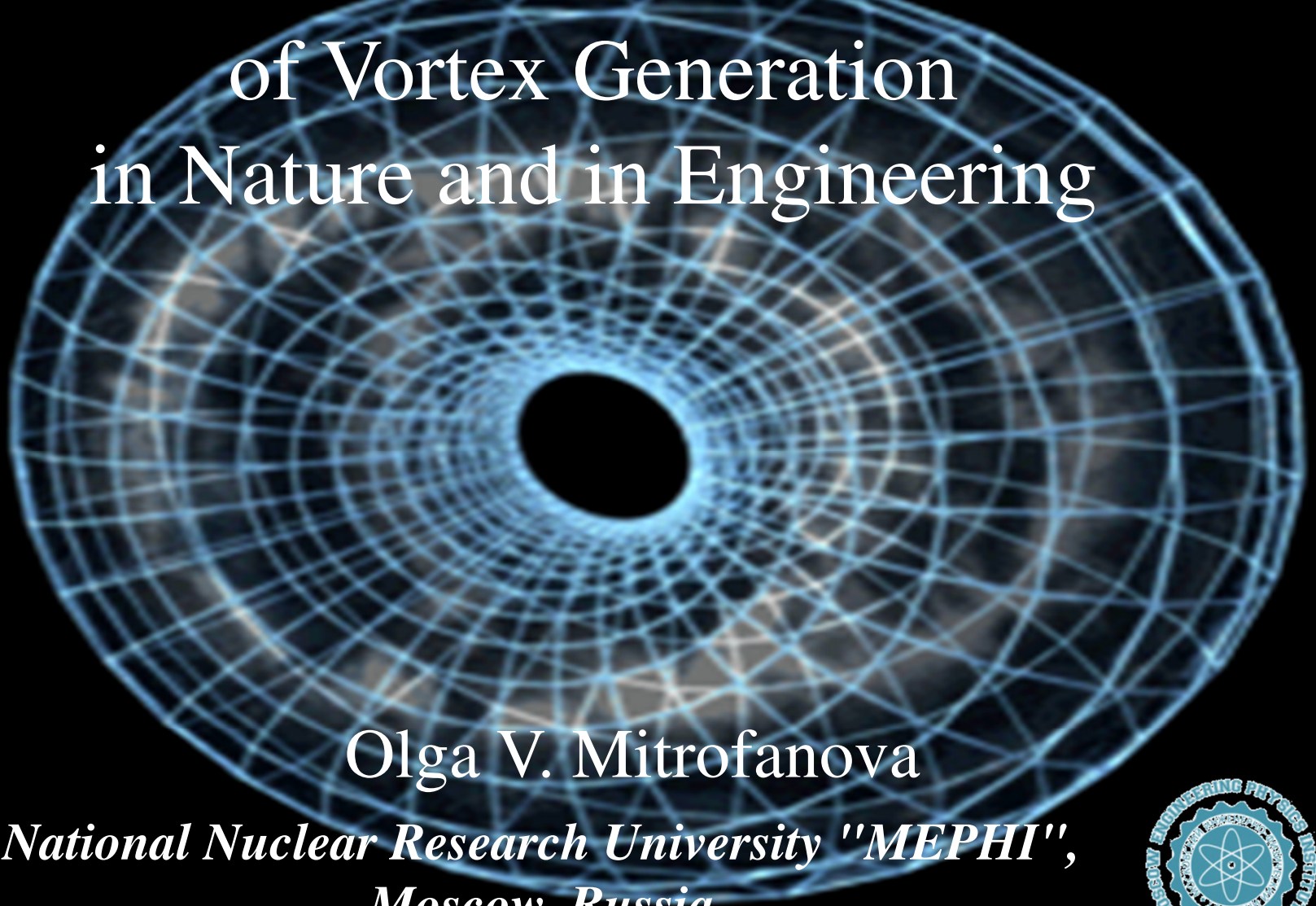
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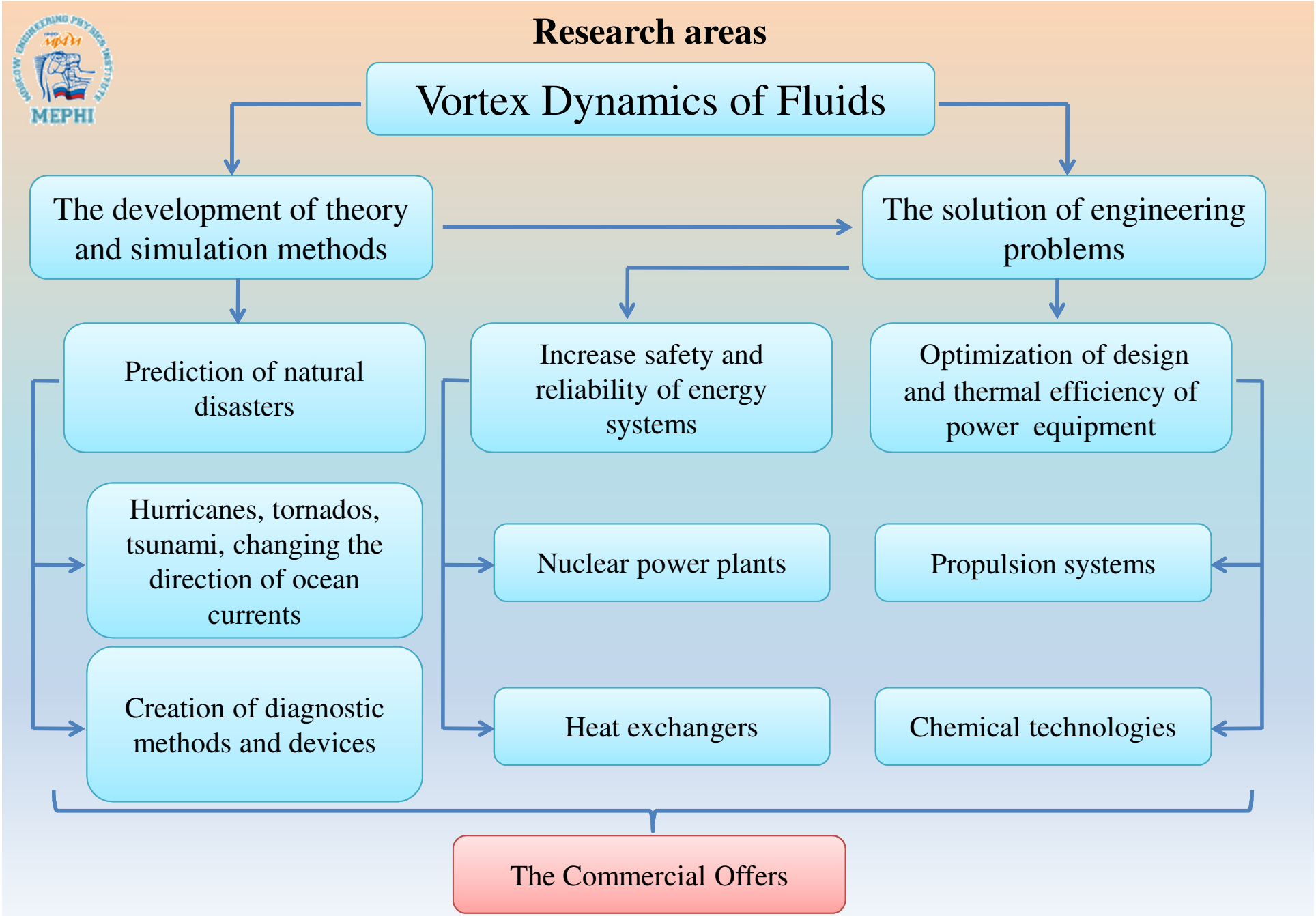
Studies of the Mechanisms of Vortex Generation in Nature and in Engineering



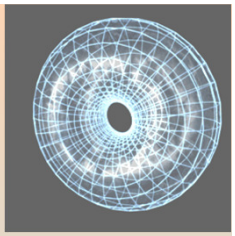
Olga V. Mitrofanova

National Nuclear Research University "MEPHI",
Moscow, Russia

Research areas



Critical phenomena in fluid dynamics of hydro-mechanical systems



1. Overflow crisis

2. Hydrodynamic instability. Secondary flows

3.Crisis of fluid flow out. Sound and shock waves

4.Critical flow rate of swirl flow

5. Turbulence (transition from laminar to turbulent, the phenomenon of intermittency)

6.The transition from quasi-solid law of rotation in a swirl flow to quasi-potential. Vortex transformation

7. The helicity. Screw flow as dissipationless form of fluid motion

8.The Ranque Effect

9. The Coanda Effect

10. Flicker-noise

Hurricane Katrina over the United States 23-30 August 2005.

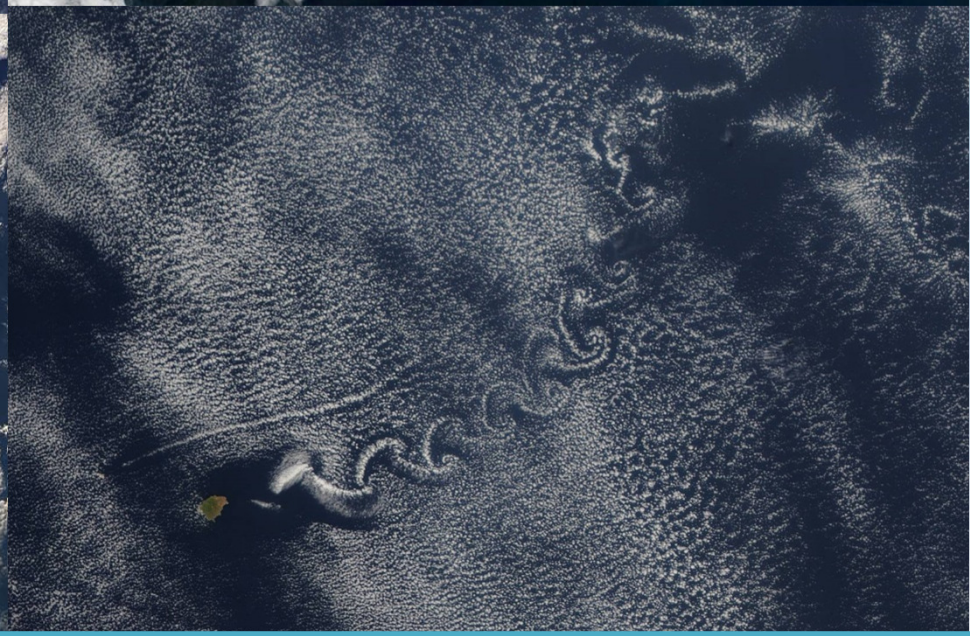
Maximal velocity of 280 km/h (77,8 m/s). The minimum pressure of 0.9 ATM. The number of deaths 1833.




Hurricane Isabel on the East coast of the USA
on 16 September 2003 (left-handed twist)


Mysterious “hot spot” in the ocean
kills marine life







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General regularity

- The crisis is accompanied by structural reconstruction of flow
- Three-dimensional vortex structures, the most typical form of which corresponds to the longitudinal or toroidal helical vortices, are formed
- The stability of the ordered vortices structure caused by presence of helicity
- Deterministic vortex structure of the flow ensures minimal energy dissipation
- Non-dissipative screw flow is an ideal case of vortex motion
- Remaking of the internal structure flow is connected with the emergence of the "crisis" of the thermodynamic stability of real system

Scientists



Jules Henri Poincare

(1854 – 1912)

French mathematician, physicist, astronomer, philosopher

The head of the Paris Academy of Sciences, member of the French Academy and more than 30 academies of the world

The founder of **topology** as science that combines physics and mathematics.



Gromeka Ippolit Stepanovich

1851-1889

Russian physicist

The founder of the **theory of screw flows** and transverse circulation (1882).

Topology

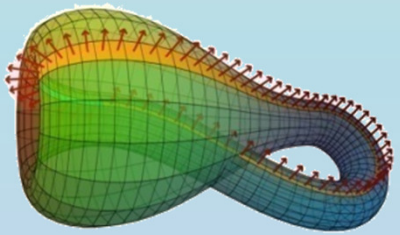
Topology — branch of mathematics studying the phenomenon of continuity, in particular the properties of space that remain invariant under continuous deformations.

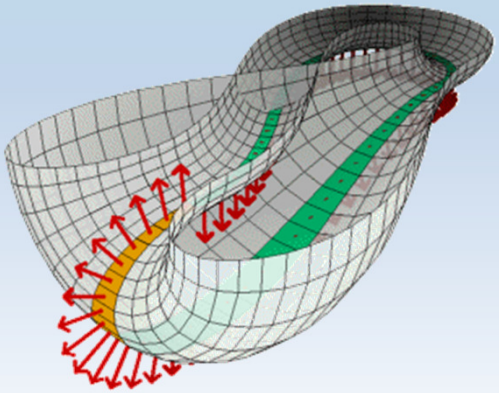
Unlike geometry, topology is not considered metric properties of objects (the distance between two points).

From the point of view of topology, a cup and a bagel (torus) are indistinguishable.









The Klein bottle is a mathematical non-orientable surface, which is indistinguishable inside and outside. The Klein bottle was first described in 1882 by German mathematician Felix Klein (Klein, Felix). This surface is closely related to another mysterious surface - a Mobius strip.

Screw flow

$$\frac{\partial \vec{\omega}}{\partial t} + (\vec{u}\nabla)\vec{\omega} - (\vec{\omega}\nabla)\vec{u} = \nu\nabla^2\vec{\omega}, \qquad (1)$$

$\vec{\omega}$ - local vorticity: $\vec{\omega}=rot\,\vec{u}$

$\vec{u}$- the full local velocity of flow,

$$rot\,\vec{u} = k\vec{u}, \qquad (2)$$

k - the intensity of the vorticity : $k = u_\phi r/\psi, \qquad \psi = u_z r^2/2$

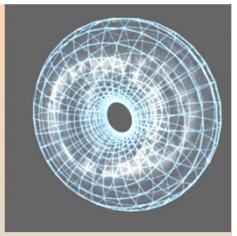
Divergent form of the energy equation:

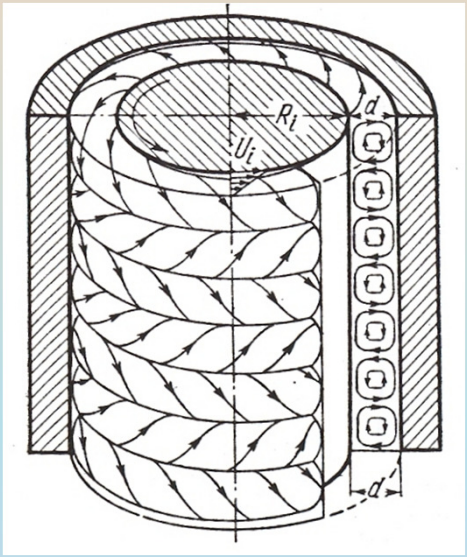
$$\rho\frac{\partial}{\partial t}(c_v T + \frac{u^2}{2}) = \rho\vec{P}_v\vec{u} - div\left\{\rho\vec{u}(i+\frac{u^2}{2}) - \mu\, grad(u^2 + \frac{i}{\mathrm{Pr}}) - \mu[\vec{\omega}\vec{u}] + \frac{2}{3}\mu\, div\,\vec{u}\right\}$$

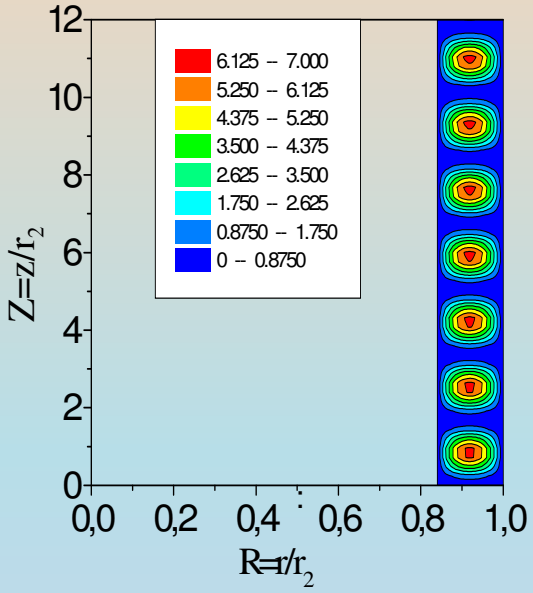
The energy equation for a screw motion :

$$\rho\frac{\partial}{\partial t}(c_v T + \frac{u^2}{2}) = \rho\vec{P}_v\vec{u} - div\left\{\rho\vec{u}(i+\frac{u^2}{2}) - 2\mu\, grad\frac{u^2}{2} - \lambda\, grad\, T\right\} \qquad (3)$$

Secondary flows. Hydrodynamic instability
The Taylor Vortices





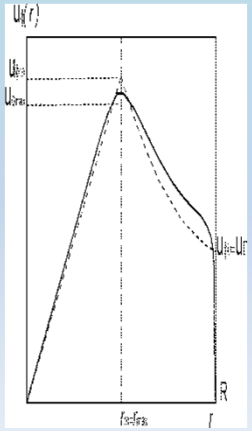


$R_1 = r_1 / r_2 = 0.84$

n	μ_n,
1	19.65
2	39.29
3	58.91
4	78.55

Before crisis

$Ta < 41{,}3$



Distribution $u_\phi(R,Z)$ $K \to \mu_1$

$$K = 2u_\phi r_2 / (ru_z) = 20.0$$

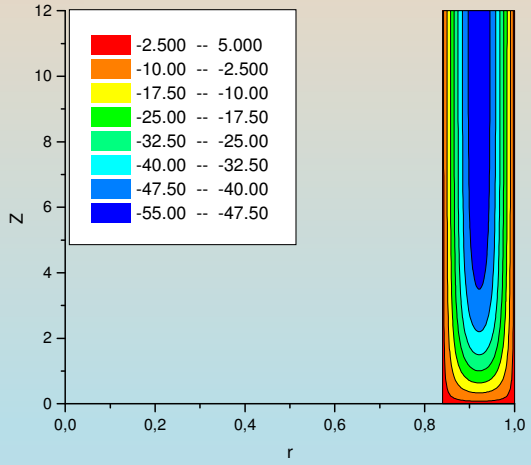
Critical condition:

$$Ta = \frac{U_1 h}{\nu}\sqrt{\frac{h}{r_1}} \geq 41{,}3, \qquad h = r_2 - r_1$$

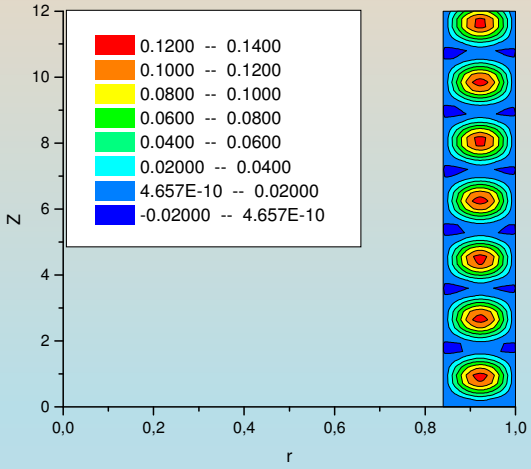
The secondary flows are time-averaged flows laying in the plane perpendicular to the direction of the main flow

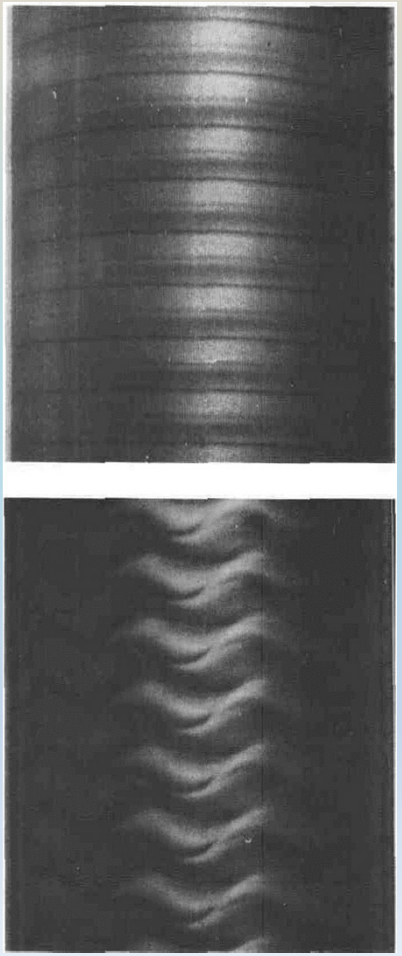
Change of flow structure at the transition through bifurcation points

K = 19,64

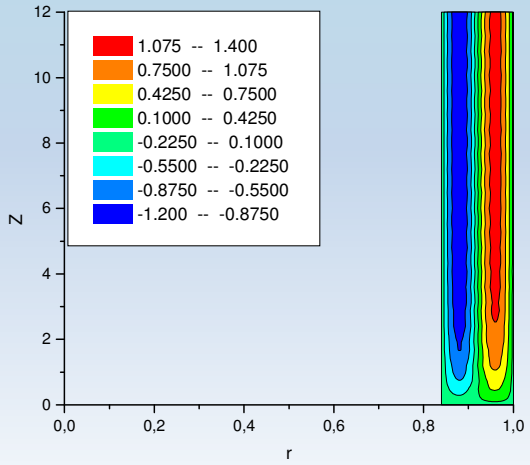


K = 20

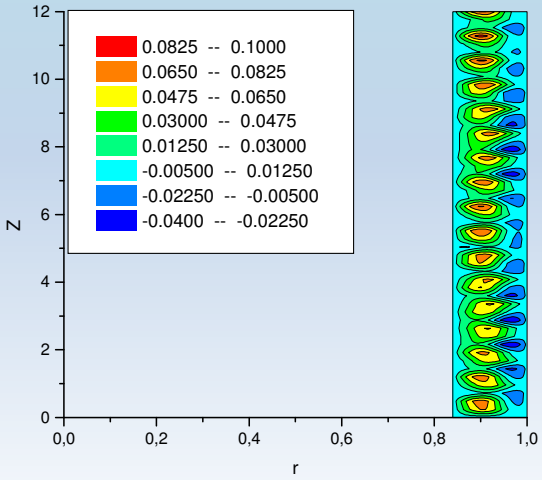




K = 39,28



K = 40



THE CONCEPT OF HELICITY

To determine the critical conditions for the rebuilding of the vortex structure of flow field of fluid it is necessary to consider the conditions of generation of helicity *H*.

The term "helicity" originally was introduced in theoretical physics. In this case it means a scalar product of the local components of the velocity and vorticity of the flow:

$$H = (\mathbf{u}\boldsymbol{\omega}) \quad (1)$$

The motion of any medium having the property of fluidity – liquid, gas, melt, may be considered

The equation for the rate of change of helicity:

$$\frac{\partial H}{\partial t} + \mathbf{u}\nabla H = \boldsymbol{\omega}(\mathbf{P_v} + \mathrm{grad}\frac{\mu^2}{2} - \frac{1}{\rho}\mathrm{grad}P) + \mathbf{u}(\nabla \times \mathbf{P_v}) - \nu\boldsymbol{\omega}(\nabla \times \boldsymbol{\omega}) - \nu\mathbf{u}(\nabla \times (\nabla \times \boldsymbol{\omega})) \quad (2)$$

The equation of change rate of helicity in criterial form

$$\frac{1}{Ho}\frac{\partial \mathrm{H}}{\partial \tau}+\mathbf{U}\nabla \mathrm{H}=\frac{\mathrm{He}_u}{U}\left[\frac{1}{\mathrm{Fr}}\frac{\mathbf{g}}{|\mathbf{g}|}+\mathrm{Grad}\frac{U^2}{2}-\mathrm{Eu}\,\mathrm{Grad}\tilde{P}-\frac{1}{\mathrm{Re}}(\nabla\times(\nabla\times\mathbf{U}))\right]- \quad (3)$$

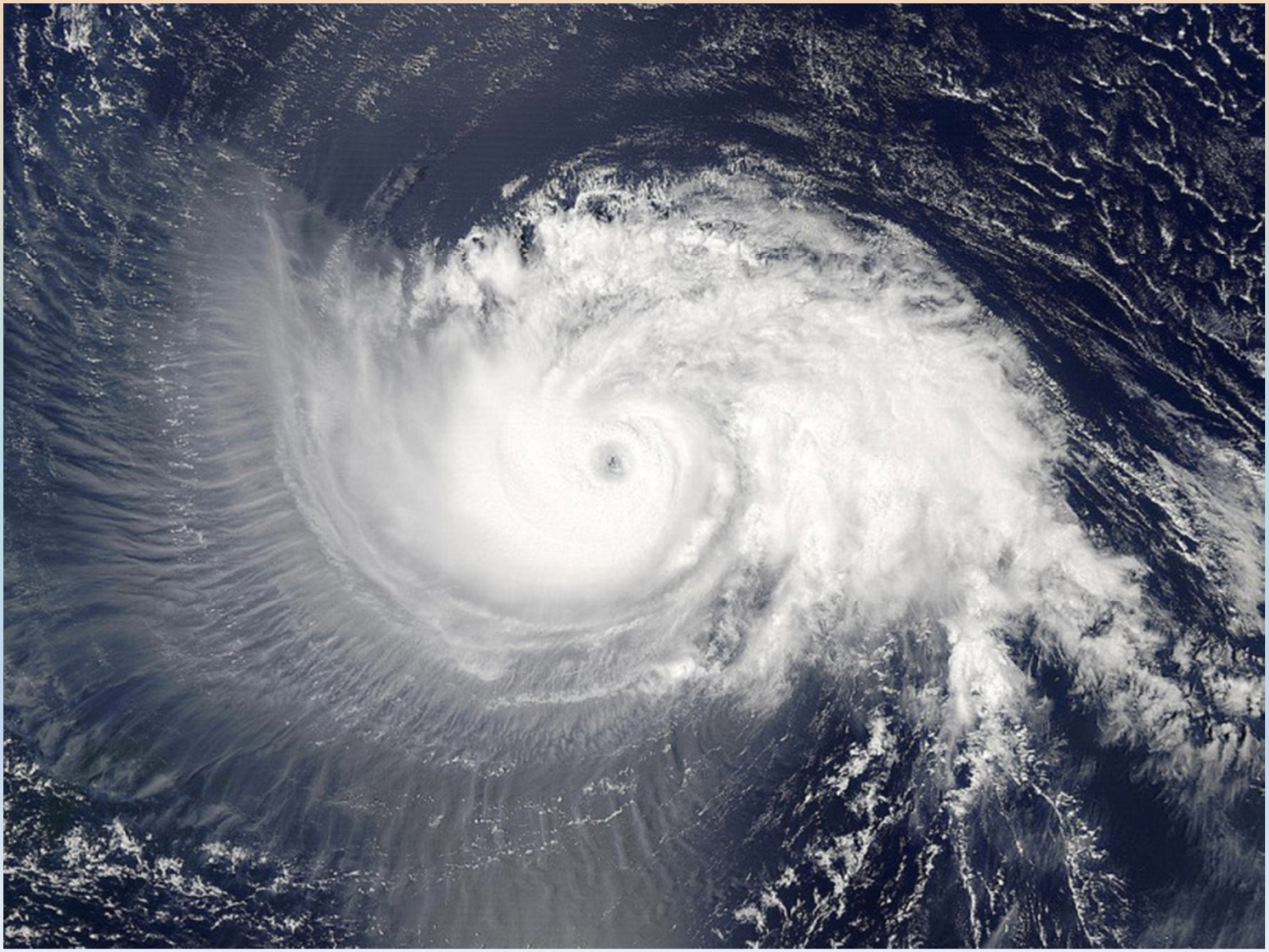
$$-\frac{1}{\mathrm{Re}}U\mathbf{e}_u(\nabla\times(\nabla\times(\nabla\times\mathbf{U})))$$

The dimensionless equation for the helicity takes the form:

$$\frac{d\mathrm{H}}{d\tau}=\frac{\mathrm{H}}{U}\left[\frac{l_0}{u_0^2}\mathbf{e}_u\mathbf{g}+\mathbf{e}_u\,\mathrm{Grad}\frac{U^2}{2}-\frac{P_0}{u_0^2\rho}\mathbf{e}_u\,\mathrm{Grad}\,\tilde{P}-\frac{\nu}{u_0 l_0}\mathbf{e}_u(\nabla\times(\nabla\times\mathbf{U}))\right]-$$

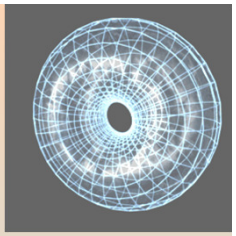
$$-\frac{\nu}{u_0 l_0}U\mathbf{e}_u(\nabla\times(\nabla\times(\nabla\times\mathbf{U}))) \quad (4)$$

Equation (4) shows that the magnitude of the total derivative of helicity in time depends on the ratio between changes along the flow lines of the kinetic energy of the flow, the density of the action of body forces, pressure gradient and work against the forces of molecular friction (dissipative losses).

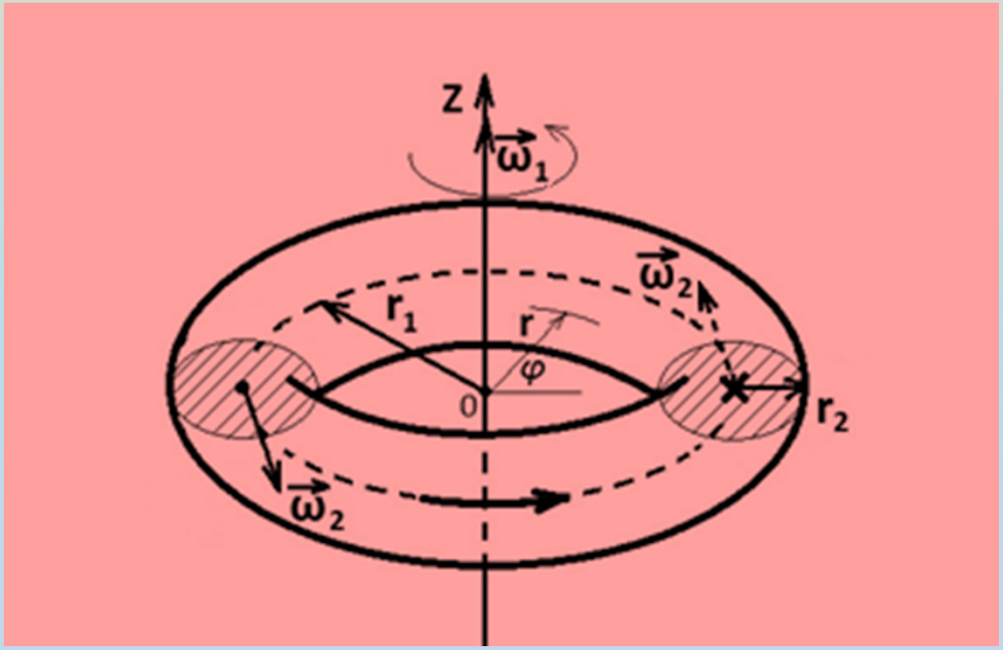


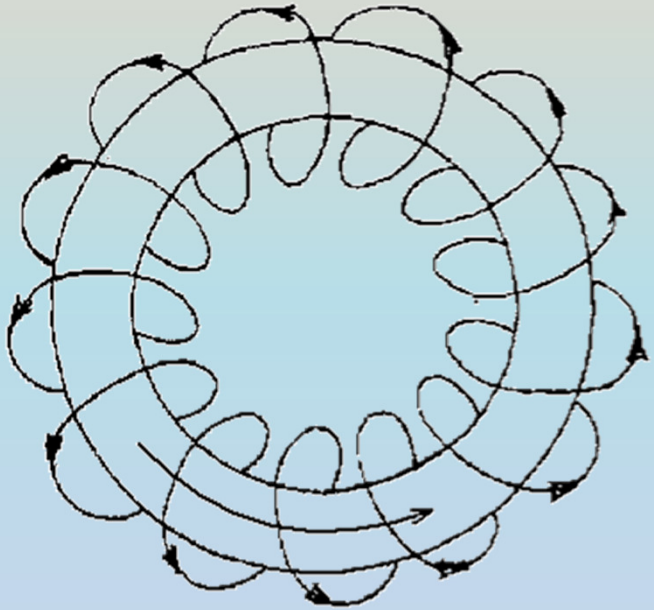
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Structural invariance of the stable form of spiral-vortex motion



Model of toroidal vortex with double rotation





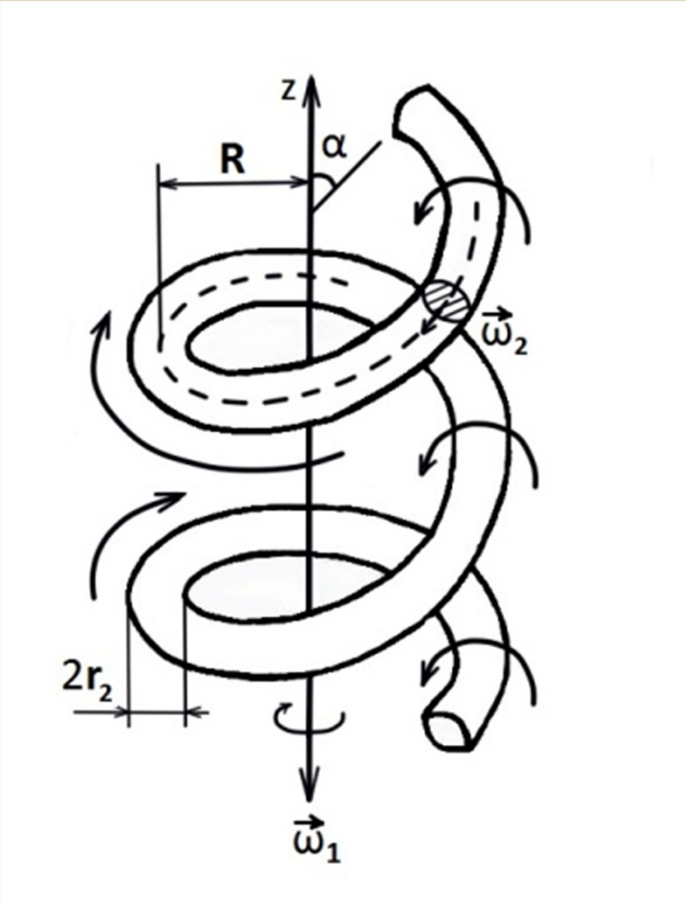
The phase surface with a quasi-periodic vortex motion under condition of irrational frequency ratio

$$\omega_1 / \omega_2$$

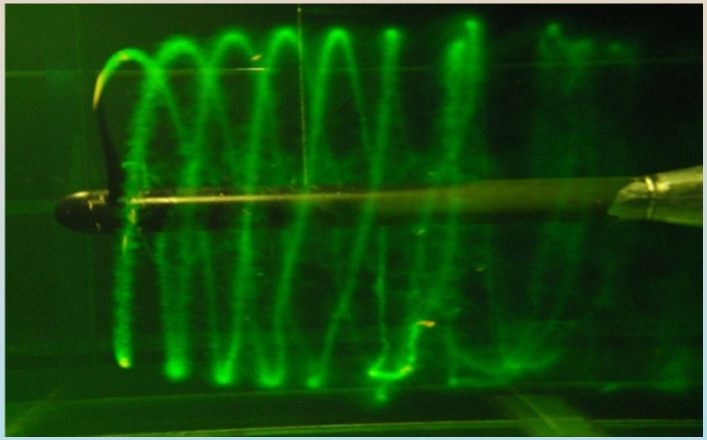
The periodic helical movement with a closed trajectory on the surface of the torus

ω_1 / ω_2 equal to the ratio 1 /13

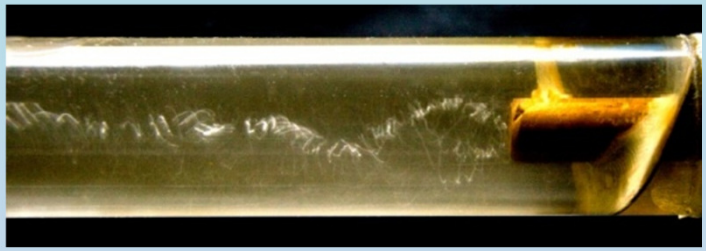
Screw-helix structure of the vortex



A



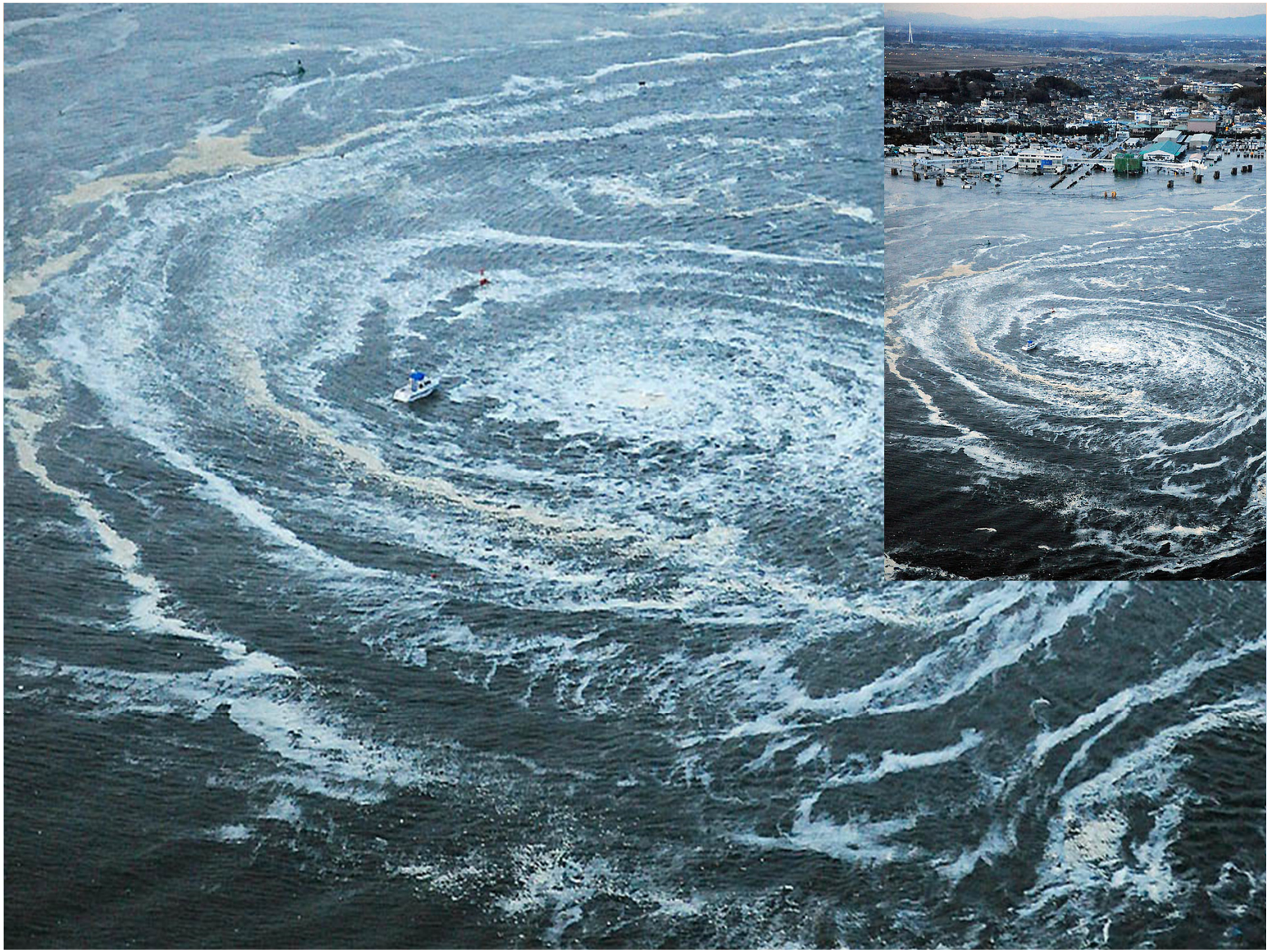
B



C



D



The Physical Nature of Tsunamis

I.I Novikov , O.V. Mitrofanova

Herald of the Russian Academy of Sciences, 2014, 84 (6), pp. 420-423



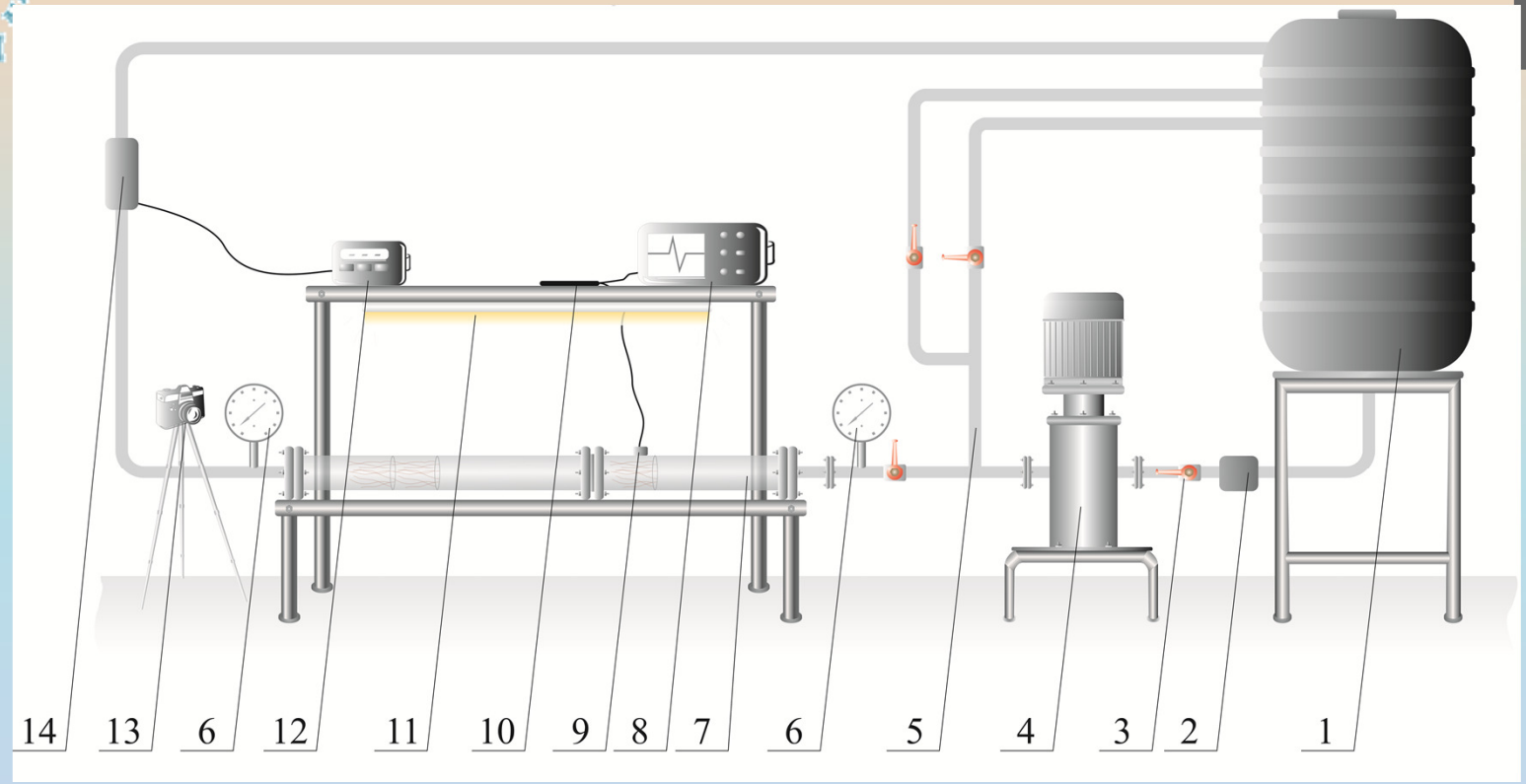
$$\frac{d\xi}{dr} = \frac{u_\lambda^2 \frac{dz}{dr} + \frac{u_\lambda^2}{2} \cdot \frac{z^*}{r} + \frac{C_f u_r^2}{2} - u_r^2 \frac{\xi}{r}}{u_r^2 - u_\lambda^2}$$

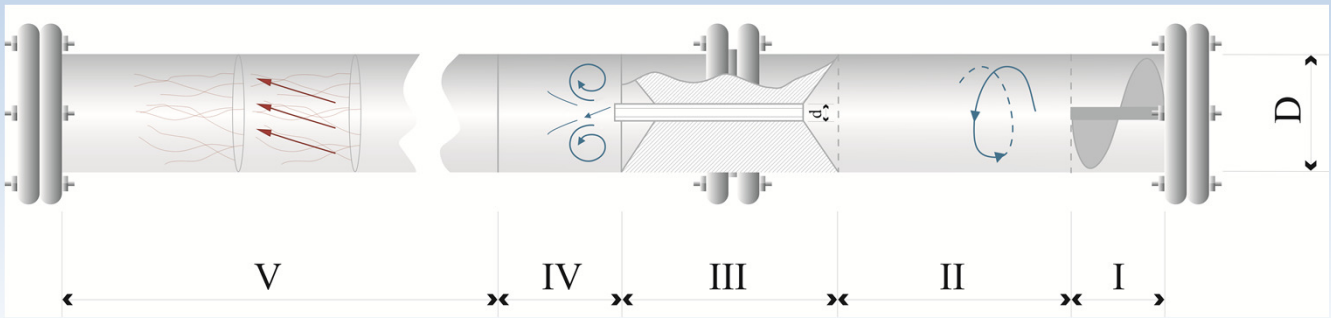
ξ – the height of the crest of a wave $\quad z^* = z + \xi$ – the total height of water,

$u_\lambda = \sqrt{gz^*}$ - the velocity of the wave in the approximation of shallow water theory

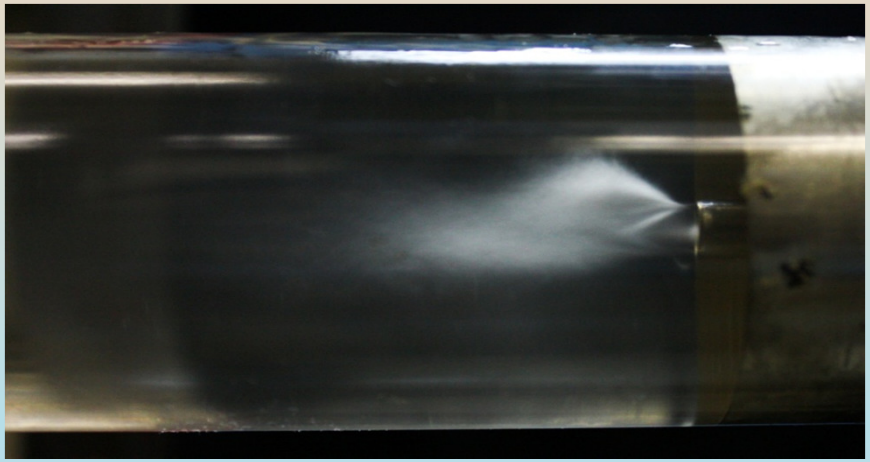
u_r – средняя скорость движения в поверхностном слое.

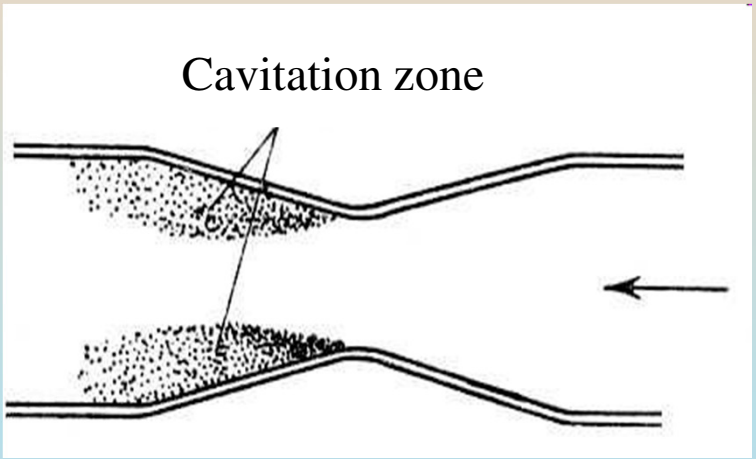
STUDY OF GENERATION MECHANISMS OF LARGE-SCALE VORTEX FORMATION IN THE INTERNAL FLOWS

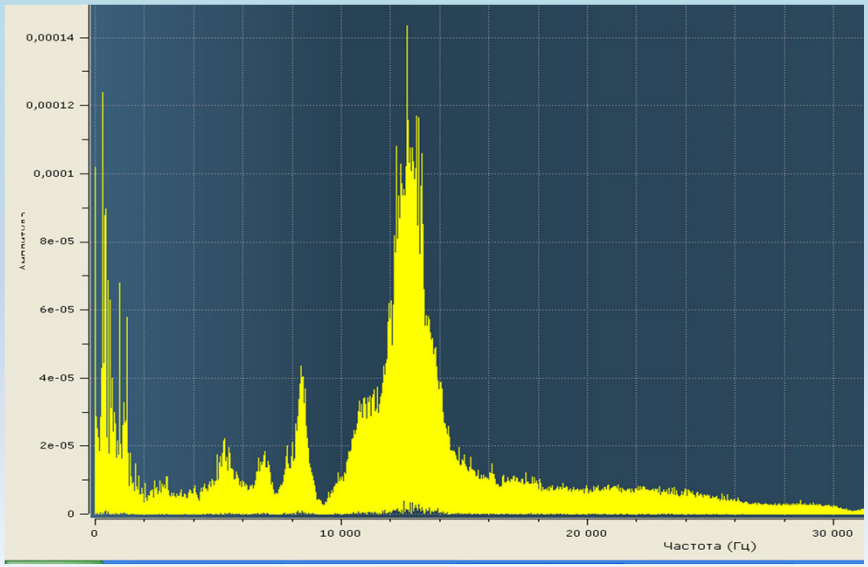


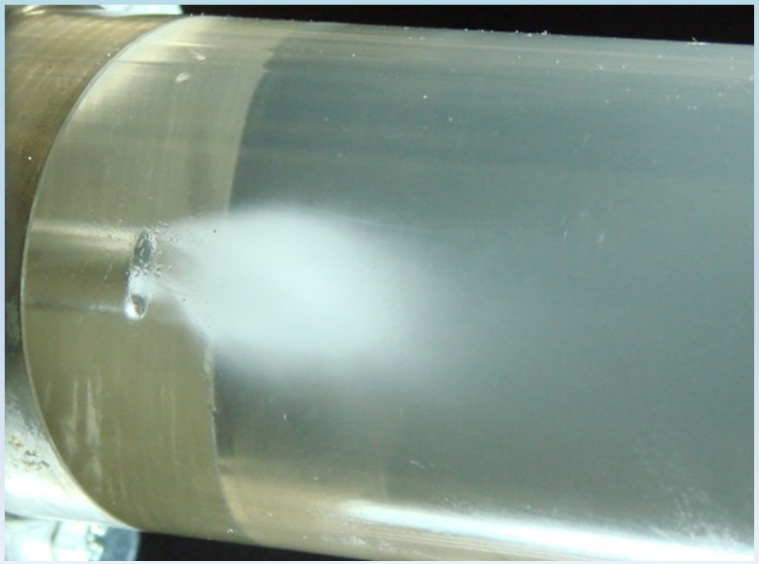


Acoustic cavitation

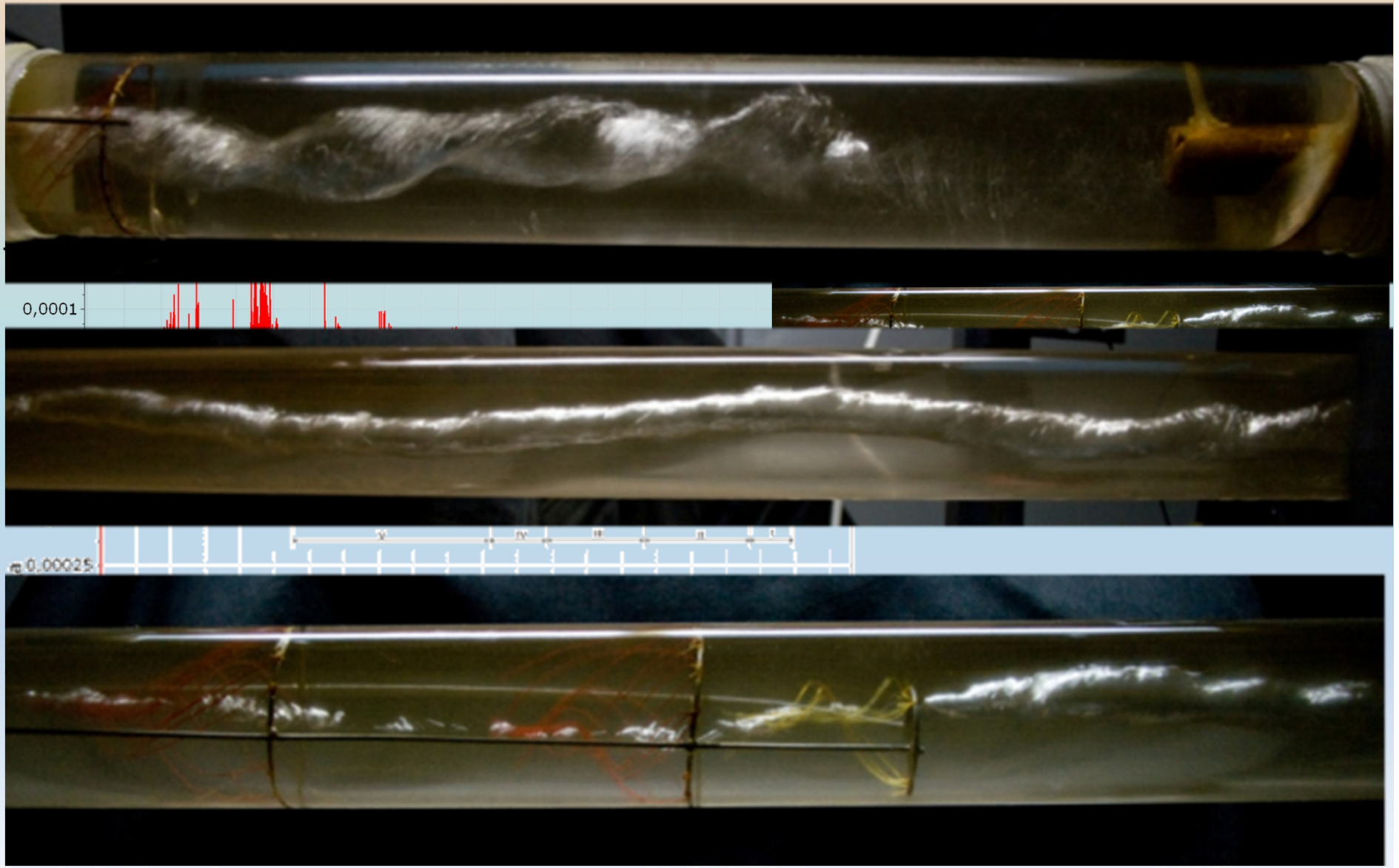




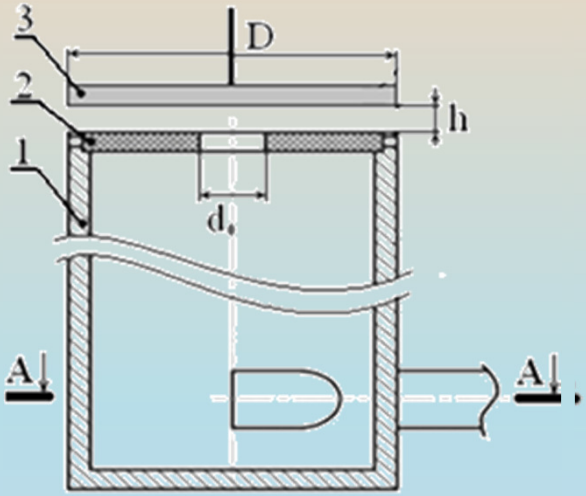




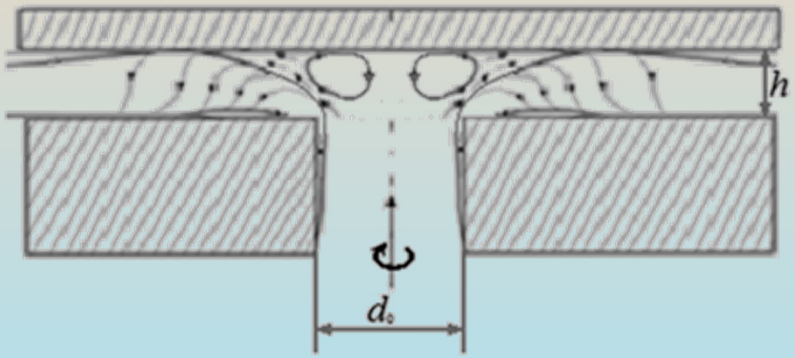
GENERATION OF ACOUSTIC OSCILLATIONS



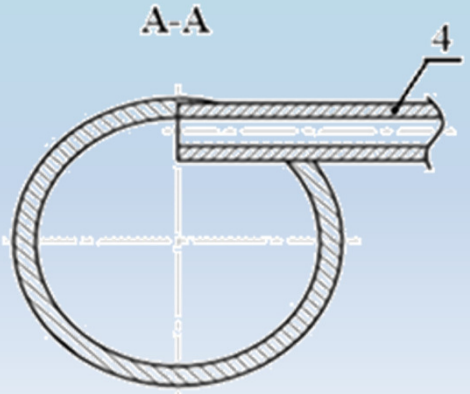
Vortex structures and sound oscillations in impact swirl flows

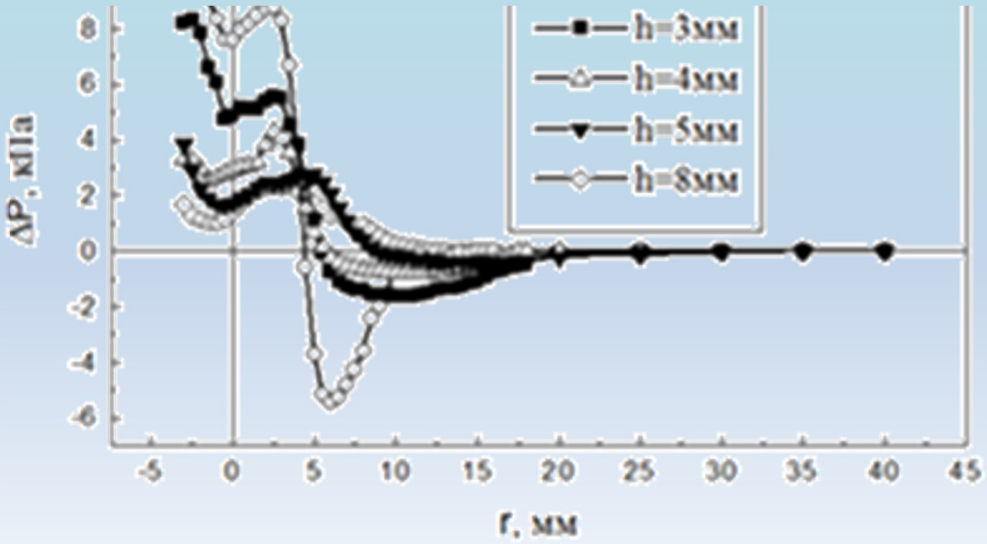


A



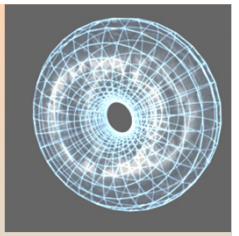
B

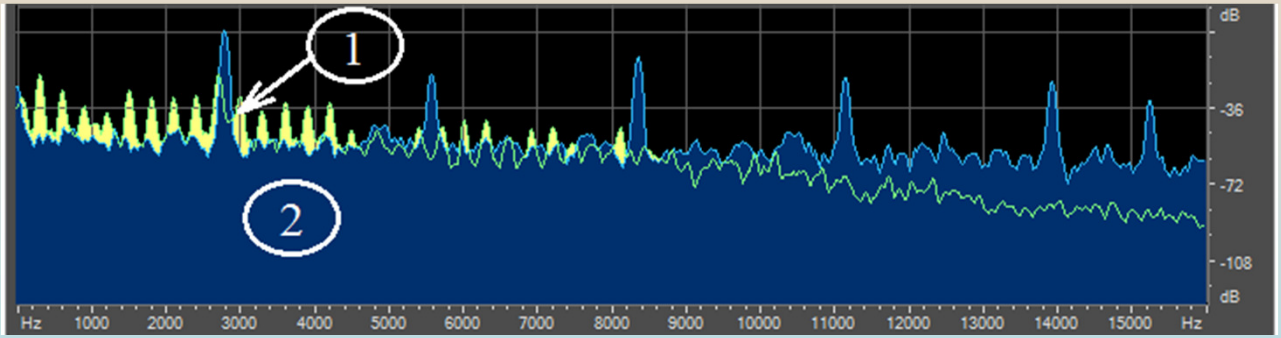




The self-regulatory effect of acoustic oscillations

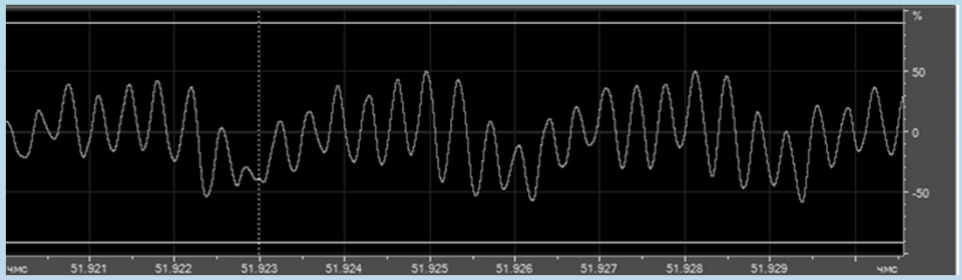
a) the amplitude-frequency characteristics: 1 –subcritical, 2 – critical regimes,
b) – time scan of the acoustic wave corresponding to mode 1,
c) – time scan of the acoustic wave corresponding to mode 2.



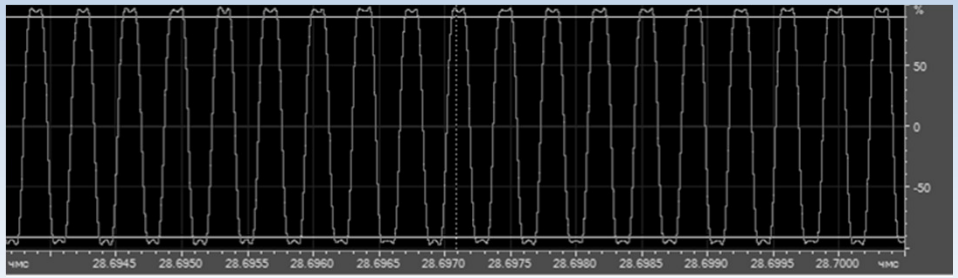


A

D = 70 mm
d_0 = 5mm
$G = 1.15 \cdot 10^{-3}$ m^3/s



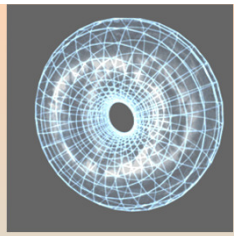
B

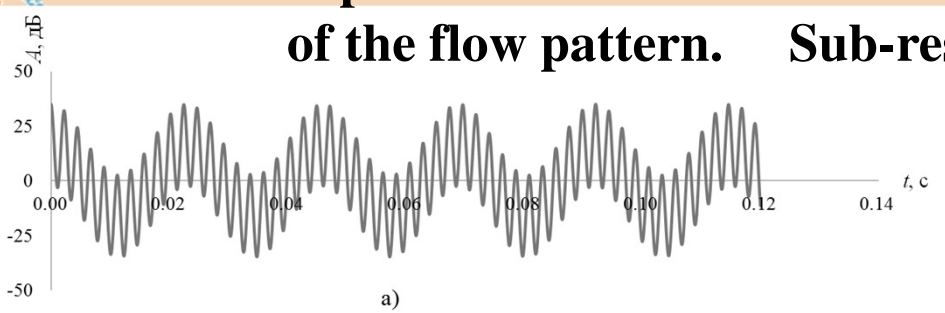


C

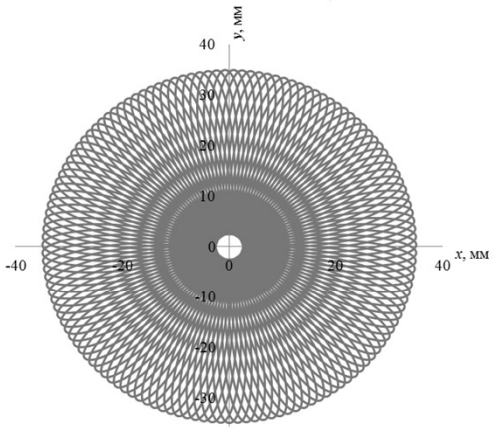
D, MM	f_3	f_2	N
30	2871	740.4	4
40	2816	617	5
50	2828	347.6	8
60	2832	296.8	9
70	2796	273	10
80	2769	265.6	11

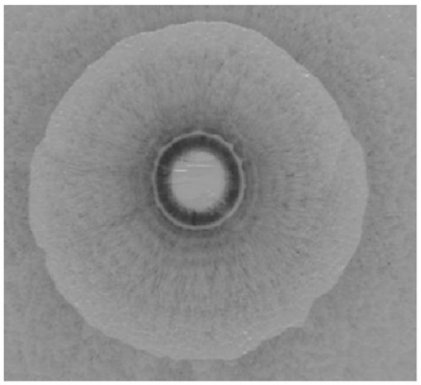
The comparison of calculation results with visualization of the flow pattern. Sub-resonant regime

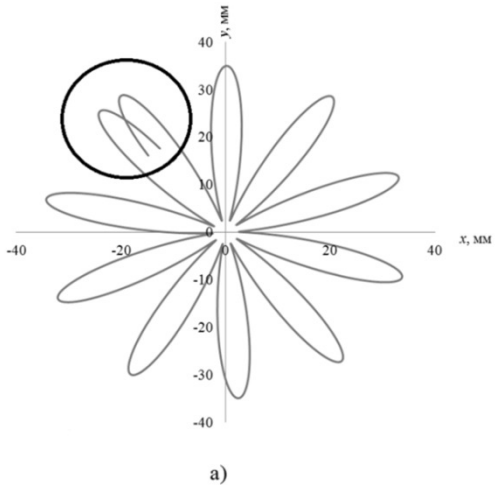




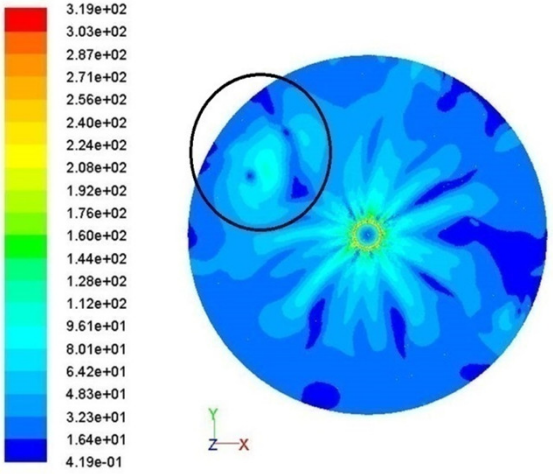
a)







a)



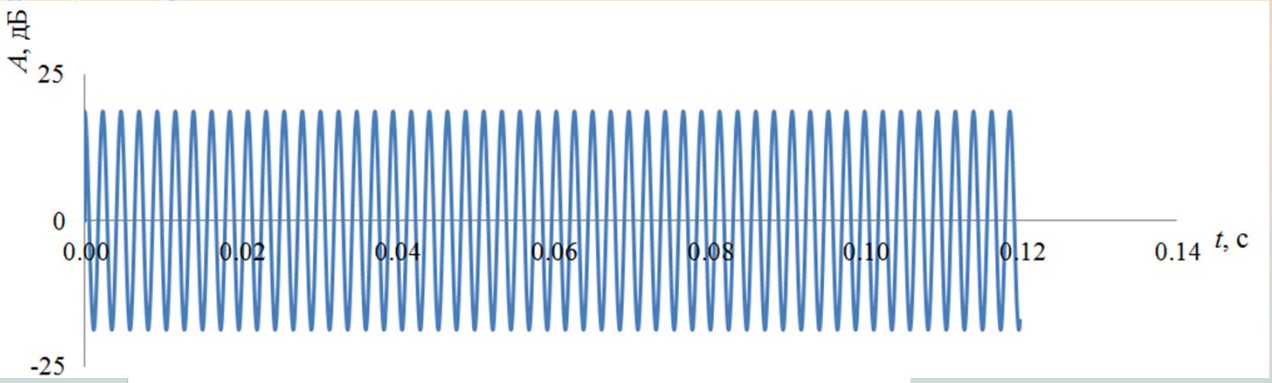
a) the result of addition of fluctuations with frequencies f3 = 2796 Hz and f2 = 273 Hz;

b) the Lissajous figure with the frequencies f3 = 2796 Hz and f2 = 273 Hz in the cylindrical coordinate system (r, φ, z);

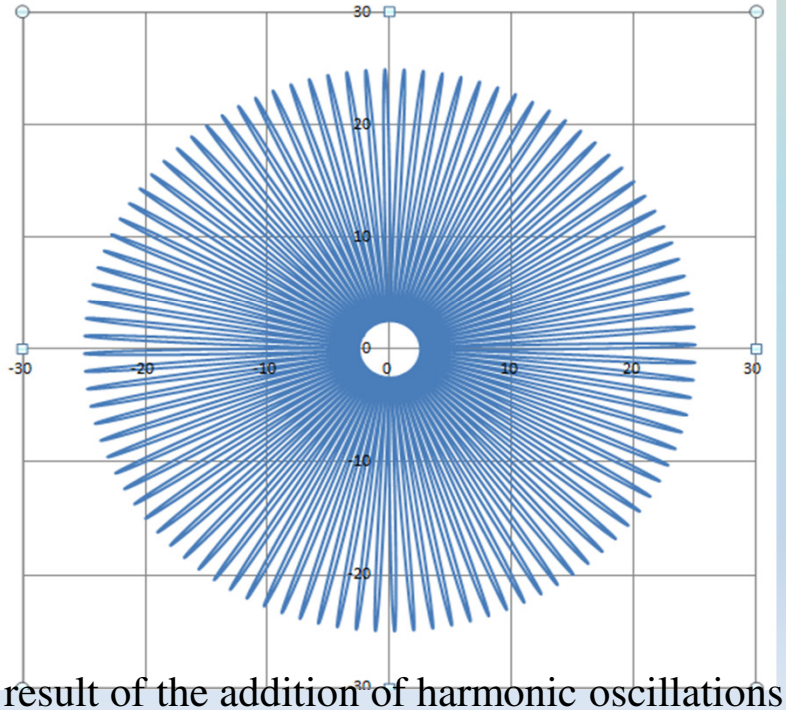
c) picture of the wake vortex on the lower surface of the obstacles

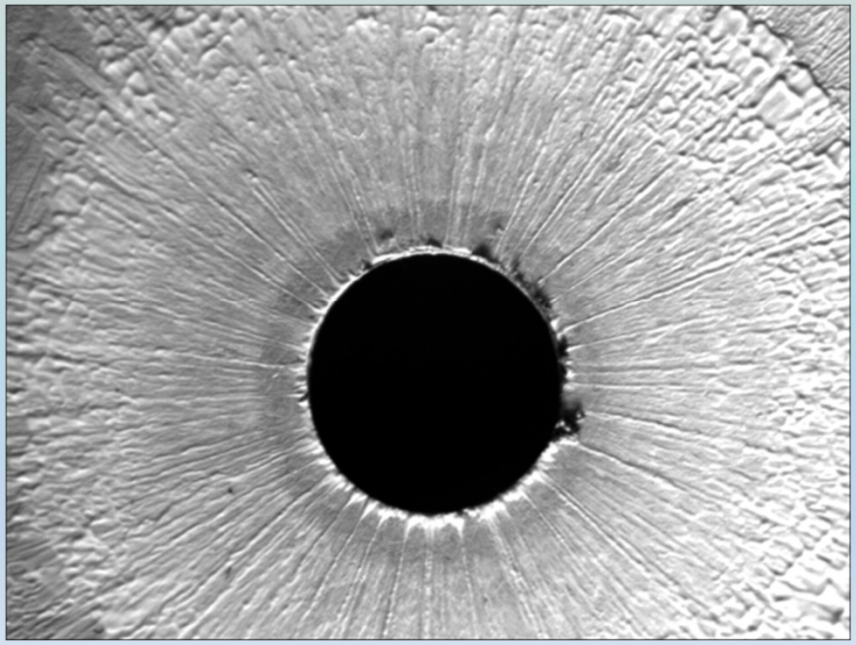
The results of the calculations:
a) a fragment of the Lissajous figures corresponding to one rotation of a vortex flow around the axis of the vortex chamber;
b) the velocity field of the flow obtained in the numerical simulation at a distance *h*/4 from the surface of the obstacles in the gap

Resonant regime

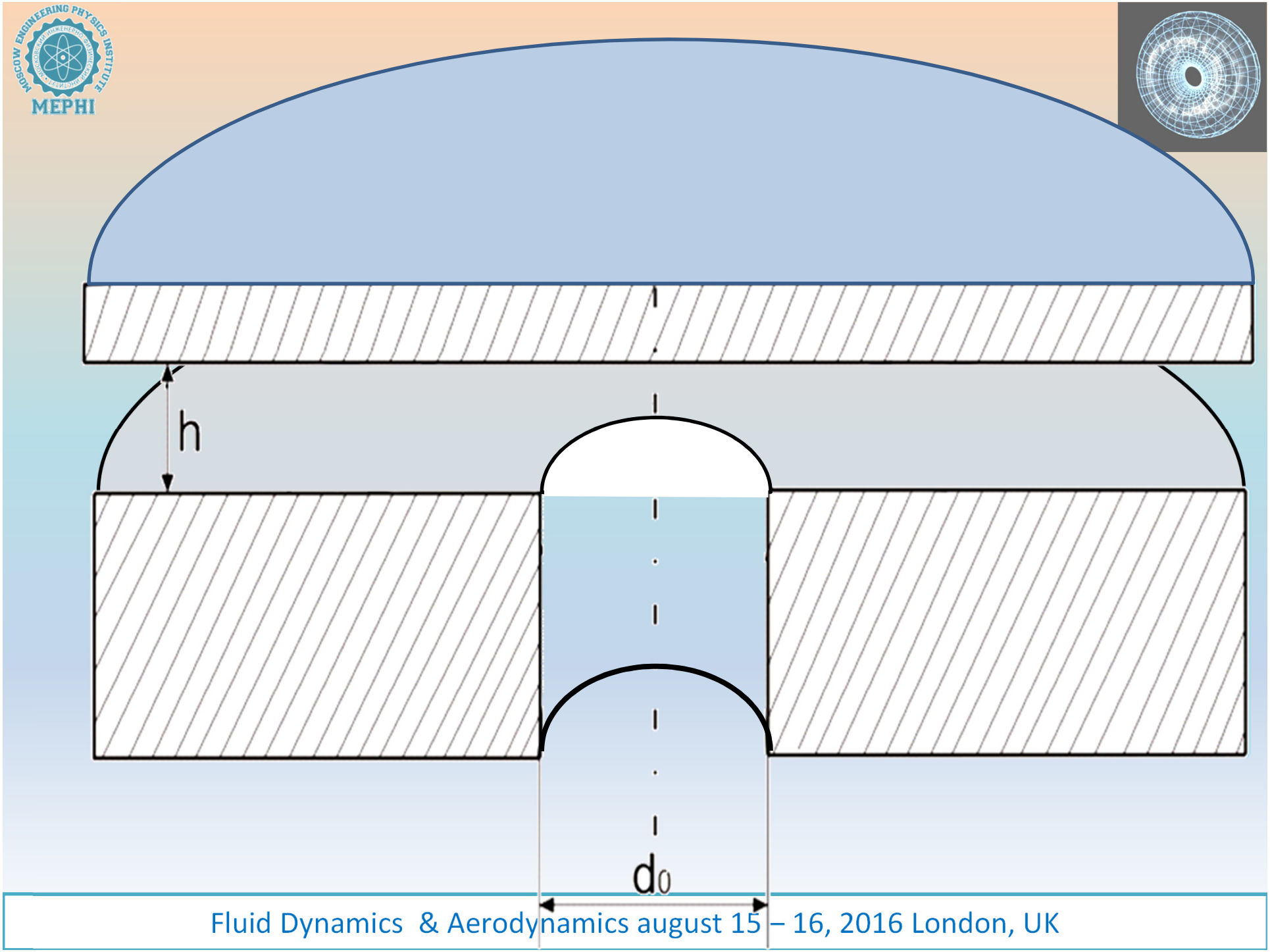


n	ω, Гц	d, мм
1	27	70
2	273	0,68
3	2796	0,0065



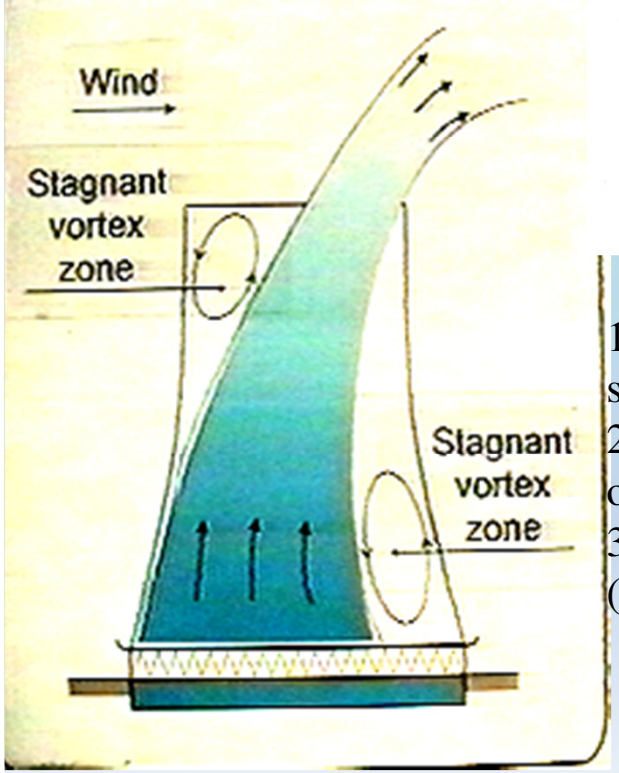


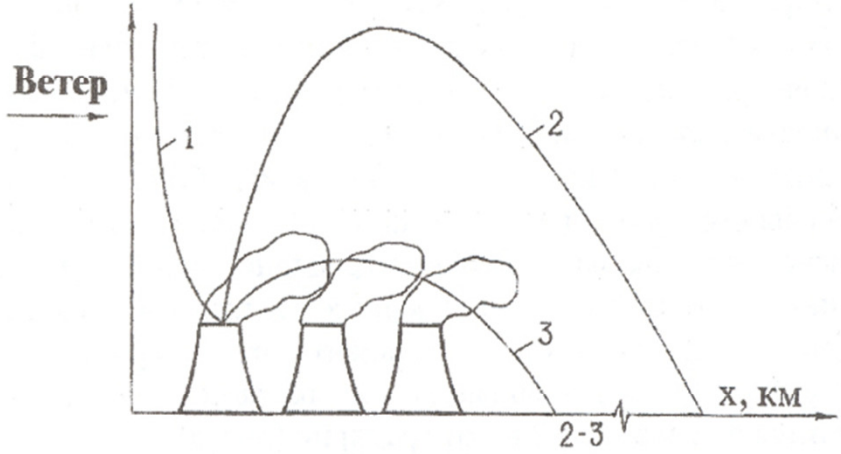
a) the result of the addition of harmonic oscillations with frequencies f3 = 2796 Hz and f1 = 27 Hz;
b) is a Lissajous figure with a frequency f3 = 2796 Hz and f1 = 27 Hz in the cylindrical coordinate system (r, φ, z);
c) picture of the wake vortex on the lower surface of the obstacles.


h
d_0

Increase of thermal efficiency of evaporative cooling towers for power and other industries







The spread of infrasound oscillations with frequencies < 10 Hz emitted by the towers

1 – the rays against the wind direction (towards stratosphere, not dangerous);

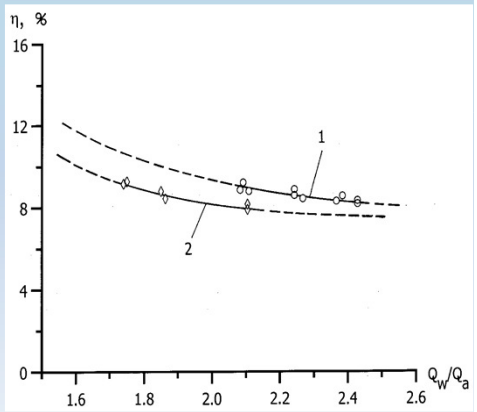
2 – the vertical rays propagating in the direction of the wind;

3 – the rays spreaded in the towers plumes (dangerous)

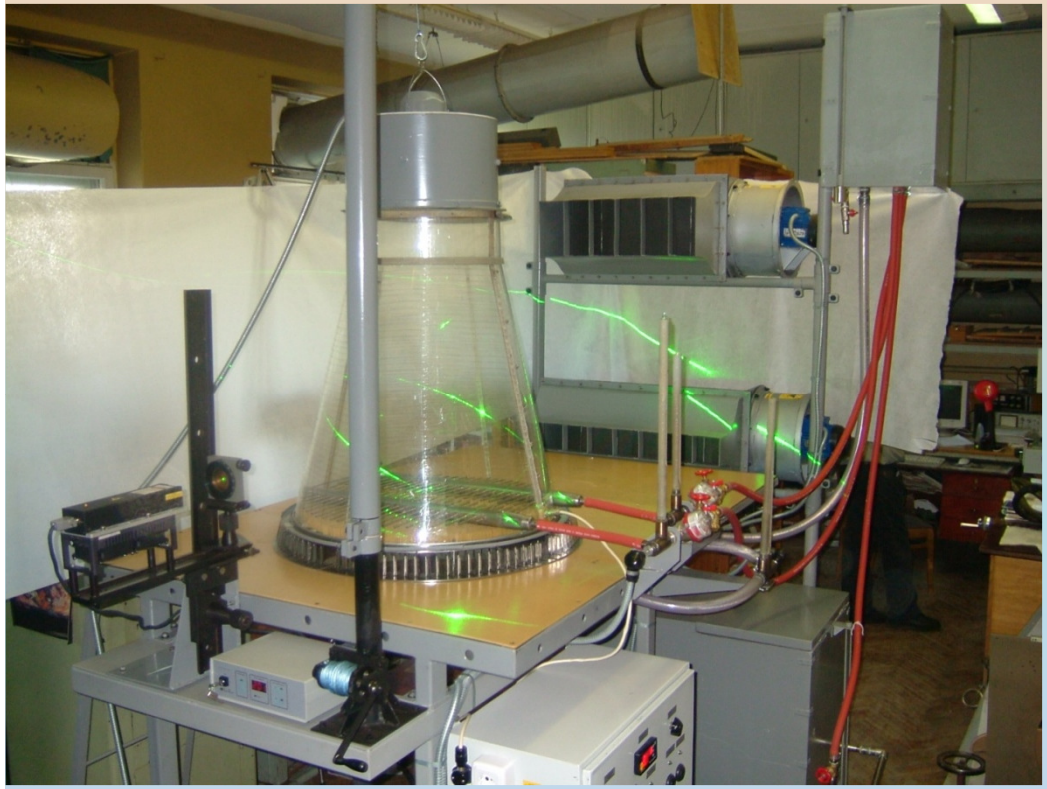
Infrasonic oscillations the most dangerous for the population living within a radius of 2-3 km from the cooling towers



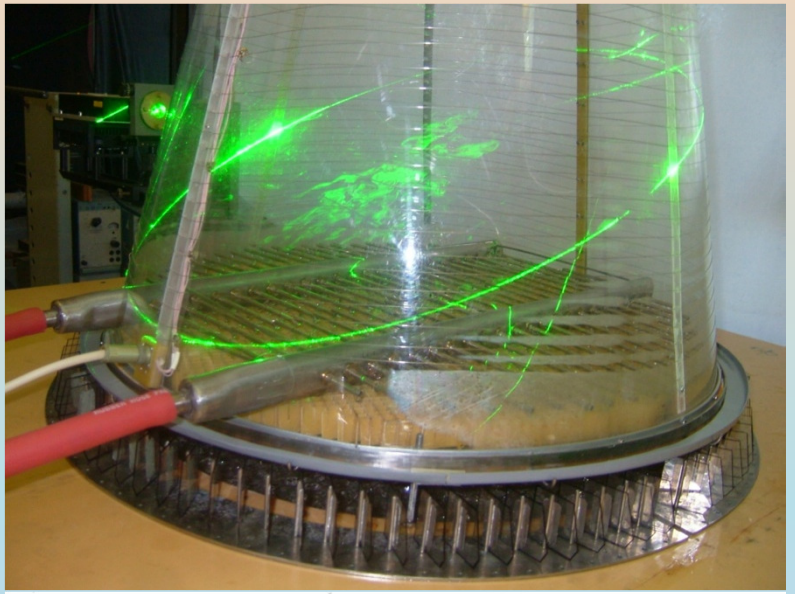


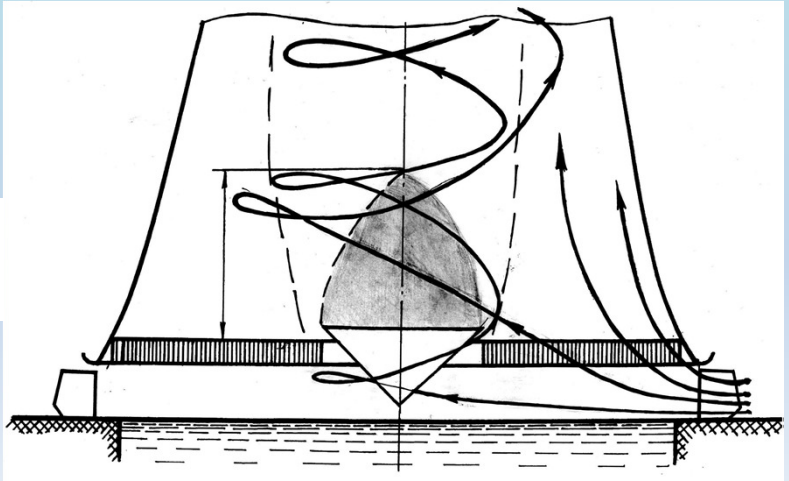


Experimental study of thermal physical and aerodynamic processes inside the evaporative cooling towers



General view of the laboratory model of the improved cooling tower and the laser technique for flow visualization

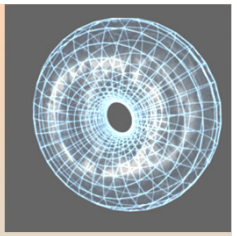




Modernization works for all types of evaporative cooling towers on base of experimental investigations

The Laboratory of Energy Transfer of the Academic Scientific Complex "The A.V. Luikov Heat and Mass Transfer Institute" National Academy of Sciences of Belarus, Chief Scientist of the Project on improvement of cooling towers Dr. Anatoly D. Solodukhin

THE STUDY OF SWIRL FLOW EFFECTS IN CONDUCTIVE LIQUIDS



The equation of motion of a conductive fluid with account of electromagnetic forces

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\vec{\nabla})\vec{u} = -\frac{1}{\rho}\vec{\nabla}P + \nu\nabla^2\vec{u} + \frac{1}{\mu_0\sigma}[rot\vec{B}\vec{B}]$$

If $\rho = const$, $\mu_0 = const$, $\sigma = const$; $\quad div\vec{u} = 0 \quad div\vec{B} = 0$

by analogy with the Bernoulli equation it can be obtained:

$$\frac{\partial \vec{u}}{\partial t} + grad\left(\frac{u^2}{2} + \frac{P}{\rho} + \Pi + \frac{B^2}{2\mu_0\rho}\right) = -[rot\vec{u}\vec{u}] + \nu\nabla^2\vec{u} + (\vec{B}\nabla)\frac{\vec{B}}{\mu_0\rho}$$

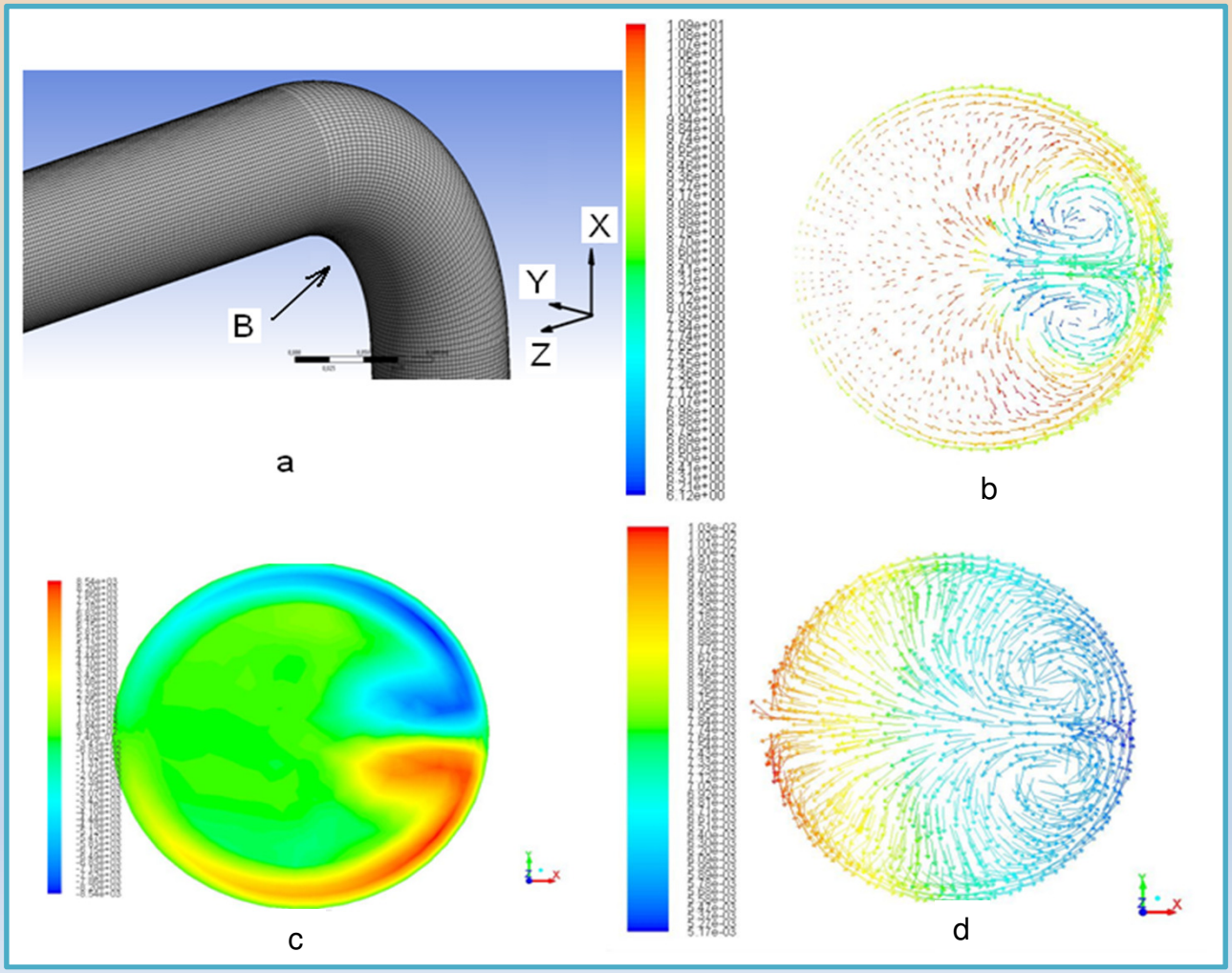
If we assume that the movement is steady and takes place along the vortex line or the line current, i.e. is helical $\quad \vec{u} \parallel \vec{\omega} \quad [\vec{u}\vec{\omega}] = 0 \quad [\vec{B}\vec{\omega}] = 0 \quad \vec{B} = k\vec{u}$

For $k = const$, : $\quad grad\left(\frac{u^2}{2} + \frac{P}{\rho} + gz + \frac{B^2}{2\mu_0\rho}\right) = 0$

$$\frac{u^2}{2} + \frac{P}{\rho} + gz + \frac{B^2}{2\mu_0\rho} = const$$

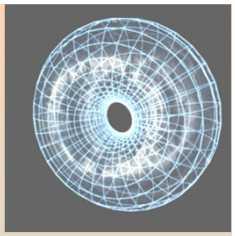
The last expression is similar to the well known Bernoulli's equation, the physical meaning of which is to ensure that along any streamline, the energy per unit mass of fluid, consisting of kinetic energy, pressure energy, potential energy in the gravity field and magnetic pressure, is constant.

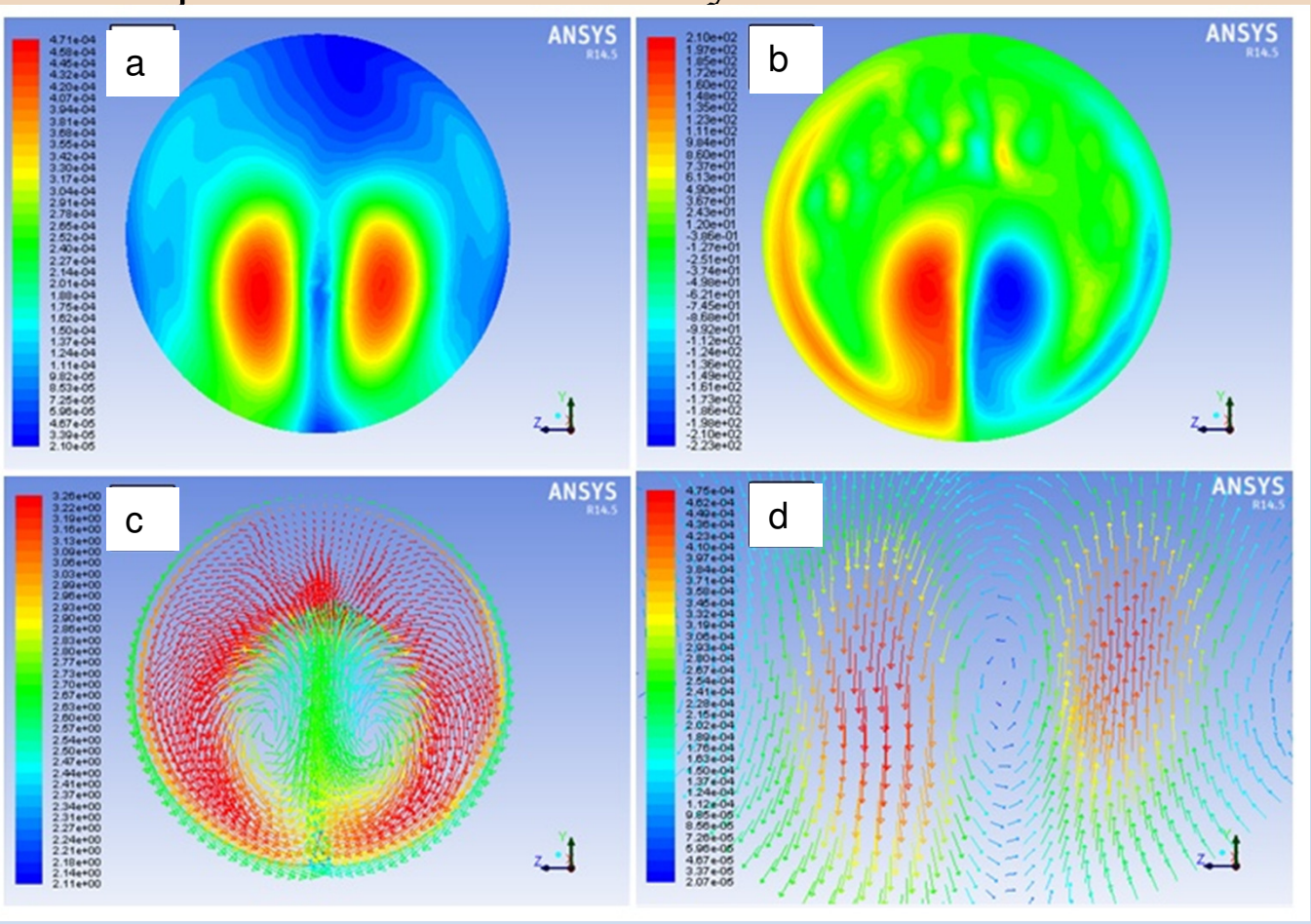
The channel with the generation of a spiral vortex flow in the area of pipe bending



a) a fragment of the computational grid; b, c, d - calculation results for cross-section Z = 0.1 m after the exit of the bend: b) velocity field, c) – distribution of helicity, d) - vectors of induced magnetic field. The external field is directed along the bisector of the bend angle.

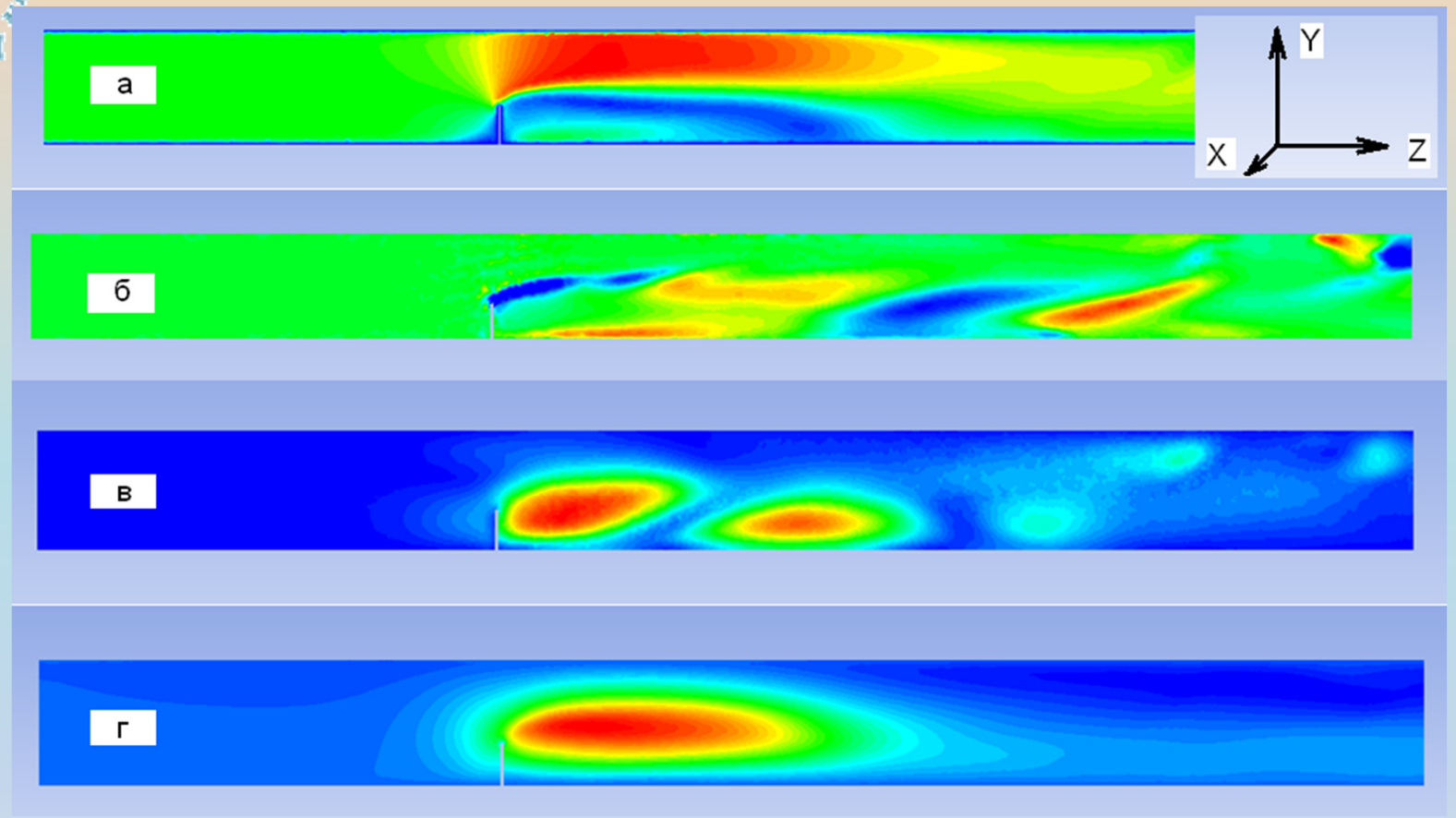
The external magnetic field is directed along the Z axis and is equal to 0.01 Tesla. The Reynolds Number Re = 8·105



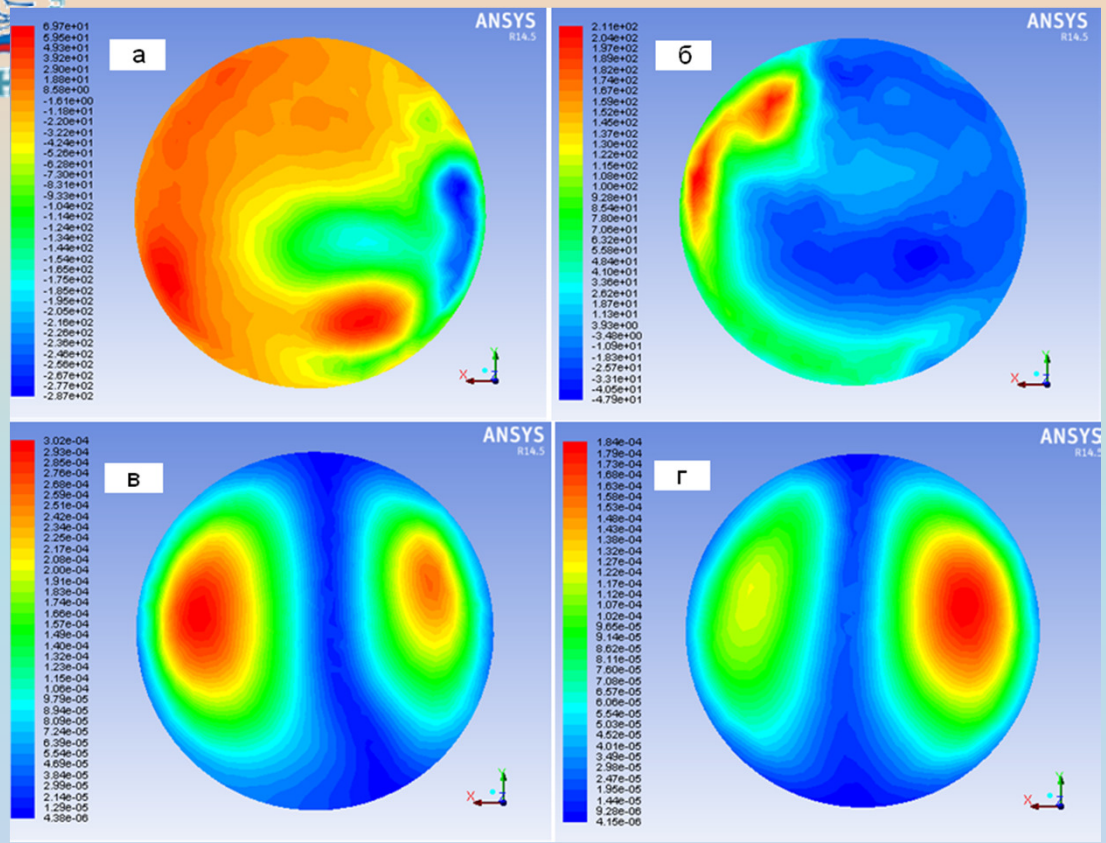


a) the distribution module induced magnetic field in the cross section X = 0.3 m after bending,
b) - distribution of helicity in the same section;
c) - distribution of the vector of total velocity of flow;
d) - the distribution of the full vector of induced magnetic field **B**

Vortex structure of the flow and induced magnetic field in the cylindrical channel with obstacles. The Hartmann's task (3D)



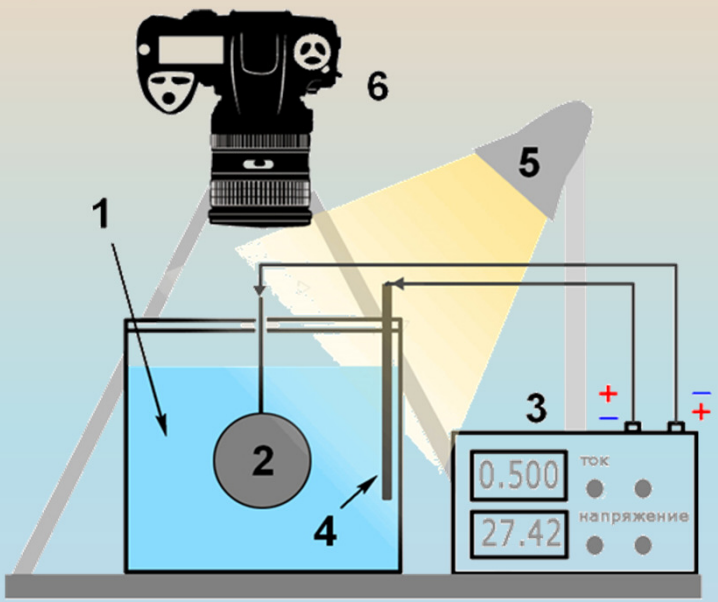
Distribution along the channel length: a) module of a full velocity; b) – helicity; c) – module of induced magnetic field under condition of the orientation of the external magnetic field along the X-axis d) idem for orientation along of the axis Y. The height of the obstacle to the diameter of the channel is equal to 1/3.

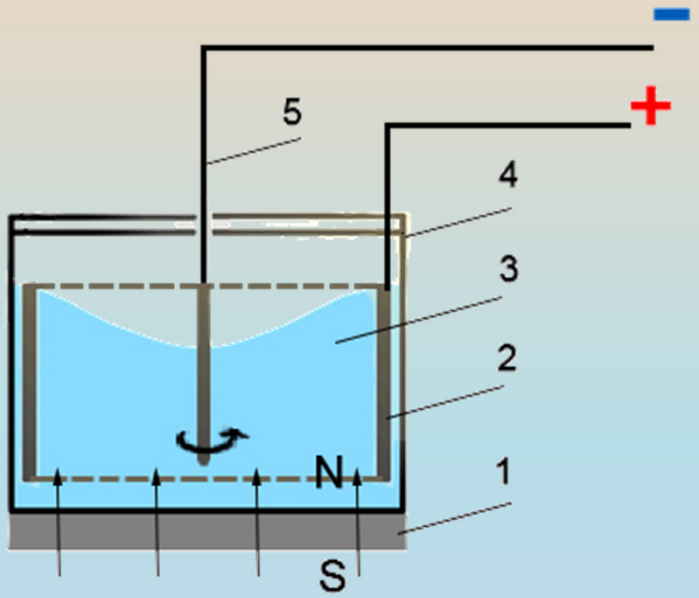


The results of the calculation for a channel with obstacle: (a, b) - field of helicity: (a) cross-section z1 = 0.34 m, b) is a cross-section z2 = 0,42 m from the entrance of the channel; (c, d) is the intensity of the resultant induced magnetic field **B** when the orientation of X-axis: – cross-section z1 = 0.34 m, g) is a cross-section z2 = 0,42 m from the entrance to the channel.

The presence of large-scale vortices leads to the generation of fluctuations of the induced magnetic field across the channel. The configuration of the induced vortex magnetic field in a moving conducting medium depends on the mutual orientation of spiral-vortex motion and direction of an external magnetic field

SCHEMES OF EXPERIMENTAL SETUPS





Scheme 1

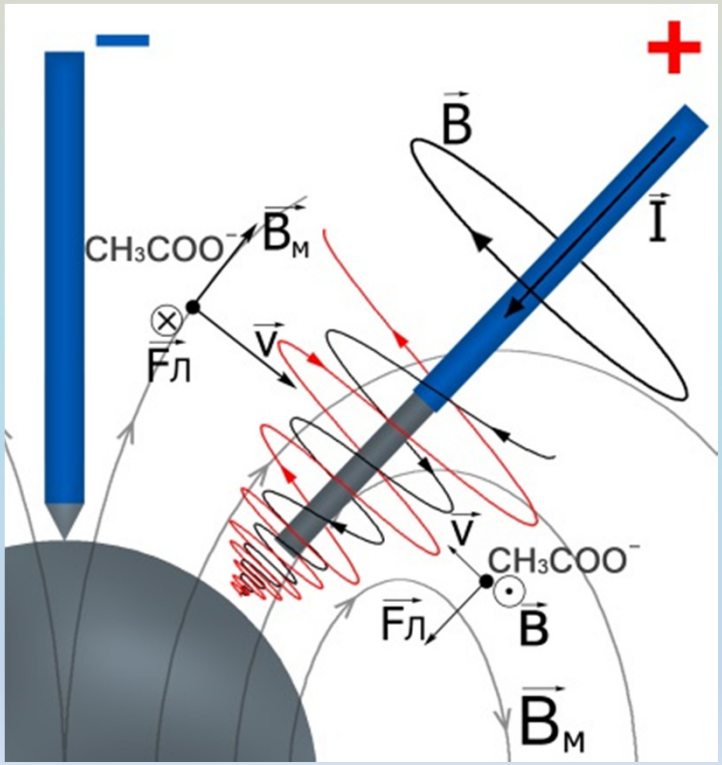
1 - electrolyte solution
2 - ball permanent magnet
3 - power supply
4 - movable electrode
5 - lamp for lighting
6 - photo-video equipment

Scheme 2

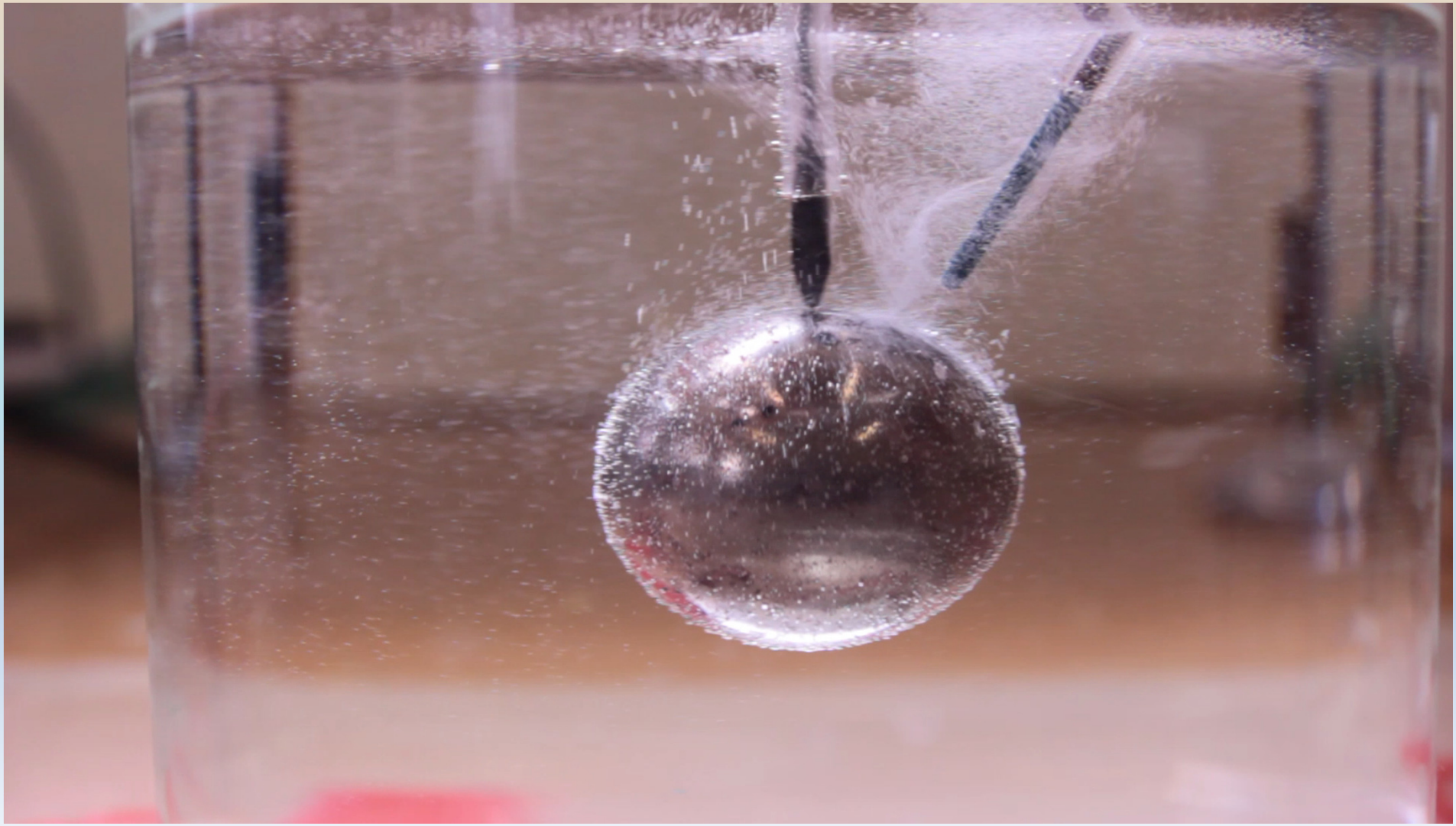
1 - flat neodymium (NdFeB) permanent magnet
2 - ring copper electrode
3 - electrolyte solution (acetic acid)
4 - glass tank
5 - central rod electrode

Visualization of the vortex motion in the electrolyte solution





Video









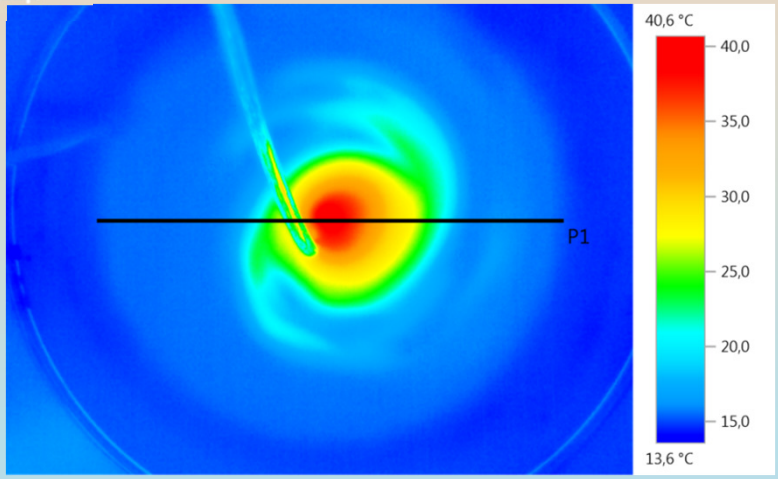




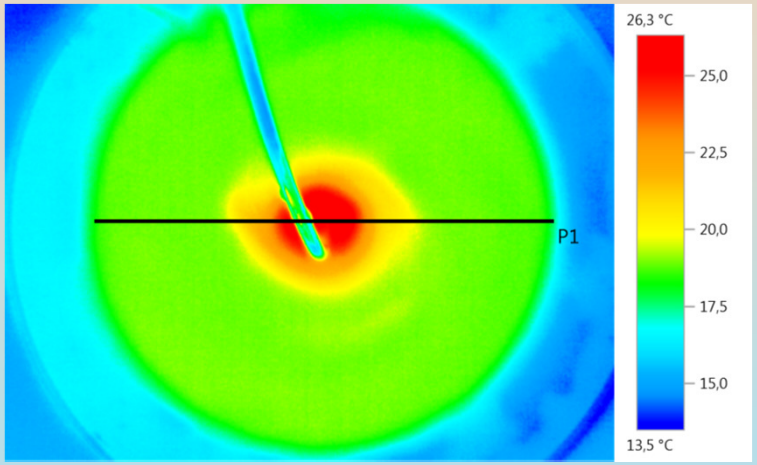


THERMAL IMAGING

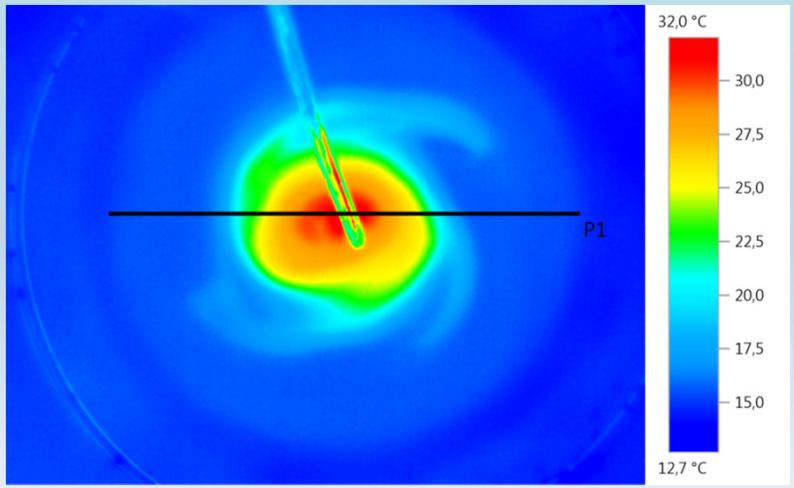
(electric charge in the center, the magnetic pole at the top)



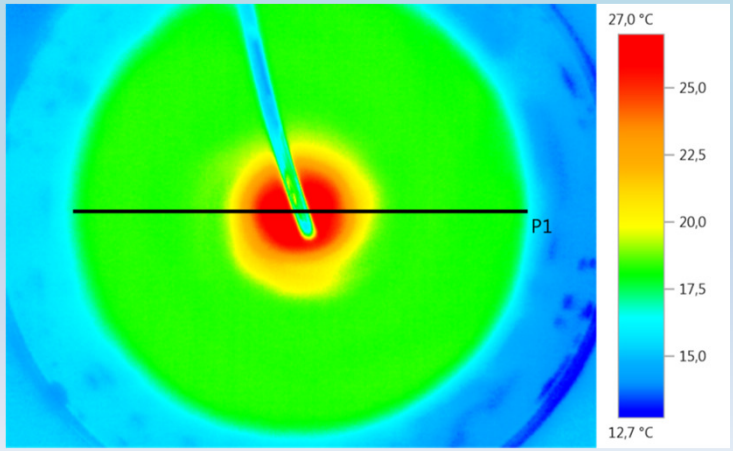
1) **+, N**



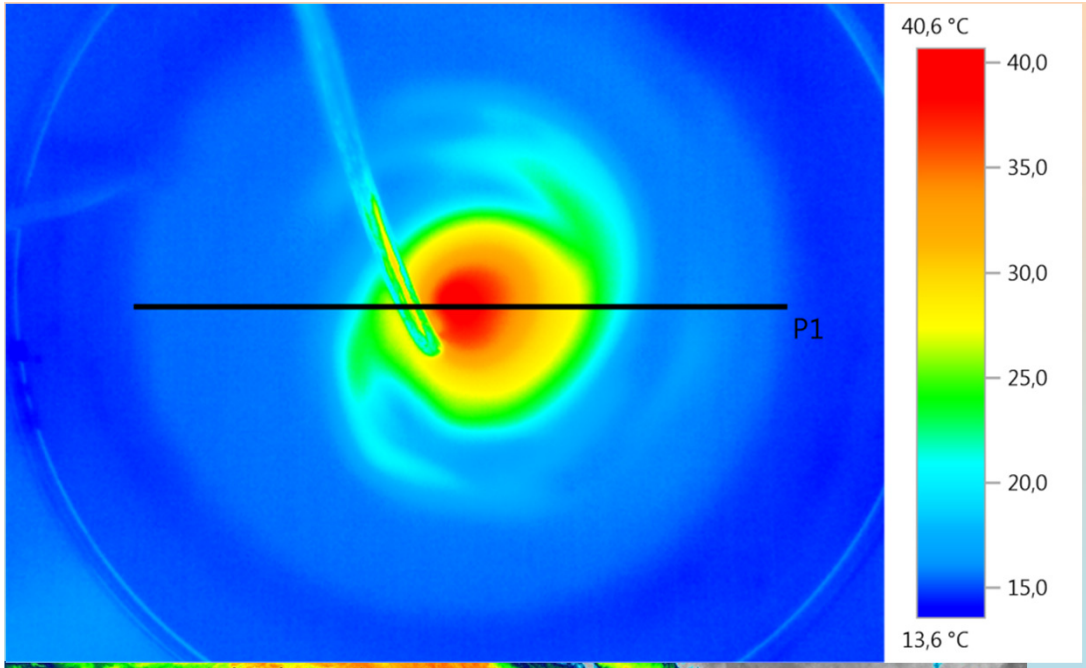
3) **-, N**

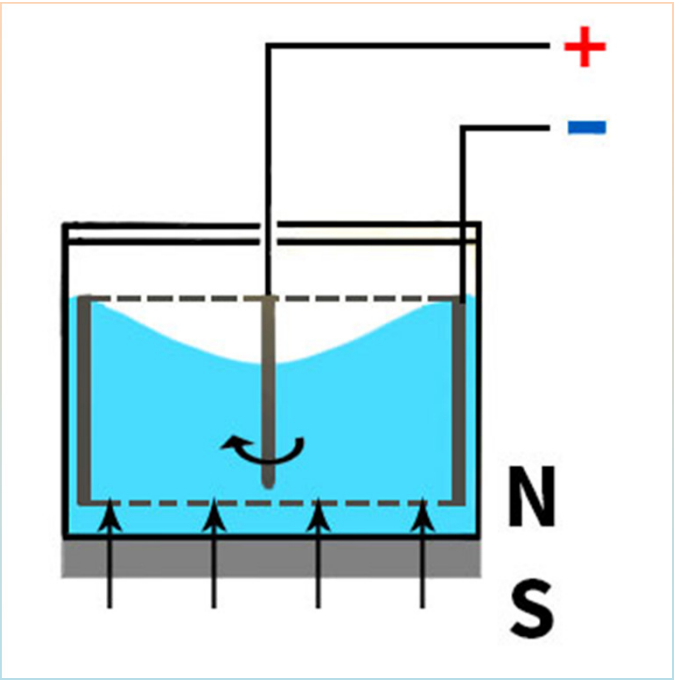


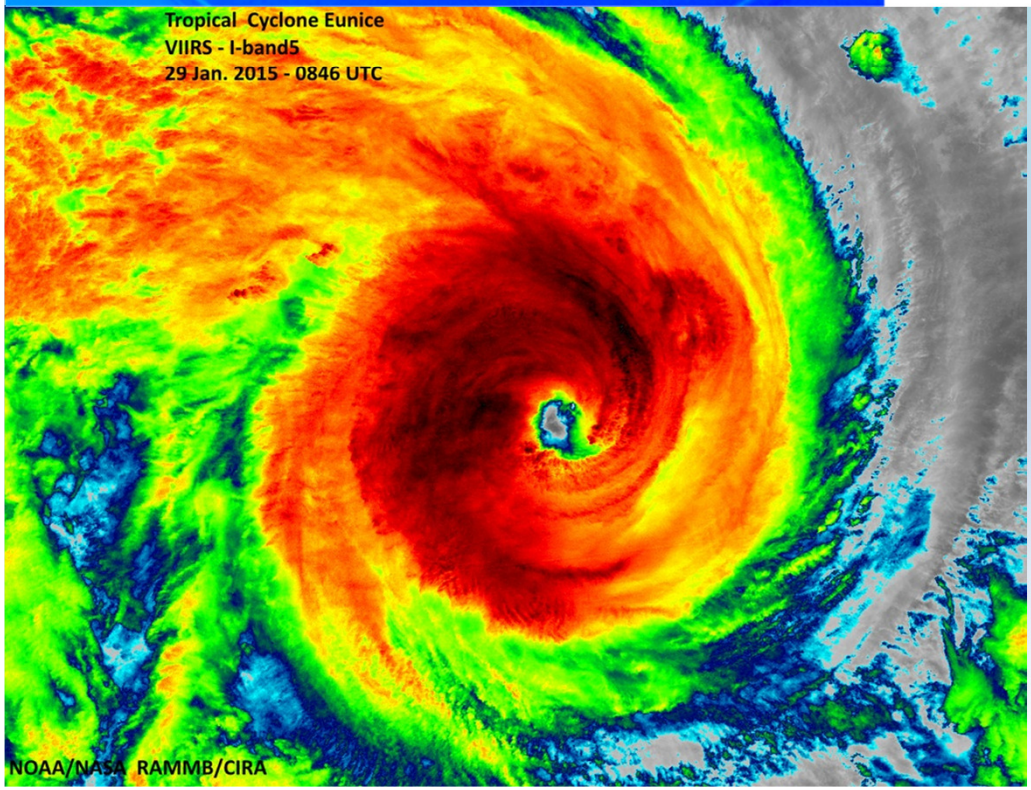
2) **+, S**



4) **-, S**



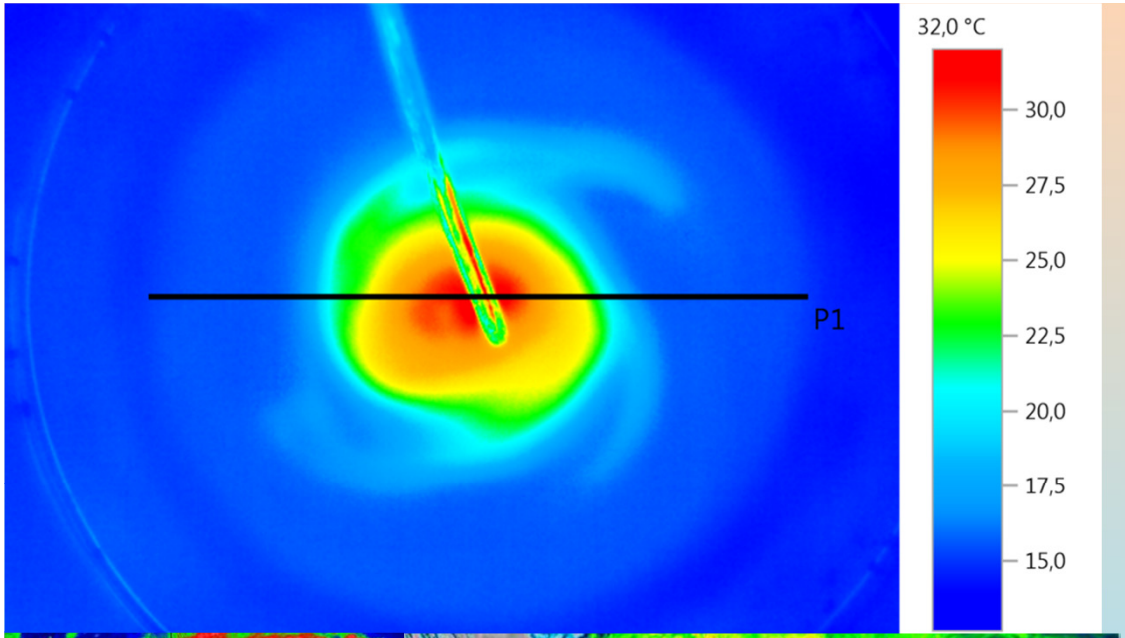


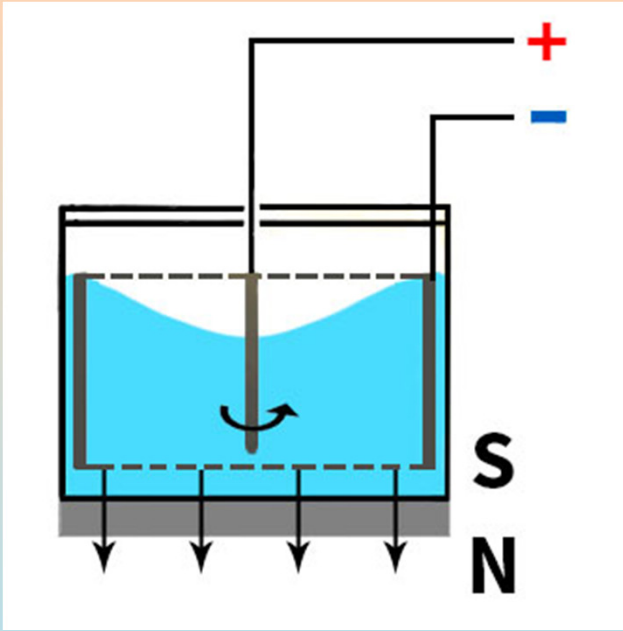


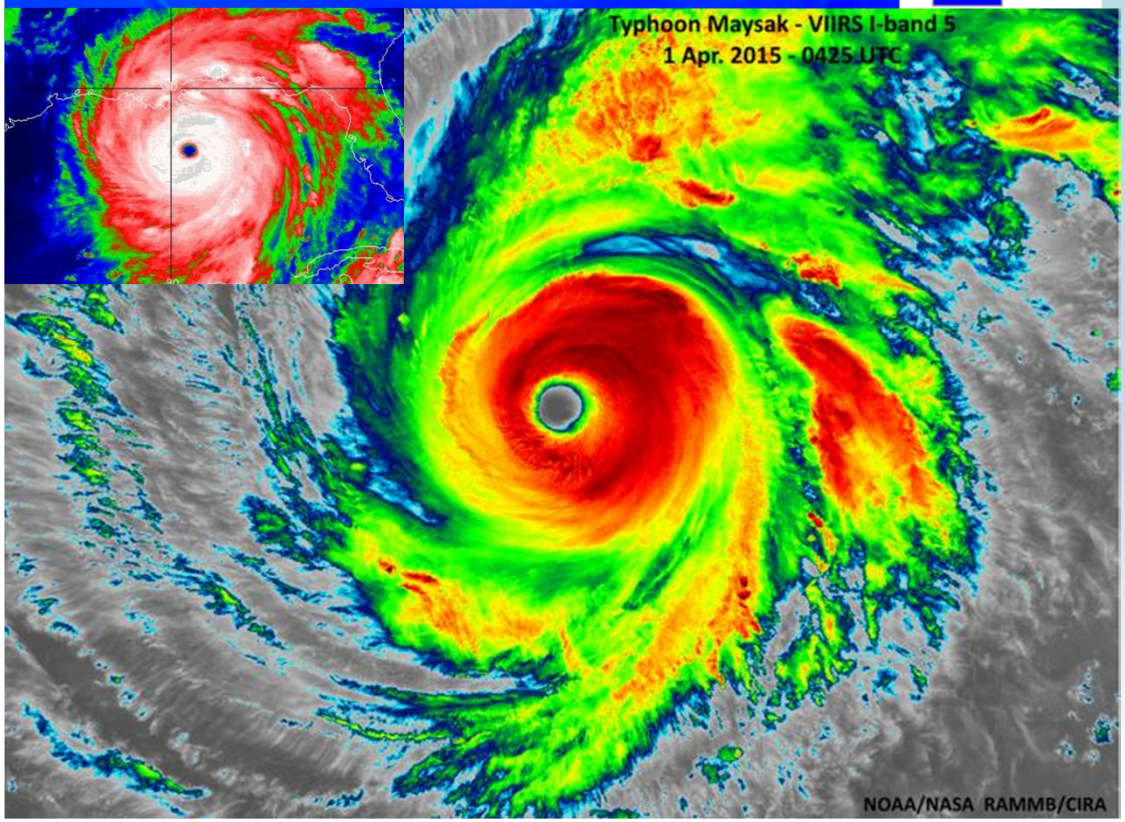
Tropical Cyclone Eunice. Category 5

Tropical cyclone Eunice became the fourth tropical cyclone of the 2015 in the Southern Indian Ocean season which was formed east of Madagascar

28 January 2015 was recorded tropical depression "Eunice" in the southern Indian ocean, South-East of Mauritius at latitude -13,2°. January 30, 2014, the cyclone was rated a category 5: wind speed reached 240 km/h Central pressure dropped to 900 MB.



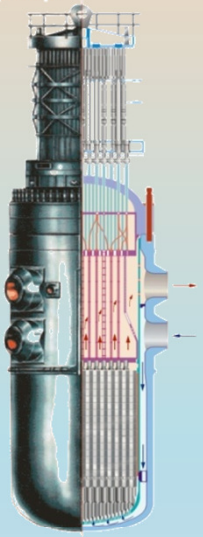


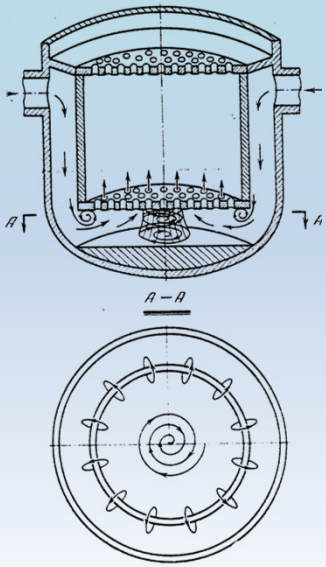


Super Typhoon Maysak rapidly intensified into the equivalent of a **Category 5 hurricane** with maximum wind velocity of 160 mph in the final days of March 2015.

Typhoon Maysak took place near the Philippine Islands at latitude of 14.2°
Typhoon Maysak" reached maximum stage of development 31 March 2015. The maximum wind speed near the center 50m/s. atmospheric pressure was taken equal to 920 hPa. The radius of the storm winds in all directions was 130 km. Destructive hurricane of the 5th category with wind speeds of up to 225 km/h, the "eye" of the Typhoon with a diameter of 60 km

Spontaneous swirling of a flow in the collectors of the nuclear power installations





The critical conditions

1. The generation of helicity

$$\frac{\partial H}{\partial t}+\left(\vec{U}\ \nabla\right)H=\vec{\omega}(\vec{P}_v+grad\frac{U^2}{2}-\frac{1}{\rho}gradP)-\nu\vec{\omega}rot\vec{\omega}-\nu\vec{U}rot(rot\vec{\omega}) \qquad (1)$$

Steady-state spiral motion

$$rot\vec{U}=\vec{\omega}=k\vec{U},\qquad \frac{dH}{dt}=\frac{\partial H}{\partial t}+\vec{U}\nabla H=0 \qquad (2)$$

$$k\vec{U}(\vec{P}_v+grad\frac{U^2}{2}-\frac{1}{\rho}gradP)=2\nu k^3\left|\vec{U}\right|^2 \qquad (3)$$

$$k=\sqrt{\frac{(\vec{P}_v+grad\frac{U^2}{2}-\frac{1}{\rho}gradP)\vec{e}_u}{2\nu\left|\vec{U}\right|}} \qquad (4)$$

2. The solution of the boundary value problem eingenvalues for helical flow.
3. The comparison of the intensity of the vorcity of the real stream with its own values μ_n.

Application of useful properties of swirl flows. Control of the hydrodynamics of the flow

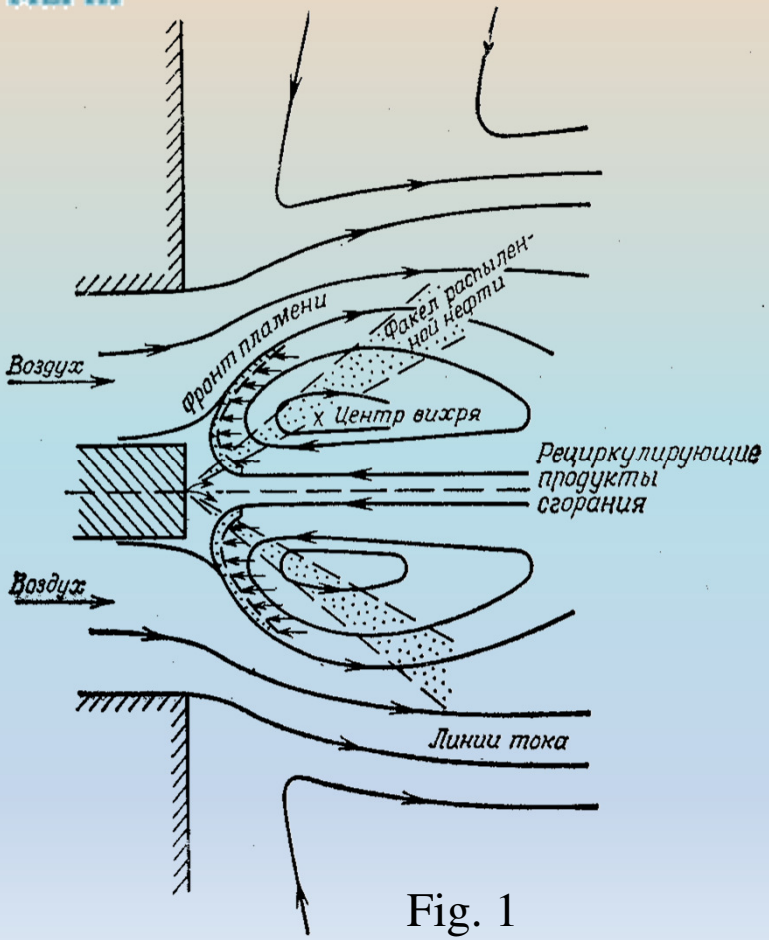


Fig. 1

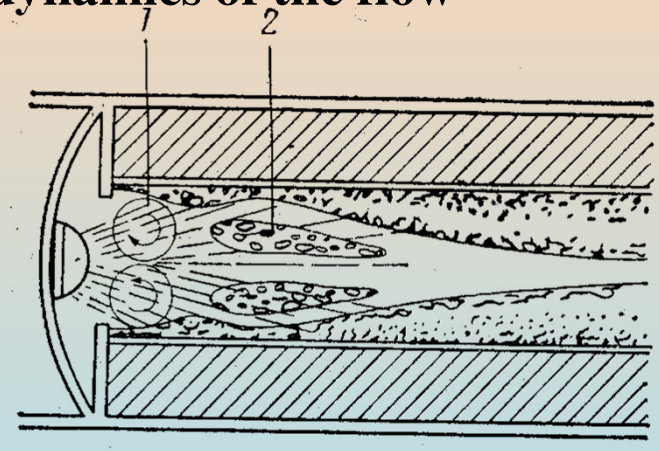


Fig. 2

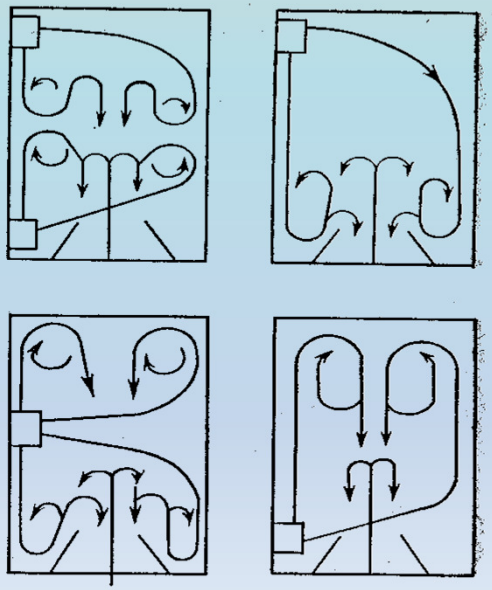
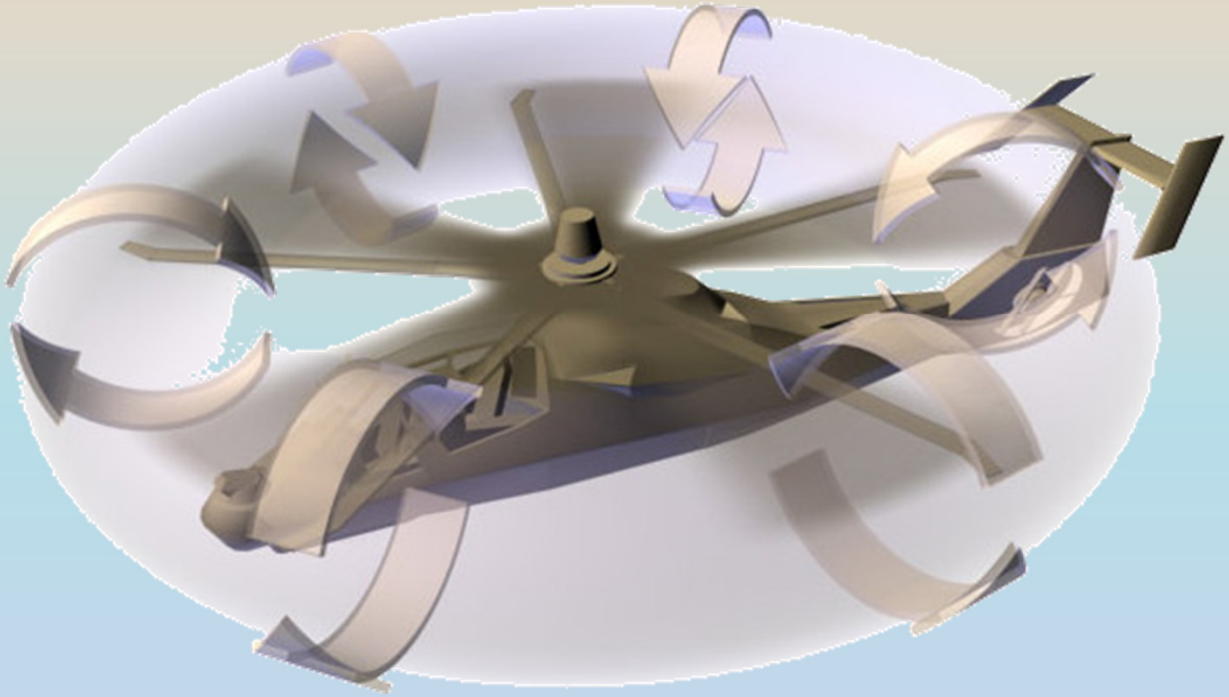


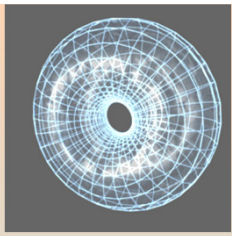
Fig. 3

Enhancement of processes of heat and mass transfer in combustion chambers (Fig. 1), rocket engines (Fig. 2) and industrial technological processes (Fig. 3)

Preventing critical mode "vortex ring" with the landing of the helicopter



The appearance of stable vortex structure in the form of a “vortex ring” (torus with double rotation) leads to the loss of the lifting force of the helicopter during landing



CONCLUSIONS

1. The influence of geometrical and regime parameters of the hydro-mechanical system on generation of sound oscillations

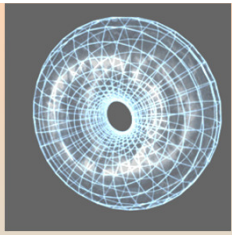
The topological regularities of complicated swirl flows were revealed on base of the use of acoustic methods and different ways of visualization of the vortex structure of the flow.

The effect of generation of a resonant sound oscillations at the flow out of impact swirl jets was confirmed.

The experiments showed that the approach of the flow rate of swirl flow to the critical value there is a rearrangement of the vortex structure of the flow with the formation of the system of helical vortices.

The effect of self-regulation of acoustic oscillations in the impact swirl flows was discovered.

2. Revealing of the mechanisms of vortex generation in conductive media



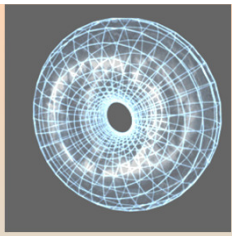
Series of experiments on generation of large-scale vortex motion in the conductive media under condition of application of external constant magnetic field while changing the potential difference between the electrodes and their different orientation relative to the force lines of constant magnetic field were carried out.

A physical model of vortex flow generated in the conductive fluids was proposed for conditions of a constant inhomogeneous magnetic field, at different mutual orientation of the force lines of electric and magnetic fields.

Numerical computations of 3-dimensional MHD flows showed that the presence of large-scale vortex structures leads to the generation of induced magnetic field at the same scale.

The configuration induced vortex magnetic field in a moving conducting medium depends on the mutual orientation of spiral-vortex motion and direction of an external magnetic field.

The results of the calculations point to the crucial role of convective transfer of magnetic field, which suggests “frozen" magnetic field, which in the considered cases is transferred by spiral-vortex structures.



3. Elaboration of theoretical modeling principles

Comparison of the results with observations allows to conclude the existence of structural invariance of the stable form of spiral-vortex motion and the possibility of using helicity to describe the structure of vortex flows.

The obtained results are intended both for engineering applications and for the development of simulation methods to predict some hazardous geophysical processes such as hurricanes, tornados, tsunami, changing the direction of ocean currents.


Thank you
for your attention!