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Piezomechanical Systems for Algae Cell Ultrasonication

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Abstract**—**Nowadays for algae cell ultrasonication the longitudinal ultrasonic piezosystems are used. In this paper a possibility of creating unique ultrasonic piezoelectric system, which would allow reducing energy losses and concentrating this energy to a small closed volume are proposed. The current vibrating systems whose ultrasonic energy is concentrated inside of hollow cylinder in which water-algae mixture is flowing. Two, three or multiply ultrasonic composite systems to concentrate total energy into a hollow cylinder to creating strong algae cell ultrasonication are used. The experiments and numerical FEM analysis results using disk-shaped transducer and the first biological test results on algae cell disruption by ultrasonication are presented as well.

Keywords**—**Algae, piezomechanical system, ultrasonication.

I. Introduction

To meet the needs of the world's energy growing demands will require an energy sources variety. One of the most attractive sources of raw materials for biofuel production can be algae oil processing into biofuels. Under favorable conditions many species of algae can be propagated in twice per day and have been possible to produce a lot of oil at a very quick rate. However, algae cultivation and efficient recycling of bio-products is a complex, time-consuming and expensive process so far. Strong algae cell wall protects from external stresses and allows them to survive, which to complicate the issue of oil extraction.

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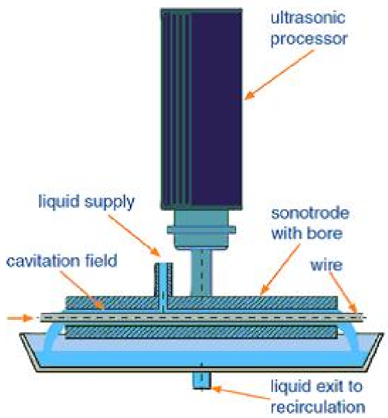

Fig. 1 Ultrasonic algae wall disruptor using longitudinal vibration system

Today, the oil production from algae uses disaggregation enzymatic, chemical degradation or mechanical-based technology [6]. The algae wall disruption by press or by cavitation using longitudinal vibrations ultrasonic systems in mechanical-based technology is well-known fact [1]-[3],[8] as shown in Fig. 1.

Our goal is to create ultrasonic systems which would reduce waste of vibration energy, concentrating it in closed volume. The ultrasonic energy concentrated in a local volume to create a high power bubbles implosion process.Their usage enables to concentrate cavitation into inner part of cylinder and increase vibration amplitudes in big closed space.

II. Compound Ultrasonic Piezomechanical(PM) Systems of Algae Disrupting

For algae cell walls disrupting the PM systems are needed to warrant high vibration amplitudes in working zone. The minimal mechanical vibration amplitude of the ultrasonic system should be about 15 µm [4]. The longitudinal vibration amplitudes of industrial algae cell disruptor are from 25 µm to 90 µm (peak-to-peak), and the working frequency is about 20 kHz [8]. It is not possible to achieve such high vibrating amplitude under loaded condition with water and algae mixture, using resonance piezosystems amplitudes of which fall down several times when loaded. To save high intensity of oscillation energy in cavitating mixture we tried to create compound PM systems. They enable to sum two, three or more ultrasonic resonance vibrations systems energy into a hollow cylinder. In this way intensive cavitation disrupting

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algae cells is created. It is possible to design compound PM system consist of three or more Langevin's actuators.

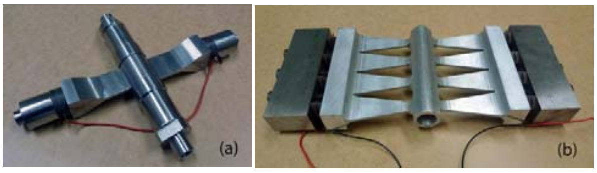

Fig. 2 Compound PM vibration systems: a) the system of two piezoelectric converters, b) the system included two Langevin's actuators with four transducers each

Two piezoelectric converter-transducer and twoLangevin's actuators with four transducers joined together systems are shown in Fig. 2. The first system consist two piezoelectric converters-transducers(Fig. 2a).The second, two Langevin's compound systems converters-transducers that are acoustically reliable joined with the hollow cylinder through which the mixture of algae is let to flow (Fig. 2b). In the cylinder part the mixture is cavitated. In current project, we used piezoceramics PI 181 (PI company) having high piezomodule and mechanical quality factor. The piezoelectric ceramics are poled through the thickness. The electrodes are placed on both sides of piezoceramics. The other parts are made from stainless steel 40X13.

As it was mentioned before, the PM resonance systems are used to create the ultrasonic cavitation. When summing the energy of separate converters the frequency match of PM systems is very important, i. e. to choose their dimension in such a way that their eigenfrequency would be so close to each other as much as possible. For this reason, created system consist many converters that are tied by common frequency lowering counterbalances. There are little piezoceramic packages placed between the abovementioned counterbalances (Fig. 2b). The counterbalances together with the piezoelements clamped between them are making the compound Langevin's package. The vibration transducers (four in this case) are led away from the counterbalance, strengthen amplitudes of vibration and cause cavitation in the long hollow cylinder. Langevin's package, common to all transducers synchronize their vibrations.

The ultrasonic PM system, which included four transducers using special exciting condition of piezoelements pairs, can create a travelling wave in hollow cylinder (Fig. 2b). In this case, into first two pairs of piezoelements we should apply harmonical signal and to the next pairs apply voltage with a 90 degree phase shift. The electrodes of the fourth pair should be connected to the electric chain RL in order that the travelling wave energy would not reflect from the liquid flows out part at end of tube.

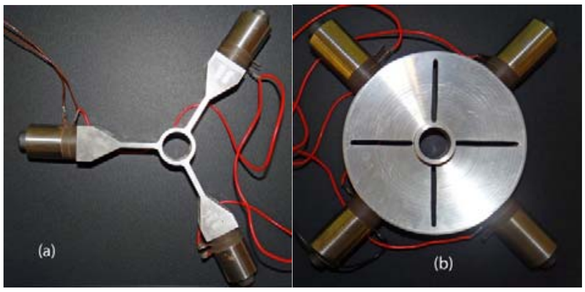

Fig. 3 Compound PM vibration systems: a) the system of three piezoelectric converters, b) the system of four piezoelectric converters with gapped disk concentrator

The previous design using the on plane design philosophy. The next type of PM systems created in our lab used the star-shape design as shown in Fig. 3. The first PM system has three similar piezoelectric converters joined to one hollow cylinder (3-star shape system) as shown in Fig. 3a. Compound PM vibration system as shown in Fig. 3b, has a 4-star shape design with additional disk-shape concentrator. The four piezoelectric longitudinal converters synchronized with radial mode of disk converter for concentrating of ultrasonic power in a closed volume inside of cylinder.

Because of paper space limitation, the proposed research is done only for systems shown in Fig. 3.

III. The Numerical Analysis

Numerical calculation contains harmonic response analysis used for evaluating transverse vibration of the converters applying external electrical signal to the piezoceramics, parametric sweep analysis for finding optimal dimension of Langevin converters. Moreover, the acoustic-piezoelectric interaction analysis for calculating acoustic pressure and sound distribution inside cylinderfilled by water for creating maximum cavitation intensity is done as well. FEM modeling of piezoelectric actuators was carried out by employing FEM software COMSOL 4.2.

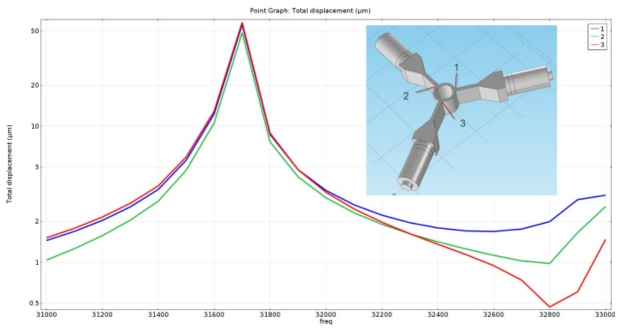

Fig. 4 Total displacement vs. frequency (Fig. 3a)

Harmonic response analysis and acoustic-piezoelectric interaction analysis was performed by using Pardiso solver with nested dissection multithreaded preordering algorithm. The harmonic response analysis was to find out trajectories of measuring point movement. It is significant, that in this study all numerical analysis not to take into account the structural losses.

The PZT-8 piezoceramics, which has the following charge coefficients: d_{33} = 225 pC/N, d_{31} = -37 pC/N is used in these projects. The piezoelectric ceramics are poled through the thickness. The electrodes are placed on both sides of piezoceramics. The longitudinal ultrasonic piezoelectric converters are made from structural steel (mass density ρ = 7.85 g/cm^3, Young modulus E = 200 GPa, Poisson ratio σ = 0.33). The 3-star shape (Fig. 3a) and disk concentrator (Fig. 3b) are made from Aluminum alloy D16T (mass density ρ = 2.7 g/cm^3, Young modulus E = 70 GPa, Poisson ratio σ = 0.33). All components are adhered together.

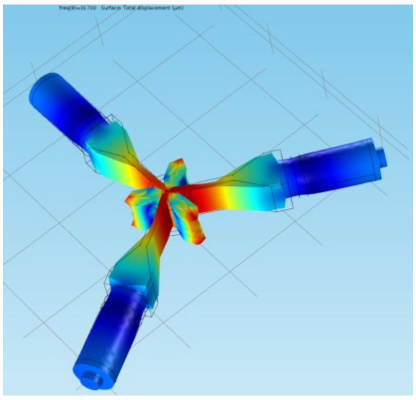

Fig. 5 The distribution of vibration amplitude (Fig. 3a)

Piezoelements were excited using AC signal (300V) applied on the executing electrodes. The longitudinal vibrations of piezoelectric converters excite the bending vibration of the cylinder and then produced the acoustic pressure inside. The intensive acoustic pressure creates cavitations in the closed volume filled by mixture (algae and water). The gain-frequencies characteristics of measuring point's movement for system in Fig. 3a are shown in Fig. 4. Measuring points are located on the cylinder and converters junction edges. A frequency range from 31 kHz to 33 kHz with a solution at 100 Hz intervals was chosen to give an adequate response curve of measuring point. The mechanical vibration amplitudes of characteristic points of PM system (1, 2, and 3) are identical as shown in Fig. 4.

Basis on numerical calculation results we can assume, that excitation frequency of 31.7 kHz should be used as operating frequency of the proposed 3-star shape PM system as shown in Fig. 5.

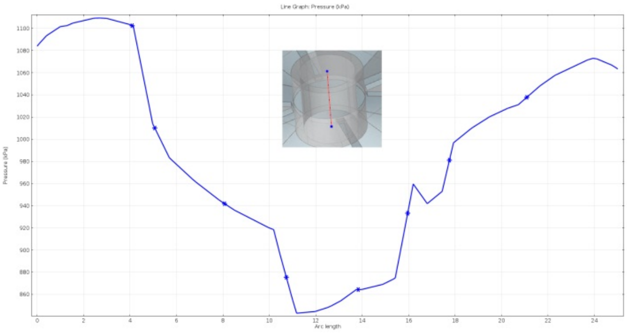

Fig. 6 Acoustic pressure distribution in cylinder with water on resonance frequency (Fig. 3a)

The acoustic-piezoelectric interaction analysis was to find out the acoustic pressure distribution in medium (mixture) to estimate the dynamic load influence on the resonance frequency. Acoustic pressure distribution in cylinder with water is shown in Fig. 6.

Acoustic pressure of the PM system inside the working hole is highest near the inlet and outlet of the cylinder as shown in Fig. 6.

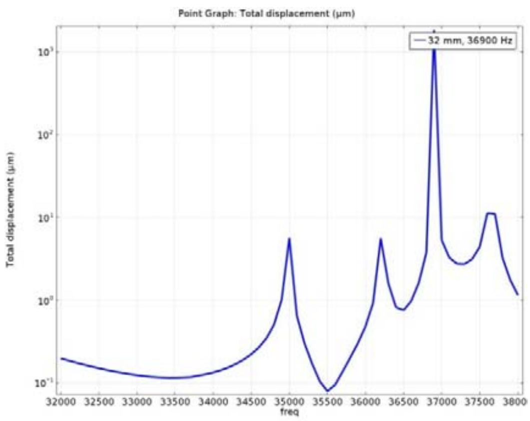

Fig. 7 Total displacement vs. frequency (Fig. 3b)

The gain-frequencies characteristic of measuring point movement for system in Fig. 3(b) is shown in Fig. 7. Measuring point is located on the top of the hollow cylinder Fig. 3(b). A frequency range from 32 kHz to 38 kHz with a solution at 100 Hz intervals was chosen.

Basis on present calculation results we can assume, that excitation frequency of 36.9 kHz should be used as operating frequency of the proposed four-star shape PM system with gapped disk concentrator as shown in Fig. 3(b) with 32mm length of longitudinal converters as shown in Fig. 8.

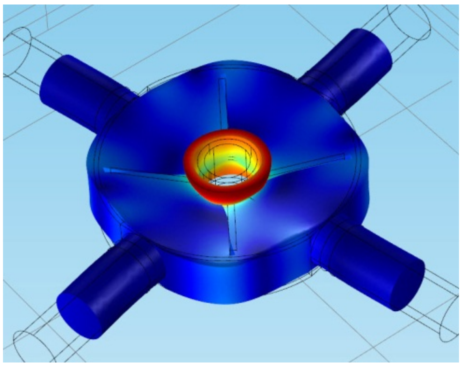

Fig. 8 The distribution of vibration amplitude (Fig. 3b)

The longitudinal converter together with disk sector compounds the ultrasonic PM resonance system. Four similar systems assembled together and have a one load – hollow cylinder inside. The high intensity ultrasonic oscillation energy concentrated in closed volume and intensive cavitation is created.

Acoustic pressure distribution in cylinder with water is shown in Fig. 9.

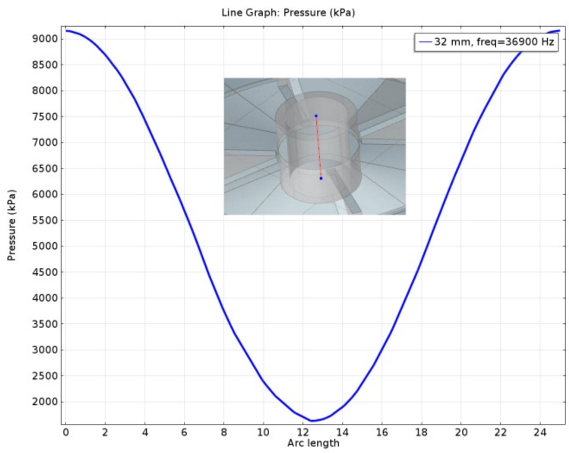

Fig. 9 Acoustic pressure distribution in cylinder with water on resonance frequency (Fig. 3b)

Moreover, Fig. 5and Fig. 8 shows that the first longitudinal vibrations mode of the converters-transducers and the third bending mode of the hollow cylinder looks like as matched cavity resonator.

IV. Experimental Research

For the experimental research the proposed PM systems shown in Fig. 3 are made. The prototype systems dimensions were chosen from previous numerical analysis results. The experimental research consists of two parts: the PM system electrical and mechanical displacement measurements and microscopical analysis of bioassay samples after algae cell ultrasonication.

A. The PM system investigation

The gain-frequency characteristics of the proposed ultrasonic PM systems were measured by non-standard analyzer from “Hesse&Knipps” company at 30% of maximum power. The empty and water-filled cylinder of ultrasonic resonance system was defined as free and loaded system respectively.

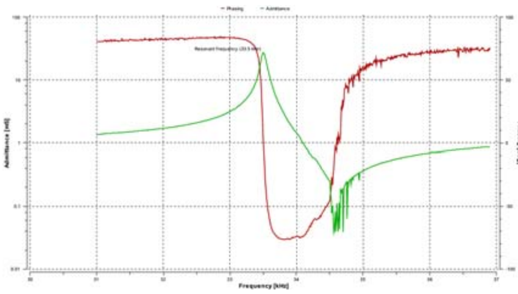

Fig. 10 Admittance-frequency and phase characteristics (free (Fig. 3a))

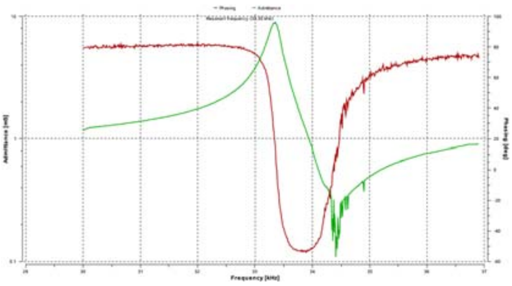

Fig. 11 Admittance-frequency and phase characteristics (loaded (Fig. 3a))

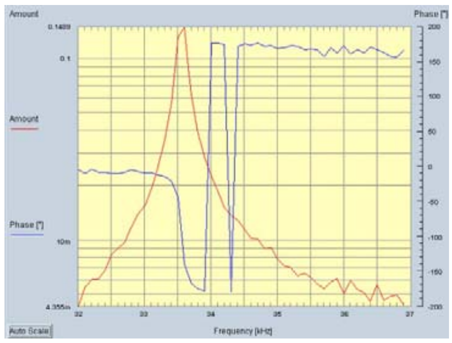

Fig. 12 The complex impedance and phase characteristics of proposed ultrasonic PM system (Fig. 3a)

For the first PM system as shown in Fig. 3a the admittance-frequency and phase characteristics in free and loaded mode were obtained (Fig. 10 and Fig. 11 respectively). We are assume, that the numerical and measured resonance frequency has a good agreement. The water damping reduced the resonance frequency and increases the phase characteristic distortion.

The water and algae mixture, based on the numerical and experimental results, is heavy load for the PM system and it should be taking into consideration for designing of electronic driver and control parts.

The amplitude-frequency and phase characteristics measured by Doppler-laser vibrometer Polytec OFV-5000. During laser measurement is difficult to change water-filled cylinder position. Therefore the measurement result is shown only in the unloaded mode (Fig. 12).

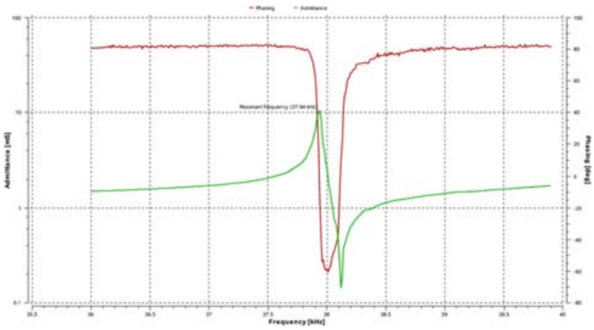

Fig. 13 Admittance-frequency and phase characteristics (free (Fig. 3b))

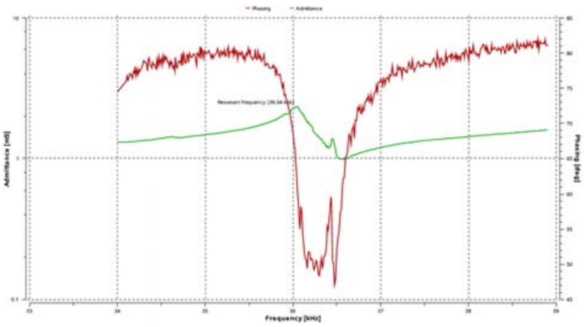

Fig. 14 Admittance-frequency and phase characteristics (loaded (Fig. 3b))

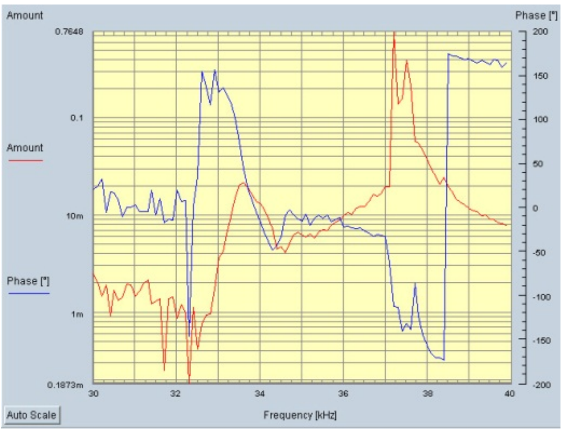

Fig. 15 The complex impedance and phase characteristics of proposed ultrasonic PM system (Fig. 3b)

For the second PM system as shown in Fig. 3b the admittance-frequency and phase characteristics in free and loaded mode were obtained (Fig. 13 and Fig. 14 respectively).

The complex impedance and phase characteristics of the ultrasonic PM system are shown in Fig. 15.

B. The Algae Cell Ultrasonication

In order that to define effectiveness of created PM systems algae cell wall disruption experiments were done. Experimental setup for 3-star shape PM systemis shown in Fig. 16, using methodology of HielscherUltrasonics GmbH company [7]. During the experiment the initial pressure of 150 kPa kept in the system. The ultrasonication process is limited to 30 seconds. No PLL system is used. In current experiments the sweeping frequency mode is obtain.

Fig. 16 The experimental setup for algae ultrasonication by system shown in Fig. 3a

Three different species of algae (*Chlorella* sp. (Fig. 17), *Scenedesmus* sp. (Fig. 18) and *Haematococcus* sp. (Fig. 19)) growing in Lithuanian lakes [5] were used for the experiment.

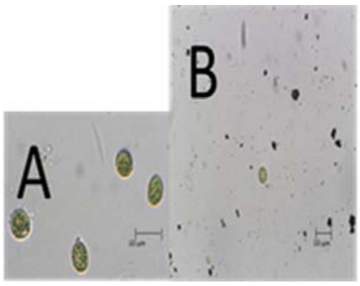

Fig. 17 Themicroscopical analysis of bioassay samples of *Chlorella* sp. cell. (A) – before, (B) – after the ultrasonication

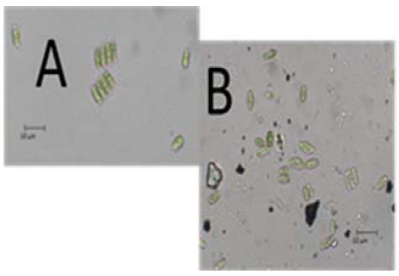

Fig. 18 Themicroscopical analysis of bioassay samples of *Scenedesmus* sp. cell. (A) – before, (B) – after the ultrasonication

After series of tests it was found that highest efficiency of the 3-star shape PM vibration system was achieved with the culture of *Chlorella* sp. (Fig. 17). It was established, that after the 30 seconds of ultrasonication the number of non-disrupted cells was about 17.2% from the total number and 31.2% were empty, without the chromatophore cells. The other cells were completely disrupted.

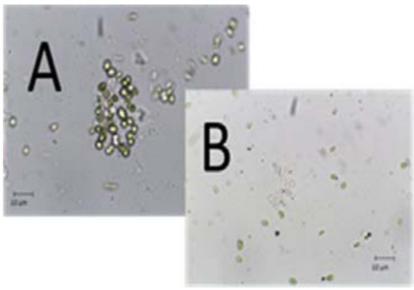

Fig. 19 Themicroscopical analysis of bioassay samples of *Haematococcus* sp. cell. (A) – before, (B) – after the ultrasonication

Experimental setup for disk-shape PM system is shown in Fig. 20.

The highest efficiency of the fourconverters disk-shape PM vibration system was achieved with the culture of *Chlorella* sp. It was established, that after ultrasonication the number of non-disrupted cells was about 41% from the total number and 28.3% were empty, without the chromatophore cells (Fig. 21). The other cells were completely disrupted.

Fig. 20 The experimental setup for algae ultrasonication by system shown in Fig. 3b

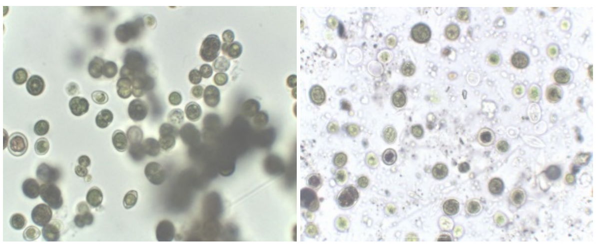

Fig. 21 The microscopical analysis of bioassay samples (*Chlorella* sp. cell). Left – before ultrasonication and right – after

V. Conclusion

The best result after ultrasonicationof investigated PM system was achieved with the *Chlorella* sp. cell.

The electronic frequency control driver forsuch compound systemsshould be havingspecial requirements, because the mixture during ultrasonication processis very heavy dynamic load for ultrasonic PM systems.

Acknowledgment

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