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Geyser Eruption Mechanism: Natural and Empirical Verification

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The theoretical mechanism of geyser eruption is analyzed and verified using the example of Geysers in Kamchatka (Russian Federation) and Yellowstone (United States). A simple experimental geyser model, confirming the basic conclusions of the theory, is described and demonstrated.

Keywords: Geyser; eruption mechanism; Kamchatka geysers; Yellowstone geysers; geyser model.

1. INTRODUCTION

The initial cause of any thermal spring is a magma chamber at a depth of several kilometers that warms up the surrounding rocks and the water which the rocks contain. The warmed water coming up from underground breaks its way to the surface as hot springs, boiling sources, steamy vents (fumaroles) and geysers. The geysers are the rarest among all the types of thermal springs [1,2].

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The major characteristic that makes the geyser different from other springs is the cyclic recurrence or reiteration of its activity. The entire cycle is typically divided into four phase: rest, preparation (overflow), eruption and steaming. In the rest phase the geyser looks lifeless. Normally there is no water in the cone, and the discharge of steam is not noticeable. Meanwhile the geyser conduit is gradually filled up with a new portion of water that can come either from the underground sources of deep horizons (the water is hot then) or from water-carrying layers close to the surface (in this case the water may be cool). In the phase of preparation the water appears in the cone, fills it up and then overflows. The water heats up to the boiling temperature all along the conduit either due to free convection (if the cross-section of the conduit is big enough) or due to bubbles coming up from the depths and containing superheated steam. The steam's temperature can be considerably higher than 100 C as the greater the depth and consequently greater the hydrostatic pressure, the higher the boiling temperature of water (for instance, at the depth of 1 km the water boils at a temperature of 300 C). The boiling initiated in the depths gradually goes upwards along the conduit, and bubbles of steam, merging in a sort of steamy "bullet", can push a large portion of the water out of the geyser. At some moment the eruption starts. Its physical origin will be discussed later. The fountain rapidly reaches the maximum height typical for the geyser. The eruption phase may last minutes or hours, then the fountain falls down and the discharge of steam intensifies. At the steam phase the water is still boiling in the geyser conduit but nothing precludes a free movement of the steam outwards. It seems that the steam is evacuating from some underground cavity. Anyway the geyser comes back to the rest phase. It is noteworthy that not at all every geyser has the standard "four-phased" cycle: some of them miss the phase of overflow, others miss the steam phase.

The classical theory of geyser eruptions [3-5] implies the water boiling in the conduit, reducing the pressure in the "water-steam" two-phase mixture, a corresponding reduction of the boiling point temperature and, like a chain reaction, water boiling over the entire height of the conduit and water column eruption. This possible mechanism, rather complicated for theoretical analysis, was opposed to the new mechanism of imbalance between the contacting column of liquid and gas volume (Gas-Liquid-Imbalance mechanism). In the case of geyser gas represents a steam produced by water boiling and accumulated in cavities inside the rocks. This previously unknown and simple mechanism has been described in 2008 [6]. Its theory developed in [7] was supported by geological arguments and field observations in the conduits of active geysers of Kamchatka [8].

This GLI-mechanism is fundamental. It is assumed that it is responsible for both the geyser eruption (liquid is water, gas is water vapor) [8] and volcanoes eruptions (liquid is magma, gases are, for example, water vapor, carbon dioxide) [9,10]. Convincing verification of this mechanism could provide an explanation of "paradoxical" behavior of a number of natural geysers in Kamchatka, Russian Federation (Valley of Geysers) and the USA (Yellowstone), as well as a demonstration of GLI-mechanism in specially made "hot" installation, where the conditions for the supposed generation of water vapor in geysers are reproduced.

2. PHYSICAL PRINCIPLES OF GEYSER ERUPTION

Recall the essence of GLI- mechanism in case of natural geysers. A necessary condition of the geyser existence is the availability of some underground cavities into which the water can come from different sources and where it can be heated to the boiling temperature T_b from underground (for example magma chamber) heat sources. Boiling water in such sort of "boilers" generates water vapor which should accumulate under the vault of the cavity, and if this cavity is connected by the conduit with the ground, it must squeeze out the water through the conduit (Fig. 1) and then erupt into the atmosphere in accordance with GLI- mechanism.

Recall physical essence of this mechanism. Suppose that there is a vertical tank with solid walls (conduit or fissure) which is filled to the brim with some liquid. There is also a closed volume filled with gas. Initially, liquid and gas are in equilibrium and have a region of direct contact in accordance with Fig. 1. The cross section of conduit in contact place is S , the volume of the gas cavity is V , p_g is the gas pressure. In the contact area at a depth $z = 0$ the hydrostatic pressure of the liquid is equal to $p_0 + \rho g H$, where ρ is density of the liquid, p_0 is atmospheric pressure at $z = H$ (Fig. 1). The gas pressure p_g obeys the equation of state of an ideal gas which in the case of an adiabatic process is as follows:

$$p_g V^{\gamma} = A = const \quad (1)$$

Where γ is the adiabatic factor for this gas. Since the change in volume of the gas represents a process running much faster than the heat exchange processes of all, it can be considered as adiabatic.

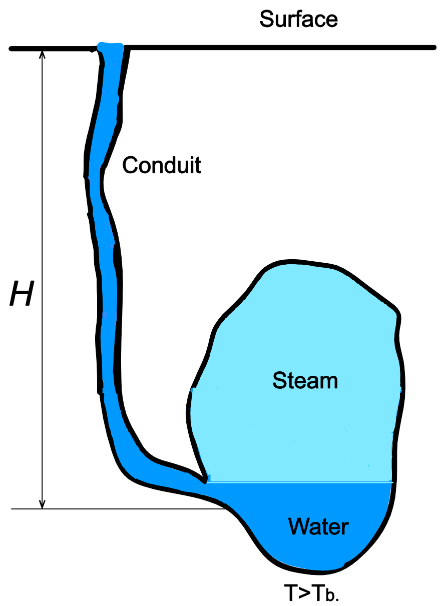

Fig. 1. Proposed geyser structure with an underground "boiler" at depth H

Assume that the volume of the gas cavity increased by a small amount ΔV due to the fact that the gas has penetrated into the conduit. In this case, the conduit is displaced from the same volume ΔV of liquid, equal to $S\Delta z$ where Δz is the reduction of the liquid column height, S is the conduit cross-section. The corresponding decrease in the hydrostatic pressure Δp_l in the contact area is equal to:

$$\Delta p_l = -\rho g \Delta z = -\rho g \Delta V / S \quad (2)$$

The pressure in the gas volume also decreased to a value Δp_g in accordance with equation (1):

$$\Delta p_g = \frac{\partial p_g}{\partial V}\Delta V = -\frac{\gamma A}{V^{\gamma+1}}\Delta V \quad (3)$$

Thus, the larger the volume of the gas chamber, the smaller the drop in gas pressure when it expands into the conduit with the liquid. If the structure parameters (H, S, V) are such that $|\Delta p_g| < |\Delta p_l|$ the hydrostatic pressure in the contact area will decrease faster than the pressure in the gas chamber and the gas will begin to expel liquid from the conduit as the plunger. We can define the critical parameters of the effect of "gas piston."

The constant A in (3) we obtain from the condition that the gas pressure is equal to the liquid column pressure in the contact area at the beginning of the process:

$$A / V^{\gamma} = p_0 + \rho g H \quad (4)$$

From (2)-(4) and the conditions of instability $|\Delta p_g| < |\Delta p_l|$ we obtain the liquid eruption criterion from the conduit:

$$V > \gamma S(H + p_0 / \rho g) \equiv V_{cr} \quad (5)$$

For example, in the case of geyser liquid is water, gas is steam accumulating due to water boiling in an underground cavity. Respectively, $\gamma = 1,4;\ p_0 / \rho g = 10m$. (5) represents a critical volume V_{cr}. If the cavity volume V exceeds considerably the volume V_{cr}, the pressure difference between the gas and the liquid column will increase, the liquid ejection will carry the accelerating nature as long as, for example, all the liquid will be erupted from the conduit and the gas comes out. If $V < V_{cr}$, there is no instability, the gas penetrates into the liquid gently without pushing it and comes to the surface in the form of bubbles. The existence of such supposed cavity was found during investigations of Old Faithful Geyser [11].

Thus, a sufficient condition for instability and water eruption needs the water vapor volume in the boiler exceeds the critical volume equal to $(H + 10)S\gamma$ m^3, where H is the depth of the boiler (Fig. 1), S is the section of the conduit at the point of contact with the boiler, γ is the adiabatic factor for water vapor equal to 1.4. The eruption begins as soon as the steam penetrates into the conduit and the water in the conduit reaches the earth's surface (Fig. 1).

If the volume of the boiler and the corresponding amount of steam are large enough, the drop in steam pressure during the eruption will be negligible, and the steam will throw out not only all the water contained in the conduit but the water of the possible dilatation of the conduit (Fig. 2). The latter circumstance explains very long time (several hours) eruption of some geysers of Yellowstone and Kamchatka.

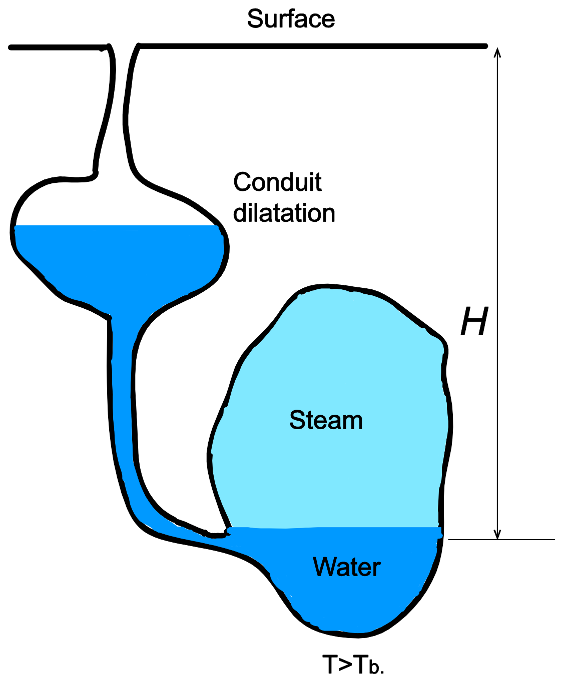

Fig. 2. The structure of the geyser with the dilatation of the conduit. The eruption could continue as long as the conduit dilatation becomes clear of all water

"Classical" theory of geyser work involves the water heating in the conduit to the boiling temperature and then its boiling up from below to the height of the conduit with a concomitant increase in volume and eruption. For GLI - mechanism in the geyser case the boiling is necessary too but only as a source of water vapor in the upper part of the "boiler" (Fig.1). The steam accumulated at boiling expands and pushes the water into the conduit and then on the surface, this process represents the overflow phase. Its duration is obviously dependent on the parameters of the boiler. By the way the "classical" theory can't explain the geyser water overflow long before the eruption. The overflow may be absent altogether if the steam penetrates into the conduit before water reaches the geyser vent. Eruption occurs in this case as soon as water reaches surface and its hydrostatic pressure decreases. Note that our GLI-mechanism easily can also explain the existence of the cold-water geysers [12].

3. EMPIRICAL OBSERVATIONS

“Experiment”, inexplicable from the standpoint of classical geyser theory was "implemented" by the Nature after the catastrophe June 3, 2007 in the Valley of Geysers in Kamchatka, where a colossal avalanche blocked the Geysernaya River riverbed and formed a dammed lake with depth of 20 meters. As a result, the Bolschoy (Big) Geyser, who was situated on a slope 15 meters above the river level (Fig. 3), plunged into the water and, of course, stopped erupting.

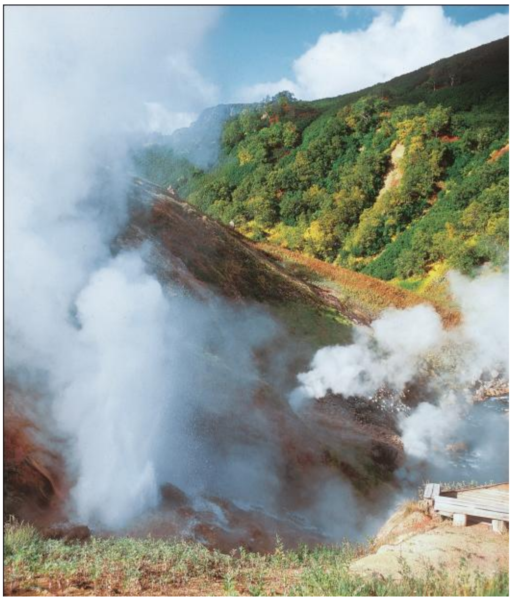

Fig. 3. Big Geyser (in the left corner) before June 3, 2007

In September 2007 the lake level fell a few meters and upper edges of the geyser cone "leaned out" from under the water. Immediately the geyser began erupting almost in the same mode as before (Fig. 4).

After the eruption the empty geyser conduit was quickly filled with rather cold water from the lake through the jagged edges of a cone (Fig. 5).

Note that the lake water temperature was 25 C, geyser conduit received several tons of such water (conduit cross-section is of about 1m x 1m, its depth 4 m). Obviously, this amount of water is impossible to be heated during one hour to the boiling-point even at the open fire, while the bottom conduit temperature is only 120 C. But within an hour the geyser eruption started again (Fig. 7), and the overflow preceded eruption (Fig. 6).

Obviously, for the GLI-mechanism is important that the internal, underground, geyser structure remained unchanged after the accident, and therefore, as soon as an opportunity to reset the hydrostatic water pressure in the geyser conduit appeared (the lake level fell below the edges of the cone), geyser began erupting.

Fig. 4. Big geyser eruption on the surface of the new lake

Fig. 5. Big geyser conduit is filled with lake water

The effectiveness of the geyser working is dependent on the ratio of the volume of steam in the boiler and the critical volume (5) that is proportional to the depth of the boiler bedding and the cross section of the conduit at the point of contact with the boiler. A number of geysers (eg, Big and Giant in the Valley of Geysers, Kamchatka) have a fairly wide conduit output to the surface, and its eruptions represents not smooth, powerful jet of water but the succession of "dagger" ejections, following each other. Perhaps this is due to the presence of a narrow gap (crack) connecting the conduit and the boiler by analogy with Fig. 8.

Fig. 6. The water overflow from the Big geyser conduit before the eruption

Fig. 7. Big geyser. Start of the eruption

The supposed existence of such a "crack" has been confirmed by the fixation of the preparatory process of the Big geyser eruption using the heat-resistant video camera lowered into a geyser conduit [8]. Immediately prior to the eruption the intense emission of steam from the side of the crack was recorded, which is near the bottom of the geyser conduit. No bubbles generation in the conduit was not observed.

A good example of GLI- mechanism verification is the explaining of the unusual behavior of the Bee Hive geyser in Yellowstone National Park (USA). This geyser is known that in 10-15 minutes before the main eruption the small fountain from the hole a few meters near the main geyser vent begins to erupt. It is called Bee Hive Indicator. Rangers of the National Park can thus predict the beginning of a major eruption. This "paradoxical" geyser behavior quite easily explains GLI-mechanism with the proposed geyser structure shown in Fig. 9.

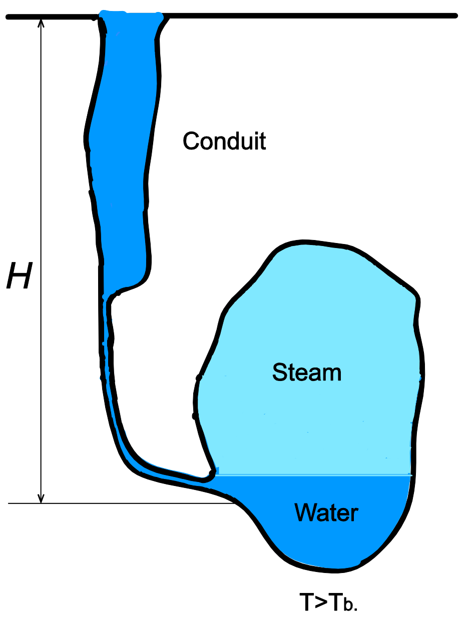

Fig. 8. Supposed geyser structure with wide conduit and a narrow crack, connecting the boiler and the conduit

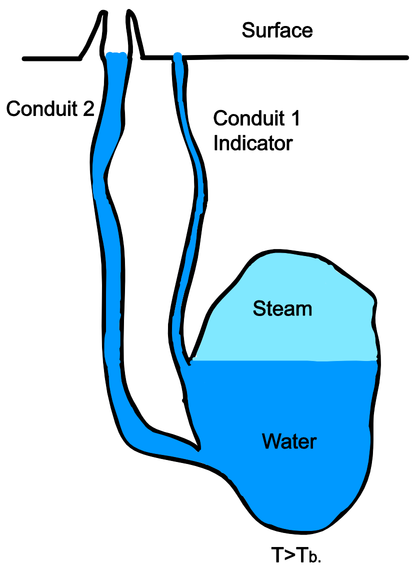

Fig. 9. Supposed structure of the Bee Hive geyser. The boiler is connected to the surface with two conduits

First the steam in the boiler reaches the conduit 1 and the Indicator eruption begins. Because, probably, this conduit is very narrow and its hydrodynamic resistance is high, so the water release rate is relatively low (a low fountain) and the eruption is not finished until the steam in the boiler reaches the main channel and a major Bee-Hive eruption starts. Thus, the vapor pressure in the boiler is maintained at a high level (both channels are filled with water), and both fountains operate simultaneously.

We can also show how GLI- mechanism provides a rather simple explanation of the notable group of Geysers of Yellowstone National Park. These are the geysers Grand, Vent and Turban.

The eruption of these, located close to each other, geysers is quite original. The rest period is 5 to 15 hours. Then the empty geysers vents are filled by water. Then the Turban geyser starts. Its low "eruption", resembling a boiling, lasts a few minutes and then may stop, then restarts, and so can be repeated up to ten times. Finally, after one of the Turban boiling up the eruption of geyser Grand starts. At the same time the Vent starts. The Grand eruption lasts up to 10 minutes and can consist of several powerful emissions, between which a fountain of Grand sharply weakens or disappears altogether. At the same time Vent continues to operate. When Grand stops erupting, Vent continues to steam, its steaming phase is well defined. Grand and Turban has no steaming phase.

It is unlikely that the classical theory of geyser can explain such a complex configuration of these three interrelated geysers behavior. GLI-mechanism, however, allows you to do it simply. Consider a hypothetical structure of a geyser with a boiler and three conduits with dilatations (Fig. 10).

Steam, accumulating in the boiler, squeezes water in the conduits, they are filled, the overflow phase begins. First steam reaches the geyser Turban conduit (Fig.10). The cross section of this conduit is probably large enough, and the critical volume for Turban geyser is always greater than the volume of accumulated vapor. Full-scale eruption of this geyser does not occur, the steam is ejected by portions, which float to the surface in the form of bubbles, imitating a small eruption. The overflow from Grand and Vent conduits continues, but their real eruption occurs when the steam in the boiler reaches the depth where there is a contact with their joint conduit with cross section S_1 (Fig. 11).

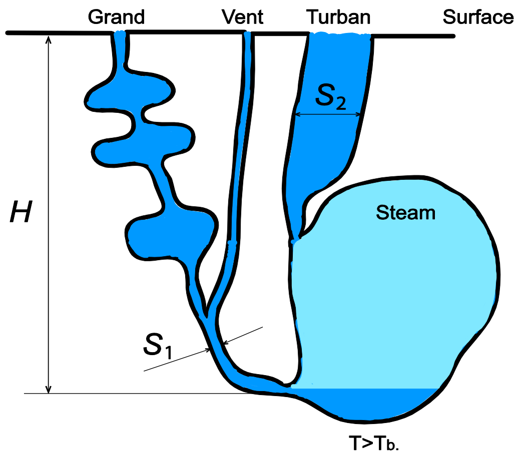

Fig. 10. Supposed structure of geysers Grand, Vent and Turban. Grand conduit has several dilatations. Vent conduit is very narrow. Turban conduit, on the contrary, is wide. Water sources that probably feed the geysers are not shown

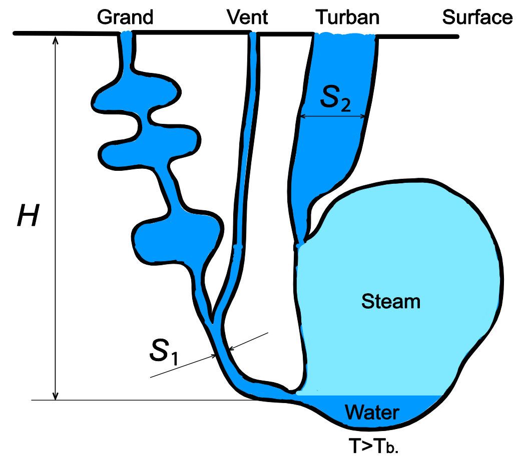

Fig. 11. The supposed structure of the Grand geyser before the main eruption

Now the volume of water vapor becomes much higher than the critical volume of approximate magnitude $1,4HS_1$ and eruption begins from both channels. Because the Vent conduit is narrow, its drag to the water flow is rather large, the rate of water release is respectively low so as its fountain. The Grand geyser conduit, obviously, is not so narrow, water flow velocity is rather big and a fountain has a height of tens of meters. During eruption and water ejection the vapor from the boiler extends into the Grand geyser conduit where it has to fill the dilatations of the conduit (Fig. 12).

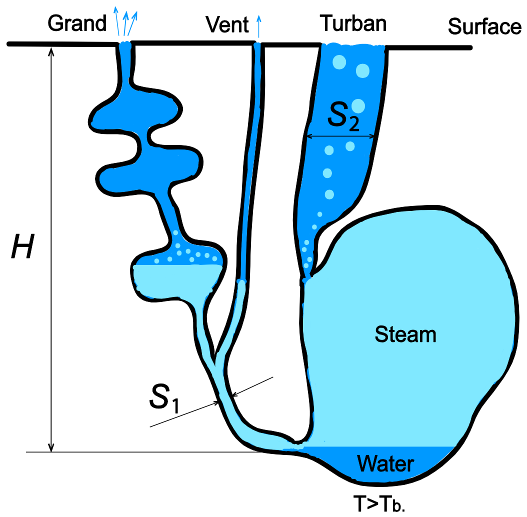

Fig. 12. Eruption of geysers Grand and Vent

At these moments the reducing of vapor pressure can be greater than the water hydrostatic pressure reducing, the fountain will weaken, the eruption can almost stop. But as soon as the steam in the conduit reaches another narrowing between dilatations, the pressure difference between the steam and water column again begin to grow and the eruption begins to increase. Then Vent enters a phase of steaming, which is clearly seen on all video spots, posted on youtube.com. Actually Vent justifies its name: in the phase of steaming it reduces the total vapor pressure in the boiler which can itself lead to a weakening of Grand eruption. Characteristically, the Turban, both before and during the Grand eruption, behaves the same "modest" style, confirming that its critical volume is much higher than the volume of steam in the boiler. Eruption comes to the end because the vapor pressure in the boiler decreases due to Vent. The remaining water in the channels of Grand and Turban geysers goes down into the structure, preventing its steaming, retaining and compressing the remaining steam in the boiler. Geyser begins a new cycle being filled with water from underground sources.

4. EXPERIMENTAL GEYSER MODEL

Finally, we give a description of a simple experiment that reproduces the functioning of the real geyser on the basis of GLI-mechanism. On special request the "bulb" of heat-resistant borosilicate glass was made (Fig. 13) with the neck at the top (for water filling and cleaning the bulb), with nozzle near the flat bottom, which allows to set the bulb on a hotplate.

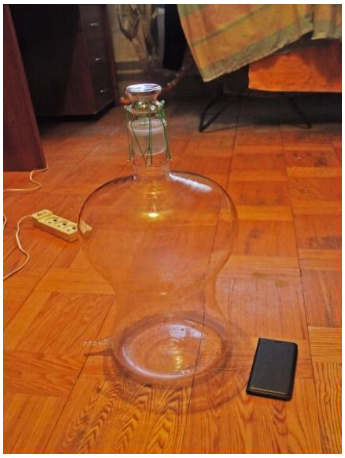

Fig. 13. Borosilicate glass bulb with a neck, hermetically blocked by the plug and the nozzle near the bottom of the bulb

The volume of the glass bulb was evaluated by filling it with water. It was 14 liters, what is much more than the critical volume of our model according to formula (5).

The whole installation included a metal rack with height of 180 cm, on the top shelf of which was placed a blue tray from heat-resistant polypropylene (diameter - 70 cm) with a corresponding sink in the center. The tray drain and a pipe nozzle were connected by the silicone tube with an internal diameter of 10 mm (Fig. 14). The water in the bulb was heated using an ordinary electric stove.

The initial water level in the bulb was several centimeters above the bulb nozzle. As the heating of water approaches to its boiling point, the water vapor in the upper part of the bulb expanded and squeezed out the water from the bulb in a silicone tube, and then into the tray: the overflow phase began (Fig. 15).

The process of instability (according to the GLI-mechanism) and the eruption begins when steam from the bulb begins to penetrate into the nozzle and the silicone tube. All water in the tube was erupted away. The fountain height did not exceed 30 cm, the duration of the eruption was several seconds (Fig. 16).

After the eruption the water from the tray merges into a bulb, and the ejection is repeated again in 10-20 seconds.

Since the critical volume for a given system in accordance with the formula (5) does not exceed one-liter, the bulb volume provided sufficient overpressure and acceleration of water in the tube, causing though low, but appreciable water emissions. Reducing of the diameter of the silicone tube (5 mm) increases the hydrodynamic resistance of water flow in the tube and adapters, resulting in the decreasing of the fountain height. Increasing the length of the tube up to 10 meters (that imitated geyser conduit dilatation) increased the duration of the eruption, but reduced the height of the eruption due to drag increasing.

Fig.14. The rack with a tray, a glass bulb and electric stove. The distance between the tray and the bulb nozzle was 160 cm. The length of silicone tube was 3 meters. The bulb imitate geyser boiler, the silicone tube imitate the conduit

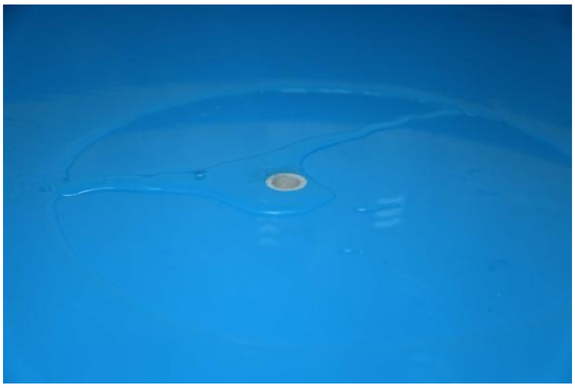

Fig. 15. Hot water overflow from the bulb nozzle into a tray. The central portion of the tray slightly swells by heating and the water flows to the edges of the tray

Fig. 16. "Geyser" eruption. Water narrow stream was ejected from the tube together with the vapor

5. BRIEF CONCLUSIONS

It is shown that the theoretical mechanism of instability between the contacting gas and liquid volumes (GLI-mechanism), previously proposed as a mechanism of geyser eruption, is able to give a simple explanation for the unusual behavior of a number of Geysers in Kamchatka and Yellowstone. An experimental geyser model working on the principles of GLI-mechanism and showing all phases of classical geyser operating is proposed and described.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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