Center of ultrasonic technologies

FEATURES OF ULTRASONIC EXPOSURE IN EXTREME CONDITIONS

(FUNDAMENTAL THEORY)

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Ultrasonic exposure

Volna-M UZTA-1/22-OM

water

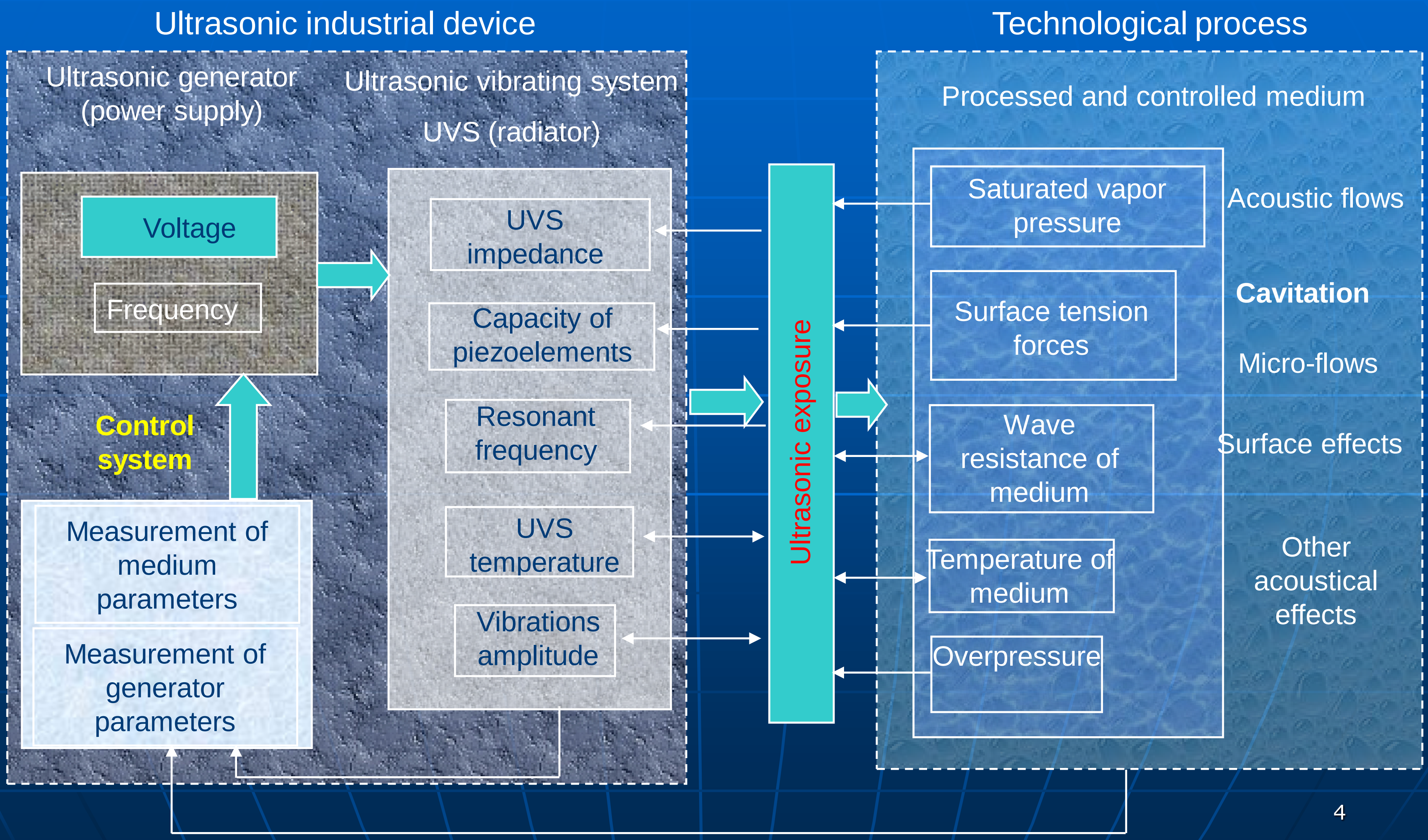
oil

Bulava UZTA-2/18-O

water

oil

Ultrasonic exposure



Ultrasonic industrial device

Ultrasonic generator (power supply)

Voltage

Frequency

Control system

Measurement of medium parameters

Measurement of generator parameters

Ultrasonic vibrating system

UVS (radiator)

UVS impedance

Capacity of piezoelements

Resonant frequency

UVS temperature

Vibrations amplitude

Ultrasonic exposure

Technological process

Processed and controlled medium

Saturated vapor pressure

Surface tension forces

Wave resistance of medium

Temperature of medium

Overpressure

Acoustic flows

Cavitation

Micro-flows

Surface effects

Other acoustical effects

Extreme conditions for ultrasonic exposure

Low temperatures
(-150…-50 °C)

High temperatures
(+200…+1000 °C)

In all cases, ultrasonic exposure can be performed for liquid, solid and gaseous media

MAIN AREAS OF RESEARCH

Determination of optimal modes of ultrasonic exposure in extreme conditions

- research of cavitation in a continuous liquid phase, taking into account phase transitions and viscoelasticity of the medium;
- research of the ultrasound influence on the destruction processes of solid materials in extreme conditions;
- research of the ultrasound influence on the dynamics of heterogeneous systems with a continuous gas phase at extremely high temperatures

Practical implementation of optimal modes of ultrasonic exposure in extreme conditions

- research of electrical properties of piezoelectric vibratory system at extreme high or low temperatures;
- development of a system for the temperature stabilization of primary piezoelectric transducer in the operating range;
- control of ultrasonic vibratory system parameters under varying external conditions;
- control of ultrasonic vibratory system parameters at varying medium properties

THEORETICAL JUSTIFICATION OF OPTIMAL EXPOSURE MODES IN EXTREME CONDITIONS

- Exposure of liquids
- Exposure of solids
- Exposure of gases

SIMULATION OF CAVITATION AREA FORMATION IN LIQUID AT EXTREME TEMPERATURES

CAVITATION BUBBLE EXPANSION MODEL
TAKING INTO ACCOUNT PHASE TRANSITIONS

$$\begin{cases} \dfrac{dm}{dt} = 4\pi K {R_B}^2 \dfrac{p_{sat} - p_v}{p_v} \\ \dfrac{dR_B}{dt} = \dfrac{C(t)}{{R_B}^2} + \dfrac{K}{\rho} \dfrac{p_{sat} - p_v}{p_v} \\ \dfrac{\partial s}{\partial t} + \dfrac{{R_B}^2 \dfrac{dR_B}{dt}}{r^2} \dfrac{\partial s}{\partial r} + \dfrac{s}{\tau} = -\dfrac{4{R_B}^2 \dfrac{dR_B}{dt} \mu}{r^3 \tau} \\ \dfrac{dC(t)}{dt} = \dfrac{C^2(t)}{2r^3} + \\ + \dfrac{r}{\rho} \left(\dfrac{R_B(0)}{R_B(t)} (p_0 - p_v(0)) + p_v(t) - p_\infty + N[s] \right) \end{cases}$$

$s = \sum_{n=0}^{\infty} \frac{A_n(t)}{r^{3n}}$ – радиальная компонента тензора вязких напряжений в жидкости, окружающей кавитационный пузырёк (учитывается вязкоупругость)

$A_0(t) \equiv 0$; для $n \geq 1$

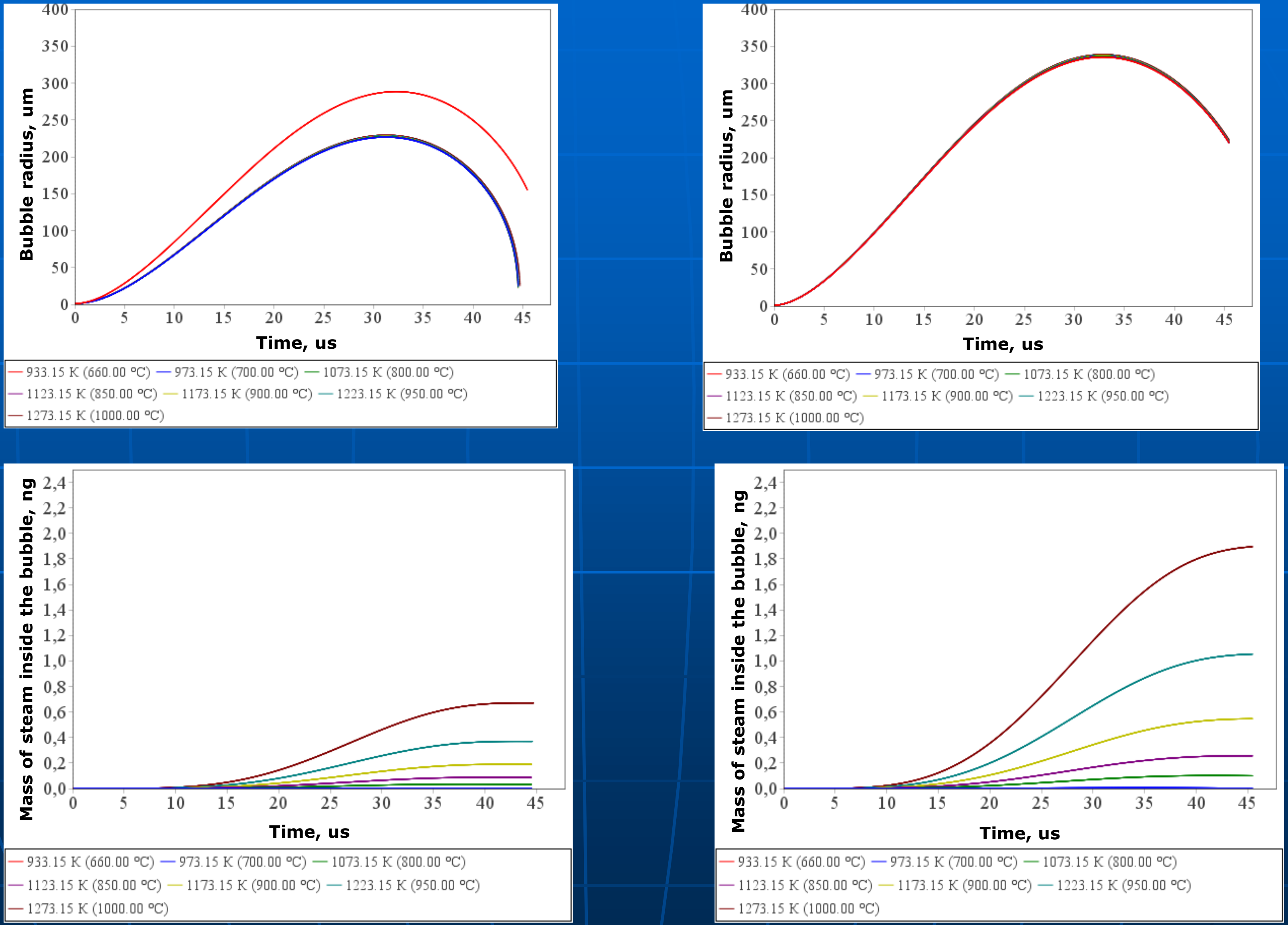
$$A_n(t) = e^{-\frac{t}{\tau}} \int_0^t e^{\frac{t_1}{\tau}} {R_B}^2(t_1) \frac{dR_B}{dt}(t_1) \left(-\delta_{1n} \frac{4\mu}{\tau} + 3(n-1) A_{n-1}(t_1) \right) dt_1 \; ;$$

R_B – радиус пузырька; m – масса пара внутри пузырька; K – коэффициент, зависящий от удельной теплоты парообразования и гидродинамических условий на стенке пузырька; p_{sat} – давление насыщенного пара жидкости; p_v – давление пара внутри пузырька; $N[s]$ – вязкие напряжения на стенке пузырька, зависящие от s; τ – время релаксации напряжений в жидкости за счёт вязкоупругости; μ – динамическая вязкость жидкости.

CAVITATION BUBBLE PARAMETERS DEPENDING ON TIME (ALUMINIUM MELT)

Bubble radius

Mass of steam inside the bubble



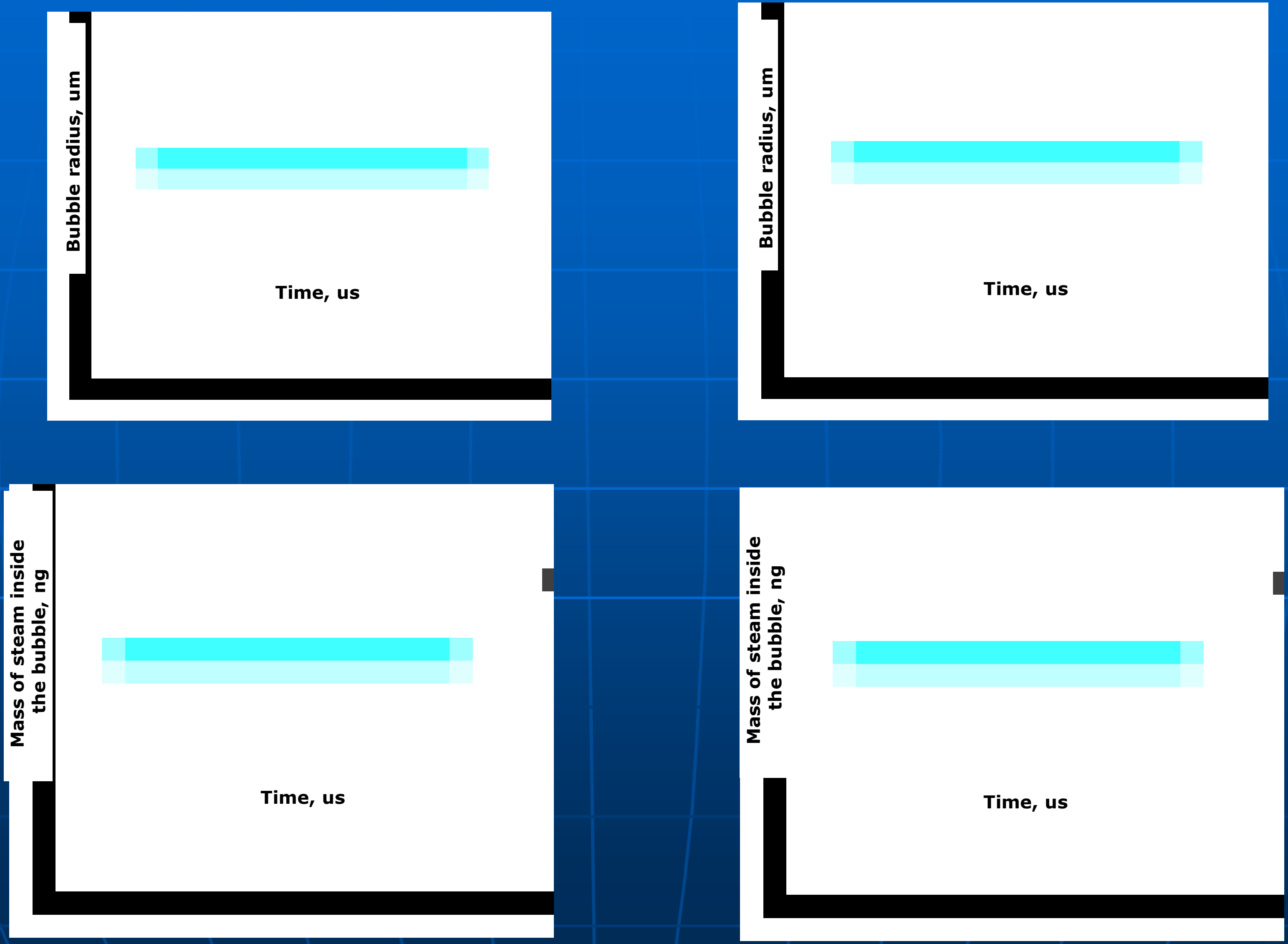
a) intensity 2,5 W/cm^2

b) intensity 4 W/cm^2

CAVITATION BUBBLE PARAMETERS DEPENDING ON TIME (LIQUID NITROGEN)

Bubble radius

Mass of steam inside the bubble



a) intensity 2 W/cm^2

b) intensity 4 W/cm^2

MODEL OF COALESCENCE AND FRAGMENTATION OF BUBBLES IN ENSEMBLE FOR CONCENTRATION DETERMINATION

Factors affecting the concentration of cavitation bubbles

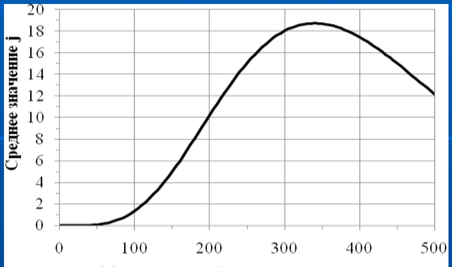
Coalescence of bubbles due to the forces of Bjerknes

Fragmentation of bubbles during collapse

Equation for the process of convergence of bubbles under the influence of Bjerknes forces, leading to their coalescence

$$\frac{4\pi R_0{}^3}{3}\rho_G\frac{\partial^2\mathbf{d}_{12}}{\partial t^2}=-2\frac{4\pi R^3}{3|\mathbf{d}_{12}|^3}\rho_L\frac{\partial\left(R^2\frac{\partial R}{\partial t}\right)}{\partial t}\mathbf{d}_{12}+\frac{1}{2}\frac{\partial}{\partial t}\left(\frac{4\pi R^3}{3}\rho_L\left(-\frac{\partial\mathbf{d}_{12}}{\partial t}\right)\right)+4\pi\eta R\left(-\frac{\partial\mathbf{d}_{12}}{\partial t}\right)$$

Dependence of the embryos number formed during the fragmentation of one bubble on its maximum radius (under normal conditions) $j(R_{MAX})$



Kirkwood-Bethe equation

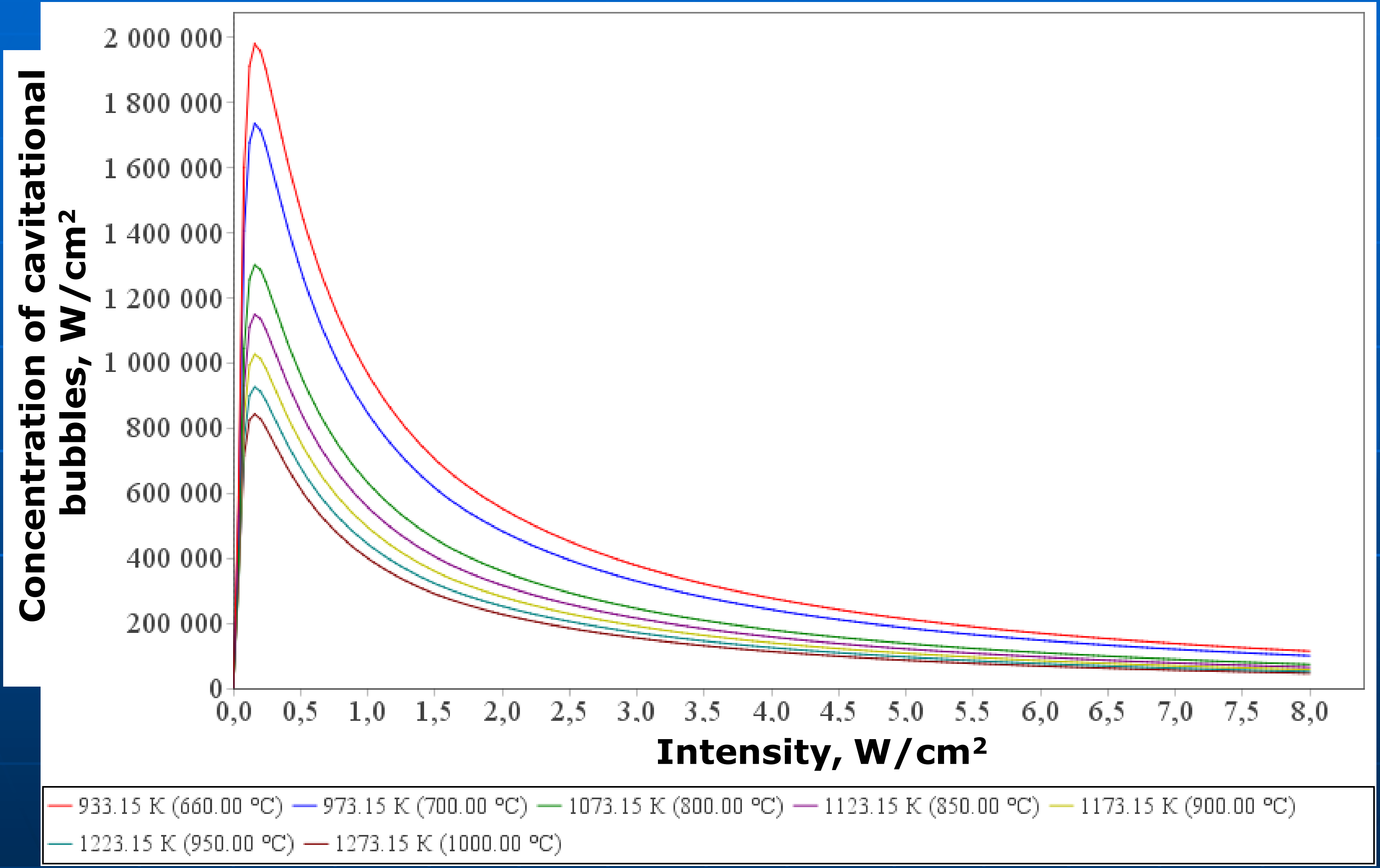
$$R\frac{\partial^2 R}{\partial t^2}\left(1-\frac{\frac{\partial R}{\partial t}}{C}\right)+\frac{3}{2}\left(\frac{\partial R}{\partial t}\right)^2\left(1-\frac{\frac{\partial R}{\partial t}}{3C}\right)=H\left(1+\frac{\frac{\partial R}{\partial t}}{C}\right)+\frac{\partial H}{\partial t}\frac{R}{C}\left(1-\frac{\frac{\partial R}{\partial t}}{C}\right)$$

Concentration of bubbles

$$n_\infty=\frac{2(j-1)}{25\pi R_{MAX}{}^2 i\left|\mathbf{d}_{12}(T)-\mathbf{d}_{12}(0)\right|}$$

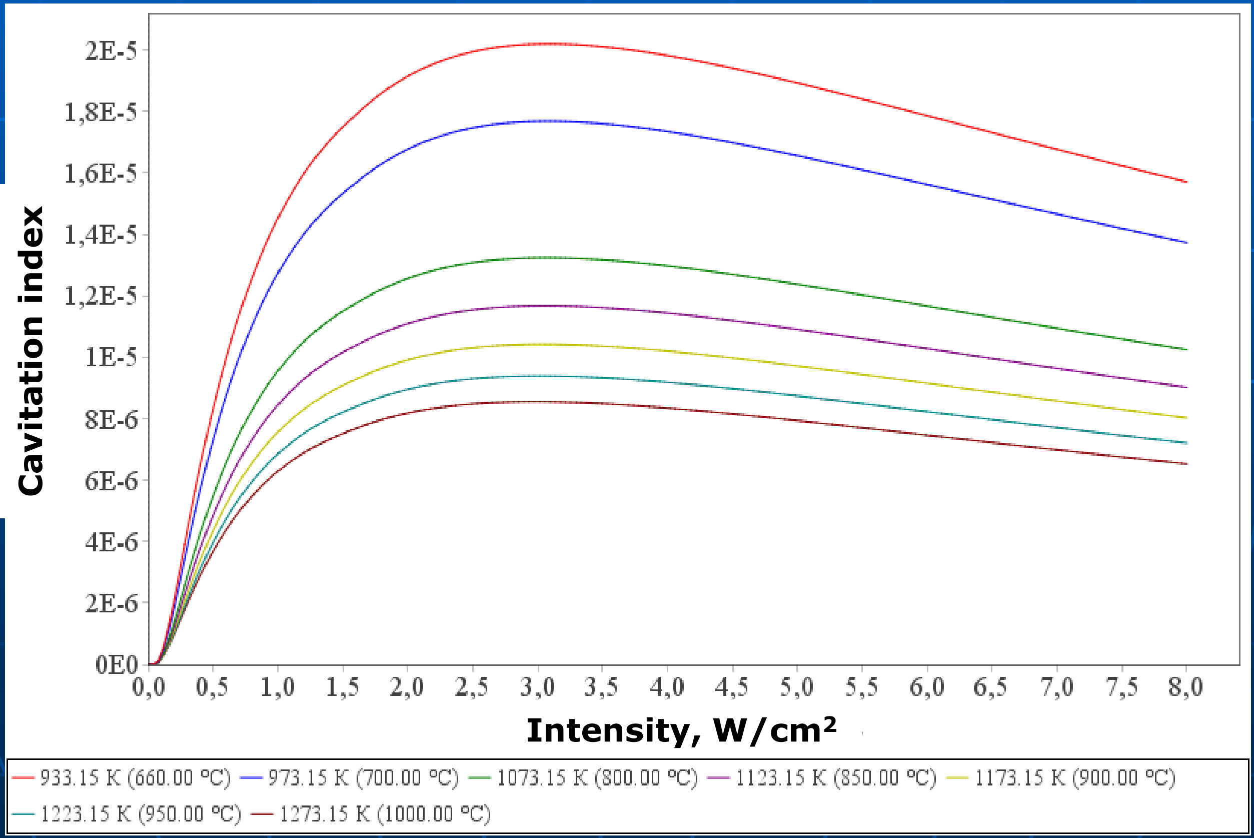
n_∞ – stationary concentration of cavitation bubbles, m^{-3}; j – the embryos number formed during fragmentation of bubble; i – integer number of ultrasonic vibration periods from the moment of initial bubble expansion to the moment of collapse; $R(t)$ – instantaneous radius of separate cavitation bubble, m; d_{12} – vector of center line of cavitation bubble pair, m; ρ_L – equilibrium density of continuous liquid, kg/m^3; H – enthalpy of the liquid phase, m^2/s^2; C – sound velocity in liquid, m/s; ρ_G – gas density inside the bubble, kg/m^3; r – distance between observed point and center of cavitation bubble, m

INFLUENCE OF VIBRATION INTENSITY AND TEMPERATURE ON CONCENTRATION OF CAVITATION BUBBLES



INFLUENCE OF VIBRATION INTENSITY AND TEMPERATURE ON VOLUMETRIC CONTENT OF CAVITATION BUBBLES (CAVITATION INDEX)

$$\langle \delta \rangle = \left\langle \frac{4}{3}\pi R^3 \left(\eta_{bub} \right) \right\rangle$$



CAVITATION AREA PROPAGATION MODEL IN LIQUID LAYER

$$\frac{1}{c_l^2}\frac{\partial^2 p}{\partial t^2} - \Delta p = \rho_l \frac{\partial^2 \delta}{\partial t^2}$$

p – disturbance of sound pressure in liquid, Pa;
c_l – sound velocity in solid liquid, m/s;
ρ_l – density of continuous liquid, kg/m^3;
δ – volumetric content of cavitation bubbles.

$$P_1 = \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} p(t)\, e^{i\omega t}\, dt; \quad \delta_1 = \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} \delta(t)\, e^{i\omega t}\, dt; \quad P_{-1} = P_1^*; \quad \delta_{-1} = \delta_1^*$$

$$-\frac{\omega^2}{c_l^2}P_1 - \Delta P_1 = -\omega^2\rho_l \frac{\delta_1(P_1)}{P_1}P_1$$

⇒

$$-\frac{\omega^2}{c_l^2}P_1 - \Delta P_1 = -\omega^2\rho_l \left(\kappa_{1\mathrm{Re}}(|P_1|) + i\kappa_{1\mathrm{Im}}(|P_1|)\right)P_1$$

EQUATION SOLUTION METHOD IN 3D-AREAS

$$P_1^{(n+1)} = -\omega^2\rho_l \left(\kappa_1\left(\left|P_1^{(n)}\right|\right) - \kappa_{1\infty}\right)\left(-\frac{\omega^2}{c_l^2} + \omega^2\rho_l\kappa_{1\infty} - \Delta\right)^{-1} P_1^{(n)}$$

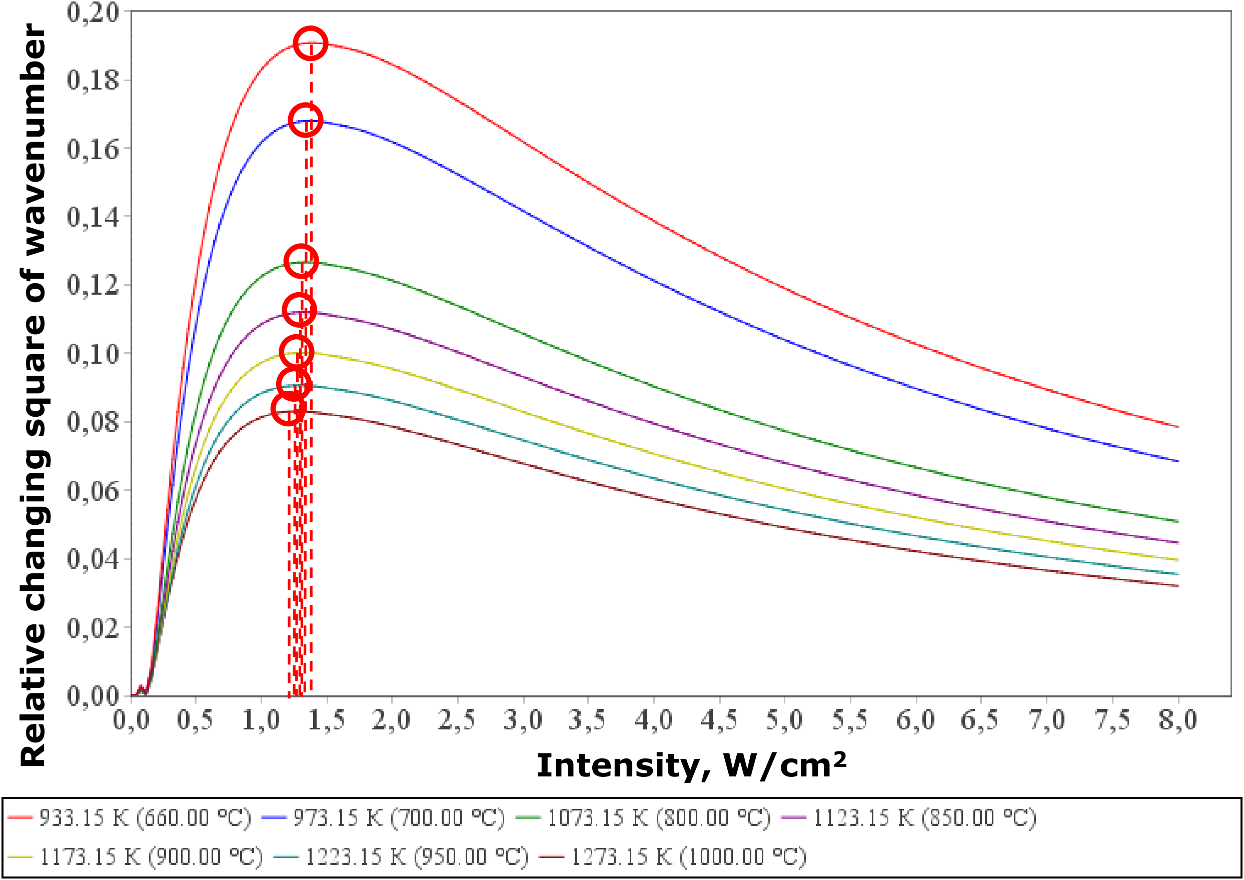
Selection of $\kappa_{1\infty}$ for

$$\left\|P_1^{(n+1)} - Q_1^{(n+1)}\right\| \le q\left\|P_1^{(n)} - Q_1^{(n)}\right\|;\ q < 1$$

DEFINITION OF OPTIMAL INTENSITIES OF ULTRASONIC EXPOSURE ON LIQUIDS AT EXTREME TEMPERATURES

INFLUENCE OF VIBRATION INTENSITY AND TEMPERATURE ON WAVENUMBER OF CAVITATING LIQUID (ALUMINIUM MELT)

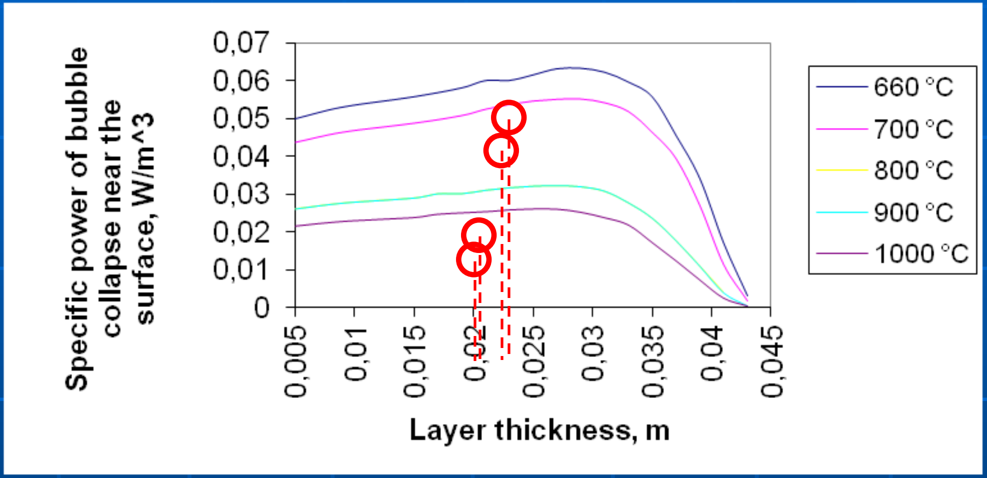
$$\left\| \frac{k_{cav}^{2}}{k_{l}^{2}} \right| - 1 \Big|$$

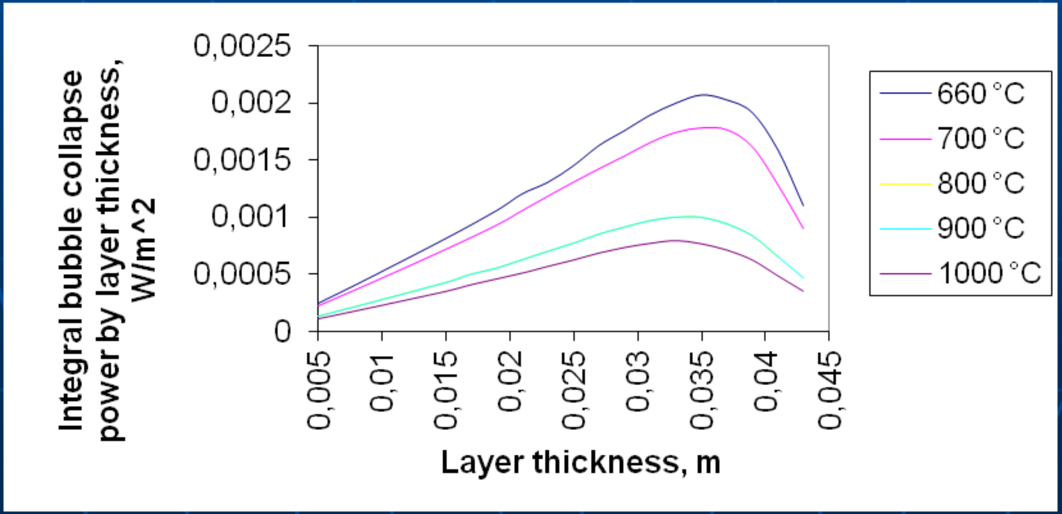


DEFINITION OF OPTIMAL CONDITIONS OF ULTRASONIC EXPOSION ON LIQUIDS AT EXTREME TEMPERATURES

INFLUENCE OF LIQUID LAYER THICKNESS ON COLLAPSE ENERGY CAVITATION BUBBLES

Sound pressure amplitude near the radiator - 500 kPa



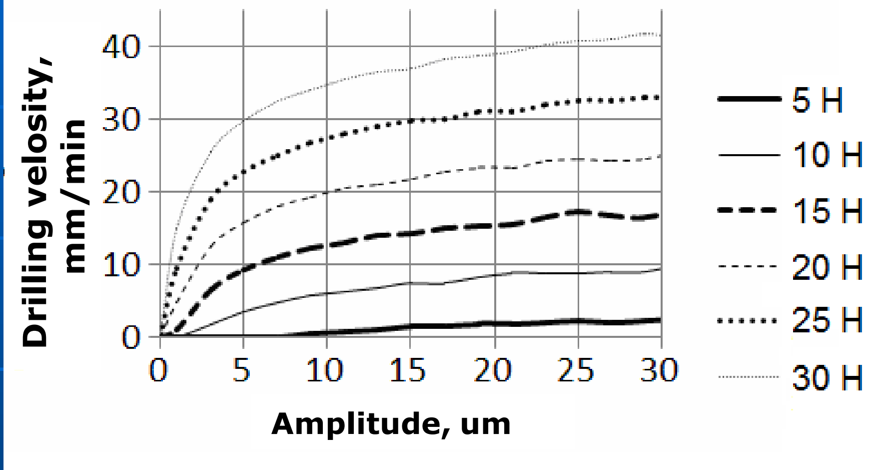


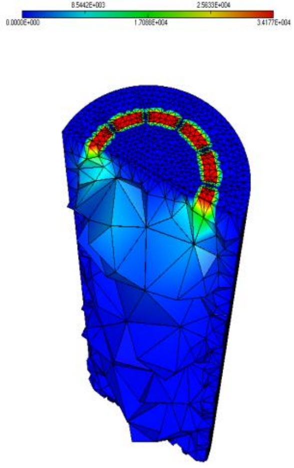
CONCLUSIONS FROM THEORETICAL RESEARCHES OF CAVITATION IN LIQUID AT EXTREME TEMPERATURES

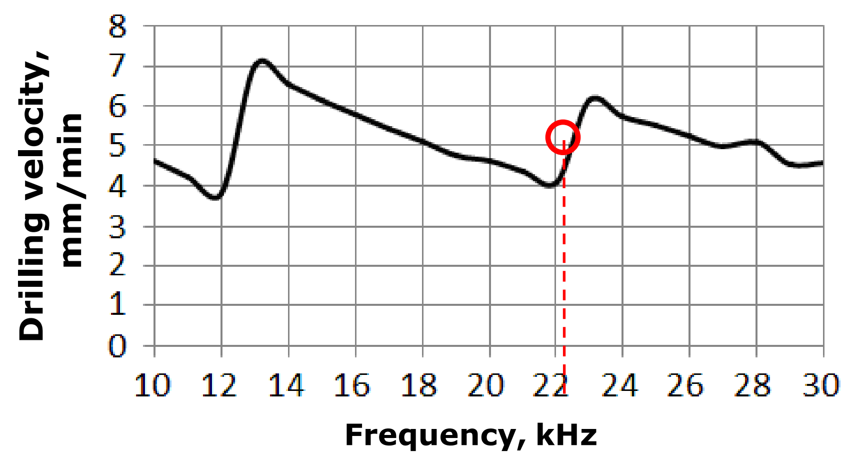
- cavitation is possible and necessary to create in liquids at a wide range of extreme temperatures - from the temperatures of cryogenic liquids (usually gases) to the melting temperatures of metals
- intensity of exposure at extreme temperatures must be not lower than intensity at normal temperatures (new working tools from new materials are needed)
- more sensitive medium property control system capable of selecting the optimal intensity at a changing temperature due to the reduced cavitation intensity (initial concentration of bubble is lower) must be developed
- the optimum distance between the radiator and the reflective surface (which depends on temperature) must be ensured

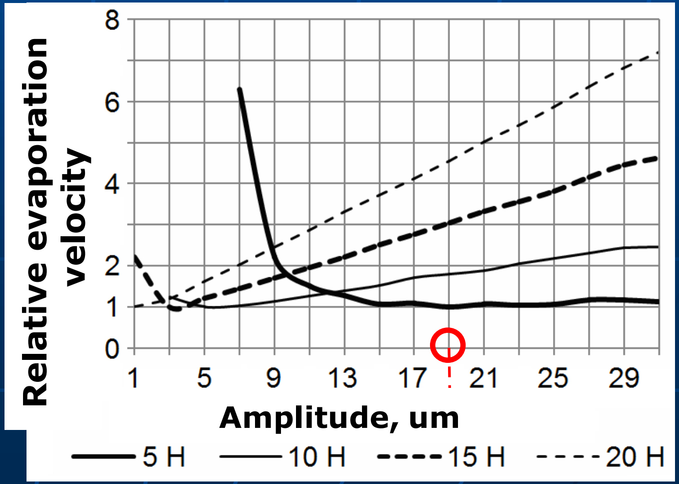
NG RATE OF SOLID MATERIAL AND EVAPORATION OF MOISTURE FROM MATERIAL PORES AT EXTREMELY LOW TEMPERATURE AND HIGH VACUUM

MODELLING OF ULTRASONIC DESTRUCTION OF SOLID MATERIAL AT EXTREME TEMPERATURES



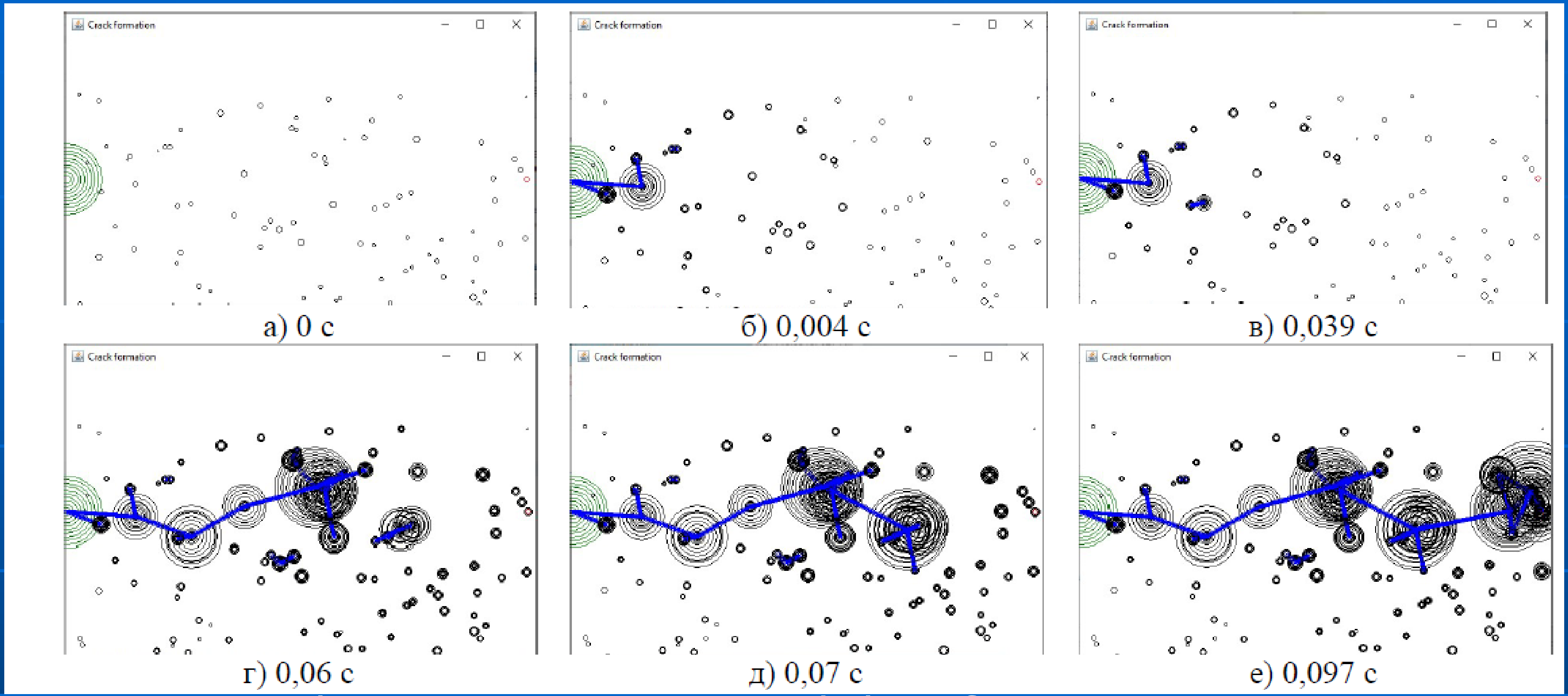






VISUALIZATION OF MICROTRACK FORMING PROCESS IN SOLID SOIL

Classic ultrasonic exposure



а) 0 с

б) 0,004 с

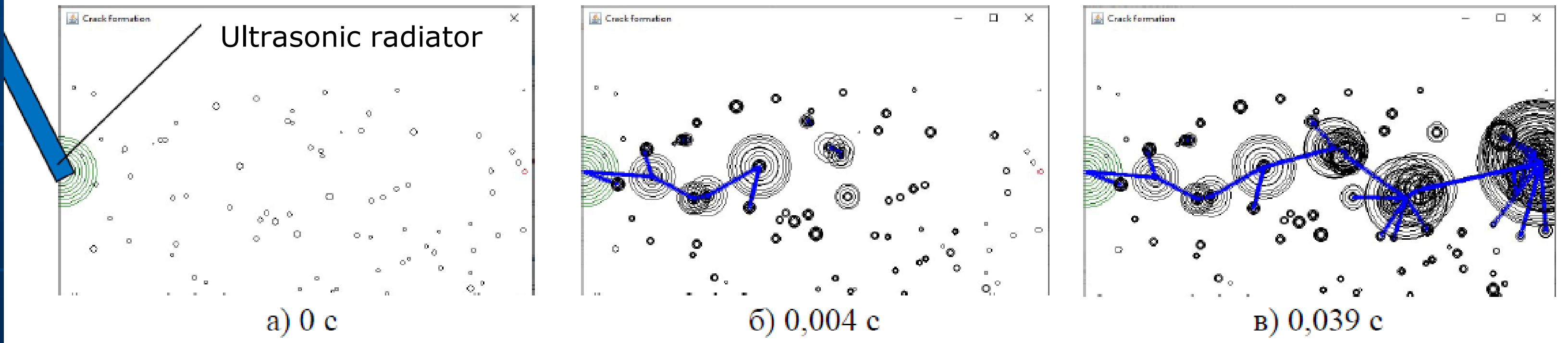
в) 0,039 с

г) 0,06 с

д) 0,07 с

е) 0,097 с

Ultrasonic exposure with low-frequency impacts (from attached free mass)



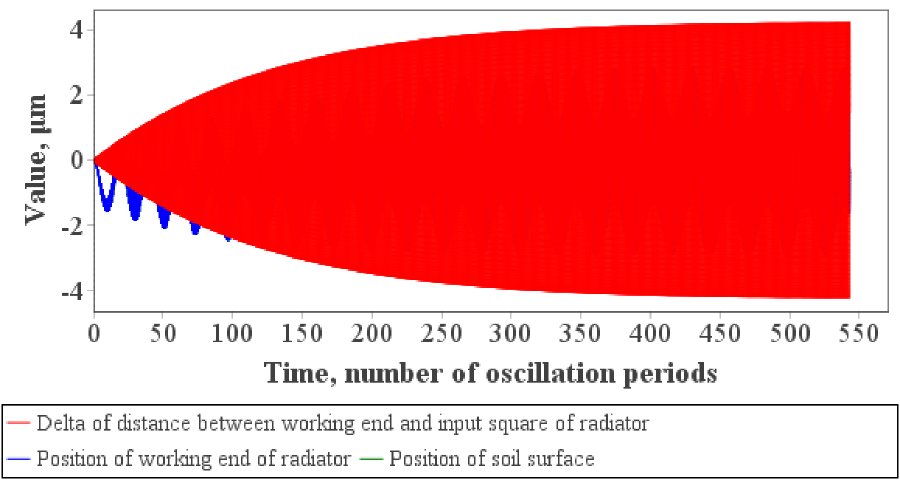
а) 0 с

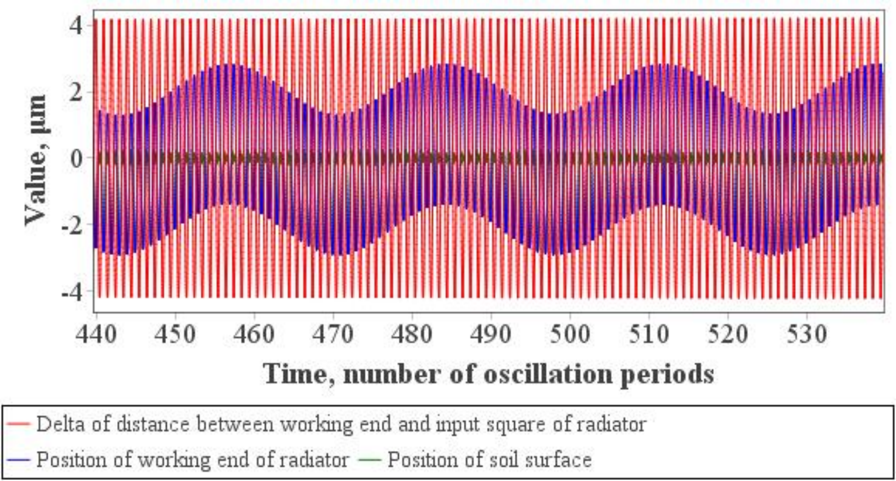
б) 0,004 с

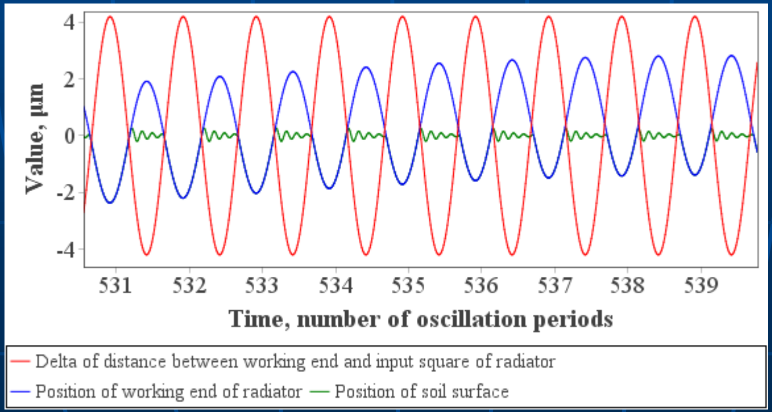
в) 0,039 с

THEORETICAL OSCILLOGRAMS OF VIBRATIONS OF WORKING END POSITIONS OF ULTRASONIC RADIATOR AND SOLID SOIL

(Soil elastic modulus $1 \cdot 10^{10}$ Pa)

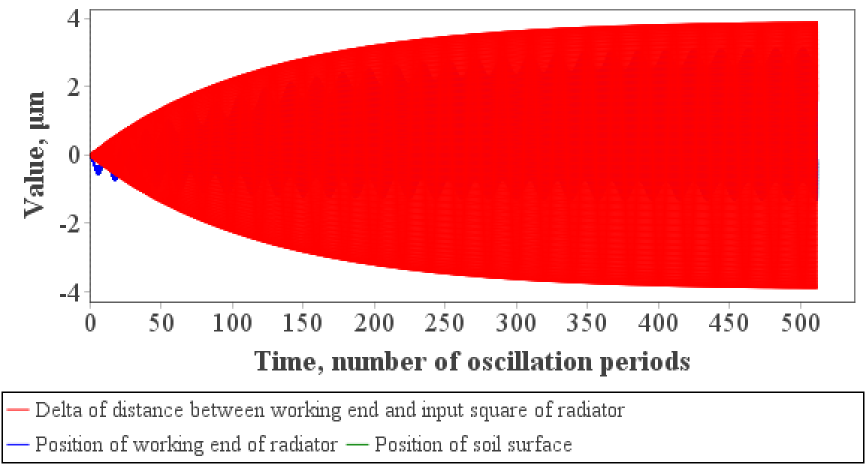


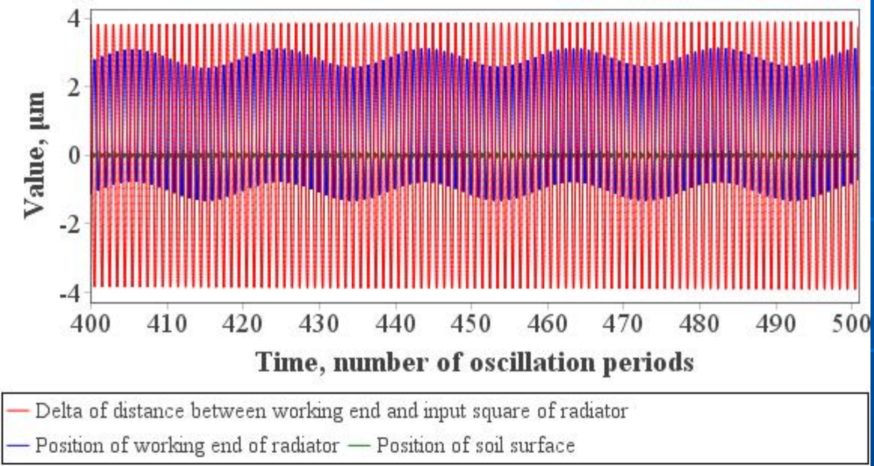


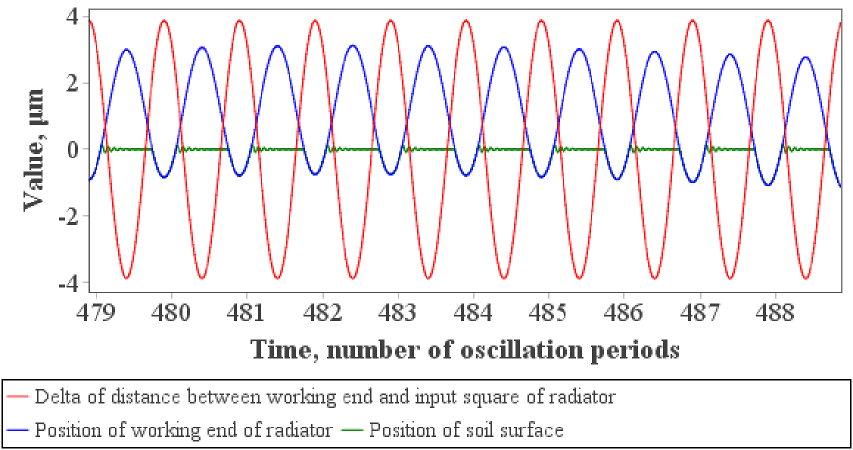


THEORETICAL OSCILLOGRAMS OF VIBRATIONS OF WORKING END POSITIONS OF ULTRASONIC RADIATOR AND SOLID SOIL

(Soil elastic modulus $3 \cdot 10^{10}$ Pa)

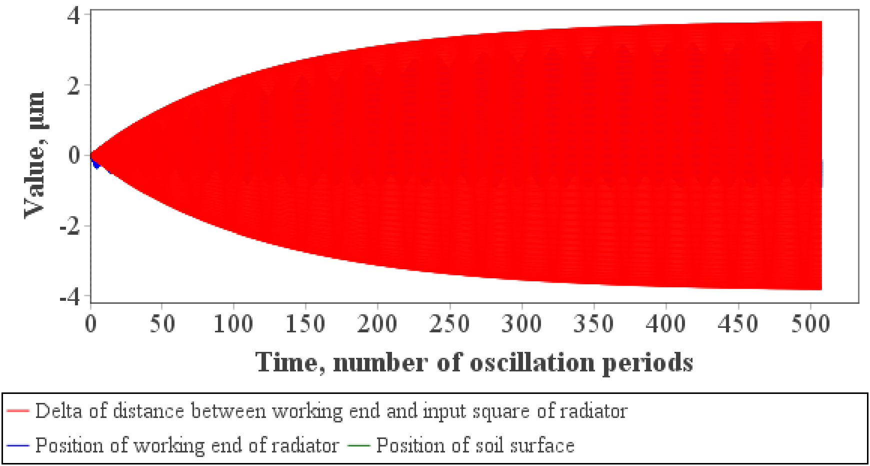


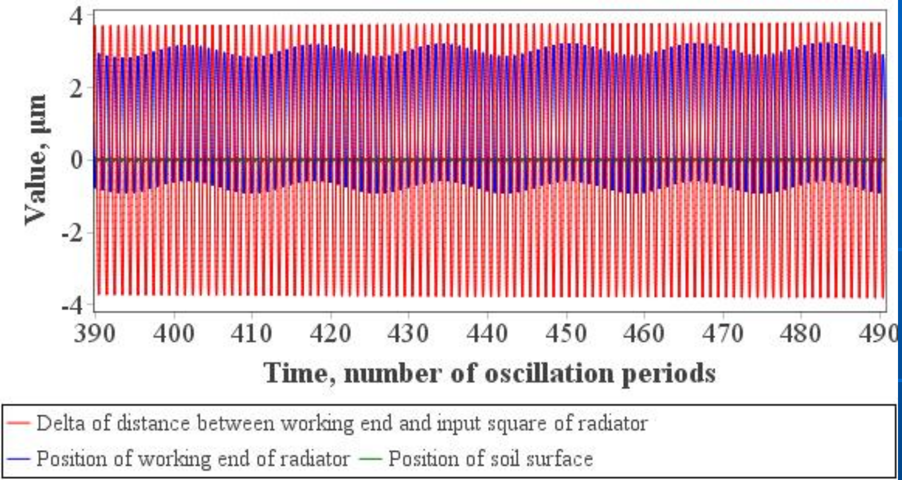


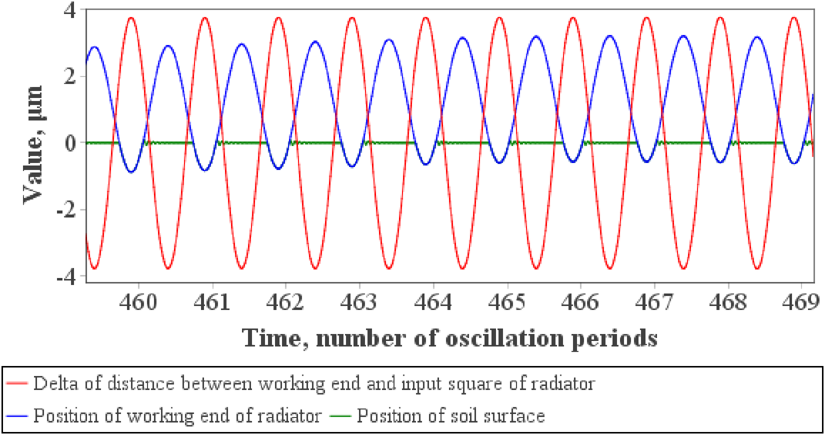


THEORETICAL OSCILLOGRAMS OF VIBRATIONS OF WORKING END POSITIONS OF ULTRASONIC RADIATOR AND SOLID SOIL

(Soil elastic modulus $5 \cdot 10^{10}$ Pa)

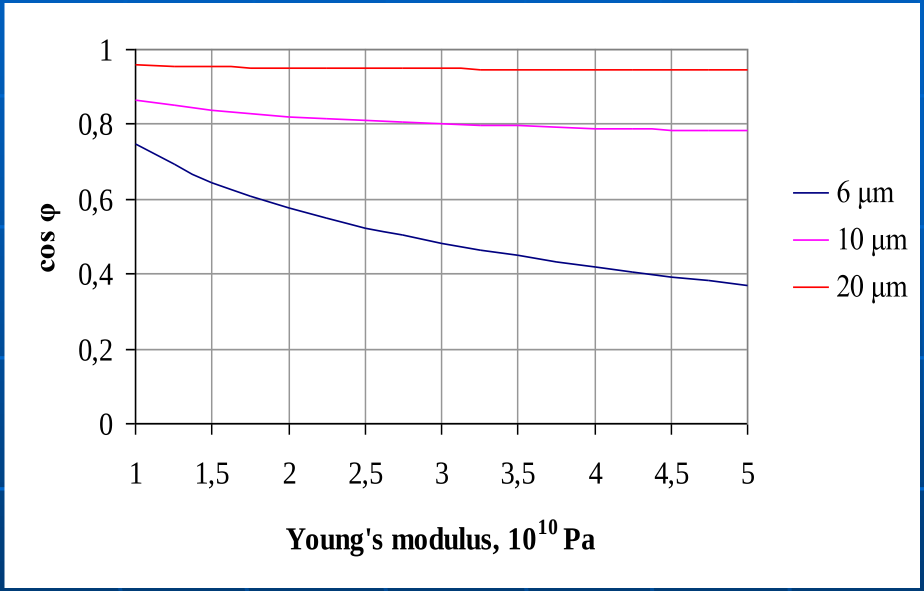


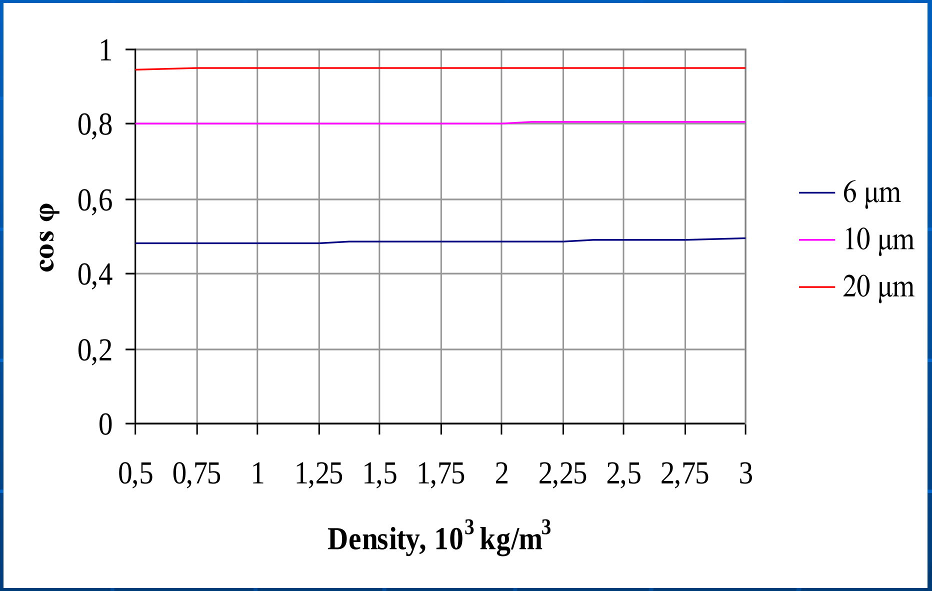


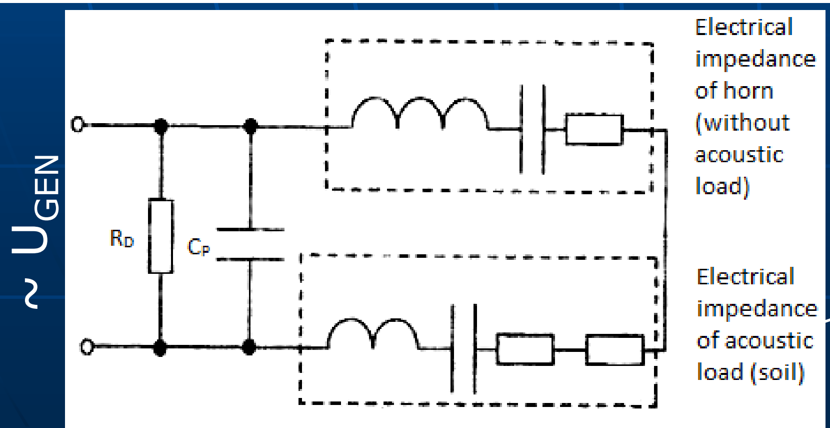


RESULTS OF THEORETICAL CALCULATIONS OF MECHANICAL IMPEDANCE OF SOLID SOIL

$$Z_M = \frac{iF_A}{\frac{2}{T_\Omega}\int_0^{T_\Omega}\frac{dy}{dt}e^{i\omega t}dt} = |Z|\exp(\varphi)$$







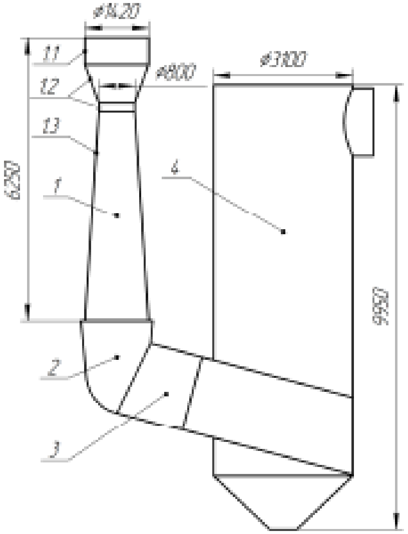
$$Z_E = \beta Z_M$$

CONCLUSIONS FROM THEORETICAL RESEARCHES OF ULTRASONIC VIBRATIONS EXPOSURE ON SOLID SOIL AT EXTREME TEMPERATURES

- optimum vibration amplitude shall be provided during ultrasonic drilling for maximum safety of water and other volatile substances;
- exposure must be carried out at the resonance frequency of this type of soil;
- frequency and optimum amplitude should be provided considering low temperature conditions;
- low-frequency impact from the attached free mass increases drilling speed;
- modulus of elasticity is a soil property, which most significantly influences on the cosine of the phase shift angle between force and speed;
- for determine the type of soil, it is advisable to measure the cosine of the phase shift angle of the mechanical impedance of the radiator-soil system and based on the calculated dependence (the mechanical impedance is determined by the electrical parameters of the radiator without using external sensors);
- it is necessary to exposure with as small an amplitude as possible so that destruction processes do not occur (not more than 6 um) for determining the type of soil.

ETECTION OF OPTIMAL MODES AND CONDITIONS OF ULTRASONIC EXPOSURE ON GAS-DISPERSED SYSTEMS AT EXTREME TEMPERATURES

MODEL AREA FOR CALCULATION OF WET DUST COLLECTION WITH ULTRASONIC RADIATOR AT HIGH TEMPERATURES



1 - Venturi pipe; 1.1 – pipe head;
1.2 - confuser with neck;
1.3 – diffuser; 2 - pipe elbow;
3 - junction pipe; 4 - drop catcher

Venturi scrubber design area sketch

Initial calculation data

Parameter	**Value**
Carrying agent:	Air
Input temperature, ^{0}C	170
Rate, 10^3m^3/h	100
Density, kg/m^3	0.78
Solid disperse-phase:	Ashes
Density, kg/m^3	1000
Particle size, um	2-90
Initial concentration, h/nm^3	17
Liquid disperse-phase:	Water
Density, kg/m^3	1000
Drop size, um	150
Input mass flow, h/nm^3	10

PHYSICAL AND MATHEMATICAL MODEL OF MOVEMENT AND COAGULATION IN VENTURI SCRUBBER

$$m_p \frac{d\overline{v_p}}{dt} = 3\pi\mu d C_{cor}\left(\overline{v_f} - \overline{v_p}\right) + \frac{\pi d^3 \rho_f}{6}\frac{d\overline{v_f}}{dt} + \frac{\pi d^3 \rho_f}{12}\left(\frac{d\overline{v_f}}{dt} - \frac{d\overline{v_p}}{dt}\right) - \frac{\pi d^3}{6}(\rho_p - \rho_f)\overline{w}\times(\overline{w}\times\overline{r}) - \frac{\pi d^3}{6}\rho_p(\overline{w}\times\overline{v_p}) + \overline{F_e}, \qquad (1)$$

где $m_p = \pi d^3 \rho_p / 6,$ – масса частицы, кг; d – эквивалентный диаметр частицы, м; ρ_p – плотность частицы, кг/м^3; ρ_f – плотность газа, кг/м^3; $\overline{v_p}$ – скорость частицы, м/с; $\overline{v_f}$ – скорости газа, м/с; μ – динамическая вязкость газовой среды, Па·с; t – время, с; C_{cor} – коэффициент вязкого сопротивления со стороны основной фазы; $\overline{w}$ – угловая скорость вращения частицы, рад/с; $\overline{r}$ – радиус-вектор; $\overline{F_e}$ – дополнительная внешняя сила, действующая на частицу.

$$F_e = \frac{4\pi d\mu (W^2-1)^{\frac{3}{2}}}{W} \times \left(\frac{cos^2\theta}{(W^2-2)arctg\sqrt{W^2-1} - \sqrt{W^2-1}} + \frac{sin^2\theta}{(3W^2-2)arctg\sqrt{W^2-1} - \sqrt{W^2-1}}\right) \times \overline{U}(\overline{r},t), \qquad (2)$$

где d – наибольший диаметр эллипсоидальной частицы, м; μ – динамическая вязкость газа, Па·с; W – отношение длины большей полуоси частицы к меньшей; θ – угол между меньшей полуосью частицы и направлением звукового поля, рад; $\overline{U}$ – возмущение скорости газового потока, м/с, которое рассчитывается с учетом двух основных механизмов взаимодействия частиц в УЗ-поле (ортокинетический и гидродинамический под действием сил Осеена) с использованием выражений, описанных в работах G.X. Zhang, J.Zh. Liu:

Расчет эффективности трубы Вентури и скруббера основан на вычислении массового расхода дисперсных частиц, проходящих через заданную выходную поверхность за время Δt:

$$\eta = \frac{\rho_p \cdot \sum_{k=1}^{N(\Delta t)} H_{d_{min}}(d_k) \cdot \frac{\pi d_k^3}{6}}{\alpha_{BX} \cdot G \cdot \Delta t} \cdot 100\%,$$

где ρ_p – плотность частиц золы, кг/м^3; d_k – диаметр рассматриваемой частицы, м; $\alpha_{вх}$ – начальная запылённость газа на входе, кг/нм^3; G – расход газа, м^3/с; $N(\Delta t)$ – число частиц, прошедших через выходное сечение за время Δt; $H_{dmin}(d_k)$ – функция-индикатор типа частицы, равная 1 при $d_k < d_{min}$ и 0 при $d_k > d_{min}$; d_{min} – минимальный диаметр капель воды, м.

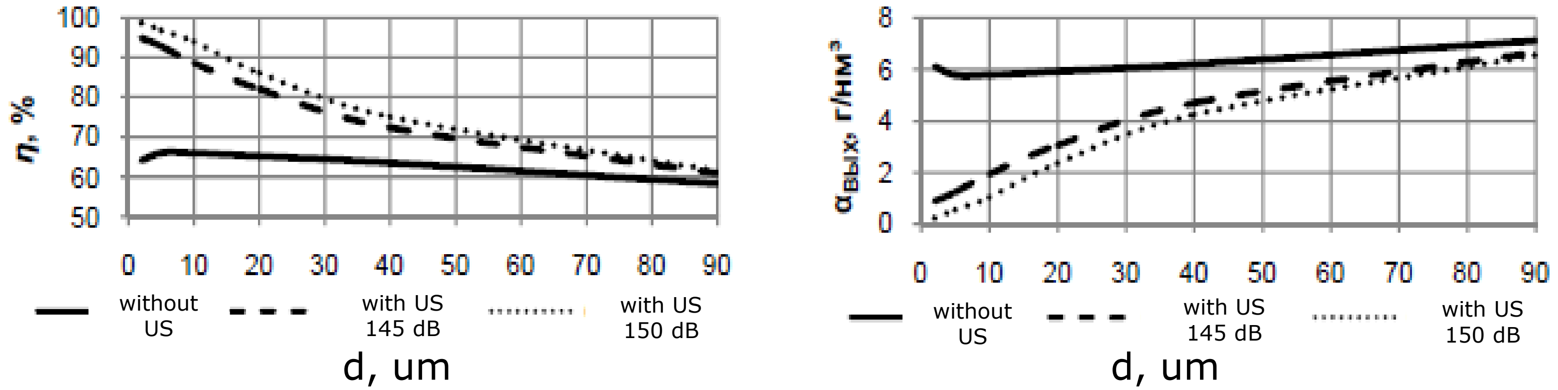
$$\overline{U}(\overline{r},t) = \left(\mathrm{Re}\left(\frac{\nabla P(\overline{r})}{i\omega\rho}\right) + \sum_{k=1}^{N}\left[\frac{3\nu R_k V_k (\overline{r}_k - \overline{r})}{2|V_k||\overline{r}_k - \overline{r}|^3}\left[1 - e^{-\frac{|\overline{r}_k-\overline{r}|}{2\nu}\left(|V_k| - V_k\left|\frac{(\overline{k},\overline{r}_k-\overline{r})}{k|\overline{r}_k-\overline{r}|}\right|\right)}\left[1 + \frac{|\overline{r}_k - \overline{r}|}{2\nu}\left(|V_k| + V_k\left|\frac{(\overline{k},\overline{r}_k - \overline{r})}{k|\overline{r}_k - \overline{r}|}\right|\right)\right]\right] - \frac{3R_k V_k^{\,2}}{4|\overline{r}_k - \overline{r}||V_k|}\sqrt{1 - \left|\frac{(\overline{k},\overline{r}_k - \overline{r})}{k|\overline{r}_k - \overline{r}|}\right|^2} \cdot \mathrm{e}^{-\frac{|\overline{r}_k-\overline{r}|}{2\nu}\left(|V_k| - V_k\left|\frac{(\mathrm{k},\overline{r}_k-\overline{r})}{k|\overline{r}_k-\overline{r}|}\right|\right)}\overline{e}_{k\theta}\right]\left(1 + \frac{3R_k|V_k|}{8\nu}\right)\right)\cos\left(\omega t + \mathrm{Arg}\left(\frac{\nabla P(\overline{r})}{i\omega\rho}\right)\right), \qquad (3)$$

где ω – угловая частота УЗ-волн, рад/с; t – время, с; φ – фазовый сдвиг колебательной скорости, рад; ρ – плотность газа, кг/м^3; $P(\overline{r})$ – комплексная амплитуда звукового давления в газовой среде, Па; ν – кинематическая вязкость газа, м^2/с; R_k – радиус k-й соседней частицы, м; V_k – проекция скорости газа на волновой вектор УЗ-поля в месте расположения k-й частицы, м/с; $\overline{r}$ – положение центра рассматриваемой частицы, м; $\overline{r_k}$ – положение центра k-й соседней частицы, м; $\overline{k}$ – волновой вектор УЗ-поля, м$^{-1}$; $\overline{e_{k\theta}}$ – единичный вектор, перпендикулярный вектору $\overline{r_k} - \overline{r}$; N – количество k-х соседних частиц.

Остаточная запыленность газа на выходе рассчитывается по выражению:

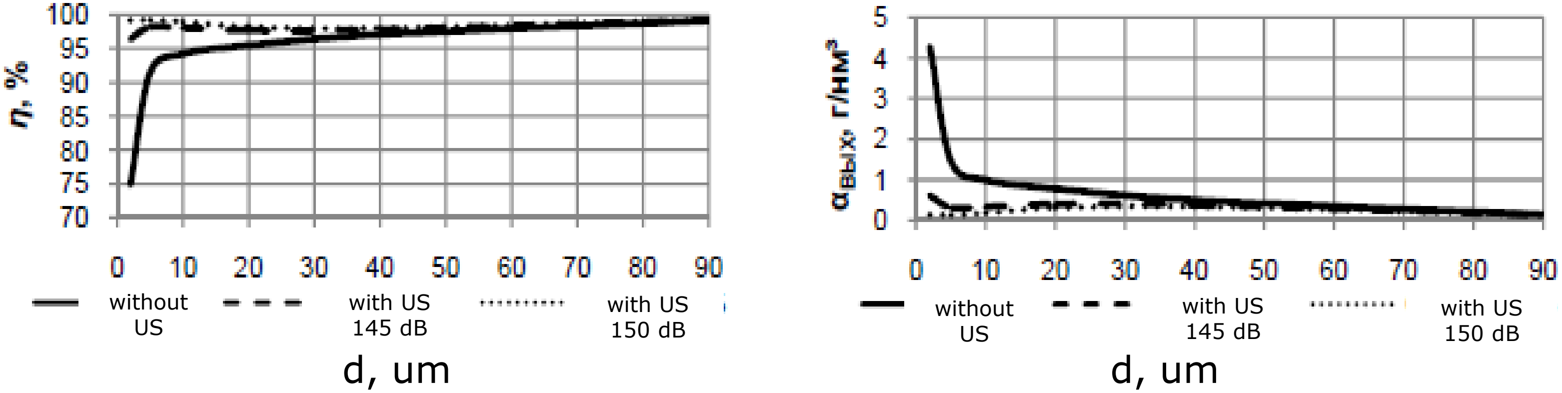
$$\alpha_{вых} = \frac{(100-\eta)}{100} \cdot \alpha_{вх}.$$

DEPENDENCE OF VENTURI SCRUBBER EFFICIENCY ON PARTICLE SIZE AT DIFFERENT SOUND PRESSURE LEVELS (FREQUENCY 22 kHz)



a) b)

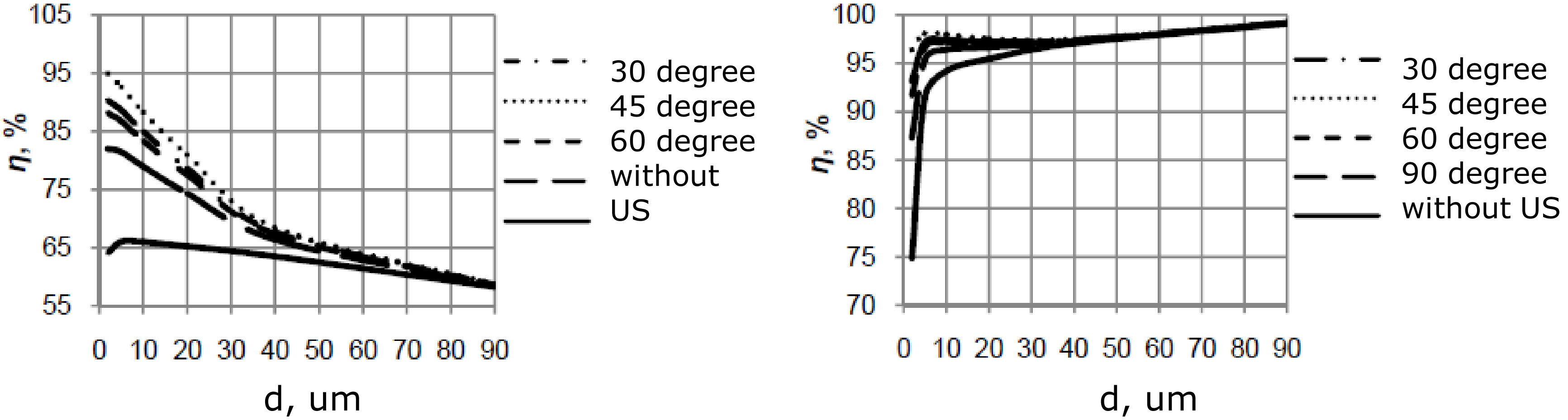
Dependence of efficiency (a) and dust content (b) on Venturi pipe outlet at various sound pressure levels



a) b)

Dependence of efficiency (a) and dust content (b) on Venturi scrubber outlet at various sound pressure levels

DEPENDENCE OF VENTURI SCRUBBER EFFICIENCY ON PARTICLE SIZE AT DIFFERENT NUMBER AND ANGLES OF LOCATION (TO VENTURI PIPE AXIS) OF ULTRASONIC REDIATOR



a) b)

Dependence of efficiency (a) and dust content (b) of Venturi pipe and scrubber at various angles of ultrasonic radiator mounting into Venturi pipe

CONCLUSIONS FROM THEORETICAL RRESEARCH OF EXPOSURE OF ULTRASONIC VIBRATIONS ON GAS-DISPERSED SYSTEMS AT EXTREME TEMPERATURES

- sound pressure level must be at least 150 dB at 170^0 C
- radiators shall be mounted at the optimum angle (45 degrees)
- uniform sound pressure shall be provided throughout the coagulation area

GENERAL REQUIREMENTS FOR ULTRASONIC DEVICES FOR EXPOSURE IN EXTREME CONDITIONS

- Ensuring the intensity of ultrasonic vibrations not lower than for ordinary conditions (room temperature at atmospheric pressure) in the entire volume of the processed medium.
- Increase the input vibration energy into the medium from the radiator due to optimization of the geometry of the acoustic path in the processed medium (optimization of the distance between the radiating surface and the reflecting border; arrangement of radiators at an optimal angle to the axis of the voiced volume) due to a decrease in the limit characteristics of the radiators at extreme temperatures.
- Realization of highly sensitive control system for the type of processing medium.
- Providing the work temperature range of the primary piezoelectric transducer due to thermostat and cooling systems.
- Using special materials for the production of the working tool of the ultrasonic radiator capable of withstanding the amplitudes of elastic vibrations of the ultrasonic frequency required for normal conditions under extreme conditions