Some research
results possible “hydraulic ram”, as a source of electrical energy without using fuel.

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The development of the theory of a water-raising device under the name of a “hydraulic ram-pump” lead to the discovery of a seminal modification of the unit. It allowed creation of a generator able to produce any industrial quantity of ecologically clean electrical power of a big commercial capacity without any fuel or solar source during several years, irrespective to weather or climate. Such generator can be used as a power station for a flat or a house, as a power plant for an industrial object, as a source of energy for an electric vehicle, an airship, an aircraft, an underwater vehicle, a surface ship and a spaceship. The output characteristics of the generator obtained during the pilot project are not very different from its design characteristics.

In 1775 one of English magazines published an article by J. Whitehurst, in which he described a device invented and manufactured by him in 1772. The device allowed raising water to a considerable height without the use of the potential energy of water at the expense of so-called “water-hammer” phenomenon. The device could not run automatically at that time. In 1776 French inventor of the balloon, J. Montgolfier, eliminated this disadvantage and obtained a patent for his improved version. In 1797 T. Jefferson and R. Fulton in England developed similar facilities. J. Madison and S. Hallet created equivalent devices in 1809 in America. The history of the inventions of these devices [1] is well known. In subsequent years, other inventors developed various modifications of the same mechanism. However, J. Montgolfier was assumed to invent a device, which became known as a "hydraulic ram" later.

The fact that a "hydraulic ram" required no additional energy for raising water attracted scholars and practitioners for a long time. The hydraulic ram was developed for melioration purposes and for different household needs in America, Australia and other countries. In these countries, there are now several dozen companies specializing in the manufacture and sale of hydraulic ram-pumps. Internet stores all names of the companies, as well as a large number of publications on hydraulic ram-pump.

In Russia, the research of a hydraulic ram-pump was started by N. Zhukovsky in 1897 [2] and continued by his students and followers. The final unification of all the theoretical and experimental studies happened in 1930 due to Professor S. Chistopolsky [3]. His method of theoretical calculation of a hydraulic ram-pump gave results, which were in good agreement with the experimental studies.

However, in spite of its simplicity and low cost, a hydraulic ram-pump, as a water-raising device, has a significant limitation. For high pressure of a certain part of the water, it requires outward overflow of a significantly larger mass of water. The water, pouring outside from the waste valve, must immediately make room for a new similar portion of water, which is expected to outflow in the next cycle. When water accumulates at the output drainage hole there appears resistance to its outflow. It can result in violation or termination of the acceleration of water in the drive pipe. This disadvantage does not allow using the device on flat areas with open ponds and rivers without slopes of the land or without dams.

After the appearance and development of such branch of science as “hydraulic gas dynamics”, there were numerous attempts to find an exact solution to the existing hydrodynamic equations - in order to explain all the processes and to find optimal characteristics for the hydraulic ram. However, a solution for the process of an unsteady or *non-stationary* flow, i.e. the process of water flow in a hydraulic ram-pump, becomes possible only with the use of numerical methods requiring knowledge of many previously unknown values. That is why those attempts were not successful. This is proved by the fact that before 2005 investigators received a number of different patents for the modernization of the device. Nevertheless, they did not touch modification or improvement of the very principle of its operation based on periodic acceleration of water driven by periodic draining and periodic "water hammer" at periodic deceleration of water. However, a closer examination of the theory of the "hydraulic ram" developed by S. Chistopolsky provided sufficient understanding of the factors and parameters affecting the "hydraulic ram" and gave an opportunity for a comprehensive analysis of the process.

The analysis revealed a possibility to create one more scheme of periodic acceleration of water or other liquid – with the same periodic "water hammer", but without its periodic draining. The principle allowed development of a water-raising device [4,5] working while fully submerged into water. A patent [6] for such a device was obtained in 2006. The device had limitations inherited from the initial hydraulic ram pump. It also used mechanical valves, which hampered the speed of the device because of the large inertia, and consequently stopped introduction of smaller dimensions and higher powers. Moreover, the device had the third inlet valve, which provided the revolutionary characteristics to the device. After further development, this third valve was replaced by a more advanced scheme of hydraulic ram - also without periodic water draining and with two valves, like in a traditional hydraulic ram pump. Such water-raising device got a patent [7] in 2007.

In the years followed, a more rigorous study of the device and the same theory of the hydraulic ram revealed opportunities for further improvement of the device. The version is devoid of the main limitations of the hydraulic ram, features maximal simplicity and maximum operational speed. The principle outline of such device is given in Figure 1.

The unit includes a pipe 1, a pipe 2, a disc shock valve 3, a leak-proof membrane 4 and an airless Chamber 5. The internal sectional area of the pipe 2 is much larger than the area of flow section of the pipe 1. The ratio of the length of the pipe 1 to its diameter does not exceed five. The device is fully submerged in the fluid 7 of the tank 6 – so that both the axis of the pipe 1 and the axis of the pipe 2 are moved from the surface at the distance “ h ”. The surface of the fluid is affected by the external pressure, which is greater than or equal to the atmospheric pressure.

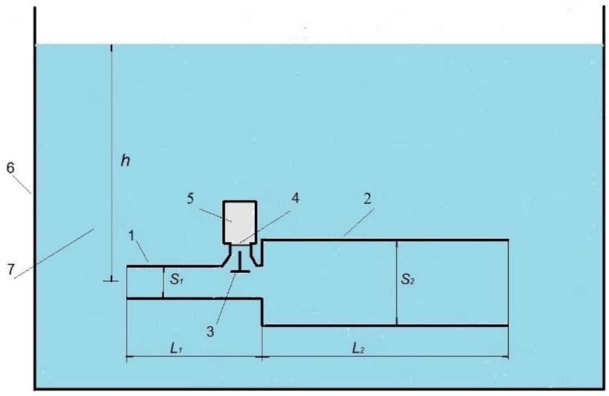

Fig.1. Schematic diagram of the device

Let us assume at the moment of the device start-up the membrane 4 is instantly and completely destroyed by some artificial means. Due to its own and the external pressure, the fluid starts flowing from the pipe 1 and the pipe 2 to the chamber 5 through the flow area of the shock valve 3 (the process is similar to the one in a standard hydraulic ram). The velocity of the fluid in this section increases during the flow, and the static pressure of the fluid in both pipes reduces.

In this device, the shock valve is designed so that after it closes (i.e. after a certain amount of fluid has flown from it) chamber 5 does not receive any new quantities of the fluid from the pipes 1 and 2. So, the effect of the «water hammer» is generated due to the almost immediate halt of the fluid (again, the process is similar to the one in a standard hydraulic ram). A part of the fluid velocity in the pipe 1 is transformed into pressure. This pressure generates pouring some amount of the fluid to the pipe 2 from the pipe 1. As a result, the water hammer causes a wave front of high pressure in the pipe 1 and a wave front of high pressure in the pipe 2, which together comprise a high pressure zone 8 (as shown in Figure 2).

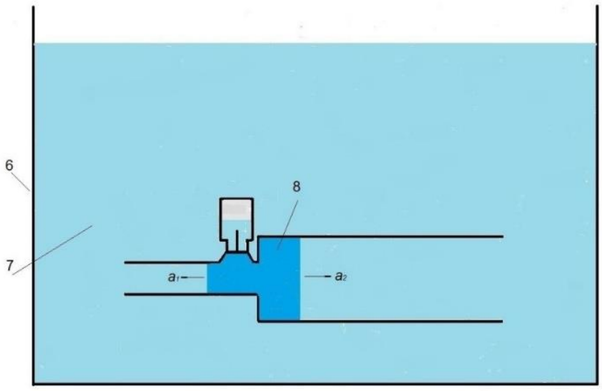

Fig.2. Zones of fluid pressure between 1/8 cycle time

The wave-front disturbance in the pipe 1 moves to its inlet with the disturbance velocity “a_1”, and the wave-front disturbance in the pipe 2 moves to its outlet with the disturbance velocity “a_2”. The behavior of the fluid flowing from the pipe 1 to the pipe 2 differs from overflowing of the non-straitened fluid from the pipe 1 at an abrupt expansion of its section. In a water hammer, the fluid from the pipe 1 with an abrupt expansion of its section is delivered into an infinitesimal volume defined by the extension of the wall of the pipe 2 due to its elastic deformation. So, the kinetic energy of the fluid coming from the pipe 1 is completely transferred to a potential energy.

In this device, the pipe 2 has such length that the wave-front disturbance in the pipe 2 and, consequently, the high-pressure zone 8 reaches the center of the pipe 2 during the time while the wave-front disturbance in the pipe 1 reaches the inlet of the pipe 1 (as shown in Figure 3).

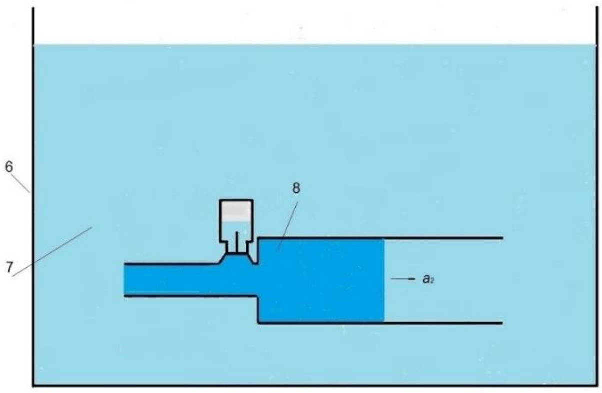

Fig.3. Zones of fluid pressure between 2/8 cycle time

The first 2/8 cycle of the fluid pumping from the pipe 1 to the pipe 2 is finished.

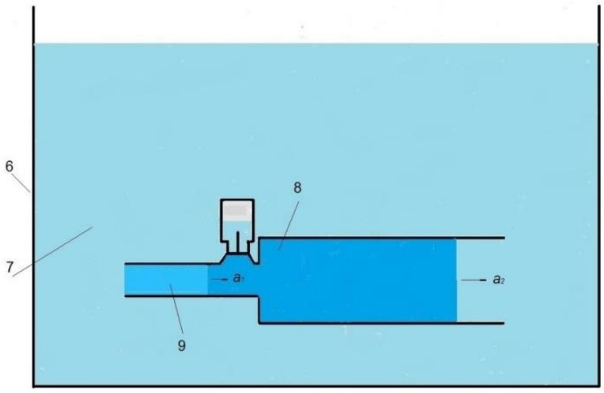

Fig.4. Zones of fluid pressure between 3/8 cycle time

In the second 2/8 cycle of the fluid pumping from the pipe 1 to the pipe 2, the disturbance wave-front in the pipe 1 reflects from the stationary fluid in the tank 7 and then starts moving to the pipe 2 (see Figure 4). The disturbance wave front in the pipe 2 continues its motion to the outlet of the pipe 2. We have a low-pressure zone 9 formed from the inlet on the pipe 1 to the disturbance front in the pipe 1 – like in a common hydraulic ram. By the moment, when low-pressure zone 9 occupies the total volume of the pipe 1, the high-pressure zone 8 of the pipe 2 occupies all the volume of the pipe 2 (as shown in Figure 5).

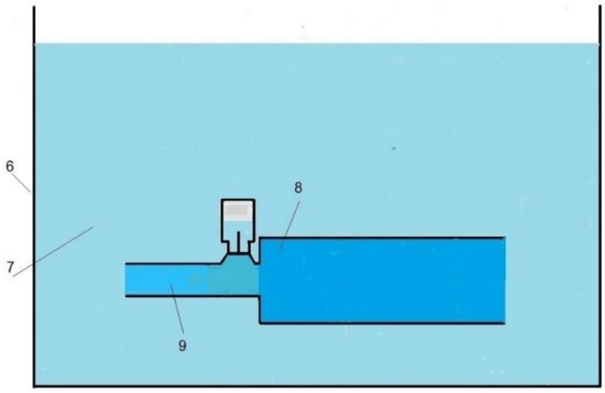

Fig.5. Zones of fluid pressure between 4/8 cycle time

The second 2/8 cycle of the fluid pumping from the pipe 1 to the pipe 2 is finished. During the third 2/8 cycle of the fluid pumping from the pipe 1 to the pipe 2, the disturbance waves in the pipe 1 starts moving again in the direction of its inlet (as shown in Figure 6).

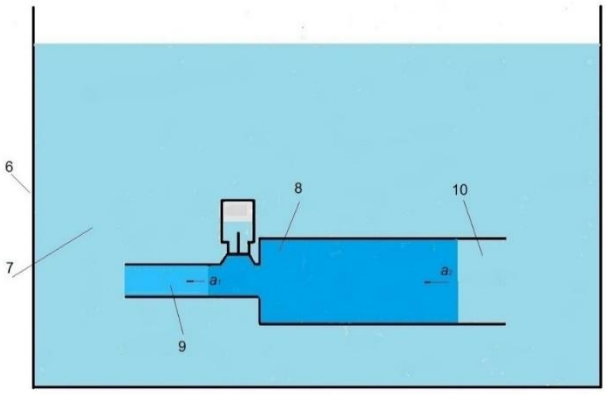

Fig.6. Zones of fluid pressure between 5/8 cycle time

The disturbance waves in the pipe 2 reflects from the stationary fluid in the tank 7 and then moves to the pipe 1. We have a low-pressure zone 10, where the fluid pressure is less than the one in the zone 8 but larger than the pressure of the stationary fluid in the tank. The fluid in the zone 10 gets some velocity directed from the pipe 2 into the tank 7 – due to the energy released by the material of the wall of the pipe 2 during removing the load from the high pressure in the zone 8 at the part of the pipe within the low-pressure zone 10. At the moment, when the disturbance waves in the pipe 1 reaches the inlet of the pipe 1, the disturbance wave-front in the pipe 2 reaches the center of the pipe 2 (see Figure 7). It is the end of the third fourth of the fluid pumping from the pipe 1 to the pipe 2. Finally, there is the last (forth) stage of the cycle of the fluid pumping from the pipe 1 to the pipe 2.

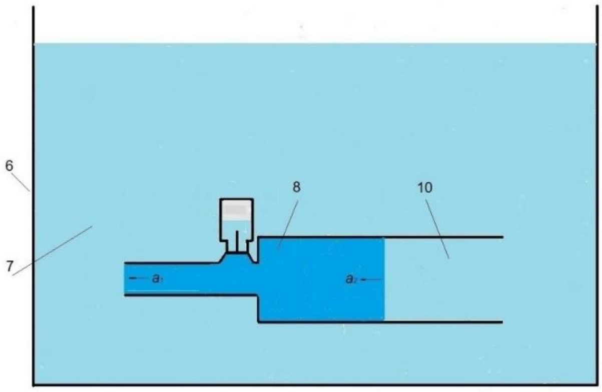

Fig.7. Zones of fluid pressure between 6/8 cycle time

During this final stage of the pumping cycle, the disturbance wave-front in the pipe 1 reverses its direction and moves towards the disturbance front of the pipe 2 (as shown in Figure 8) - due to transformation of overpressure into velocity and due to another reflection from a stationary fluid in the tank 7.

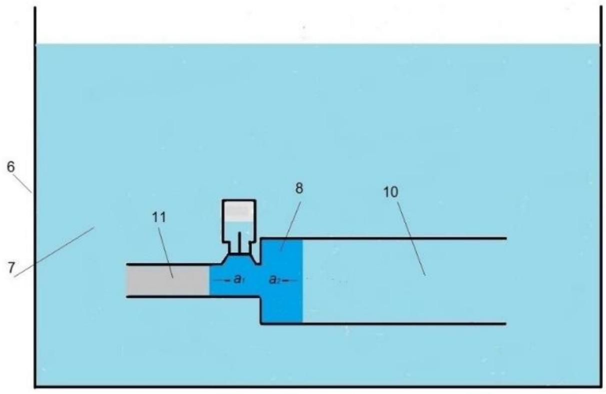

Fig.8. Zones of fluid pressure between 7/8 cycle time

In the pipe 1, a zone of low pressure 11 appears from its inlet to the disturbance wave front. Like the process in a common well-designed hydraulic ram, the fluid pressure in the zone 11 becomes less than the pressure of the stationary fluid in the tank 7. The fluid velocity in the low-pressure zone 11 is directed to the inlet of the pipe 1, i.e. to the stationary fluid of the tank 7.

When the disturbance wave front in the pipe 1 reaches the end of the pipe 1 (= ending of the pipe 2), the high pressure in the zones 8 of both pipes ceases (please, see Figure 9).

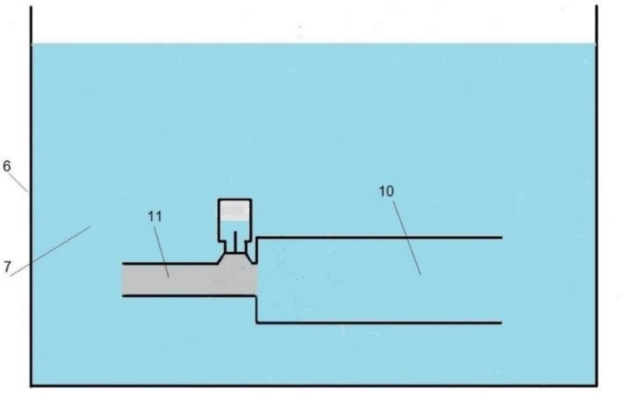

Fig.9. Zones of fluid pressure between 8/8 cycle time

Confrontation of the fluid pressure zone 10 in the tube 2 and the zone of lower fluid pressure 11 in the tube 1 leads to a new disturbance wave in the fluid, which begins to spread in the direction of the inlet of the pipe 1. From one side, the fluid in the pipe 1, with a velocity directed to the inlet of the pipe 1, is completely inhibited by the contact with a stationary fluid in the tank 7. On the other hand, it aims to break away from the fluid column in the pipe 2. So, in the pipe 1, we observe a zone of vacuum, known from the theory of a common hydraulic ram pump. A standard hydraulic ram, the low-pressure zone and the vacuum zone are protected from leaks of fluid from the pumping chamber by a closing pressure valve. In this device, the low-pressure zone and the vacuum zone are protected the inertia of the fluid in the pipe 2. Because this inertia is enormous due to the relatively larger volume of the pipe 2 compared to the volume of pipe 1 and due to an extremely small time during which these zones exist at a small relative length of the pipe 1. Proper selection of the initial parameters for the device makes it possible that the volume of fluid coming from the pipe 2 to the low-pressure zone 11 in the pipe 1 will not exceed 5% of the initial volume of fluid in the pipe 1. The contact of the disturbance waves front of the moving fluid with the fluid in the tank 7 at the inlet of the pipe 1 generates full inhibition of the fluid in the pipe 1. So, in spite of pouring additional amount of the fluid from the pipe 2, such contact causes an increase of the total fluid pressure in the pipe. However, this fluid pressure is much lower than the pressure of the stationary fluid in the tank 7.

The contact of the disturbance wave front of the moving fluid with the fluid in the tank 7 generates a new disturbance front in the pipe 1, which moves towards the pipe 2 with a disturbance velocity “a_1”. The fluid in the disturbance zone 11 of the pipe 1 obtains the velocity, the magnitude of which is determined by the difference between the pressure of the stationary fluid in the tank 7 and the pressure of the fluid in the low-pressure zone 11. The pressure increment of inhibiting fluid and receipt of some quantity of the fluid from the pipe 2 have to be considered. This velocity can be called the velocity of the fluid acceleration after a pumping cycle. When the disturbance waves front 11 reaches the coupling the pipes 1 and 2, the fluid pressure in the entire volume of the pipe 1 is aligned to become equal to a pressure of fluid in the tank 7. After the contact of the moving fluid with the stationary fluid in pipe 2, there occurs "water hammer".

The equations and formulas obtained by the method used by S. Chistopolsky show that the parameters of this device depend mainly on

- the values of the fluid velocity “υ_{01}” at the moment of liquid halt in the pipe 1 and closing the shock valve 3
- the ratio of this velocity to the disturbance velocity in the fluid “a_1”
- the ratio of the fluid disturbance velocities “a_1 / a_2”.

If the ratio "υ_{01} / a_1" is more than a certain number, the acceleration speed of the fluid after the pumping cycle can be greater than a part of the velocity at the increasing pressure in the first water hammer slightly less than the velocity "υ_{01}". Then, with a new inhibition of the fluid in the pipe 1 against almost static fluid in the pipe 2, the water hammer occurs, and the second pumping cycle begins. At the end of the second pumping cycle (i.e. before the third pumping cycle), with a stable temperature of the fluid and its pressure in the tank 7, the new fluid acceleration velocity in the pipe 1 is equal to the fluid acceleration velocity before the second pumping cycle. The fourth, fifth and other pumping cycles are carried out similarly. As a result, after the time "$12L_1 / a_1$", all the parameters of the fourth, fifth and other pumping cycles are also similar. A pumping cycle with such intact terminal parameters becomes an established pumping cycle. Nevertheless, for creating an established pumping cycle, in addition to a certain fluid velocity "υ_{01}", it is necessary to properly implement a certain ratio "S_1 / S_2" and existence of a certain fluid pressure "P_h" in the tank 7. For creation such established pumping cycle we need to know the calculated value of the ratio "S_1 / S_2", the parameter "$\gamma a_2^2 / gP_h$", by which it is possible to find P_h via a known specific fluid gravity "γ", and the ratio "υ_{01} / a_1". They are given in the Figures 10, 11, 12.

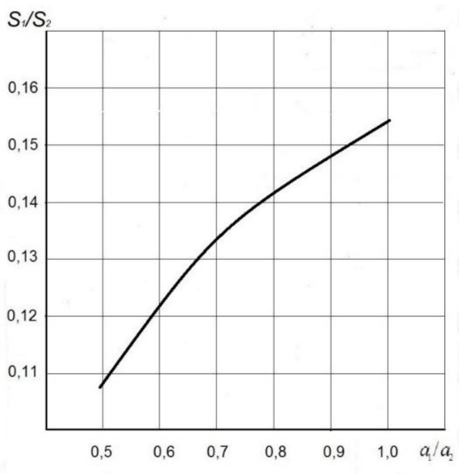

Fig10.Dependency of ratio S_1/S_2 on the ratio a_1/a_2

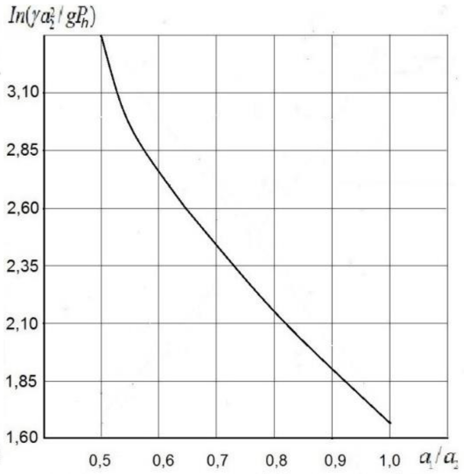

Fig11.Dependency of ratio $\gamma a_2^2/gP_h$ on the ratio a_1/a_2

The value of the fluid pressure "$P_k^/$", which appears in the zone 8 of the pipe 2 under the parameters listed above, is given in Figure13.

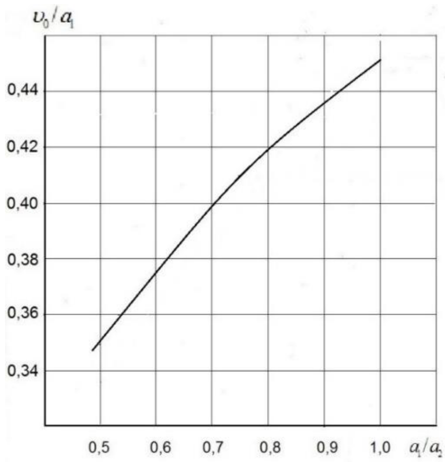

Fig12.Dependency of ratio υ_0/a_1 on the ratio a_1/a_2

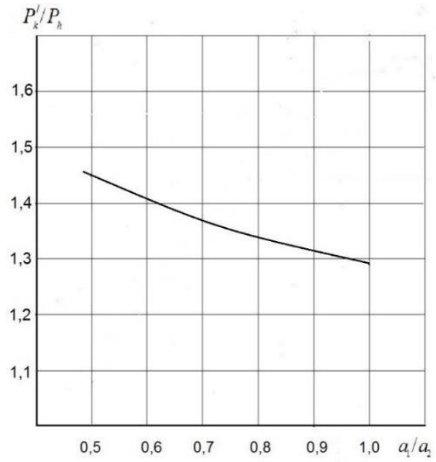

Fig.13.Dependency of ratio P_k/P_h on the ratio a_1/a_2

In this device, the time of every pumping cycle is equal to "$6L_1 / a_1$". During this time, the pipe 1 receives fluid in the quantity equal to the quantity of the fluid flowing back to the tank 7 from the pipe 2. The level of the fluid in the tank 7 after it goes to the pipe 1 decreases pro rata the increase of the fluid level in the tank 7 during its outflow from the pipe 2. It is a consequence of the law of conservation of mass. The process of the fluid pumping happens during the same time (during "$4L_1 / a_1$" to be exact). It means the transfer of the fluid energy to the walls of the pipe 2 and the expansion of the section of the pipe 2 and the return of energy back into the liquid due to elastic forces at restoring the section of the pipe 2. The potential energy acquired by the amount of the flowing fluid during pumping from the pipe 2 into the tank 7 during increasing the fluid level in the tank is necessary for the next pumping cycle. It is greater than the energy required for the fluid acceleration in the pipe 1 before the current cycle. This potential energy is less than the energy spent for fluid acceleration and the energy left in the pipe 1 after the previous pumping cycle in total. The ratio of the potential energy acquired by the quantity of fluid during pumping from the pipe 2 to the tank 7 and the total energy of the fluid from the pipe 1 before each pumping cycle can be considered the efficiency factor of the device. With the parameters indicated in Figures 10,11,12,13 this efficiency factor is less than 1. So, the work of this device does not break the principle of conservation of energy.

This device can be called an «undamped fluid oscillatory circuit» - due to ability to generate identical and non-damped cycles of increasing and decreasing of fluid pressure with a frequency equal to "$a_1 / 6L_1$". The exciter for its operation is a one-time artificially created acceleration of the fluid in the pipe 1 and the pipe 2. The ability to produce non-damped cycles of increasing and decreasing the fluid pressure is a result of the elasticity of the material of the pipe 1 and the pipe 2, as well as a result of a certain transformation of gravitational energy.

However, such a unit cannot be used as water-raising device in the form as it is presented. Because the outlet of the pipe 2 is to contact with the stationery liquid and should not be blocked even partially for withdrawal of the outflowing pressurized fluid. Besides, it theoretically can work only in an open tank at a depth of immersion into the liquid equal at least 30 m – even if the pipe 1 is made of engineering plastic with minimum currently possible coefficient of elasticity.

However, if the ratio "S_1 / S_2" is made less than the ratio from Figure 10, then the pressure required for normal operation can be reduced to pressures close to atmospheric. Such devices [8] can be applied in the situations when effective power is generated by a jet of liquid.

A required fluid pressure can be created artificially in case this unit is placed to a closed tank. Such pressure can be created by gas pressure above a fluid surface provided by a pump or any other means. The volume for the gas in the closed container must be large enough – so that increase and decrease of the fluid level during the work would comprise fractions of a percent of this amount and would not lead to a noticeable increase or decrease in gas pressure or to periodic heating and cooling the gas. Although during the pumping cycle time "$6L_1 / a_1$", which is fractions of a millisecond with a small length of the pipe 1, increase of the gas temperature, the walls and the fluid must be absent due to the equality of the increasing and decreasing fluid levels.

At a high initial fluid pressure, the "undamped fluid oscillatory circuit" can be utilized as an electric generator – in case the pipe 2 is made fully or partially of a piezoelectric material.

Let us consider a simple case, when the pipe 2 is made fully of a piezoelectric material. Here it represents a cylindrical capacitor, since the opposite sides of the surfaces of a piezoelectric material always have thin metal layers for accumulation and removal of electric charges. During expansion of the pipe walls under fluid excessive internal pressure, the number of generated electrical charges are proportional to this pressure. Since the tension of the electric field of accumulated charges in the capacitor is proportional to the number of charges, the accumulated electric energy is proportional to the square of the overpressure. The average rate of accumulation of this energy is the ratio of the accumulated energy to the pumping cycle time. If during the cycle time the discharges occur in the quantities equal to the generated number of charges, the average rate of accumulation of energy is equal to the average electric power of energy.

If piezoelectric material is placed between two metal shells, which have much greater thickness than the usual thin plating of silver, the pressure on the piezoelectric material can be made larger in magnitude than the difference " $P_k^/ - P_h$ ". For this, the outer shell must have thick walls, high strength, with the elastic modulus several times larger than that of the piezoelectric material, and play the role of an elastic, hardly deformed platform. The inner shell must have thin walls, high strength, with the elastic modulus close to the modulus of elasticity of the piezoelectric material. Then the pressure on the piezoelectric material can reach the value " $0,9P_k^/$ ". Besides, a design of the tube 2, where the ends of the pipe are closed with strong dielectric plugs, allows the piezoelectric material to withstand a greater pressure than the admissible pressure, without its destruction. All possible gaps between the shells should be eliminated.

PVDF-based piezoelectric ceramics, composites and films are examples of piezoelectric material for the use in the pipe 2. The materials are also utilized in a device named 'water hammer electric generator" [9].

In such version of the pipe 2, the electric power of the generated electric charges is proportional to the square of the pressure on the piezoelectric material and the ratio of the square of the piezoelectric module of the material to the value of the dielectric constant of this material. The latter is called "elastic compliance." A piezoelectric material with greater elastic compliance is more suitable for pipes 2.

Modern piezoelectric industry manufactures various piezoelectric materials. Piezocomposites have highest values of "elastic compliance". But they cannot yet be used in this device, because they have a porous structure and therefore collapse under hydrostatic pressure. Out of all PVDF-based piezoelectric ceramics and films the piezoelectric ceramics, the piezo ceramics "APC-855" [10] and "ЦТС-19М" [11] are preferable. Figure 14 shows the calculated dependence of the parameter " N_z / P_h^2 " from the parameter " a_1 / a_2 ". The case is done for a composite pipe 2 with the outer diameter 100 mm and the inner diameter 73 mm. The pipe can include a standard piezoelectric ceramic tube "APC-855" with the outer diameter 85 mm and the inner diameter 77 mm. The outer shell is assumed to be made of alloyed steel with yield limit 1000 MPa. The inner shell is assumed to be made of titanium alloy with yield limit 500 MPa.

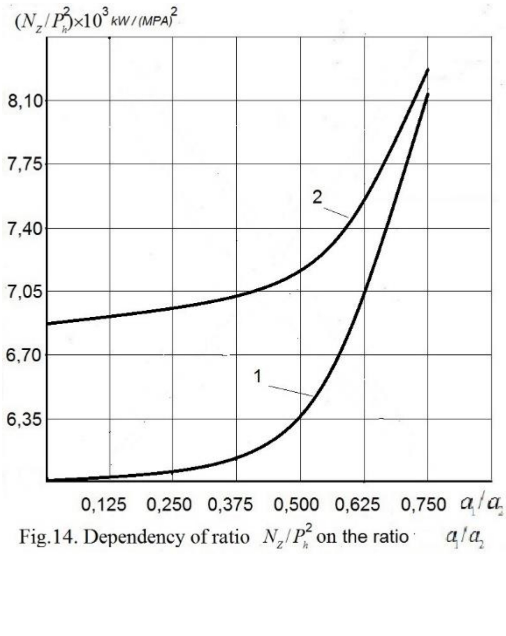

Fig.14. Dependency of ratio N_z/P_h^2 on the ratio a_1/a_2

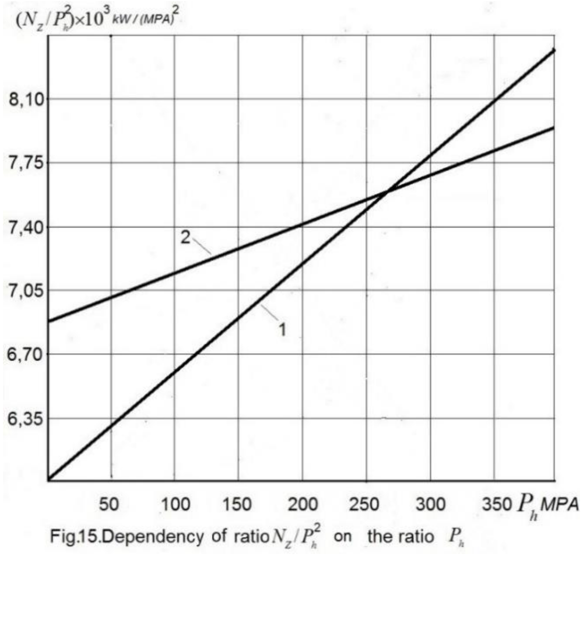

Fig.15.Dependency of ratio N_z/P_h^2 on the ratio P_h

By the ratios from Figures 14,15 and 11, we can determine the power of generation of electric charges “ N_z ” from the pressure “ P_h ” for the given pipe 2. The dependency “ N_z ” from the pressure “ P_h ” is given in Figure 15. The dependency 1 illustrates the case where the fluid is distilled water. The dependency 2 is the case where the fluid is glycerol. Maximal possible power “ N_z ” is determined by the strength of the pipe 2.

For the sample pipe 2, Figures 16 and 17 show calculated dependencies of the tensions “ σ_{21} ” in the shell 1 and the tensions “ σ_{23} ” in the shell 3 during the expansion of the pipe 2 under the pressure “ $P_k^{/}$ ”, depending on the initial fluid pressure “ P_h ”.

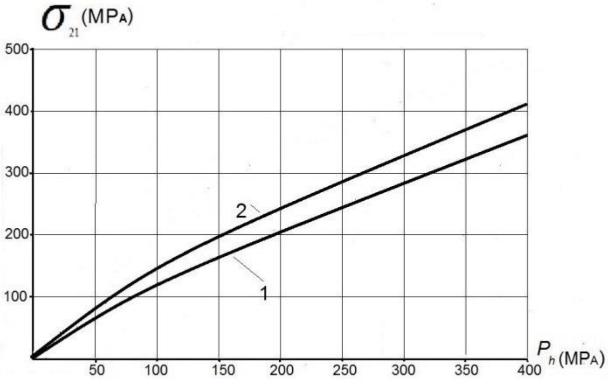

Fig.16.Dependency of ratio σ_{21} on the ratio P_h

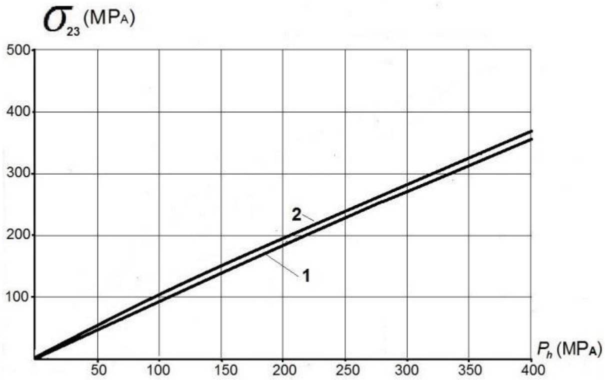

Fig.17.Dependency of ratio σ_{23} on the ratio P_h

The dependency 1 illustrates the case with distilled water. The dependency 2 is the case with glycerol.

Let us we assume that the tensile stress of the shell 1 does not exceed half of the yield limit of its material, i.e. stress safety factor for this shell must be more than two. Then for this example, the admissible fluid pressure “ P_h ”should not be more than 260 MPa for distilled water and 290 MPa for glycerol. Therefore, the maximal power “ N_z ”of the example based on the values “ N_z / P_h^2 ” from Figure 15 can be 528 kW for distilled water and 513 kW for glycerol. The values of tensile stress of the shell 3 are also almost identical for these fluids.

For distilled water, the power $N_z \cong$528 kW must be achieved at $a_1 / a_2 =$0,6875, $a_2 =$1866 m/sec, $a_1 =$ 1283 m/sec, $S_1 / S_2 =$0,1317. So, at $S_2 = 4{,}1833 \times 10^{-3}$ m², which corresponds to the given inner diameter of the pipe 2, the dimension of the inner diameter of the pipe 1 must be 26.5 mm. If the assumed ratio of the length of the pipe 1 to its inner diameter is equal to 4, then $L_1 =$106 mm and $L_2 =$308 mm. Then, with the outer diameter of the pipe 2 of 100 mm, the capacity of the “undamped fluid oscillatory circuit” does not exceed 3230 cm³. And the ratio of the power “ N_z ” to the volume of the circuit producing this power is not less than 163.6 kW/dm³, which is more than twice bigger than any hydrocarbon fuel electric generator.

Thus, use of piezoelectric material in the pipe 2 and dielectric fluid as the working fluid makes this device a compact and simple source of electric current of high industrial power.

If such piezoelectric material is simply attached to a sequential load, there will be no substantial current through the load, because the resistance of piezoelectric material with smallest thickness is millions of times more than the load.

The electric charges generated by the piezoelectric material can be transformed into electric current only by certain electrical circuits with electronic components, which provide the required parameters of the electric current, e.g. by a simple electrical circuits [12] given in Figure 18.

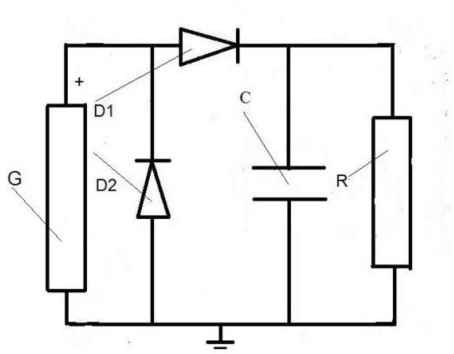

Fig.18.Driving piezoelectric conversion into electric charges

The main element of such electrical circuit is the reservoir capacitor “C”, which is constantly discharged to the load “R” for producing electrical current. The diodes “D_1, D_2” are used to prevent the outflow of the charges from the capacitor “C”. The charges are produced by a piezoelectric generator “G” in a period when the piezoelectric material is affected by pressure.
Large initial fluid pressure may cause high voltage of an electric field of generated charges. The ratio of this voltage to thickness of the piezoelectric material tube cannot exceed a certain value, at which the piezoelectric material begins the process of changing the polarity of the voltage and excessive energy is absorbed. The ratio of the maximum possible voltage of the electric field to the thickness of the piezoelectric material is not more than 7000 volts / mm for most brands of piezoelectric ceramics. While using the piezoelectric ceramics «APC-855» and distilled water as the fluid at the dimensions of this piezo ceramics and the pipe shells listed above, the maximal voltage is obtained with the initial fluid pressure 310 MPa. Creating the indicated initial fluid pressure is possible if the shell 1 is made of titanium alloy with a yield stress not less than 600 MPa. In this case, the calculated power of the device using water will be 746 kW. Reducing the tension of the electric field of generated charges requires electrically parallel connection of an additional capacitor to the metal shells of the pipe 2. Such method is applied for all explosion piezoelectric generators [13]. Any structural element of the pipe 2 can serve as an additional capacitor.
The equations and formulas used for calculation the parameters in Figures10-17 do not consider volumetric flow of the fluid, presence of breaks in the fluid column in the pipe 1 forming local vacuum zones, possible change in the energy balance from the cyclic compression and expansion of the gaseous medium, the influence of possible technological gaps between the shells of the tube 2 on the piezoelectric material, and a number of other factors.
In this connection, we carried out an experimental verification of results of calculation of these equations and formulas. We created a real electric power generator with the maximal capacity 156 kW. The principle scheme of this electric generator is shown in Figure19.
The experimental generator is a cylinder with diameter 200 mm, length 1000 mm and mass 180 kg and has a sectional sealed casing 4,5 made of high-strength alloy steel, which is capable to resist internal pressure up to 500 MPa. The inner area of the casing 4 and 5 contains a vertically located “undamped fluid oscillatory circuit”. The latter is formed by the pipe 2, the shock valve 3 and the pipe 6 consisting of the metal shells 6 and 8, between which there is a tube 7 of piezoelectric ceramic “APC-855”. For creation of uniform compression, the ends of the tube 7 are tightened in the shells 6 and 8 by the spacers 9 made of conventional ceramic without any piezoelectric properties.

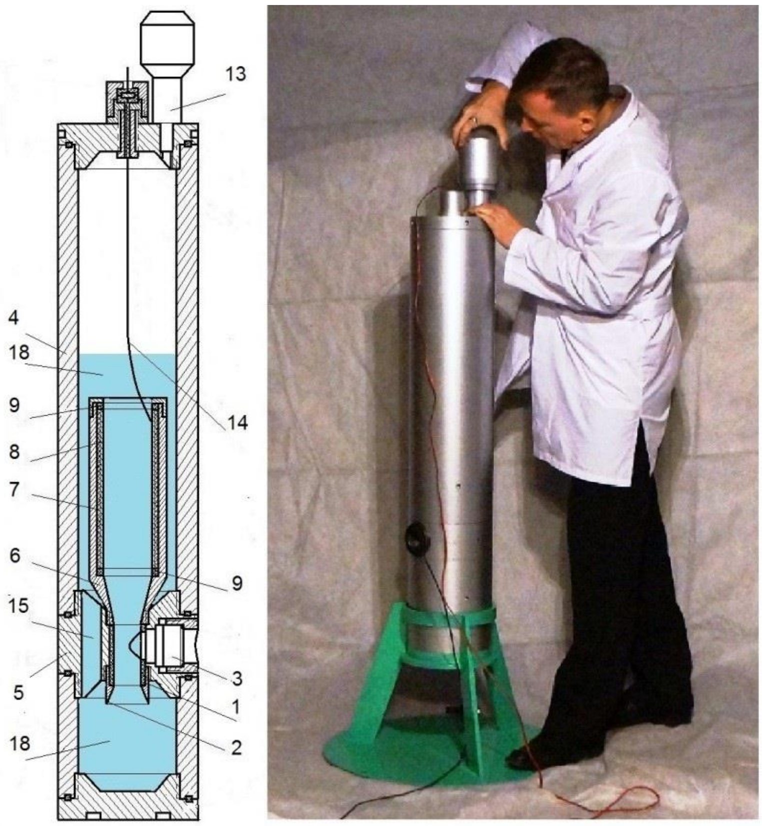

Fig.19. The main elements of the desing and appearance of the electrogenerator

The “undamped fluid oscillatory circuit” is totally immersed into distilled water 18. For free flow of the water from the upper part of the inner area of the casing 4 and 5 to its lower part and, consequently, for return of the water flow from the pipe 6 to the pipe 2, the casing parts 5 has a perforating hole 15. For supporting the given ratio “a_1 / a_2” in the cylinder part of the pipe 2, we use a cylindrical insert 1 made of engineering plastics.

The electric generator utilizes a shock valve 3, its design is shown in Figure 20.

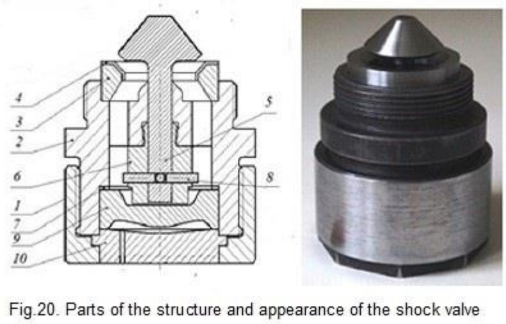

Fig.20. Parts of the structure and appearance of the shock valve

The valve has a movable metal rod 5 a semi-conical front section, capable to move freely in the parts 2 and 6 under the water pressure. In its initial position, the rod 5 is fixed in the cage 6 by four pins 8. The fluid in the valve, pressurized by gas, is held by the part 9, the sealing gasket 7 and the membrane 10. The part 9, the sealing gasket 7 and the membrane 10 are tightened by the nut 1 for better strength and impermeability. Shock valve opening is achieved by shearing the clamped edges of the membrane 10 due to the gases of a powder charge, which is located in the cavity formed by the part 9 and the membrane 10 and combusted

through the hole in the membrane 10. As a result, the water begins to run with increasing velocity through the opened orifice formed by the contours of the parts 2,3,4,5 before the movable rod 5 blocks this orifice.
The design and weight of the parts 5,8,9,10 provided a much lesser time of the membrane 10 shearing compared to the time of water acceleration in the shock valve.
For creation a required initial gas pressure over the fluid surface, we use nitrogen, injected in advance after pouring the fluid through the check valve 13. There is no drain chamber for draining water through the shock valve in this power generator, as its initial parameters provide that the water pressure at the end of each pumping cycle is greater than the atmospheric pressure.
The appearance of several parts and elements of the electric generator are shown in Figure 21.

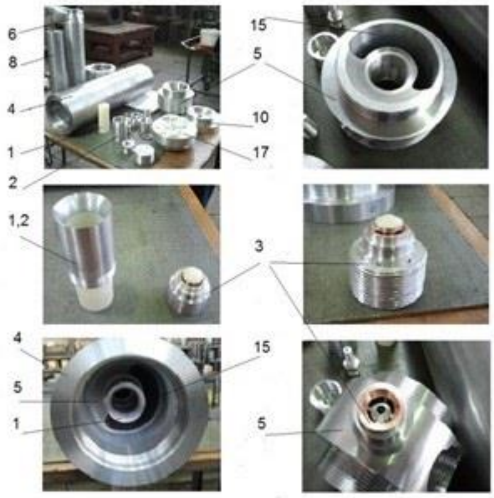

Fig.21. Elements of design of electric generator

There were two stages of testing electric generator. The testing, as well as the evolution of a common water hammer to an undamped fluid oscillatory circuit and a generator with a piezoelectric source of energy, are described in the documentary film "Evolution" [14].
At the first stage, instead of a piezoelectric material shell, we used a duralumin shell, because the tensile modulus of duralumin is very close to that of the piezoelectric material, and several shells 6 of the pipe 2 with different lengths of the conical segment. The length of the shell 7 was invariable.
Such conditions allowed determination of the parameters of the "undamped fluid oscillatory circuit" without any possible impact of the processes connected with electrical breakdown of the fluid, destruction of the piezoelectric material or invalid solutions of obtaining some output characteristics of the electric current.
This stage included determination of the powder charge mass for shearing the clamped edges of the membrane 10, the stress of shear of the material of pins 8 of the shock valve, the values of the parameters "$P_{k1}^{/}$", "a_1, a_2", the value of the velocity "υ_{01}" and the optimum length of the conical segment of the pipe 2.
In the section of the pipe 1 with the shock valve 3, we installed a low-inertia pressure sensor [15]. A similar sensor was placed in the metal tube of a relatively small diameter; the tube was arranged in the pipe 2 along its central axis. A metal pipe probe with a sensor was mounted so that one of its ends approached the area of conjugation of the pipe 2 with the pipe 1, and its other end came out from the top cover of the casing 4 and 5 - via a special insulation and sealing unit, utilized for output the generated electric charges in the second test stage.
At shearing of the pins 8, during the time from the cut of the membrane 10 till the close of the shock valve, the pressure sensor in the metal tube probe measured the static pressure drop, caused by acquisition of the

water velocity in the pipe 2, and the value of this velocity (based on the pressure drop). Then, with the help of the charts of the measured pressure in the pipes 1 and 2 (see Figure 22), we defined the pressure "P_{k1}" in the pipe 1 and the pressure "P_{k2}" in the pipe 2 produced till the moment of occurrence of a steady cycle. The values of the disturbance propagation velocity "$a_1 = L_1 / 2t_2$" and the disturbance velocity "$a_2 = 2L_2 / t_3$" were determined by the periods of pressure duration (t_2 in the pipe 1, t_3 in the pipe 2) .

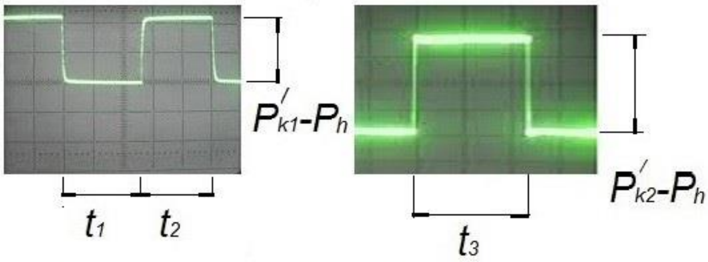

Fig.22. Flow pressure in the pipe 1 and the pipe 2

By variations of the impact of the powder charge mass, the nitrogen pressure, the material strength of the pins 8 on the cut and lengths of the conical part of the shell 6, we got the equations "$t_1 = t_2$" and "$P_{k1}^{/} = P_{k2}^{/} = P_k^{/}$". It testified to obtaining steady operation.

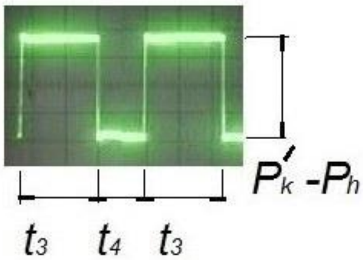

Fig.23. Flow pressure in the pipe2

In the diagram of the measured pressure in the pipe 2 (Figure 23), the pressure in the pipe 2 after the time "t_3" equal to 0.342 milliseconds ("t_3" = 0.333 milliseconds - calculated value) turned out to be 243 MPa (247 MPa - calculated value) and remained unchanged during any time of the measurement. The pressure in the pipe 2, which is equal to 243 MPa, was periodically and consistently repeated with an interval with duration t_4. It testified existence of a steady cycle with pressure "$P_k^{/}$" equal to 243 MPa. The maximum value of pressure equal to 243MPA was simultaneously recorded in the pipe 1.
So, under the reference data taken in the design of the generator, we experimentally obtained the following main parameters: "a_1=1021 m/sec", "a_2=1665 m/sec", "a_1 / a_2= 0,613", "L_2= 0,277 m", "υ_{01} =392,1 m/sec". These parameters are not significantly different from the theoretical parameters.
At the second stage of tests of the electric generator with the length of the shell 6 (Figure 19), equal to 0,277 m, we used a shell 7 (Figure 19) of a piezoelectric material. These tests demonstrated recurrence of the pressure diagrams presented at Figure 22 and 23.
With the pressure "$P_k^{/}$", equal 243MPa in the shells 6 and 8, the theory expected the voltage of the electric charges equal to 19500 volts. This voltage should have corresponded to the maximum electric power "N_z", equal to 144 kW.

In the design of the electric generator (Figure 19), a steel wire 14 brought out the electric charges generated by the piezo ceramic. It was attached to the shell 8 by a screw at one end and, at the other end, to the electrical terminals coming out through an electrically insulating ceramic tube of insulation and sealing unit in the top cover of the casing 4 and 5. The wire14 was the positive electrode; the casing 4 and 5 was the negative electrode.
For transformation of the generated electric charges into electric current we used by an original circuit scheme shown in Figure 24.

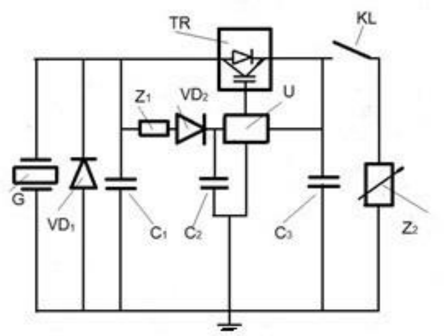

Fig.24. Scheme of transformation of electric energy

The scheme contained:
- high voltage diode "VD_1" consisting of two serially connected diodes "SSDF10H6004" [16]
- transistor "TR" ("T0900DF65A" [17] in our case)
- capacitor "C_1" = 4.7 μF, to limit the voltage at the input of the transistor "TR" to 5400 volt,
- resistor "Z_1",
- diode "VD_2" and capacitor "C_2", for to supply of the control unit "U",
- storage capacitor "C_3" = 240 μF (a powerful capacitor "КПЕ-8-240" [18] in our case)
- resistor "Z_2", consisting of six multifunctional parallel connected load modules "АКИП-1341" [19] with a total power handling of up to 180 kW.

With the expected electric power of 144 kW and the identical power at the resistor "Z_2", we had a task to receive a stabilized voltage of 220 volts at the resistor "Z_2" and the capacitor "C_3".
The work of this electrical circuit is as follows:
With the open key "KL", the transistor "TR" was opened for a limited time and not completely by the block "U". The load circuit received an added transfer resistance of the transistor and the diodes. So, the capacitor "C_3" was charged only to a voltage 220 volt. Then the transistor "TR" was closed by the block "U". Following the natural reduction of voltage at the capacitor "C_3" by a certain value, the transistor "TR" was opened again by the block "U" – for a time, which is much less than the time of one operational cycle of the "undamped fluid oscillatory circuit". The capacitor "C_3" was charged again to 220 volts. Such charge-discharge of the capacitor "C_3"could theoretically be repeated endlessly.
With the closed key "KL" and the load value "Z_2" greater than the load value at the expected power 144 kW, the transistor "TR" was completely opened by the block "U" for a time required for restoring voltage at the capacitor "C_3" to 220 volts - due to a rapid drop of the voltage in the capacitor "C_3".The capacitor "C_3"

was momently discharged to the resistor "Z_2". There was electric current of a certain value at the resistor "Z_2".

Let us take a case, when the load value "Z_2" was less than load value at the expected power 144 kW, or a case of a short-circuit of the capacitor "C_3". Here, a faster drop of the voltage at the capacitor "C_3" caused a corresponding drop of voltage of electric charges in the piezoelectric generator "G". It was the reason of voltage drop in the capacitors "C_1" and "C_2" and of drop of supply voltage of the block "U", which switched the transistor "TR" to a closed state and disconnected the load from the power supply.

Direct measurements of the voltages at the capacitors "C_1" and "C_3" showed that, with proper regulation of the block "U", with any load corresponding to the power from zero up to 127 ± 3 kW, the voltage at the capacitor "C_1" was 5140±50 volts and the voltage at the capacitor "C_3" and at the load was 215±5 volts. With the load corresponding to the power 127 ± 3 kW, the voltage at the capacitor "C_3" and, accordingly, at the load was equal to zero.

Therefore, the maximum electrical power of the given electric generator was 127 ± 3 kW, which is less than the expected power 144 kW by average 12%, and less than the theoretical power 156 kW by 18%.

The lesser voltage of capacitor "C_1" is the estimated one can be attributed to a practically lower value of the piezoelectric modulus of the piezoelectric material, or to unaccounted additional contents in the chain, formed by the elements of the pipe 2 casing design, or to hydrodynamic energy losses due to the conical part of the pipe 2.

After these tests, the electric generator with the indicated electric circuit transforming the generated electric charges periodically connected to different loads (from household electric appliances to large industrial devices using single-phase DC voltage) worked non-stop for two years - at different ambient temperatures, without any changes in the pressure, power and voltage. Its casing was not significantly heated. However, a long-term operation of such generators should reduce their power in practice – due to the reduction of storage of the internal energy. Reducing the energy content is caused by decrease of the magnitude of the piezoelectric modulus of the piezoelectric material over time.

The results of the test of an experimental generator with the project power 156 kW give reasons to consider the developed theory of the "undamped fluid oscillatory circuit" and electricity-generating unit with a piezoelectric source of electric energy and the suggested scheme of electrical power conversion suitable for design and creation of similar generators with any required maximum electric power. You can become acquainted with this theory, containing 120 basic equations and formulas, in the full version [20] of this article.

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