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Negative Pressure Waves in Hydraulic Systems

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Abstract**—**Negative pressure phenomenon appears in many thermodynamic, geophysical and biophysical processes in the Nature and technological systems. For more than 100 years of the laboratory researches beginning from F. M. Donny's tests, the great values of negative pressure have been achieved. But this phenomenon has not been practically applied, being only a nice lab toy due to the special demands for the purity and homogeneity of the liquids for its appearance. The possibility of creation of direct wave of negative pressure in real heterogeneous liquid systems was confirmed experimentally under the certain kinetic and hydraulic conditions. The negative pressure can be considered as the factor of both useful and destroying energies. The new approach to generation of the negative pressure waves in impure, unclean fluids has allowed the creation of principally new energy saving technologies and installations to increase the effectiveness and efficiency of different production processes. It was proved that the negative pressure is one of the main factors causing hard troubles in some technological and natural processes. Received results emphasize the necessity to take into account the role of the negative pressure as an energy factor in evaluation of many transient thermohydrodynamic processes in the Nature and production systems.

Keywords**—**Liquid systems, negative pressure, temperature, wave, metastable state.

I. Introduction

NEGATIVE pressure is known to be one of the metastable states in which liquids can be extended up to a certain limit. Negative pressure appears in many thermohydrodynamic and biophysical processes in the environment e.g., it is a proved scientific fact that plant juice rises up the trees mainly due to negative pressure. There are several facts providing negative pressure to play an important role in some vital systems in living organisms, e.g., in the blood vessel system.

Theoretic evaluations show that in pure liquids (without admixture, gas bubbles, etc.) negative pressure may reach large values while the liquid may stand significant extending efforts. For instance, the maximum negative pressure that may be sustained by ideally pure water is estimated as $-10^9 N/m^2$. It means that an imaginable rope of completely pure water with the diameter of 0.01m can sustain a huge extending effort more than 10^5 N.

It is evident that the real experimental values of negative pressure are much less than the corresponding theoretic estimations. It is connected with the impossibility of obtaining ideally pure liquids without any "weak places" (gas bubbles, admixture, etc.) and with the circumstance that in experience, the rupture often happens not in the liquid volume but on the surface touching the walls of the vessels weakened by the existence of thin films, embryos, etc.

There are numerous results of the experimental work of static and dynamic character, where negative pressure has appeared in one, or another degree. In laboratory conditions, negative pressure apparently was first revealed in the experiences made by F. M. Donny, who used degassed sulfuric acid and obtained negative pressure only –0.012 MPa. Among the further attempts of receiving bigger negative pressure, it is worth mentioning the experiences made by O. Reynolds, M. Bertelot and J. Meyer. Basing upon a centrifugal method and using mercury, L. J. Briggs has obtained the record value of negative pressure (- 42.5 MPa). All these and other results obtained for more than a hundred years of investigations have been entirely described in the review article by Hayward A.T.J. [1]. entitled "Negative pressure in Liquids: Can it be Harnessed Serve Man?". Such a rhetorical title of the article is not occasional. As a matter of fact, beginning from the first experiences by F. M. Donny, the main conditions in the investigations for the appearance of negative pressure has been the homogeneous character of the liquid and high degree of the purity the liquid–vessel system. Significant negative pressure has been obtained under those conditions, but the results have not been practically implemented, as real liquids in the Nature and technological processes are mainly heterogeneous and compound systems. Under certain conditions regular pressure waves with positive pulse could rebound from free surface, various obstacles, interface boundary between phases, like a reflected negative pressure waves, and a wide range of theoretical and pilot modeling investigations had been carried out on this basis [2], [3].

II. Experimental

The goal of our investigations was to obtain negative pressure in real impure, unclean, heterogeneous liquid systems. The basic idea here was reaching the negative pressure due to the sudden character of extending efforts.

The invasion into the metastable (overheated) zone in the phase diagram liquid–steam is possible both by a quasi-static and an impulse methods. The gist of the impulse method is that the pressure falls so quickly that the existing centres of steam generation as bubbles, embryos, admixture, etc. have no opportunity to appear during this time. In these conditions the "purity" of system is not that decisive, and herewith there may be some states of an overheated liquid with negative pressure.

On this base long-term experimental work has been done to create impulsive negative pressure in real heterogeneous compound liquid systems, such as tap water, petroleum, solutions, etc., and to use the phenomenon of negative pressure for raising the effectiveness of various technological

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processes. Initial results of the investigations have been received more than thirty years ago [4].

The experiments were conducted the following sequence of steps: the test liquid was filled into the tank of $3m^3$ and the attached horizontal steel pipe with the internal diameter of 0.04 m and the length of 30m, and certain initial pressure P_0 , was created in the closed system with the help of compressed air. Then, the valve placed on the free end of the pipe helped to quickly open the liquid system ($\sim 10^{-2}$ sec) and oscillograms indicating the changes in the pressure and temperature in two points of the stream (0.5m and 30m away from the valve) were taken recorded by relevant transducers mounted inside of the pipe. As pressure sensors, semi-conductor strain -gauge ones were used, having uninterrupted linear characteristics in the areas of extension and compression. Tap water and such "dirty" liquids as crude oil, clay solutions were used in the tests.

The results of the numerous tests show that if the liquid system under initial surplus pressure considerably exceeding atmospheric one is opened enough quickly (the process' characteristic time is much less than the time of relaxation $t<<\tau$), then the pressure in the system falls sharply and may become negative for a short time under certain conditions with following process of its stabilization.

Fig. 1 represents the typical variation of pressure with time in crude oil ($\rho=934kg/m^3$) stream in two mentioned test points under the initial values of pressure and temperature P_0=0.7MPa, T_0=298K.

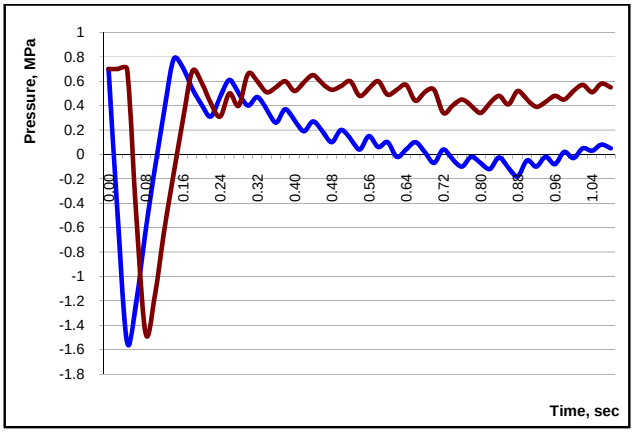

Fig. 1 Variation of pressure in two test points of a stream

As one can see the generated negative pressure appears for a short time, reaching the maximum value of –1.5 MPa during of 0.04 sec. Nevertheless it leads to the significant overheating of the liquid and to spontaneous steam generation and gas emission.

The liquid at the mouth of the pipe is like boiling system. The process is followed by quick considerable fall in the temperature of the stream (~7°-10°) after which it is slowly restored apparently due to heat transfer process accompanied by processes of cavitation, reverse condensation of steam, dissolving of the extracted gas (Fig. 2).

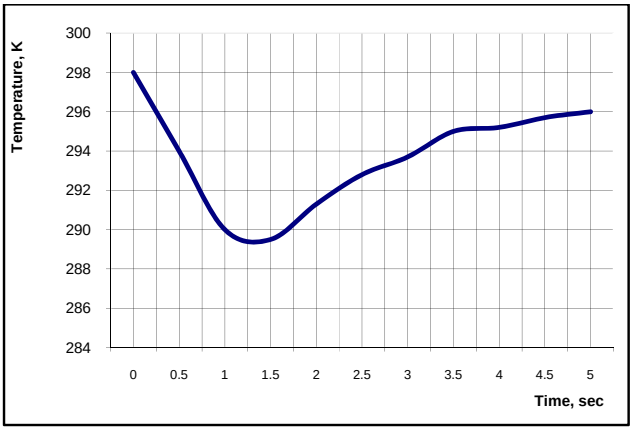

Fig. 2 Variation of a stream's temperature

The full structural restoration of the system is a long process. It may be proved by the fact that in repeated tests, for half an hour after the first one, under the same P_0, T_0, though the pressure falls sharply, the negative pressure is expressed considerably less or is not reached at all. The practically complete restoration of the system in static conditions can only be observed in 4-5 hours and the maximum negative pressure is reached again only in the first opening of the system. The temperature behaves in the same way – its maximum fall is observed in the first opening of the system, while in the next openings it is much less. E.g., in first opening of the oil stream, the maximum fall in the fluid temperature is 8.9°, whereas in following second, third and fourth openings of the unrestored system the fall of the temperature respectively equals to 2.3°, 0.6°, 0.3°. The analogous results have been obtained for a tap water, clay solutions. It has been revealed that under the less initial temperature the effect of the negative pressure appears more expressively. E.g., for water under P_0=0.5 MPa, T_0=301K, the maximum value of the negative pressure is –1.0 MPa, whereas under P_0=0.5MPa, T_0=286K the value reached is -1.4 MPa. This fact corresponds to the results obtained by L.J.Briggs who has revealed that for water at the range 278-323K the ultimate tensile strength gradually rise according to the decrease in the temperature.

Several tests have also been conducted with tap water, crude oil containing additives of various polymers and surface–active surfactants. It was revealed that the effects considerably weakened here, and under the certain concentrations of the additives no negative pressure appears in the system, that meets the known theoretic ideas on the role of surface tension in the appearance of negative pressure. The tests also show the considerable weakening of the negative pressure effect due to the increase of the gas percentage in the stream. It has been revealed that the ultimate value of the negative pressure does not appreciably rise in connection with raising P_0 within 0.5-1.0 MPa. This result shows that there is a limiting value for maximum tension which the liquid can sustain in considered conditions.

The important result of the investigation is the possibility of generation negative pressure waves in real liquid systems. As one can see from the Fig. 1, the starting phase shift between the pulses of negative pressure in two tested points is about 0.03 sec, i.e., the negative pressure as a single wave spreads with an acoustic sound velocity. The wave of negative pressure is like a turned soliton wave with one hump that is negative. It is a rather conservative wave, which mainly keeps its shape reaching the second sensor almost without loss.

There was no inverse negative wave in the conducted tests. It was evidently caused by the essential structural changes of the fluid owing to direct wave of negative pressure. It is characteristic that the passing of negative pressure wave results in essential decrease of hydraulic resistance of the system.

III. Natural Effects and Technological Applications

A. Breakdowns and Complications during of Oil Wells and Exploitation Processes

Analysis of numerous facts of complications, troubles in wells as water-oil-gas showings, crushing of columns, collapses, gryphon formation demonstrates that they arise usually as a result of round-trip operations in drilling of wells and their capital repairs. The negative pressure wave may be initiated by a sudden pulling of pipes or drilling equipment, as well as their sudden braking, quick opening of a valve at the well exit, etc., resulting in metastable extension of the working fluid agent. Though impulse negative pressure manifests itself as a significant dynamic factor, its structural consequences are more dangerous for an oil well. Moving along a well the negative pressure wave results in the spontaneous boiling of the water in the drilling fluid, and as a result of considerable reduction of its specific weight the hydrostatic column is "switched-off" for some seconds and this may be sufficient for oil and gas showings of the well to be appeared accompanied often by crushing of columns and collapsing of wells due to great destroying energy manifestation.

B. Geophysical Effects

The main area of the arising and manifestation of the negative pressure waves in the Nature may be geologic medium which is the anisotropic system with a global spectrum of physical, chemical and structural features, huge masses and volumes, strong initiating factors, intensive processes of transfer and phase transitions [5].

Extreme dynamic processes in the underground medium as a matter of fact can be considered as a synergetic manifestation of the negative pressure together with other thermohydrodynamical factors. The waves of negative pressure in the underground environment may be initiated by tectonic dislocations and faults as a result of different dynamic processes, dramatic decrease of pressure during the displacement of fluids and rocks. They may arise also in the form of a reverse waves as a result of reflection of ordinary seismic waves from different underground surfaces. The negative pressure wave may start "excitation" of the underground environment in sources rather remote from the point of the wave arising, but already metastable and unsteady as a result of the previous evolution. Some anisotropic structures in the geologic environment may stand high compression forces, but they may be broken by very low stretching forces as a result of negative pressure. While propagating the negative pressure waves result in spontaneous boiling and evaporation in an underground hydraulic system, intensive emanation of gas, cavitation processes, increase of permeability, decrease of hydraulic resistance, pseudo-fluidization, intensification of diffusion processes, i.e., they result in processes preceding and concomitant to extreme geologic processes as earthquakes, volcanic eruptions, etc. Inevitability of generation of negative pressure waves in the Earth interior must be taken into account in evaluating of geophysical processes. For complete assessment of the role of negative pressure waves in geologic events, their registration and monitoring in underground medium special comprehensive investigations by using of deep wells equipped with up-to-day measuring systems are required. The role of negative pressure phenomenon in geophysical processes may be studied also through artificial generation of negative pressure waves in control wells.

Required investigations can be realized completely through adoption and implementation of global scientific program for field registration and monitoring of negative pressure waves in different regions, especially, in zones of high seismic activity. Revelation and control of negative pressure waves in the Earth's entrails would be a result of a paramount importance for science and practice. It would completely change views on mechanisms of evolution and appearance of different geodynamic processes, give as a matter of fact an additional chance for control of geologic medium, elaborate principally new approach in evaluating of geophysical processes, create highly effective energy saving technologies.

C. Energy Saving Technologies

On the basis of received results the method of artificial creation of negative pressure waves has been created. The essence of the method is that negative pressure waves can be generated by means of discharge in hydraulic systems (pipes, wells, etc.) when the drop of the pressure takes place during the characteristic time much less than that of pressure relaxation in the system. The greater is the volume of hydraulic system and the higher is the depression of the pressure, the more intensively the negative pressure wave may manifest itself.

This method was taken as a basis of elaboration of principally new technologies and installations to increase effectiveness and efficiency of some oil recovery processes.

It has been worked out and widely tested in field conditions new technologies on using of the negative pressure phenomenon for cleaning of oil producing hydraulic systems / well bore, pipeline/from various accumulations and increasing of effectiveness of oil producing at different well operation methods. The technology provides generation negative pressure waves in the well using the special mechanisms that leads to the shock depression impact upon the oil stratum, and

as a result, to considerable growth in the oil influx, bottom-hole cleaning, accompanied by essential saving both reservoir and lifting energies, elimination and prevention of sandy bridging, paraffin, silt, water, etc. accumulations.

For implementations of these technologies corresponding installations have been elaborated, in part, equipment for cleaning out of oil holes from sand plugs, increasing of efficiency and effectiveness of gas-lift well operations and bottom-hole pumping. The introduced technologies have passed broad test in field conditions. The operative and complete cleaning of numerous oil wells was carried out, where the altitude of sand plugs varied from 20m to 180m; oil output of wells and their overhaul period have been increased and specific gas discharge reduced significantly.

IV. Conclusions

The possibility of generation of direct waves of negative pressure in real heterogeneous compound liquid systems has been confirmed experimentally. Obtained results give a ground for the statement that the swift pressure drops ($t<<\tau$) in hydraulic system (pipeline, well, entrails of the Earth, etc.) can generate the rarefaction waves, in particular, the waves negative pressure in the system. The more the depression and volume of the hydraulic system, the more expressive the negative pressure wave would be.

Negative pressure may produce a destroying impact in certain conditions. Our results prove that the negative pressure is one of the main factors causing hard troubles in the drilling and petroleum reservoir engineering, e.g., the showings of oil and gas leading sometimes to dreadful open fountains, borehole wall collapse, column crushing, gryphon appearance. Negative pressure waves may be considered also as one of the dominant factors in geophysical processes, especially, in evolution and appearance of volcanic eruptions and earthquakes.

Special technologies and technologies to raise the effectiveness and efficiency of various processes on the basis of negative pressure phenomenon have been elaborated and widely used in oil production.

No doubt, the negative pressure phenomenon will be effectively applied also in several other spheres of human activity. Obtained results will probably help evaluate the importance of negative pressure effect as an energy factor, its role in environmental and technological processes, and the large profit that can be received from practical adoption of this remarkable phenomenon.

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