Parametric Excitation and Suppression of Oscillations at the Interfaces of Continua for the Processes' Control in Jet and Film Flows, Channel Flows with Phase Change and in Granular Media

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Abstract: - The problem is interesting theoretically and important for the practical applications in three aspects: 1. Excitation of parameters' oscillations in continua in touch with intensification of various technological and technical processes: heat and mass transfer, mixing, decreasing the viscosity, improving the quality for crystallizing metal and many other phenomena. 2. Excitation of parameters' oscillations in touch with necessity of disintegration of jet and film flows: air spray, spray-coating, metal spraying, dispersing and granulation of materials (e.g. particles' producing from molten metals), etc. 3. Suppression of oscillations for stabilization of unstable regimes and processes: jet-drop and film screens for protection of diaphragm of experimental thermonuclear reactor, thermal instability and fusion control in reactor, control of electromechanical and electrochemical instabilities, combustion stability, decreasing the hydrodynamic and acoustic resistance, etc. In some cases, parametric control makes possible not just intensification the processes but also running such processes, which are impossible without parametric control.

A lot of different linear as well as nonlinear model situations have been considered. As a result some interesting peculiarities of parametric wave excitation and suppression in film flows including three new phenomena of parametric film decay were revealed: resonant decay, soliton-like decay and shock-wave decay. The phenomena were first theoretically predicted and then experimentally invented and investigated.

Based on these new phenomena we developed, created and tested the prospective dispersion and granulation machines for some metals and other materials.

Key-Words: - Parametric, Wave, Excitation, Suppression, Instability, Stabilization, Control, Disintegration, Film Flow, Jet, Solidification Front, Granular Media

1 Introduction to the Problem

Parametric excitation of oscillations (vibrations) is an excitation of oscillations (vibrations) in some system by temporal variation of one or several parameters of a system (mass, momentum of inertia, temperature, stiffness coefficient; for the fluids: pressure, viscosity, etc.).

The parametric oscillations are excited and maintained by parametric excitation. Examples of parametric oscillations are given as follows:

1. Oscillations of temperature in loaded elastic solid are able to evoke oscillations of its stiffness coefficient with the next its vibrations.
2. Oscillations of temperature (pressure) in fluid (gas) flow are able to evoke oscillations of its pressure (temperature) or (and) viscosity with the consecutive oscillations of other flow parameters.
3. External vibrations in fluid (gas) flow are able to evoke oscillations of its velocity with further oscillations of another parameters of flow.
4. Electric or magnetic fields are able to evoke oscillations in flow of conductive fluid producing the oscillations of other parameters, etc.

1.1 Basic conceptions of the problem

The following attendant conceptions are useful for further analysis of the problem:

- Vibration: The motion of mechanical system by which though one generalized coordinate and (or) generalized velocity increase and decrease by turn in time.
- Exciting force: Time alternating and independent from system state force causing the vibrations of this system.

- Force excitation: Excitation of mechanical system vibrations by exciting force.
- Kinematic excitation: Excitation of mechanical system vibrations by moving of some its points.
- Harmonic excitation: Forced or kinematic excitation of vibrations by harmonic law.
- Autonomous oscillating (vibrating) system: Oscillating (vibrating) system by which energy source is absent or is its part.
- Self-excited system: Autonomous oscillating (vibrating) system that is able to do periodical oscillations (vibrations) exciting by energy receiving from no oscillating (no vibrating) source, which is regulated by evolution (motion) of the system itself.

1.2 Classification of parametric oscillations

Classification of the parametric oscillations by the types of controlled objects and actions may be done as follows.

1.2.1 The controlled objects

The types of controlled objects are as following:

- linear controlled object,
- non-linear controlled object,
- lumped-parameter controlled object,
- distributed-parameters controlled object,
- determinate/stochastic controlled object,
- stationary/non-stationary controlled object,
- single-loop (multi-loop) controlled object,
- one-dimensional/multi-dimensional object, etc.

1.2.2 The parametric actions

The types of parametric actions could be:

- internal/external action,
- main parameter of the action (single-parameter action, multi-parameter action),
- feedback action and deviation action,
- analogue action and quantized action,
- impulse-time and impulse-amplitude action,
- periodic action and periodic amplitude action,
- frequency action and phase action,
- determinate and stochastic action, etc.

1.2.3 The types of control

Classification of the parametric oscillations by the types of control is considered as:

- coordination;
- coordinating control, stabilization;
- stabilizing control (linear and nonlinear),
- extreme control and feedback control,
- disturbance control,
- autonomous control, etc.

1.3 History of the theory of parametric oscillations

At first the parametric excitation of surface waves was studied [25] by M. Faraday (1831) who investigated that in vibrating tank with liquid the surface waves of double period of excitation relatively to external periodic action are excited.

The theory of this phenomenon was developed later on [1-4,8-15] by N.N. Moiseev (1954), T.B. Benjamin, F. Ursel (1954), V.V. Bolotin (1956), V.I. Sorokin (1957), R. Skalak, M. Yarymovych (1962), R.H. Buchanan, C.L. Wong (1964), S.I. Krushinskaya (1965), F.T. Dodge, D.D. Kana, H.N. Abramson (1965), R.P. Brand, W.L. Nyborg (1965), V.E. Zakharov (1968), G. Schmidt (1978), E. Hasegawa (1983), Y. Warisawa (1983), etc.

1.3.1 Increase of process effectiveness by parametric action

The possibility for increase an effectiveness for technological processes using the parametric oscillations was at first observed by D.K. Chernov [21] (1879) for the crystallization. The phenomenon of crystal structure improving was investigated by R.F. Ganiev, V.F. Lapchinsky [27] (1978), G.A. Slavin, E.A. Stolnner et al. (1974), etc.

A lot of the problems on parametric wave excitation on liquid surfaces were investigated [17-39] with regard the possibility to stabilize the unstable states as follows:

- Rayleigh-Taylor instability,
- Kelvin-Helmholtz instability,
- Tonks-Frenkel instability,
- electrohydrodynamical instability,
- various combinations of instabilities, etc.

The common feature for all cases of parametric wave excitation on the boundary interfaces is perpetual sequence of unstable areas. For the wave excitation it is necessary that a periodic amplitude action exceeds some value which is critical for an unstable area [41, 46].

1.3.2 Critical value for parametric excitation

The existence critical value is caused by energy dissipation. Therefore energy of an external action must exceed this energy dissipation in a system.

By periodical excitation with a frequency ω the least of the critical values is at the oscillation frequency $\omega/2$, then at the oscillation frequency ω, $3/2\omega$ and so on. Moreover from all unstable areas the widest one is the area that corresponds to the oscillation frequency ω/2. The other areas are too narrow and usually they are quite absent except a big amplitude action. Therefore instability of a first (ground) unstable area is often observed in experiments.

1.3.3 Mathematical methods for investigation

Mathematical methods for investigation of parametric oscillations are implemented both numerical (FEM, BEM, FDM), as well as analytical ones. Numerical methods have such advantage that they fit to any complicated systems (for the linear as well as for the non-linear problems). But their disadvantages are:

- complicated interpretation of obtained results and distinguish the numerical and physical oscillations;
- indistinct interconnection of parameters.

Analytical methods applied are: integral transformations, averaging the differential and integral-differential operators, factorization the differential operators, reductive perturbation method [6, 7, 44], fractional differentiation, etc. Their advantages are:

- distinct parameter connection and interpretation of obtained results,
- good possibility to analyze an obtained solution of the problem.

The best results are got by implementation of all numerical and analytical methods in their best combination according to the task being solved.

2 Basics of the parametric oscillations in continua

Parametric excitation of oscillations (vibrations) is an excitation of oscillations (vibrations) in some system by temporal variation of one or several parameters of the system (mass, moment of inertia, temperature, stiffness coefficient; for the fluids: pressure, viscosity, etc.).

2.1 Definitions and some examples

Parametric oscillations (vibrations) are oscillations (vibrations) that are excited and maintained by some parametric excitation (action).

The examples are:

1. Oscillations of temperature in loaded elastic solid are capable to evoke oscillations of its stiffness coefficient with following its vibrations.
2. Oscillations of temperature (pressure) in fluid (gas) flow are capable to evoke oscillations of its pressure (temperature) or (and) viscosity with following oscillations of other parameters.
3. External vibrations in fluid (gas) flow may evoke oscillations of its velocity with following oscillations of other parameters.
4. Electric or magnetic fields may evoke oscillations in flow of conductive fluid with following oscillations of other parameters, etc.

2.1.1 Some attendant conceptions

The attendant conceptions are as follows:

- Vibration: The motion of mechanical system by which though one generalized coordinate and (or) generalized velocity increase and decrease by turn in time.
- Exciting force: Time alternating and independent from system state force causing the vibrations of this system.
- Force excitation: Excitation of mechanical system vibrations by exciting force.
- Kinematic excitation: Excitation of mechanical system vibrations by moving of some its points.
- Harmonic excitation: Force or kinematic excitation of vibrations by harmonic law.

2.1.2 The autonomous oscillating systems

Oscillating (vibrating) system for which an energy source is absent or is its part is called the autonomous oscillating system. Self-excited system: Autonomous oscillating (vibrating) system that is capable to do periodical oscillations exciting by energy receiving from no oscillating (no vibrating) source, which is regulated by evolution of the system itself.

2.2 Numerical and analytical methods for parametric oscillations

2.2.1 Numerical methods

The following numerical methods are applied for study of the parametric oscillations:

- Finite Element Method
- Boundary Element Method
- Finite Difference Method.

Advantages of them are:

- the methods fit for any complicated systems (for the linear as well as for the nonlinear problems.

Disadvantages:

- complicated interpretation of the obtained results and

- distinguish of numerical and physical oscillations;
- indistinct parameter connection.

2.2.2 Analytical methods

The following analytical methods are applied to study the parametric oscillations:
- Integral Transformation Method
- Averaging Method for Differential and Integro-Differential Operators
- Method of Factorization of Differential Operators
- Reductive Perturbation Method (reduction to standard evolutional equations)
- Fractional Differentiation Method (non-field method)
- Asymptotic Decomposition Method
- Method of Differential Connections, etc.

Advantages: distinct parameter connection and interpretation of obtained results, good possibility to analyse obtained solution of the problem. Disadvantages: complication in use for the nonlinear and complicated linear systems, presence of some limits and approximations, limited specific area of applications of each method.

Some of these methods give good results in diverse combinations and also together with numerical methods.

2.3 Jet and film flows, solidification fronts in the channels, granular media

Now some parametric oscillations and their control are studied on the examples of three classes of mechanics of continua: jet and film flows and their disintegration, stability and stabilization of the solidification front in the channel, thermal hydraulic oscillations in heterogeneous granular layers.

3 Stability and stabilization of the solidification front

Cylindrical channel is considered, the wall of which in general case consists of the N layers of different materials. On the internal wall surface there is thin solid sheet of the material that flows in channel in liquid state (Fig. 1). This thin solid sheet named garnissage sometimes is forming naturally (e.g. in metallurgical aggregates) and breaks the normal technological regimes due to solid overgrowing the channel cross-section.

If the garnissage layer is controlled, it suits perfect for the wall's protection. As far as a solid sheet and a flowing liquid represent two phases of the same material, the control system redoes garnissage locally in case of its partial destroying (due to shear stresses in the flow and interaction with aggressive high-temperature flow).

3.1 Solidification front on the walls in cylindrical multilayer channel

The controlled heat flux system allows dynamical maintaining of a garnissage interacting with each and every mode of perturbation in the system.

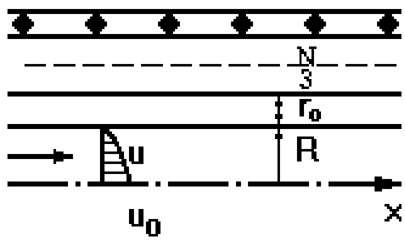

Fig.1 Flow in cylindrical channel with solidification on the wall with heat flux control system

In an effort to raise the effectiveness and specific capacity of metallurgical electric welding and various other devices, the engineers are faced with the problem of overcoming the instability of phase transition boundaries, or vice versa, destroying these boundaries, etc. For example, it was suggested that the walls of metallurgical aggregate machine be protected against thermal, chemical and other destructive effects through a maintaining of a thermal regime of the walls that would make the surface melt produce a thin solid phase layer. This layer could then constantly be renewed when worn out, thus reliably protecting the walls of such an aggregate machine against destruction.

Besides, in the presence of strict melt purity requirements this problem could be solved simultaneously, since while being torn off the walls and acquiring liquid form, particles of that same substance would not alter the melt's composition. But this outwardly unsophisticated multifunctional anti-destructive fettling technique proves difficult to introduce in daily practice. The main obstacle is the need to automatically control and keep the form of the solidified front within the present parameters.

In metallurgical aggregate machines, natural garnissage more often than not produces negative effects, hindering the machine's effective operation, causing overgrowth within the channels, and bringing forth other unwelcome phenomena. Therefore the key task was studying an instability of the solidified front and possibilities of controlling, stabilizing or destroying the phase-transition boundaries. The first possibility would be important in solving the problem of fettling protection with the aid of automatically stabilized, artificial garnissage. The second possibility would be instrumental in combating natural garnissage hindering as it does the metallurgical process.

3.2 Parametric oscillations and their control

The theory of parametric oscillations in flat and cylindrical solidified fronts and their control by electromagnetic high-frequency fields and heat influx regulators is dealing with linear small-amplitude perturbations.

As for the non-linear occurrences, these haven't been studied well enough, to say the least. Problems on stability and stabilization involving unstable phase transition boundaries were studied here in regard to influence of many factors simulating various real physical systems. For example, such complications are caused by multilayer composition of the channel's wall; convection; change and regular perturbations in the thermodynamic medium, melt viscosity, current regime, etc.

3.2.1 Mathematical model of the system

Schematically represented, any given system can be illustrated in a simplified way as shown in Fig. 1.

In controlling a phase transition boundary with the aid of an automatic heat flux regulator, the parameters of the regulating system's effects are programmed at the boundary line with the regulator. The latter is then considered to be hooked onto a powerful energy source, so that here the reverse effects of the object can be ignored. As for the solidified front, it is supposed to be a surface having constant temperature, whereas the phase transition stage is allegedly "zero thin". The transition from a liquid to a solid phase is a "leaping" process occurring at the phase transition boundary lines. In using heat flux regulators, considering that perturbation boundaries of the solidified front lead to disturbances in the magnetic field, with the concurrent alterations in the winding electric current which, amplified in the thin skin-layer close to the interface, suppresses or reinforces the relevant perturbation by Joule heat release, then we arrive at:

$$dT_{m,k} / dn = G_{m,k} T_{m,k}, \qquad (1)$$

where m,k is the value denoting the harmonic number (wave number as per circumferential and longitudinal coordinates); T is the temperature; n is the phase distribution surface normal vector; $G_{m,k}$ is the control system's feed-back factor.

The $G_{m,k}$ value may vary on a large scope, in that it can be altered constructively, so that it is possible to select the factor $G_{m,k}$ for energy harmonic reading, necessary in solving the given problem.

3.2.2 Axially symmetrical perturbations

In case of an axial symmetry the mathematical model of the considered system for perturbations of the solidification front for moving liquid, in a linear approach, is the following:

$$div\vec{v}_1 = 0, \quad \partial\vec{v}_1/\partial t + u_0 \partial\vec{v}_1/\partial x = -1/\rho \nabla p_1,$$

$$\rho_j c_j [\partial\tau_1/\partial t + (2-j)(u_0 \partial\tau_1/\partial x + \vec{v}_1 \nabla T_1)] = \kappa_j (\partial^2\tau_j/\partial r^2 + +1/r\,\partial\tau_j/\partial r + 1/r^2\,\partial^2\tau_j/\partial\varphi^2 + \partial^2\tau_j/\partial x^2), \qquad (2)$$

where j=1,2, $\vec{v}_1 = \{u_1, v_1, w_1\}(r) u_0 expi(kx + m\varphi - \omega t)$, p_1, τ_1- perturbations of the velocity, pressure and temperature of a fluid. Index 2 corresponds to the parameters of a solid phase. Here T is the temperature of undisturbed system; ρ_j, c_j are density and specific heat of j-th phase (j=1 - liquid, j=2- solid, from j=3 - wall layers as shown in the Fig.1). The perturbation of a boundary of the solidified front is modeled as

$$r=R[1+\zeta\, expi(kx+m\varphi-\omega t)].$$

3.3 Perturbation of the solidified front

Boundary conditions at the perturbed solid-liquid interface in a channel where liquid phase is moving along its axis are stated as follows:

1) from the symmetry assumption:

$$r=0, \quad u_1=0, \quad \tau_1=0; \qquad (3)$$

2) on the perturbed boundary of solidified front $r=R[1+\zeta\, expi(kx+m\varphi-\omega t)]$:

$$\tau_j(R,\varphi,x)+R\zeta(\partial T_j/\partial r)_{r=R} expi(kx+m\varphi-\omega t)=0, \quad j=1,2; \qquad (4)$$

$$r=R, \quad u_1=(1-\rho_{2/1})\partial r/\partial t,$$
$$\kappa_2 \partial\tau_2/\partial r = \kappa_1 \partial\tau_1/\partial r + \rho_2 \lambda_{21} \partial r/\partial t; \qquad (5)$$

3) on the wall surface ($r=R+r_0$), the impedance condition (1) is stated.

Here are: $\rho_{2/1}=\rho_2/\rho_1$, $\partial r/\partial t$ is velocity of solidification front (movement of the boundary due to solidification-melting on it), λ_{21} is the heat of phase change (solidification). When all layers of the wall are considered in a thermal problem, also heat transfer equations for the wall layers and corresponding boundary conditions at the boundaries of these layers are analyzed as well.

3.4 Instability and stabilization of the front

The system of partial differential equations (2) with the boundary conditions (1), (3)-(5) was solved for the perturbations' amplitudes using the asymptotic decompositions by small parameter $\lambda=i\omega$. The solution in a zero approach by eigen values is next:

$$\lambda=1/R_\lambda\{k\chi^0_1[I'_m(\delta_{10})/I_m(\delta_{10})(1-i\mathbf{Pe}/(k\underline{a}^2_1))^{1/2}+ \tag{6}$$
$$(A_1\mathbf{Bi}_{k,m}+A_2k)/(A_3\mathbf{Bi}_{k,m}+A_4k)]+\mathbf{Pe}/\underline{a}^2_1(\partial T_1/\partial x)_{r=1}\},$$

where $\chi^0_1=-(\partial T_1/\partial r)_{r=1}>0$, $R_\lambda=\rho_2\lambda_{21}/(\rho_{1*}c_{1*}T_*)$ is the ratio of melting/solidifying heat to a heat capacity on the interface, $\mathbf{Pe=u_0R}/a^2_1$- the Peclet number, $a^2_1=k_1/(\rho_1c_1)$, $\delta_{10}=k^2\text{-}ik\mathbf{Pe}/\underline{a}^2_1$, $\underline{a}^2_1=a^2_1/a^2_{1*}$.

$\mathbf{Bi}_{k,m}=G_{m,k}R/k_N$ is the modified dimensionless Bio criteria coinciding with the regular Bio number, in the absence of a heat flux regulating system. Here k_1 is the thermal conduction coefficient in regard to the liquid, k_N is the thermal conductivity in regard to the wall secreting the control shell, k,m are the wave numbers in the x and φ directions correspondently (in cylindrical coordinate system: r, φ, x), $i=\sqrt{-1}$.

3.4.1 The case of immovable liquid in a channel

If liquid is immovable in a stable state, then it is the following solution for the problem:

$$\lambda=k\mathbf{Ja}/\mathbf{ln}s_0[(A_1\mathbf{Bi}_{k,m}+A_2k)/(A_3\mathbf{Bi}_{k,m}+A_4k)+A_5/A_6], \tag{7}$$

where s_0 is dimensionless thickness of the preaxle layer with a stable temperature, $s_0=R_0/R$, $\mathbf{Ja}=(\mathbf{K}\rho_{2/1})^{-1}$ is the Jacob number characterizing the phase transition thermal indices, and those of liquid surplus heat output, as per solidifying temperature. $\mathbf{K}$ is the Kutateladze number: $\mathbf{K}=\lambda_{21}/(c_{1*}T_*)$.

Here are the following important functions:

$$A_1=K_m(ks)I'_m(k)-K'_m(k)I_m(ks)>0,$$

$$A_2=K'_m(ks)I'_m(k)-K'_m(k)I'_m(ks)>0,$$

$$A_3=K_m(k)I_m(ks)-K_m(ks)I_m(k)>0, \tag{8}$$

$$A_4=K_m(k)I'_m(ks)-K'_m(ks)I_m(k)>0,$$
$$A_5=K'_m(k)I_m(ks_0)-K_m(ks_0)I'_m(k)<0,$$

$$A_6=I_m(ks_0)K_m(k)-K_m(ks_0)I_m(k)<0,$$

where I_m, K_m are the modified Bessel and Hankel functions, $s=r_0/R$. The stroke indicates the derivative of corresponding function.

3.4.2 Calculation of the wave numbers

The terms (6), (7) with the conditions (8) make possible to calculate the m,k wave number pairs in conformity with the stable (reλ>0), unstable (reλ<0), neutral (reλ=0) system perturbations.

The intrinsic values of A_j (j=1-6) are expressed through the modified Bessel and Hankel functions. Every type of such perturbations providing for appropriate heat flux control system yielding the desired effect in each case, e.g. suppression or stabilizing system; excitement of oscillations (destroying solidified front boundary lines). In different physical situations the terms under which garnissage stability and/or stabilization was achieved proved similar to those by our works.

Here one had to reckon with a number of real factors (e.g. viscosity, heat convection, multilayer walls, non-linearity of the process, etc.). This made possible correct estimation of the effects of different factors and calculate the "optimal" parameters from a standpoint of stability, or (vice versa) of the solidified front for the relevant applied systems.

Thus, by taking into consideration the melt viscosity indices, one can achieve a slight increase in the threshold stability count, at the expense of losses in perturbation dissipation energy. By properly selecting properties of multilayer fettling materials it is possible to suppress a number of harmonic modes (e.g., thermodynamic distributed damper).

3.4.3 Stability and stabilization of the garnissage

The results thus obtained were used in computer-simulated experiments which revealed a number of regularities in the stability and stabilization of the garnissage layer in cylindrical aggregate machines:

- in slight forced convection, long-wave perturbations at phase transition boundaries cause disturbances in the system's parameters over the entire region having the same order, whereas the short-wave ones tend to attenuate close to the boundary line;
- for the Peclet number $\mathbf{Pe}$>>1, the linear theory produces resonant perturbations with a frequency of ω=k$\mathbf{Pe}$;

- there is a sharp increase in the $\mathbf{Bi}^*_{k,m}$ critical values with reductions in the thickness of the garnissage layer;
- for big Peclet numbers and small garnissage layer's thickness, those of $\mathbf{Bi}^*_{k,m}$ are big and the automatic regulation system is difficult to adjust to the programmed "moods";
- with **Pe**>>k, short-wave garnissage disturbances can also gain in time, provided the garnissage layer does not go beyond the critical mark: $s<<1+1/k$, where s is the layer's dimensionless thickness in regard to the radius of the undisturbed liquid zone.

3.4.4 The results of numerical simulation on computer

The calculated parameters correspond to a number of practical systems for various metals and automatic heat flux regulating systems. These systems are made to stabilize the unstable artificial garnissage regimes (e.g., fettling protection and production of pure materials) and to destroy natural garnissage (means of combating "overgrowth" in the channels of metallurgical aggregate machines and breaches of the metallurgical regime).

Such system boast high efficiency, are ecologically "clean" and economic in term of a use of the resources. The results of numerical simulation are given in Figs 2-4:

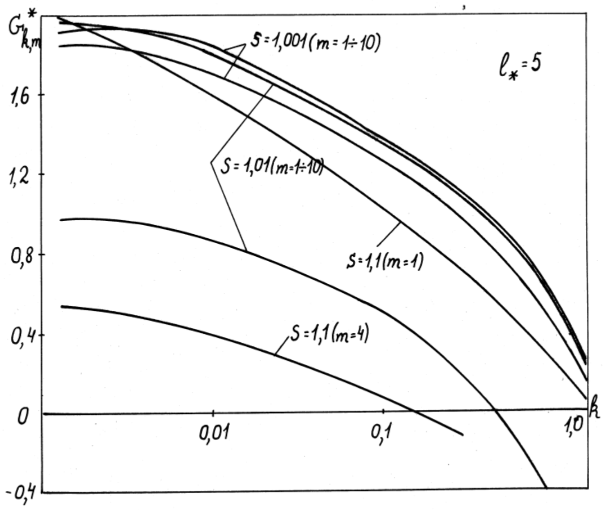

Fig. 2 Modified Bio numbers depending on the wave numbers and garnissage thickness. Pe=5

As shown in Figs 2-4, the modified Bio numbers required for stabilization of the unstable modes of perturbations group by value of the dimensionless garnissage thickness. The wave number m by circular coordinate increases stability (decreases the critical Bio number).

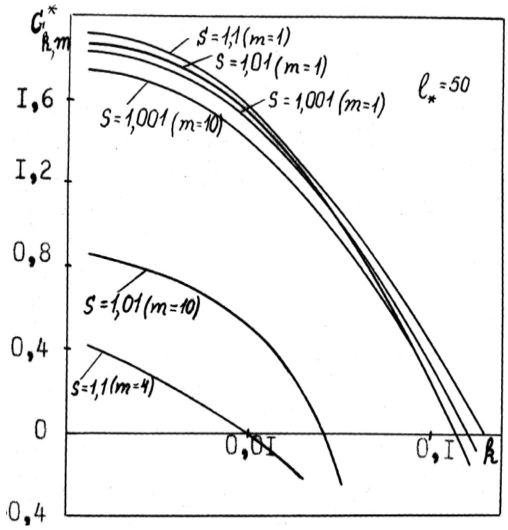

Fig. 3 Modified Bio numbers depending on the wave numbers and garnissage thickness. Pe=50

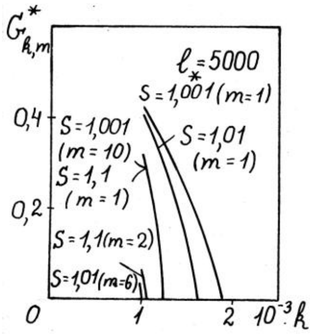

Fig. 4 Modified Bio numbers depending on the wave numbers and garnissage thickness. Pe=5000

The higher is the Peclet number (l_* in figures), the shorter is region of the unstable k numbers. For example, for Pe=5000 (Fig.4) when convective heat transfer is about 5000 stronger than the conductive one, only the long-wave perturbations of the solidification front may be unstable, and only for small thin solid layer thickness (s~1, s-1<<1). Thus, inertia forces due to fluid flow may smooth the interface between the moving liquid and its thin solid sheet on the wall (garnissage).

The problems studied in this field and their applications are presented in the Table 1.

4 The new phenomena on parametric film flow control and their application

The next class of the problems considered is parametric control of the jet/film flow and their disintegration on the drops of given shape and size.

Table 1 Stabilization of the solidification front

Problem	Study of interchange instability of liquid-solid front of crystallization	Automatic control of the liquid-solid front of crystallization
Obtained results	Mathematical models and computer code for the simulation of the process	Calculation of the parameters of automatic heat flux control system
Applica-tions	Simulation of interchange instability of liquid-solid front of crystallization in metallurgical and semiconductor devices	Garnissage channel wall protection against destroying and molten metal protection against contamination

4.1 Parametrically controlled jet/film flow

Control of film flow decay (dispersion) by means of parametric excitation (electromagnetic, vibration, etc.) is an actual problem of the modern industry because it has a wide application for injectors, chemical and other reactors, metallurgical devices.

Another problem - dumping of perturbations of a free film surface (stabilization of film flow) is directly opposite to the previous one.

And the third case: the excitation and keeping of special wave regimes of film flow which are suitable from the point of view of mass- and heat-exchange processes.

The film devices are distinguished by the simplicity, presence of developed specific surface of a liquid and as a result of which - high intensity of running processes. That is why they considerably surpass the traditional devices with a working liquid body and appear as the ecologically pure devices.

Many high-efficiency and ecologically pure processes and devices for the cleaning, degassing, heat withdrawal, heat- and mass-transport etc. can be constructed on the basis of the film flows.

4.2 Parametric jet/film flow control

The theories of liquid films have been inculcated. Theory of parametric excitation and dumping of oscillations, its application especially for the case of rapidly spreading films on the rigid surface has been studying from the beginning of the 80-th years. The results obtained allowed designing and successful testing the new prospective granulators of metals and some other devices as well. Our investigations of non-linear wave processes in film flows revealed the three new phenomena of film flow decay:

- electromagnetic parametric resonance;
- vibrating soliton-like film flow decay;
- vibrating shock-wave decay.

In the first case moving liquid film can be broken down in a drops of the given size depending on frequency of parametric excitation (e.g. alternating electromagnetic field), with comparatively low energy consumption.

In the second case the system of solitons is excited and the solitons throw off drops as unit jets in the phase of modulation.

The third case is a shock wave, it displays with excess of critical vibrating Euler’s number (10-100 depending on the parameters of the system) and is realized very simply: when the base vibrates with given frequency and vibrating Euler’s number excides the critical value.

4.2.1 Jet and film flow fragmentation

The problem of jet and film flow fragmentation and drop formation is of paramount interest for a lot of the modern industry and technology tasks: metallurgy, chemical technology, energy, etc. Because of complexity of the real physical systems there is need to consider such processes together with the other ones, e.g.: phase crystallization and flows through porous (granular) media. Studying such complicated problems came true only in the last decades due to computer science and mathematical simulation theory achievements.

Now the problem is not only to simulate the processes but also to control them with regards to the task being stated. So the problem of parametric control in continuous media is important for the practical applications in three aspects:

- Excitation of the parameters’ oscillations in continua in touch with intensification of various technological and technical processes: heat and mass transfer, mixing, decreasing of viscosity, improving the crystallization metal quality and many other phenomena.
- Excitation of the parameters’ oscillations with regards the necessity of the jet and film flows’ disintegration: air spray, spray-coating, metal spraying, dispersing and granulation the materials (e.g. particles producing from the molten metals), etc.
- Suppression of the parameters’ oscillations (stabilization of some unstable regimes and processes): the jet/drop and film screens designed for the protection of the diaphragm of the experimental thermonuclear reactor, thermal instability and control of the fusion reactor, of

electromechanical (and chemical) instabilities, the plasma and combustion stability, decreasing the hydrodynamic and acoustic resistance, etc.

In some cases the parametric control makes possible not only the processes' intensification but also to realize processes which are impossible without it.

4.2.2 Why the processes are difficult to describe and what are the benefits to describe them well?

The processes are difficult to describe because of:
- lack of the models that fit the processes in questions adequately,
- complexity of the mathematical models,
- absence or inaccuracy of the physical properties of media to be strongly dependent on the changeable regimes.

The benefits to describe the processes are:
- possibility to simulate them and predict the regimes taking into account the real physical properties of media and external perturbations,
- optimize the processes for given criteria,
- control them for specified criteria.

The considered problems and their applications are presented in the Table 2.

Table 2 Problems and their applications

Process	Jet and film flows	Channel flow with crystallization on the wall	Multiphase flow in granular media
Problem	Stabilility, fragmentation, controlled drop formation	Stability and stabilization of the front of crystallization	Nonstationary nonisothermal vapour flow in granular medium
Applications	Development of granulators for producing the monodisperse metal powder and drop curtain for tokamak	Solution of automatically controlled garnissage for channel wall protection	Calculation of heat and mass transfer processes in geothermal system

4.2.3 The methods to control the processes

The methods to control the processes are:
- electromagnetic force or heat action,
- influence on the physical properties through heat or force action on the media,
- vibrations,
- various combinations of these methods.

4.3 Jet flows, fragmentation, drop formation

The jet and film flows have to be considered taking into account different external perturbations and variability of physical properties. The mono- and polyharmonic instability modes should be studied in linear and non-linear approaches. The drops forming due to jet and film decay were investigated with focus on the free surface forms in time for different physical situations. The tasks on jet/film flow control considered and their applications are given in the Table 3.

The task was to reveal the crucial regimes and possibilities to control them. Since the modern technology of physical modeling does not allow us to study the evolution of free boundaries of jets and films effectively enough and to determine the dynamic and kinematic parameters of continuous flow (disperse flow - after decomposition), thus for these purposes the mathematical models were developed.

Table 3 The tasks on jet/film flow control

Problem	**Controlled jet decay with formation of the drops of given size and shape**	**Controlled film flow decay**
The obtained results	Linear analytical model of jet decay Numerical model of resonance jet decay, drop formation and evolution Experimental study of phenomenon Jet granulator for particles' producing Drop curtain for tokamak	Nonlinear analytical models of parametric film flow control Numerical model of film flow control Experimental studies of phenomena Electromagnetic and vibration film granulators
Discovered new phenomena	Forced resonance jet flow decay on the drops of given size and shape	Electromagnetic resonance film decay Vibration soliton-like and shock wave film decay on the drops of given size
Feasible applications	Dosage of metals Simulation of the drop formation and evolution by severe accidents in NPP using adapted numerical model	Materials' dispersement, granulation Film flow simulation and control in chemical technology, severe accidents in NPP and other processes

4.3.1 Jet fragmentation and parametric control

The molten-metal jet decomposition was performed by introduction of periodical electromagnetic (or other) forces with the frequency $f=\sqrt{2}\pi d_0/u_0$, where d_0 and u_0 are the diameter and velocity of a jet, respectively.

Aforementioned forces are formed for example with the interaction of current flowing through the melt and the magnetic cross field. The behavior of current changing in time, the form and dimension of molten metal drops are interconnected. In order to obtain the particles of the predetermined dimensions and shapes the current in metal has a series of the harmonics with the present harmonic composition.

The decomposition mode is acceptable when the drops are formed on the distance equal to the present number of wavelengths $z=\lambda n=\sqrt{2}\pi d_0 n$, where λ is the wave length on the decaying free jet.

Thus, the position of jet decomposition point should be connected with the amplitude of the disturbing electromagnetic forces at the inputs into the nozzles. Velocity in a jet source is smaller than the axial one, the jet swirl is absent, the jet radius is much smaller than the length of its non-decayed part, the mode of outflow is laminar and magnetic Reynolds number is much less than 1.

The periodic analytical solutions were found as $\zeta = r_0 + \alpha \exp(\omega t - kz)$, where $\alpha=\alpha(t)$ is a relative radial deviation of a free surface from the equilibrium position, corresponding to a cylindrical surface.

The density of a disturbed force in a jet's source and the deformation velocity of generatrix appearing due to this fact are connected by the condition on the magnetic Euler number: $\mathrm{Eu_m} \geq \sqrt{2}/\left[\pi(1+5n)\right]$. On assuming the demanded value *n*, in accordance with this condition, the current was supplied in molten metal under which the level of sufficient disturbance for the jet decomposition was provided.

In a similar way - at the first wave-length of melt disturbed jets - the working process occurs in MHD granulators for technological purposes. The appearance of oxide films on the drop surface of real metals in metallurgy (such as aluminum, copper) results however in removal of jet decomposition point from its source. In this case the drops form is considerably non-spherical; the process of decomposition appears to be unstable.

This circumstance has been managed to avoid either by putting the sources of decomposing jets in neutral gaseous atmosphere or by passing the current of polyharmonic composition through a melt. In the latter case, the particle form correction has been carried out due to sharp decay of outflow velocity at the end of drop formation period.

4.3.2 Numerical simulation of a drop's formation
The computing of jet decomposition process with considerable displaying the inertia forces was performed by way of the numerical solution of the Navier-Stocks non-stationary equations (Dr. N.V. Lysak [33], see in Figs 5, 6).

The calculations were done for different values of the ratio b of external electromagnetic force to the pressure at the jet's outlet (b from 40 to 0.4), for the same Ohnesorge number $Oh=\sqrt{We}/\mathrm{Re}$, where We and Re are the Weber and Reynolds numbers, respectively. The Ohnesorge number is kinematic parameter, which is completely determined by physical properties of the fluid. The equation array with correspondent boundary conditions has been solved numerically using the Arbitrary Lagrangian-Eulerian approach and that has regulated in determination of free surface forms in time for different physical situations [33].

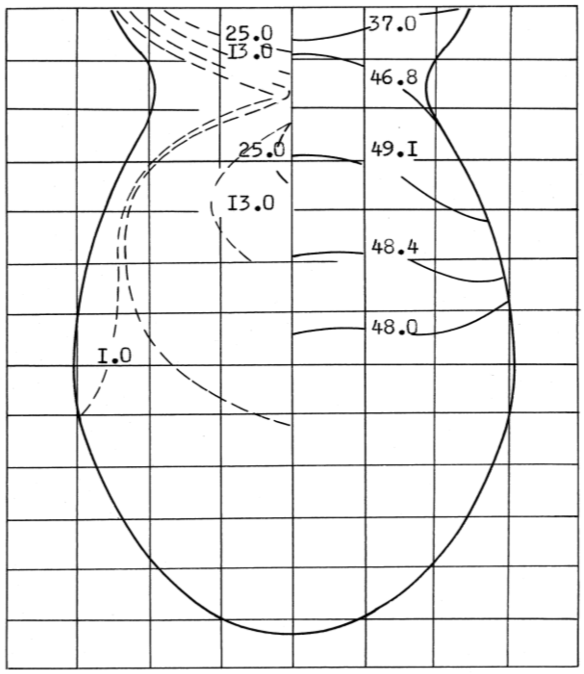

Fig. 5 Isobars and isotachs in a drop for b=40

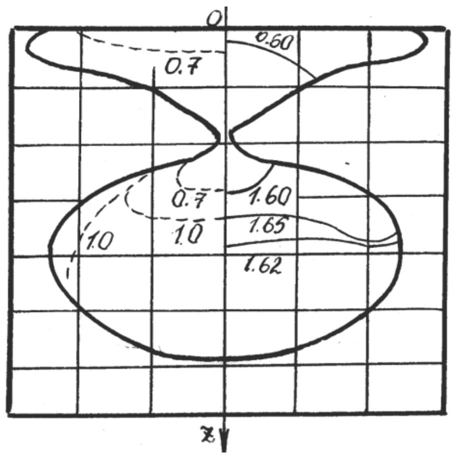

Fig. 6 Isobars and isotachs in a drop for b=0.4

4.3.3 Experimental study of the drop's formation
Some comparison with experiments to show validation of the model presented in Fig. 7, where

the filming of the drop decay's process is shown below the analytical results:

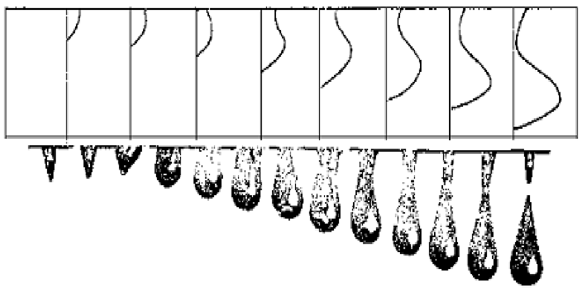

Fig. 7 Analytical solution vs. experimental data

One can see that even computation by the linear model fits reasonably to the filming of the process in general. The jet's disintegration phases are shown in time up to its decay and forming the drop, which detaches at the end of the process.

Another parametric excitation of the jet's disintegration using the vibration action is presented in Fig. 8, where the multiple series of the drops are produced after parametric disintegration of the jets on a vibrating horizontal plate:

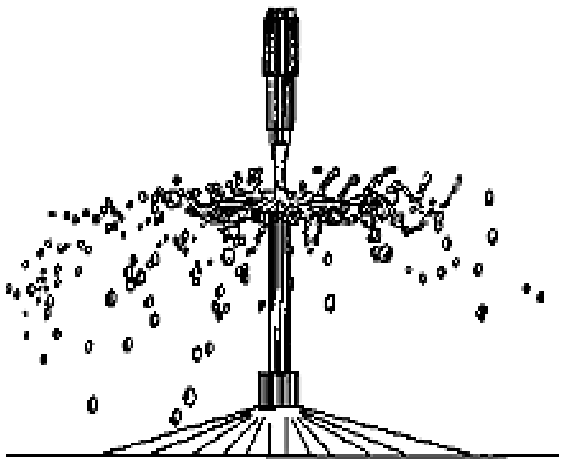

Fig. 8 Vibration jet decay

4.4 Film flow fragmentation, drop formation

Some of our investigations of determined case of film flow and parametric control of wave regimes are presented here.

The real velocity profile of undisturbed film flow is considered and unexplored problem on film flow foundation as a result of encounter of high-velocity jets with a horizontal obstacle is also considered.

4.4.1 Electromagnetic film flow control

An external alternating electromagnetic field is applied in the direction perpendicular to the horizontal plate base as it is shown in Fig. 9.

The radially spreading film flow is forming as a result of a vertical jet flow blowing on a horizontal plate. The problem on parametric wave excitation and suppression in film flow affected by progressive electromagnetic wave of the following type:

$$h=h_m(z,r)exp\,i(kr+m\varphi-\omega t), \qquad (9)$$

is considered, where k,m are the corresponding wave numbers by coordinates r,φ and ω is frequency of electromagnetic field, h is the vertical component of the magnetic field strength, h_m is the strength amplitude.

4.4.2 Vibration film flow control

The other parametric oscillations in a film flow was considered for the case of the vertical harmonic vibration of the horizontal plate:

$$d^2z/dt^2=g_v cos\Omega t, \qquad (10)$$

where g_v is the acceleration due to vibration, Ω is the frequency of vibration.

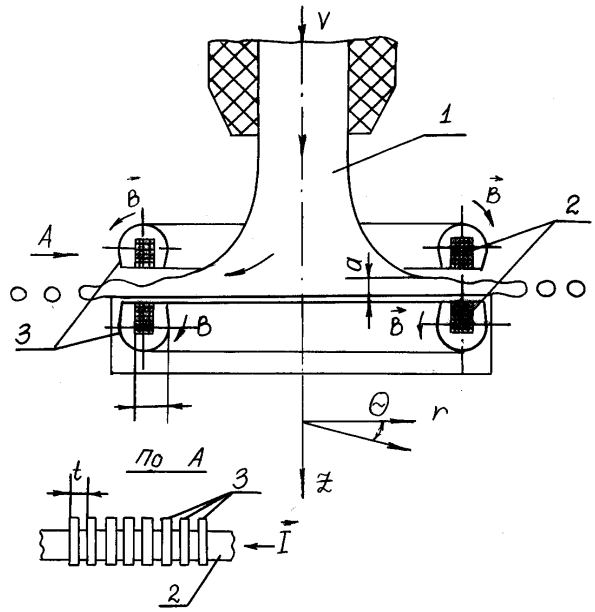

Fig. 9 Electromagnetic system for film flow decay

4.5 Mathematical model for film flow

The mathematical model for these two cases of parametric excitation (9), (10) was considered partially, as well as also together.

4.5.1 General case of axisymmetrical film flow

The general case of axisymmetrical film flow is described with the following dimensionless system of partial differential equations:

$$\partial\zeta/\partial t+1/r\partial\zeta/\partial r+1/r\partial q/\partial r=0,$$

$$1/r\partial q/\partial t+\partial/\partial r(q/r^2)+\zeta/2\partial\zeta/\partial t[\alpha_u+\partial/\partial r(\partial\zeta/\partial t+$$
$$+1/r\partial\zeta/\partial r)]+\zeta\partial\zeta/\partial r(1/\mathbf{Fr}^2-\mathbf{Eu}_g\cos\Omega t)+ \quad (11)$$
$$+2\zeta\mathbf{Al}h_m\partial h_m/\partial r+1/\mathbf{Re}[3\alpha_u+4\partial/\partial r(\partial\zeta/\partial t+$$
$$+1/r\partial\zeta/\partial r)]-\zeta/\mathbf{We}\partial K_c/\partial r=0,$$

$$\partial h/\partial t+1/r\partial h/\partial r=1/\mathbf{Re}_m(\partial^2h/\partial r^2+1/r^2\partial^2h/\partial\varphi^2+ \quad (12)$$
$$+1/r\partial h/\partial r),$$

where are: $q=\int_0^\zeta urdz$, $\alpha_u=(\partial u/\partial z)_{z=0}$,

$K_c=\{\partial^2\zeta/\partial r^2+1/r\partial\zeta/\partial r[1+(\partial\zeta/\partial r)^2]\}/[1+(\partial\zeta/\partial r)^2]^{3/2}$,

$\mathbf{Eu}_g=g_v a/u_0^2$- vibrating Euler's number, a- thickness of undisturbed film, u_0- velocity of vertical jet (characteristic velocity of a film flow), ζ- dimensionless perturbation of the film surface, $\mathbf{We}=au_0^2/\sigma$- Weber number, σ- surface tightness coefficient, $\mathbf{Al}=\mu_m h_m^2/(\rho_1 u_0^2)$- Alphven number, $\mathbf{Fr}=ga/u_0^2$- Froude number, $\mathbf{Re}=u_0a/\nu$- Reynolds number, $\mathbf{Re}_m=u_0a/\nu_m$- magnetic Reynolds number. The equation array (11) was obtained by the integration of the film flow equations with correspondent boundary conditions in a cross-section from the rigid plate (z=0) to the disturbed free surface ($z=\zeta$). The similar equation array was also considered in a simpler flat case.

4.5.2 Analytical solution of non-linear problem

In case of vibrating wave excitation in film flow the approximate solution of equation array (11) was obtained the following:

$$\zeta=B\exp(r-1+\mathbf{Eu}_g/\Omega\sin\Omega t-t/\mathbf{Fr}^2), \quad (13)$$

where B is a constant determined by experiments.

In a flat case a magnetic field excitation, a similar to the equation array (11), (12) dimensionless system of the equations obtained was:

$$\partial q/\partial t+\partial q/\partial x+0{,}5(\partial^2\zeta/\partial t\partial x+\partial^2\zeta/\partial x^2-\alpha_u)\zeta\partial\zeta/\partial t+$$
$$+\zeta/\mathbf{Fr}^2\partial\zeta/\partial x+3/\mathbf{Re}(\partial^2\zeta/\partial t\partial x+\partial^2\zeta/\partial x^2-\alpha_u)+2\mathbf{Al}\cdot$$
$$\cdot\zeta h\partial h/\partial x-\zeta/\mathbf{We}\partial/\partial x\{\partial^2\zeta/\partial x^2[1+(\partial\zeta/\partial x)^2]^{-1.5}\}=0, \quad (14)$$

$$\partial\zeta/\partial t+\partial\zeta/\partial x+\partial q/\partial x=0,$$

$$\partial h/\partial t+\partial h/\partial x=1/\mathbf{Re}_m\partial^2h/\partial x^2;$$

where $q=\int_0^\zeta udz$ is. The equation array (14) was solved by the reductive perturbation method. First it was reduced to the following matrix form:

$$\partial\mathbf{U}/\partial t+\mathbf{A}(\mathbf{U})\partial\mathbf{U}/\partial x+\mathbf{C}(\mathbf{U})\partial^2\mathbf{U}/\partial x^2+\mathbf{B}(\mathbf{U})=0, \quad (15)$$

where: $\mathbf{U}=[h, q, \zeta, \partial h/\partial t, \partial q/\partial t, \partial\zeta/\partial t, \partial h/\partial x, \partial q/\partial x, \partial\zeta/\partial x, \partial^2\zeta/\partial x\partial t, \partial^2\zeta/\partial x^2]^T$, and the matrices **A**, **C** are 11 by 11.

The nonzero elements of the vectors and matrices are the following ones:

$$b_1=-\partial h/\partial t, \quad b_2=-\partial q/\partial t, \quad b_3=-\partial\zeta/\partial t,$$

$$b_5=\alpha_u/2[\partial\zeta/\partial t(\partial q/\partial x+\partial\zeta/\partial x)+\zeta\partial^2\zeta/\partial x\partial t+2\mathbf{Al}\partial h/\partial x\cdot$$
$$\cdot(\partial^2h/\partial t\partial x+\partial^2h/\partial x\partial t)+(\zeta\partial^2\zeta/\partial x\partial t+\partial\zeta/\partial x\partial\zeta/\partial t)/\mathbf{Fr}^2+$$
$$+3(\partial^2\zeta/\partial x^2)^2\{[1+(\partial\zeta/\partial x)^2]^{-5/2}/\mathbf{We}\}\{\partial\zeta/\partial t\partial\zeta/\partial x+$$
$$+\zeta\partial^2\zeta/\partial x\partial t-5\zeta\partial^2\zeta/\partial x\partial t(\partial\zeta/\partial x)^2/[1+(\partial\zeta/\partial x)^2]\};$$

$$b_9=-\partial^2\zeta/\partial x\partial t; \quad a_{4,1}=1; \quad a_{5,4}=2\mathbf{Al}\partial h/\partial x;$$

$$a_{5,5}=0{,}5\zeta(\alpha_u-\partial^2\zeta/\partial x\partial t-\partial^2\zeta/\partial x^2)+1; \quad c_{4,4}=-1/\mathbf{Re}_m;$$

$$a_{5,8}=0{,}5[\partial\zeta/\partial t(\partial q/\partial x+\partial\zeta/\partial x)+\zeta\partial^2\zeta/\partial x\partial t];$$

$$a_{6,5}=a_{6,6}=1; \quad a_{7,4}=a_{8,5}=a_{11,10}=-1;$$

$$a_{5,10}=6\zeta\partial\zeta/\partial x\partial^2\zeta/\partial x^2[1+(\partial\zeta/\partial x)^2]^{-5/2}/\mathbf{We};$$

$$a_{5,11}=\{3\zeta(\partial\zeta/\partial x\partial^2\zeta/\partial x\partial t-\partial\zeta/\partial t[1+(\partial\zeta/\partial x)^2]\}[1+$$
$$+(\partial\zeta/\partial x)^2]^{-5/2}/\mathbf{We}; \quad c_{5,5}=0{,}5\zeta(\partial q/\partial x+\partial\zeta/\partial x)-1/\mathbf{Re};$$

$$c_{5,10}=-\zeta[1+(\partial\zeta/\partial x)^2]^{-3/2}/\mathbf{We}; \quad c_{10,5}=c_{10,6}=1.$$

4.5.3 Solution of standard evolutionary equation

The solution of the obtained standard evolutionary equation (14) was found in the following form (Asano N., Taniuti T., Yajima N., 1969; Asano N., 1974) [6,7]: $\mathbf{U}=\sum_{\alpha=0}^{\infty}\varepsilon^\alpha\mathbf{U}^{(\alpha)}$, where are: $\varepsilon=o(1)$, $\mathbf{U}^{(\alpha)}=\sum_{l=-\infty}^{+\infty}\mathbf{U}_l^{(\alpha)}(\xi,\tau)\exp i\boldsymbol{l}(kx-\omega t)$; $\xi=\varepsilon(x-v_gt)$; $\alpha\geq1$; $\tau=\varepsilon^2(t)$; $\mathbf{U}_1^{(1)}=\mathbf{R}\varphi$; $\mathbf{W}_1\mathbf{R}=0$; $\mathbf{LW}_1=0$; $\mathbf{W}_1=\left|\left|-il\omega\mathbf{I}+ilk\mathbf{A}^{(0)}+\nabla\mathbf{B}^{(0)}+l^2k^2\mathbf{C}^{(0)}\right|\right|$; $\mathbf{U}_0$=const-undisturbed solution of matrix equation (15); $\mathbf{A}^{(0)}=\mathbf{A}(\mathbf{U})$ by $\mathbf{U}=\mathbf{U}_0$; $(\nabla\mathbf{B}^{(0)})_{j,k}=(\partial\mathbf{B}_j/\partial\mathbf{U}_k)$ by $\mathbf{U}=\mathbf{U}_0$; $\mathbf{U}\sim\exp i(kx-\omega t)$; $v_g=\partial\omega/\partial k$- the group wave velocity. Here ξ,τ are the "slow-acting" ("compressed") variables introduced by Gardner-Morikawa procedure (Gardner C.S., Greene J.M., Kruskal M.D., Miura R.M., 1967; Gardner C.S., Morikawa G.M., 1969) [28].

4.5.4 The non-linear Schrӧdinger equation

Taking into account all the above-mentioned yielded for the fundamental harmonic the following equation (Whitham G.B., 1974):

$$i\partial\varphi/\partial t+0{,}5(\partial^2\omega/\partial k^2)\partial^2\varphi/\partial\xi^2+\mu|\varphi|^2\varphi-\delta\varphi=0. \quad (16)$$

There is taken an assumption that the fundamental harmonic in considered time interval is dominant and the mode's interaction can be neglected. The coefficients in equation (16) are as follows [31]:

$$\mu=C/|\mathbf{LR}|;\ \mu=\mu_r+i\mu_i;\quad C=C_A+C_B+C_C;$$

$$C_A=ik\mathbf{L}\{2(\nabla\mathbf{A}^{(0)}\mathbf{R}^*)\mathbf{R}_2^{(2)}-(\nabla\mathbf{A}^{(0)}\mathbf{R}_2^{(2)})\mathbf{R}^*+$$

$$+(\nabla\mathbf{A}^{(0)}\mathbf{R}_0^{(2)})\mathbf{R}+(\nabla\nabla\mathbf{A}^{(0)}:\mathbf{RR}^*)\mathbf{R}-0{,}5(\nabla\nabla\mathbf{A}^{(0)}:$$

$$\mathbf{RR})\mathbf{R}^*\};\quad C_B=\mathbf{L}\{(\nabla\nabla\mathbf{B}^{(0)}(\mathbf{RR}_0^{(2)}+\mathbf{R}^*\mathbf{R}_2^{(2)})+$$

$$+0{,}5\nabla\nabla\nabla\mathbf{B}^{(0)}:\mathbf{RR}^*\mathbf{R}\};\ C_C=-k^2\mathbf{L}\{(\nabla\mathbf{C}^{(0)}\mathbf{R}_2^{(2)})\mathbf{R}+$$

$$+(\nabla\mathbf{C}^{(0)}\mathbf{R}_0^{(2)})\mathbf{R}+(\nabla\nabla\mathbf{C}^{(0)}:\ \mathbf{R}^*\mathbf{R})\mathbf{R}+0{,}5(\nabla\nabla\mathbf{C}^{(0)}:$$

$$\mathbf{RR})\mathbf{R}^*+4(\nabla\mathbf{C}^{(0)}\mathbf{R}^*)\mathbf{R}_2^{(2)}\};\ \delta=-d/|\mathbf{LR}|;$$

$$\delta=\delta_r+i\delta_i;\quad d=\mathbf{L}\{ik\mathbf{A}'^{(0)}+\nabla\mathbf{B}'^{(0)}-k^2\mathbf{C}'^{(0)}\};$$

$$\mathbf{R}_0^{(2)}=-\{ik[(\nabla\mathbf{A}^{(0)}\mathbf{R}^*)\mathbf{R}+c.c.]+0{,}5(\nabla\nabla\mathbf{B}^{(0)}\mathbf{RR}^*+c.c.)-$$

$$-k^2[(\nabla\mathbf{C}^{(0)}\mathbf{R}^*)\mathbf{R}+c.c.]\}/||\mathbf{W}_0||;$$

$$\mathbf{R}_2^{(2)}=-\{ik(\nabla\mathbf{A}^{(0)}\mathbf{R})\mathbf{R}+0{,}5\nabla\nabla\mathbf{B}^{(0)}\mathbf{RR}k^2(\nabla\mathbf{C}^{(0)}\mathbf{R})\mathbf{R}\}/$$

$$||\mathbf{W}_2||;\quad \nabla\mathbf{A}^{(0)}\mathbf{U}^{(1)}=\mathbf{U}_j^{(1)}(\partial\mathbf{A}/\partial\mathbf{U}_j)\quad \text{by } \mathbf{U}=\mathbf{U}_0;$$

$$\nabla\nabla\mathbf{A}^{(0)}\mathbf{U}^{(1)}\mathbf{U}^{(1)}=\mathbf{U}_j^{(1)}\mathbf{U}_k^{(1)}(\partial^2\mathbf{A}/\partial\mathbf{U}_j\partial\mathbf{U}_k) \text{ by } \mathbf{U}=\mathbf{U}_0;$$

$$||\mathbf{W}_0||=\det\mathbf{W}_0;\ ||\mathbf{W}_2||=\det\mathbf{W}_2;$$

$$\nabla\nabla\nabla\mathbf{A}^{(0)}\mathbf{U}^{(1)}\mathbf{U}^{(1)}\mathbf{U}^{(1)}=\mathbf{U}_j^{(1)}\mathbf{U}_k^{(1)}\mathbf{U}_m^{(1)}(\partial^3\mathbf{A}/\partial\mathbf{U}_j\partial\mathbf{U}_k\partial\mathbf{U}_m)$$

by $\mathbf{U}=\mathbf{U}_0$; c.c.- complex-conjugated.

The solution procedure is described in detail in [31].

The complex-conjugated values are signed with star. For the **A**, **B**, **C**, ω the asymptotic decompositions by order of ε^2 were used.

Thus, a rapid wave $\exp i(kx-\omega t)$ has an amplitude multiplier satisfying the non-linear Schrӧdinger equation (16) with dissipation, which has soliton-like solutions (strict solitary waves are impossible due to dissipation). Therefore the soliton-like wave amplitude is filled with the rapid oscillations.

4.6 Soliton-like solutions for the film flow

The solution of the equation (16) for each harmonic having its own equation according to a value of ω (second term in (16)) can be found in the form $\varphi=\psi\exp i(\theta+k_b\xi)$, where $2\pi/k_b$ is a wave length for the amplitude-solution (big wave). Then the following solution is obtained by $\mu_i\neq0$:

$$\theta^{(j)}=\{\mu_r^{(j)}[\psi_\tau^{(j)}]^2-0{,}5(\partial^2\omega^{(j)}/\partial k^2)_k^{(j)}(k^{(j)})^2+\delta_r^{(j)}\}\tau+2\pi n; \quad (17)$$

$$[\psi_\tau^{(j)}]^2=|\delta_i/\mu_i|[1\pm\exp(-2\delta_i\tau)]^{-1};$$

$\psi<\sqrt{|\delta_i/\mu_i|}$ corresponds in second equation of (17) to "+", while $\psi>\sqrt{|\delta_i/\mu_i|}$ - to "-"; $k^{(j)}=k_b^{(j)}$; $n\in N$. The obtained approximate expression (17) allows analyzing stability of excited non-linear waves. Instability is available by $\delta_i<0$, while by $\delta_i>0$ the film flow is stable.

4.6.1 Critical level of perturbations

In a non-linear case the critical value of the perturbations in a film flow must be estimated because these stability conditions are only necessary and not sufficient ones.

For the stability of the excited soliton-like waves the critical value of an excitation should be exceeded. In the case considered, this critical value is $\psi_{cr}=\sqrt{|\delta_i/\mu_i|}$. By $\delta_i<0$, $\mu_i<0$, the stability of a soliton-like wave depends on an initial amplitude ψ^2 ($\tau\to-\infty$). For the $(q,\zeta)=R[\varphi]\exp i(kx-\omega t)+c.c.$ there is $q^2=\varphi^2\exp 2i(kx-\omega t)+2|\varphi|^2+c.c.$ Then in case of $\alpha_u=0$ (non-moisten surface) it is obtained the dispersive appropriate correlation:

$$(\omega-k)^2+3i/\mathrm{Re}k^2(\omega-k)+\{k^4(\omega-k)^3[(\omega-k)^2+4k^4|\varphi|^2]\}/ \quad (18)$$
$$\{\mathrm{We}[2k^4|\varphi|^2-(\omega-k)^2]^{5/2}\}+2i\mathrm{Al}kh\partial h/\partial x-k^2/\mathrm{Fr}^2=0,$$

For magnetic field $H=H_o+h_1\exp[i\omega_m=\pm k_m(im/\mathrm{Re}_m-1)]$ sign "+" corresponds to electromagnetic wave spreading in opposite to the surface wave direction while "-" – to the opposite direction [31,50]. Here ω,k are supposed to be the weak non-linear functions of x. In this approach, the non-linear dispersive correlation (18) is justified for the non-linear small-amplitude waves (with corresponding requirements to the magnetic field).

In case of $\sqrt{2}k^2|\varphi|<<|\omega-k|$, the correlation (18) is simplified:

$$(\omega-k)^2+3i/Rek^2(\omega-k)-k^4/We[1+9k^4|\varphi|^2/(\omega-k)^2+$$

$$+30k^8|\varphi|^4/(\omega-k)^4]+2iAlkh\partial h/\partial x-k^2/Fr^2=0.$$

For the $\xi=\varepsilon(x-v_{gj}t)$, $\tau=\varepsilon^2 t$, from equation (16) yields

$$i\partial\varphi^{(j)}/\partial\tau^{(j)}+0{,}5\partial v_{gj}/\partial k\partial^2\varphi^{(j)}/\partial\xi^{(j)2}+$$

$$+\partial\omega_j/\partial|\varphi^{(j)}|^2|\varphi^{(j)}|^2\varphi^{(j)}-\delta^{(j)}\varphi^{(j)}=0.$$

4.6.2 Critical values for the non-linear waves

The critical values for the non-linear wave excitation are:

$$|\psi^{(j)}_{cr}|=[2We+Fr^2(k_b^{(j)})^2]\{Re^2[2We+Fr^2(k_b^{(j)})^2]^2+$$

$$+9We^2Fr^2(k_b^{(j)})^2\}^{1/2}/[6\sqrt{2}ReFr^2We^{3/2}(k_b^{(j)})^2];$$

$$q^{(j)}_{cr}=[2We+Fr^2(k_b^{(j)})^2]\{We[4(1/Fr+0{,}5Fr(k_b^{(j)})^2/$$

$$We)^2+9(k_b^{(j)})^2/Re^2]\}^{1/2}/[6\sqrt{2}FrWe(k_b^{(j)})^2];$$

$$\zeta^{(j)}_{cr}=q^{(j)}_{cr}[k_b^{(j)}/(\omega_j-k_b^{(j)})].$$

4.6.3 Case of the high Reynolds numbers

For the Re>>1 the dissipation effects are negligibly small, therefore the non-linear Schrödinger equation (16) has solitary solutions when $\varphi^{(j)}\to 0$ by $|\xi^{(j)}|\to\infty$:

$$\varphi^{(j)}=[-2A^{(j)}/\mu_r^{(j)}]^{1/2}\mathrm{sech}\{[-0{,}5(\partial^2\omega_j/\partial k^2)/A^{(j)}]^{-1/2}\xi^{(j)}\}\cdot$$

$$\cdot\exp(-iA^{(j)}\tau^{(j)}),\quad A^{(j)}=-0{,}5\mu_r^{(j)}[\varphi_0^{(j)}]^2,$$

where $\varphi_0^{(j)}$ is the value of $\varphi^{(j)}$ by $\tau=0$, $\xi^{(j)}=0$. The solitary wave's width $\Delta_s^{(j)}=[(\partial^2\omega_j/\partial k^2)/(\mu_r^{(j)}\varphi_0^{(j)})]^{1/2}$, where $A_s^{(j)}=\varphi_0^{(j)}$ is the wave's amplitude and $v_s^{(j)}=\partial^2\omega_j/\partial k^2$ is its velocity. The non-linear addition to solitary wave's frequency is $\Delta\omega_s=0{,}5\mu_r^{(j)}(\varphi_0^{(j)})^2$.

Electromagnetic modulation in linear approach:

$$\omega=k-1.5ik^2/Re\pm\{k^2(1/Fr^2-{,}25k^2/Re^2+k^2/We)+2ik\cdot$$

$$\cdot k_mAl[h_0+2h_m\cos(k_mx-\omega_mt)][2h_m\sin(k_mx-\omega_mt)]\}^{1/2}.$$

Moreover, the soliton-like excitation for a film flow requests also the Lighthill's condition:

$$We(k+1)(1+k^2Fr^2/We)>k^4Fr^2, \qquad (19)$$

that is a limitation on minus-plus signs of the coefficients by a terms $\partial^2\varphi/\partial\xi^2$ and a non-linear term of a standard evolutionary equation.

As follows from the equation (19), this criterion is easier to satisfy by small value of k. Therefore the short-wave solitons are harder to excite than the long-wave solitons.

4.6.4 Critical parameters of soliton-like solutions

The calculations have shown critical parameters:

$|\psi_s|_{cr}=3*10^{-2}$ - in general case;
$|\psi_s|_{cr}=3*10^{-3}$ - by k>>1 (short-wave solitons);
$|\psi_s|_{cr}=10^{-6}$-10^{-8} - by k<<1 (long-wave solitons).

4.7 Three new phenomena of the parametric film flow decay

A number of different linear, as well as non-linear modeling situations were considered. As a result there were obtained some interesting peculiarities of the parametric wave excitation and suppression in the film flows including the three new phenomena of parametric film decay [31,50]:

- electromagnetic controlled resonance film flow decay,
- soliton-like vibration film flow decay,
- vibration shock-wave film flow decay.

The phenomena were first theoretically predicted and then experimentally invented and investigated. Based on these new phenomena, the prospective dispersing and granulation machines were developed, created and tested for some metals and other materials [33,50].

5 Experimental study and applications of the new phenomena

Controlled film flow decay (dispersion) by means of the parametric excitation (electromagnetic field, vibrations, etc.) is an actual problem of the modern industry because of wide applications for the injectors, chemical and other reactors, metallurgical devices.

Another problem - dumping of perturbations of a free film surface (stabilization of film flow) is directly opposite to the previous one. And the third case: the excitation and keeping of special wave regimes of a film flow which are suitable from the point of view of mass- and heat-exchange processes.

The film devices are distinguished by simplicity, presence of a developed specific surface of a liquid and as a result of which - high intensity of the running processes. That is why they considerably surpass the traditional devices with a working liquid body and appear ecologically pure. The many high-efficiency withdrawal, heat- and mass-transport, etc. devices can be constructed on the basis of a film flows.

5.1 Electromagnetic and vibration type devices for controlled film decay

For the experimental studies of the controlled film flow decay we developed two electromagnetic and one vibration type devices, which general views are presented in Figs 10-12. The scheme of the vibration type granulation machine built on the principle of the parametrically controlled film flow decay with nitrogen atmosphere and liquid nitrogen coolant is shown in Fig. 13.

Fig. 10 Electromagnetic deep vacuum film flow device

The vibration type granulation machine is working using the standard 10 kW vibrator but with special membranes, which characteristics a presented in Fig. 14. These types of membranes were used in the experiments allowed obtaining the required vibration frequency and vibration acceleration up to 2000 m/s^2.

The discovered and investigated three new phenomena of resonant, soliton-like and shock-wave film disintegration were used for the development of prospective film granulators and dispersers.

These devices were developed at first in the world and have no analogues.

Fig. 11 Electromagnetic light vacuum film flow device

The shock-wave regime (with conical shock wave on the vertical jet) is showed only schematically because the particles producing by it are too small. This process could be used for spraying on coatings.

5.2 Electromagnetic controlled film decay

Electromagnetic controlled film flow decay process studied in the device shown in Fig. 10 is presented in Figs 15, 16. Fig. 15 shows the process of the film flow decay on the drops of different size due to film flow instability. The drop's distribution by size is chaotic and very wide.

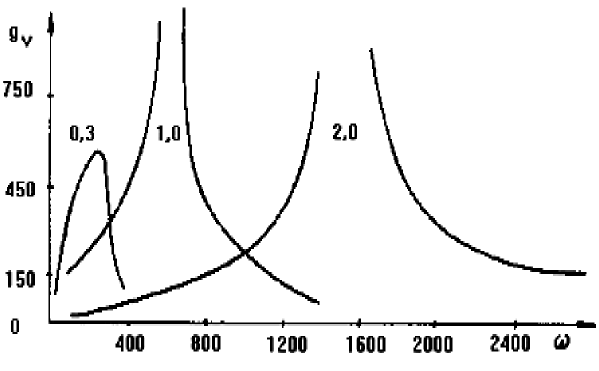

Fig. 14 Resonance curves for the vibration acceleration for three types of the membranes

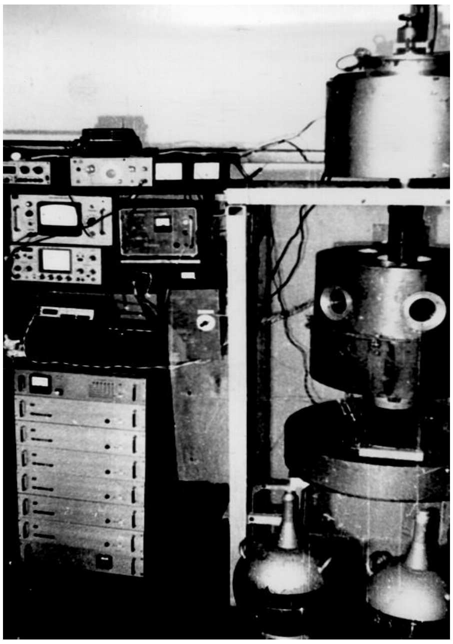

Fig. 12 Vibration film flow device with nitrogen atmosphere and liquid nitrogen coolant

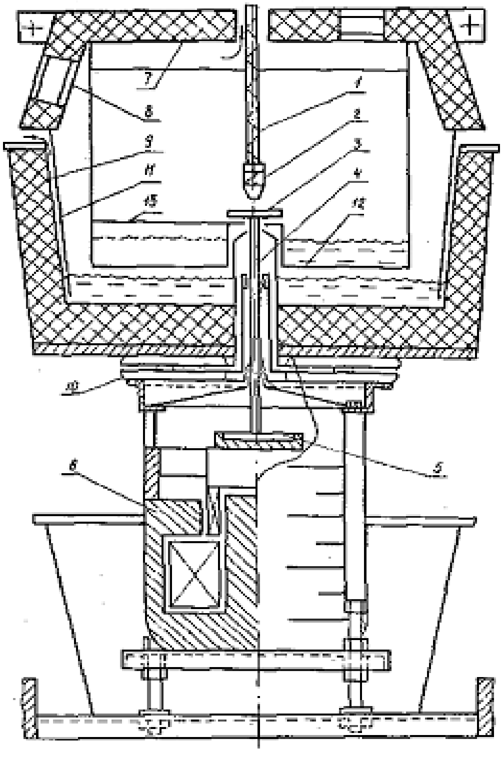

Fig. 13 The scheme of the Vibration type granulation film flow device with nitrogen atmosphere and liquid nitrogen coolant

In contrast to the free film flow decay the electromagnetic resonant controlled film flow decay shown in Fig. 16 clearly demonstrates that the drops' size is nearly uniform. The drops of controlled size are regularly produced from the film flow, which important for the granulation machines. This process was proven on different metal melts and was used for granulation of the metals for special metallurgy (in production of the new materials).

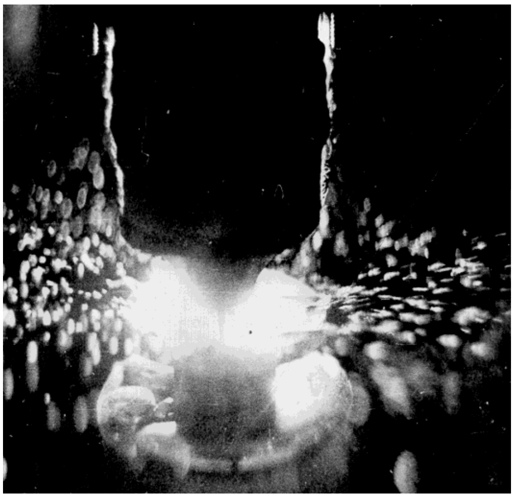

Fig. 15 Free film flow decay due to instability

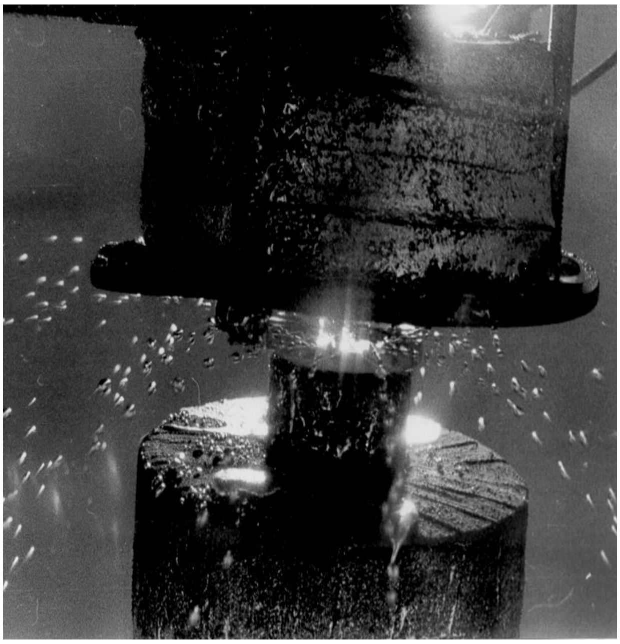

Fig. 16 Electromagnetic resonant controlled film flow decay

5.3 Vibration controlled film flow decay

The vibration controlled film flow decay is shown in Fig. 17. This is an element of the device presented in Figs 12, 13. In this type of granulation machine the new phenomena of the soliton-like film flow decay and shock-wave film flow decay were implemented. The first one is observed in Fig. 17, where drops are levitating over the vibrating plate looking chaotic but being not chaotic indeed.

Fig. 17 Vibration controlled soliton-like film flow decay

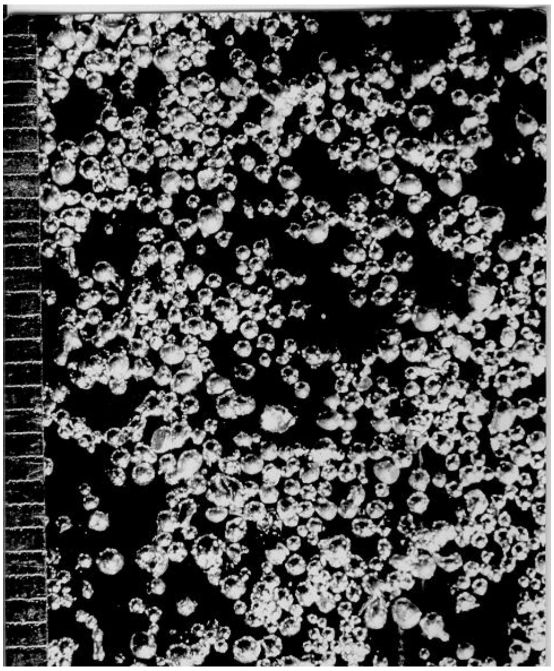

Fig. 18 Particles of metal produced in soliton-like regime on vibration type granulation machine

The process is controlled and regular as far as the drops are produced from the solitons, which are all nearly the same. Here we got drops' size distribution with deviation of about 50% as shown in Fig. 18 (for comparison, in a free film decay it is over 1000%).

The shock wave regime is got by nearly ten times higher vibration Euler number and looks like conical shock-wave on the vertical jet, which produces fine particles from the jet (Fig. 19). The film flow does not exist in this case. It may be used for production of small particles or for the spraying of materials. Vibration type devices are applicable for any appropriate melts except highly viscous – conductive, as well as non-conductive melts.

By comparably low vibration Euler numbers film flow decay is ineffectively controlled as shown in Fig. 20, where the drops are produced from the edges of the vibrating film flow bell. Here only some regularization of the process is available, e.g. to narrower the drop's size distribution about twice.

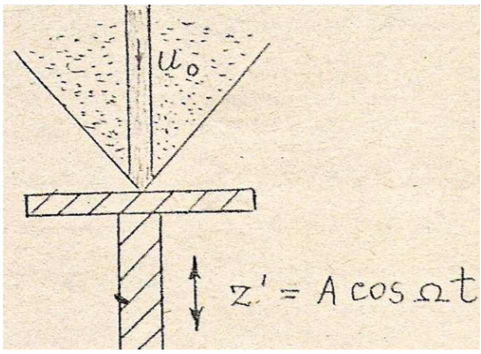

Fig. 19 Shock-wave film flow decay regime

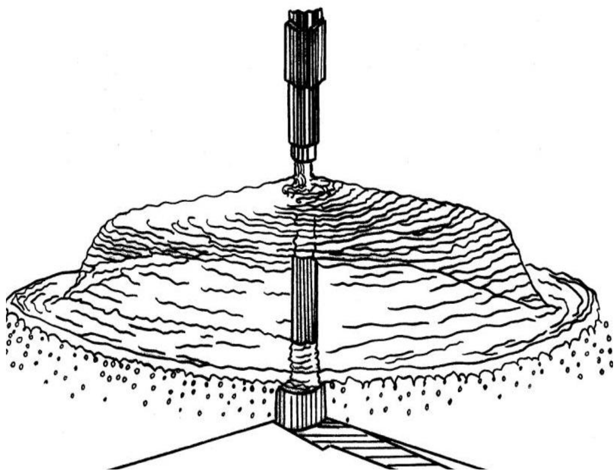

Fig. 20 Vibration controlled film flow decay

6 Heat transfer in granular media

6.1 Description of the multiphase system

The problem of a non-stationary non-isothermal gas (steam) flow in porous granular media with account of the real physical properties of the media, which can strongly depend on the temperature spatial distribution, is of paramount interest for a lot of modern industrial, technological and natural processes, for example the following ones:

- Coolability of a heat-generating porous beds in a severe accidents at the Nuclear Power Plants.
- Gas and steam flow through the underground permeable layers in Geothermal and Gas Industry as well as Vulcanology.
- Diverse gas and steam flows in Chemical Reactors, porous elements of the Avionic Components, etc.

6.1.1 Assumptions about the system

The study of steam flow through granular medium was performed taking into account:

- heat transfer between flow and particles of porous medium and surrounding medium,
- local heat sources,
- non-linearity of physical properties.

This new model allowed revealing the crucial regimes such as localizations of dissipative processes and abnormal heat up/flows regions appearance. The studied processes are their fileds of applicability are presented in the Table 4.

6.1.2 Non-thermal equilibrium in granular layer

The non-thermal equilibrium flow through a porous medium is of special interest. R.I. Nigmatulin [47] derived the equations of a saturated monospherical particle layer in heterogeneous non-thermal equilibrium approach, with account of the deformable properties of the layer. Based on his equations, the two-dimensional mathematical model and numerical algorithm were developed and successfully applied to a few complex real problems [48, 49] for the steam flow in a particle layer surrounded by the impermeable medium. The model was applied for numerical simulation of a non-stationary non-isothermal filtration in geothermal systems, also for severe accidents at NPP, etc. the The system' structural scheme is shown in Fig. 21.

6.2 The mathematical model of the system

By a development of the mathematical model, the following assumptions were employed:

- Flow is single phase, compressible (gas, steam)
- The particles' sizes are significantly larger than molecular-kinetic scales but significantly less than the characteristic scale of the system
- The physical properties of the media such as thermal conductivity, viscosity, density, etc. are temperature dependent functions
- Solid particles are immovable, porosity is constant in each monolayer.

Table 4 Multiphase processes in granular media

Problem	Mathematical simulation of steam flow though granular media taking into account the local heat transfer between particles and flow and surroundings
The obtained results	Numerical nonstationary 2D model of the multiphase system with nonlinear physical properties of media
Discovered new phenomenon	Localization of heat transfer process because of the nonlinearity of heat transfer coefficient
Feasible applications	Numerical simulation of the heat and mass transfer in granular media in granulators, chemical technology devices, NPP

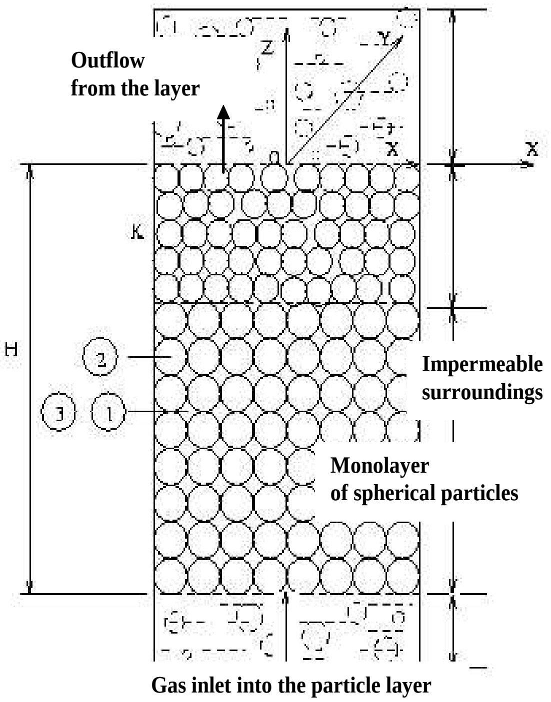

Fig. 21 Structural scheme of heterogeneous media

6.2.1 Dimensionless equation array

The mathematical model obtained [48, 49] includes the following equation array:

$$u_1 = -\frac{\partial p_1}{\partial x}\left(\frac{T_{10}}{T_1}\right)^m, \qquad \frac{\partial \rho_1^0}{\partial \mathbf{Fo}} = -\rho_1^0\left(\frac{\partial u_1}{\partial x}+\frac{\partial w_1}{\partial z}\right),$$

$$w_1 = (1-\alpha_1)\left[\mathbf{Pe} - \kappa_\rho \mathbf{Ra}^*(T_2 - T_{20}) - \mathbf{Re}_*^2\frac{p_1}{T_1}\right]\left(\frac{T_{10}}{T_1}\right)^m,$$

$$\frac{\partial p_1}{\partial z} = \mathbf{Pe}(\alpha_1 - 1)\left[1-\Delta_2(T_2 - T_{20})\right] - \mathbf{Re}_*^2\frac{\alpha_1 p_1}{T_1},$$

$$\frac{\partial T_1}{\partial \mathbf{Fo}} = (1-\gamma_1)T_1\left(\frac{\partial u_1}{\partial x}+\frac{\partial w_1}{\partial z}\right) - \left(u_1\frac{\partial T_1}{\partial x}+w_1\frac{\partial T_1}{\partial z}\right)+(\gamma_1-1)(u_1^2 +$$

$$+w_1^2)\left(\frac{T_{10}}{T_1}\right)^m\frac{T_1}{p_1}+\frac{\gamma_1\mathbf{Pe}\left(T_1/T_{10}\right)^m}{\alpha_1\kappa_a\kappa_\rho\mathbf{Re}_*^2 p_1}\bullet \tag{20}$$

$$\bullet\left\{T_1\left(\frac{\partial^2 T_1}{\partial x^2}+\frac{\partial^2 T_1}{\partial z^2}\right)+m\left[\left(\frac{\partial T_1}{\partial x}\right)^2+\left(\frac{\partial T_1}{\partial z}\right)^2\right]+\xi\mathbf{Nu}_1 T_1(T_2 - T_1)\right\},$$

$$\frac{\partial T_2}{\partial \mathbf{Fo}} = \frac{(1-\alpha_1)^{-1}}{1-\Delta_2(T_2 - T_{20})}\left[\frac{\partial^2 T_2}{\partial x^2}+\frac{\partial^2 T_2}{\partial z^2}+\xi\frac{\mathbf{Nu}_1}{\kappa_k}\left(\frac{T_1}{T_{10}}\right)^m (T_1 - T_2)\right],$$

$$\frac{\partial T_3}{\partial \mathbf{Fo}} = a_{32}\left(\frac{\partial^2 T_3}{\partial x^2}+\frac{\partial^2 T_3}{\partial z^2}\right).$$

The boundary problem for the non-stationary 2-D equation array (20) is stated in a dimensionless form. For this purpose, the following length, time, velocity, pressure and temperature scales were introduced: H, H^2/a_2^0, a_2^0/H, $\mu_{10}a_2^0/K_0$ and ΔT as the characteristic temperature in a system.

6.2.2 The initial and boundary conditions

The initial and boundary conditions for the system (20) have the following dimensionless form:

$$\mathbf{Fo}=0,\; p_1 = p_1^0(x,z),\; T_j = T_j^0(x,z), \quad \text{j=1,2,3;}$$

$$z=0,\; p_1 = p_1^{top},\; \frac{\partial^2 T_1}{\partial z^2}=0,\; \frac{\partial T_j}{\partial z} = N_j^{top}(T_j - T_{top});$$

$$z=-1, \quad T_j = T_{jH}, \quad \text{j=1,2,3;} \tag{21}$$

$$x=0, \quad \frac{\partial T_1}{\partial x}=\frac{\partial T_2}{\partial x}=0; \qquad x=x_\infty, \quad \frac{\partial T_3}{\partial x}=0;$$

$$x=x_L,\; u_1=0,\; T_j = idem, \qquad \frac{\partial T_2}{\partial x}=k_{32}\frac{\partial T_3}{\partial x}.$$

Here are the following dimensionless criteria: $\mathbf{Pe}=w_0 H/a_2^0$ - Peclet number, $\mathbf{Re}_*^2 = gH/(R\Delta T)$, $\mathbf{Ra}^* = \mathbf{GrPr}^*\mathbf{Da}$ - Rayleigh number, $\mathbf{Gr}=g\Delta_2 H^3\nu_{10}$, $\mathbf{Pr}^*$ and $\mathbf{Da}=K/H^2$ - Grasshoff, Prandtl and Darcy numbers, respectively, $\mathbf{Fo}=a_2^0 t/H$ is the Fourier number.

Then $w_0 = \rho_{20}^0 Kg/\mu_{10}$ is the character filtration velocity, a is the heat diffusivity coefficient, e.g. $a_1^0 = k_1^0/(c_{p1}\rho_{10}^0)$. The other parameters are the following: $\kappa_a = a_2^0/a_1^0$, $\kappa_\rho = \rho_{20}^0/\rho_{10}^0$, $\kappa_k = k_2/k_1^0$, $k_{32}=k_3/k_2$, $\gamma_1 = c_{p1}/c_{v1}$, $a_{32}=a_3/a_2^0$, $\xi = s_{12}H^2/b_1$ (parameter of the structure of the granular layer), s_{12} is a specific interfacial area, $b_1 = b\sqrt{2(2-\pi/3)\pi}$ is the character pore radius, b - particle radius (constant in each monolayer), $\Delta_2 = \Delta T\beta_{T2}$, β_{T2} is the particle's thermal expansion coefficient.

6.2.3 The features of the multiphase system

The system considered is multiphase, interactions of the three different processes occur:

- non-thermal equilibrium between gas and solid particles in the layer,
- non-linear processes' mutual influence and
- non-linearity of the physical properties of gas and particles (mainly, gas properties strongly depend on temperature and pressure).

The first above-mentioned peculiarity is touched with the term $\xi(T_1 - T_2)$, which describes the local heat transfer between particles and flow. From the mathematical point of view it causes some limitation on the parameter ξ because the term $\xi(T_1 - T_2)$ in the energy equations for solid particles and gas flow is huge by the very small particles. And these energy equations have terms like "$\infty\cdot 0$" because by small particles the temperature difference $(T_1 - T_2)$ is going fast to zero.

Therefore as far as the temperature difference between particles and gas flow is going to zero, in limit there is a homogeneous mixture. Then heterogeneous model considered should be replaced with a homogeneous one to avoid this peculiarity causing numerical inaccuracy.

The most important new phenomenon is a localization of the dissipate processes due to non-linear heat conductivity. This phenomenon was studied at first by A.A. Samarskii et. al. [51] for the quasilinear parabolic equations, e.g. one-dimensional heat conductivity equation with a non-linear heat conductivity $k = k_0 T^m$ (m=0.5–1.0).

Some gases and steam follow this law under certain range of the temperature and pressure. In our case all these phenomena are interconnected.

6.3 Numerical solution of the problem

For the numerical solution of the boundary problem (20), (21), the method of fractional steps was employed. The strategy of the method is in a split of a basic equation into several equations each of those is one-dimensional equation.

A few results from numerical simulation of the problem are presented in Figs 22-25 below:

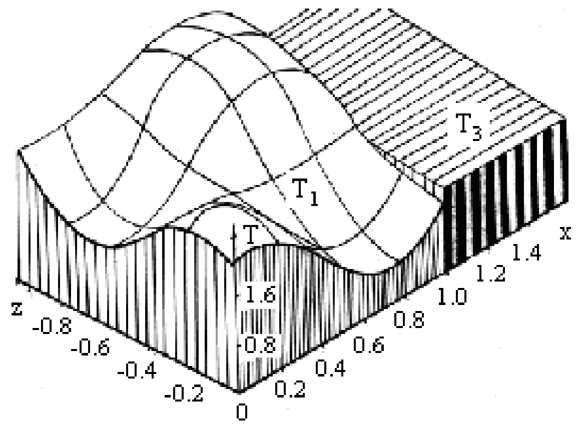

Fig. 22 Initial temperature perturbation in a steam flow T_1 and surrounding T_3 ($Fo = 0$), computed by time step $\Delta Fo = 2 \cdot 10^{-8}$.

Further evolution of the temperature field, vapour density and filtration velocity in the granular medium due to this initial perturbation is shown in Figs 23-25 for the temperature, density and velocity:

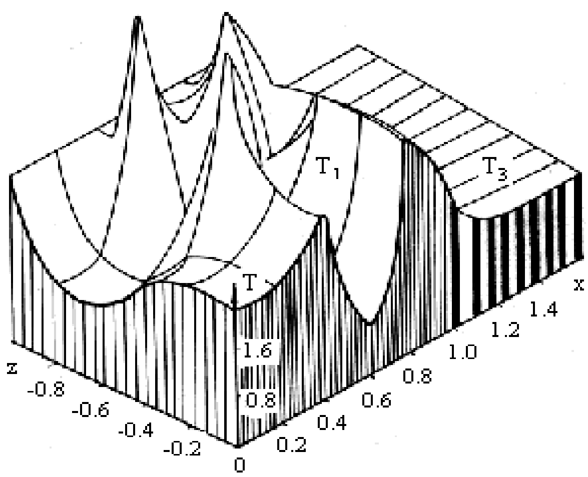

Fig. 23 Local abnormal heating in a particle layer with internal heat generation ($Fo = 2 \cdot 10^{-5}$)

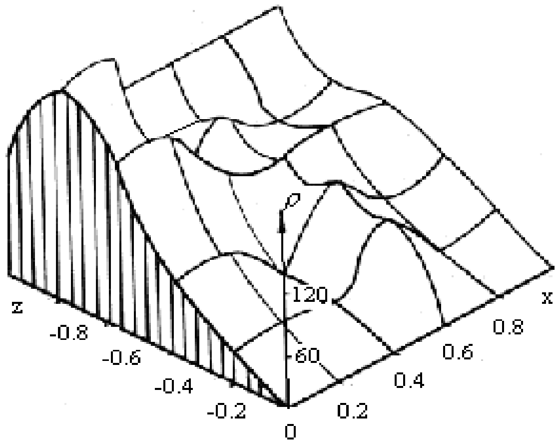

Fig. 24 Local abnormal density distribution due to abnormal heating in particle layer ($Fo = 2 \cdot 10^{-5}$)

With a local abnormal heating due to non-linear heat conductivity of steam temperature escalation in some narrow regions causes local vicosity increase, which, in turn, leads to decrease in steam flow velocity. Therefore heat conductivity becomes higher while convective heat transfer falls down.

Inversely, in the local regions with lower temperature viscosity is lower, thus, velocity of steam flow grows and convective heat transfer dominates, so that in such localities temperature is lower. Local abnormal heating due to non-linear conductivity and non-linear interaction of the processes results in a complex non-uniform distribution of the parameters of steam flow in a particle layer.

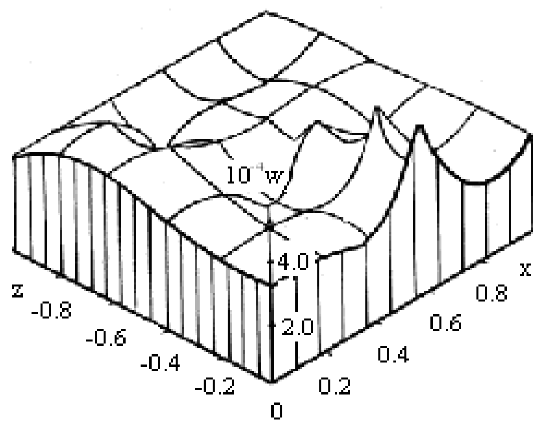

Fig. 25 Local abnormal filtration velocity due to abnormal heating in particle layer ($Fo = 2 \cdot 10^{-5}$)

7 Conclusions by the results obtained

The classes of the problems studied and their field of applicability are presented in the Table 5.

Table 5 Classes of problems and their applicability

Process	Jet and film flow stability, fragmentation and drop formation	Stability and stabilization of the front of crystallization	Vapour flow in granular media with phase interaction
Why the process is difficult to discribe	Nonlinearity of processes and physical properties of media, instability, energy exchange between modes, new phenomena of fragmentation and drop formation. Limited possibilities to experimental study	Lack of instability models for the flow in channel with crystallization on the wall and heat transfer between liquid and solid phases and the wall of channel. Lack of physical simulation	Nonlinearity of processes and physical properties of media, phase interaction, lack of models to discribe such multiphase systems. Lack of experimental study
What are benefits to discribe the process well	Mathematical models and computer codes to simulate the processes taking into account real pecularities and instabilities. Possibility to predict new phenomena and calculate their parameters. Development of new technologies	Mathematical models and computer code to simulate the instabilities and possibility to control the front of crystallization. Development of new garnissage wall protection for melt transport in channels	Model and code to simulate unknown characteristic properties of multiphase system including the phenomenon of heat transfer localization because of nonlinearity of physical properties

Based on the results obtained the following conclusions have been made:

- **The three new phenomena** of parametric film flow decay were discovered and studied [32,50]:
  - **electromagnetic controlled resonance film flow decay,**
  - **soliton-like vibration film flow decay,**
  - **vibration shock-wave film flow decay.**
- The phenomena were first theoretically predicted and then experimentally invented and investigated. Based on these new phenomena, the prospective dispersing and granulation machines were developed, created and tested for some metals and other materials.
- Particularly complex are the behaviors of free boundaries in case of essential physical properties variation with the non-linear wave interaction and energy exchange.
- Especially serious problem appears to be confined in case of high-speed jet/film flows. But this process determines the flow instability and peculiarities of a drop formation/evolution.
- The instability conditions, drop formation, features, for example the drop size and shape, their further evolution seem to be poor studied yet. Therefore it needs further investigations.
- The linear and non-linear mathematical models and computer codes were developed for the jet and film flows including peculiarities of the drop formation and evolution.
- The results may be applied in case of essential physical properties' variation: surface tension coefficient, viscosity, density, heat transfer coefficient, which could be strongly dependent on the temperature spatial distribution.
- Specific advantages of the methods developed by us, compared to other ones worldwide, consist in the results obtained on the subject considering practically complicated cases. This activity is continued taking into account the additional real physical properties.
- The both analytical, as well as numerical methods were grasped and developed for solving the non-linear boundary problems.
- The original method and computer code for an investigation of the stability and stabilization of the thin solid layer on the channel wall have been developed to be used for studying the more complicated practical cases taking into account the solidification of the one phase with corresponding heat transfer between the phases and melting of the other phase.
- The obtained new model and computer code for heterogeneous system of the particles and steam were developed for study the steam flow through porous medium accounting the heat transfer between the particles and flowing steam, physical properties' variation, etc. The local abnormal heating due to non-linear heat conductivity was revealed and studied.

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