size reduction of the disperse phase are also initiated. By selecting the temperature of the mixture, the pressure at the nozzle inlet, and the pressure in the evacuated chamber, one can choose optimum emulsification regimes in each particular case.

Production lines for homogenization of milk and various milk products with an output of 5 to 10 ton/h have been developed on the basis of this apparatus. The distinctive features of the technology of homogenization and pasteurization of milk products make it possible to decrease nonproductive energy consumption even more, in particular, to maintain a lowered pressure in the evacuated chamber due to steam condensation on the dispersed jet of the cooled product fed to the inlet of the production line, which simultaneously provides preheating of the product prior to its pasteurization. However, it is mainly rational use of DPIE methods and mechanisms that contributes to decreasing nonproductive expenses. A vacuum homogenizer with the 5-ton/h output provides a high degree of dispersion at a specific consumed power of 2.4 kW, which is 3–4 times less than that of standard valve homogenizers with the same output. At the same time, this apparatus is distinguished for its small dimensions, lowered metal content, and high reliability in operation.

We have considered here just several examples of units in which some DPIE mechanisms are used. Most of these appartuses are commercially produced and operate successfully in various branches of industry. Presently, a number of technological apparatuses are being designed in which DPIE mechanisms are used more efficiently and rationally, which makes it possible to raise the level of energy- and material-saving in implementation of new technologies.

Conclusion. Practice shows that technological equipment based on purposeful and substantiated application of the principles of discrete pulsed introduction of energy is extremely promising from the viewpoint of energy- and material-saving. By using the DPIE concept as a guideline in choosing methods of intensification of heat and mass transfer and hydromechanical processes, one can always obtain optimum solutions and achieve the required result by the most rational and efficient method. The experience of our Institute shows that comprehensive experimental and theoretical investigations of these mechanisms of discrete pulsed introduction of energy and their practical implementation are one of the ways of developing modern high-efficiency equipment and new technologies for various branches of the national economy.

NOTATION

p_g, p_{liq}, pressure in the gas and liquid phases; r, radial coordinate; R, bubble radius; w_R, velocity of the liquid at the bubble boundary; W, specific power; ε_k, ε_p, density of kinetic and potential energy; ρ_{liq}, density of the liquid; $\Delta\tau_{ac}$, $\Delta\tau_{tr}$, duration of energy accumulation and transformation.

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