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High Voltage Electric Pulse Treatment of Water-Containing Foodstuffs

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Abstract—This study deals with the energy efficient and enviromentally safe methods of electronic treatment of water-containing foodstuffs in order to extend their shelf life without changing their initial nutrition and biological properties. It is shown that high-voltage electric pulse treatment of fluid foodstuffs, instead of thermal pasteurization and sterilization, is less power consuming in both the processing time and the temperature of heating the medium. It is found that the following requirements must be satisfied to reach the total inactivation of microorganisms in the treated fluid medium: temperature of heating the medium in the discharge chamber must be higher than the critical one in the range of ~70°C; the high electric field intensity between the electrodes must not cause a breakdown of the medium; the pulse amplitude should be maximal; the pulse front should be minimal (up to 20 ns); and the pulse duration has to be optimally long (no less than 100 ns). It is ascertained that the high-voltage pulse treatment with these parameters leads to the improvement of the properties of the treated beverages, the acquisition of new curative properties, and the extension of their shelf life.

Keywords: electric pulse treatment, water-containing medium, raw milk, juice extracts, red wine, pulse front, pulse duration, high-voltage facility, inactivation of microorganisms, electric field intensity, heating temperature

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INTRODUCTION

In recent years, the accelerated development of modern environmentally safe and less energy consuming technologies have appeared, which are extensively used in various branches of the national economy [1–3]. Many works are devoted to elaboration of methods and devices aimed at environmental protection from various toxic wastes, decontamination of water resources and wastewaters, their recycling, etc. [4, 5]. In addition to the ecological aspects of the technologies that are being developed, their primary advantage is energy efficiency. In this respect, the transition from the usual electrophysical facilities which use electromagnetic energy at the industrial frequency to pulsed devices with a maximal application of electric energy at the load is of great interest. Many works are known in this field concerning decontamination of drinking water and wastewater from pathogenic microorganisms [6–8] and inactivation of pathogenic agents in food products using strong pulsed electric fields. The latter arouses a great amount of interest among researchers from the viewpoint of a more effective impact on pathogens and guarantee of long-term storage of foodstuffs without changes in their nutritive and biological properties.

In [9–20], the known theories on inactivation of microorganisms in foodstuffs are described the most completely. The existing methods of treatment, such as thermal pasteurization and high temperature sterilization, are quite old. In spite of the fact that these technologies make it safe to use foodstuffs, they are highly energy consuming. Hence, the development and creation of facilities consuming less energy for the treatment of foodstuffs in order to extend their shelf life are of primary importance for the whole food industry.

The most widespread theory of inactivation is the theory of electroporation, under which an external electric impact on the microorganism cell increases its transmembrane potential (the voltage of the cell membrane), which is a very important parameter for any cell structure [14]. It is also well known [13, 21] that pulsed treatment conserves much better the nutrition and biological values of fresh food products compared to traditional thermal pasteurization, to say nothing of high-temperature sterilization.

This article is aimed at elaboration of high-voltage facilities for electric pulse impact on microorganisms in water-containing food products in order to improve their qualitative characteristics and to extend their shelf life.

EXPERIMENTAL

The experimental facility includes the following: a high-voltage transformer with an output nominal voltage of 140 kV, a rectifier of alternating voltage, a generator of pulsed voltages, and a discharge chamber with the product being treated. The generator of the pulsed voltages is assembled according to the Arkadyev-Marx scheme based on capacitive energy storage with the output voltage of 100 kV, the pulse front of ~18 ns, the pulse full width at half maximum of ~350 ns, and the frequency of pulse repetition of ~1000 Hz. The average power yield in the working chamber was approximately P_{av} = 10 kW. In order to prevent spark breakdown in the gap, a uniform plate-to-plate electrode system was chosen (Fig. 1).

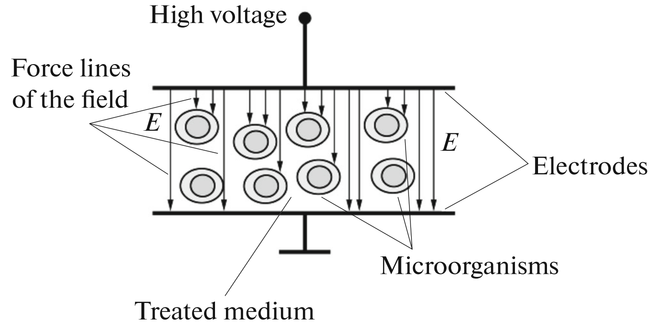

Fig. 1. Electrode plate-to-plate system.

As the objects for the study, we selected fluid food products, with samples of various juice extracts, semidry red wine, and raw milk among them. They all contained microorganisms. Each of the media to be treated and their components were characterized by the corresponding parameters, namely, relative dielectric permeability ε_{rel} and specific conductance γ.

Note that, during the electron treatment of fluid foodstuffs, the electric discharges in the gap are prohibited, and the treatment of each elementary volume of a fluid medium must be maximally uniform. That was why we proposed a uniform model from geometrically identical plane electrodes with the dimensions of 40 × 40 mm that ensure a uniform distribution of the field force lines at the interelectrode spacing of ~10 mm. The reason for the inadmissibility of discharges in fluid foodstuffs is an irreversible deterioration of organoleptic properties and nutrition quality caused by the discharge products.

In the technology under consideration, the treated object and the electrode system are the load for the generator of the electromagnetic pulses, which can have its own peculiarities depending on the purpose and aim of the application. It is noteworthy that, in all variants of the treatment of the object using high-voltage pulses, a short-term heating of the object can occur (lower than during the thermal pasteurization or sterilization) caused by the energy release of the electromagnetic field.

Nutritive and biological qualities of the foodstuffs treated depend strongly on the operating parameters of the thermal treatment, in particular, on its maximum temperature in the treated products, the rise time of temperature to its maximum value, the time of temperarure at its maximum, and the time of temperature drop to the nondestructive values for the nutritive quality.

The biological effect (inactivating) is determined by the electrical parameters of the device, namely, by the power of the pulse generator, amplitude and duration of the pulses, field intensity, treatment time, and characteristics of the biological object. These parameters determine the measure of the effect of strong pulsed electric fields on microorganisms and the degree of their inactivation.

In the experiments performed, the electric field intensity in the interelectrode spacing was on the order of ~100 kV/cm. The samples with microorganisms were of two kinds: control samples (without being exposed to the electric field) and experimental samples (the ones being treated).

Note that, in the practice of experimental studies of inactivation using pulsed treatment carried out by different scientists, the following error is committed. The degree of inactivation, which in itself is a ratio between the initial quantity of microorganisms and the minimum quantity left alive after the treatment, is determined in the standard way using a single sowing of a corresponding cultivation (in physiological solution or distilled water) of suspensions of microorganisms for nutrient solutions in Petri dishes. Such single sowings, whose growth parameters are defined after 1–3 days according to the standard methods, can give fine results displaying a high-degree of inactivation. However, by example of some microorganisms, their low number can remain for 4 days after treatment, and after that, their population explosion can start unless the conditions of a complete irreversible inactivation are observed. Even if the degree of inactivation of the microorganisms is 10^6, and after the electric pulse treatment of the microorganisms at field intensities of 120 kV/cm one out of 10^6 survives, the growth in the number of the survivors is possible in a few days. This growth can be explosive and fast (a biological explosion). In order to avoid this phenomenon and to ensure the irreversibility of inactivation, the critical temperature in the medium with microorganisms must be overcome. In any case, this temperature is lower than that of traditional thermal pasteurization. It briefly heats the medium and makes it possible to conserve the nutrition and biological values in the foodstuffs treated. The critical temperarure ensures inactivation irreversibility (it prevents the repeated insemination of the medium with particular microorganisms). The critical temperatures tend to decrease with an increase in the field intensities. For most kinds

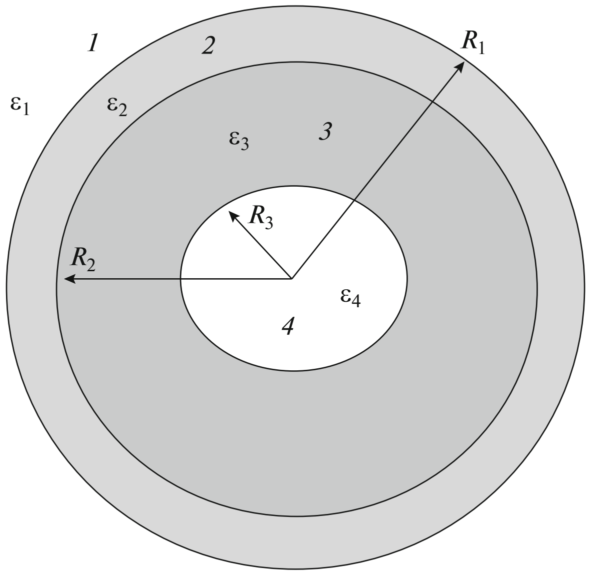

Fig. 2. Structure of the two-layed biological cell: (*1*) external medium of the cell (treated water medium); (*2*) cell membrane; (*3*) cell cytoplasm; (*4*) cell nucleus.

of microorganisms during pulsed treatment at the intensity $E \leqslant 100$ kV/cm in water-containing media, $T_c = 55–65°C$. Therefore, to reach a total inactivation of the treated medium without its repeated insemination, the temperature of the treatment should somewhat exceed the value of the critical temperature for a certain microorganism. In our experiments, the temperatures of the treated media were ~65°C for juice and wine samples and ~70°C for milk samples.

To avoid the repeated insemination of the treated medium, at least two sowings must be performed, i.e., immediately after the pulse treatment and 5 days after it, if it is required to increase the storage period of a product to more than 5 days without the growth of microorganisms in it.

Note that the process of electric pulse treatment of a biological cell, its response to it, and a mathematical description of the process itself are very complicated. To date, there is no clear description of the process of this effect [6]. The microorganisms that are considered in foodstuffs have mainly a two-layered dielectric structure. To construct this model and describe the processes affecting it under strong electric fields, one has to take into acount all important parameters of the electric field and the treated medium and the obtained experimental data. The model of a two-layered biological cell is shown in Fig. 2.

Table 1. Electrical characteristics of the main elements of a biological cell

Name of the cell element	Relative dielectric permittivity ε_{rel}	Specific conductance γ, Ω^{-1} m^{-1}
Membrane	2–5	$\sim 10^{-7}$
Cytoplasm	~81	$\sim 10^{-1}$
Nucleus	~10	$\sim 10^{-7}$

As is seen in Fig. 2, the cell consists of central nucleus *4* and external dielectric membrane *2*, inside and outside of which there is a polarized medium: fluid food stuff *1* and cell cytoplasm *3* [8]. The values ε_{rel} and γ inside the objects can vary greatly with ε_{rel} being from 1 for gases to >100 for milk or human body tissues and with γ being from 10^{-10} Ω^{-1} cm^{-1} for dry air to 10 Ω^{-1} cm^{-1} for water-containing food liquids. The values ε_{rel} and γ for the main elements of cells are taken from [22, 23] and are listed in Table 1.

Note that the nucleus is present in eukaryotic (complex) cells, whereas in prokaryotic (the elemental) cells the role of the nucleus belongs to the prokaryotic chromosome. For the nucleus of cells, ε_{rel} and γ should be considered as preliminary. It is known from [23] that flexibility of biomolecules supports their dielectric nature which is incompatible with high specific conductance, and the internal content of the nucleus, or prokaryotic chromosomes, has a small amount of water, which is indicative of a low conductance of the nucleus of a cell (or prokaryotic chromosome). Biomolecules, both protein and DNA, have many polar groups; therefore their relative dielectric permittivity must be substantially higher than that in lipids, but markedly lower than that in water. The density of biomolecules in a nucleus is high, and a prokaryotic chromosome represents a DNA molecule which carries hereditary information on a prokaryotic cell; therefore, the approximate dielectric permittivity of a nucleus can be taken equal to the characteristic permittivity of a biomolecule.

Except for the fact that food products are a nutritive medium for microorganisms, the factor that makes the treatment complicated is the presence in the products of more than one type of microorganisms with different concentration and sensitivity to the electric pulse treatment. In addition, among them, there are microorganisms in various phases of development, which as well makes it difficult to reach the required degree of inactivation.

RESULTS AND DISCUSSION

The analysis of the results of the treated samples display the effectiveness (economy) of the high-voltage electric pulse treatment of fluid products by both the degree of inactivation of microorganisms and the shelf life of products, which are equal to the traditional thermal pasteurization, and by the specific energy consumption, since the treatment was carried out at

Table 2. Results of the study of nutritive and biological values of raw milk

Name of the index	Actually obtained results	
	Reference sample	Test sample
Proteins, g/100 g	3.35	3.28
Fats, g/100 g	7	6.4
Carbonhydrates (lactose), g/100 g	4.8	4.7
Calorific capacity, kcal/100 g	104.6	99.7
Vitamins, mg/100 g		
Vitamin B_1	0.018	0.01
Vitamin B_2	0.170	0.145
Vitamin C	0.45	0.34
Amino acids, mg/100 g:		
Valine	152	130
Isoleucine	148	123
Leucine	207	203
Lysin	232	200
Methionine	70	64
Threonine	141	119
Triptophane	25	18
Phenylatanyan	100	94
Cycteine	29	27
Tyrosine	165	133
Peroxidase	Present	No
Macroelements, mg/100 g:		
Phosphorus	86.5	86.5
Potassium	118	117.8
Calcium	105.8	102.6
Magnesium	10.1	10.5
Microelements, μg/100 g:		
Iron	37.0	34.0

lower temperatures than during thermal pasteurization and without any exposure to the maximum temperature. The effect of the energy savings at an equal degree of inactivation is reached owing to the complexity of action of the synchronized factors of the electric pulse treatment: the electric field intensity, voltage, current (conductivity and offset), sharply rising temperature to maximum values that are lower than during thermal pasteurization. However, the main advantage of electric pulse treatment in our opinion is the maximum conservation and in some cases upgrading of the initial biological and nutritive value of the products after the treatment. As a result of the high-voltage pulse treatment, the degree of inactivation of microorganisms in food products was 10^5–10^6, and the maximum shelf life reached ~2 years for various juices and ~6 years for wine stored in the light at room temperature and ~15 days for milk stored at +5°C.

The results of the study of the effect of high-voltage pulsed electric fields on the nutrition and biological qualities of the treated samples of raw milk, apple juice, and red wine are presented in Tables 2–5.

Table 2 shows that the high-voltage electric pulse treatment of the samples of raw milk conserves its nutritive and biological values and taste properties. The contents of carbohydrates and micro- and macroelements in the test sample almost remained at the reference level. The nutritive and biological values of the test sample are relevant to the sanitary standard of the quality.

Table 3 shows that the high-voltage electric pulse treatment of the samples of apple juice does not affect its nutritive and biological qualities, and it does not deteriorate its organoleptic properties.

Table 4 shows that, as a result of the electric pulse treatment, red wine not only conserves its initial prop-

Table 3. Results of investigations of nutritive and biological values of apple juice prior to and after the electric pulse treatment

Name of the index	Obtained results	
	Reference sample	Test sample
Carbonhydrates (lactose), g/100 g	103	11.2
Including glucose	1.35	1.42
Vitamin PP (niacin), mg/100 g	0.095	0.082
Vitamin C, mg/100 g	3.1	1.7
Macroelements, mg/100 g:		
Phosphorus	4.32	4.51
Potassium	101.6	99.5
Calcium	9.8	10.8
Magnesium	4.5	4.7
Microelements, μg/100 g:		
Iron	1135	1090

Table 4. Results of organoleptic analysis of the samples of red semidry wines treated with strong pulsed electric fields

Organoleptic indices	Reference sample	Test sample
Color	Dark red	Dark red, More intense
Transparence	Transparent	Transparent
Sediment	Absent	Absent
Aroma (flavor)	Pure, flowery	Pure, flowery, developed
Taste	Light, harmonious	Light, harmonious, soft

erties but acquires new curative properties of bioregulators which are peculiar to the high-quality brands of cognacs.

According to the results presented in Tables 4 and 5, one can conclude the following:

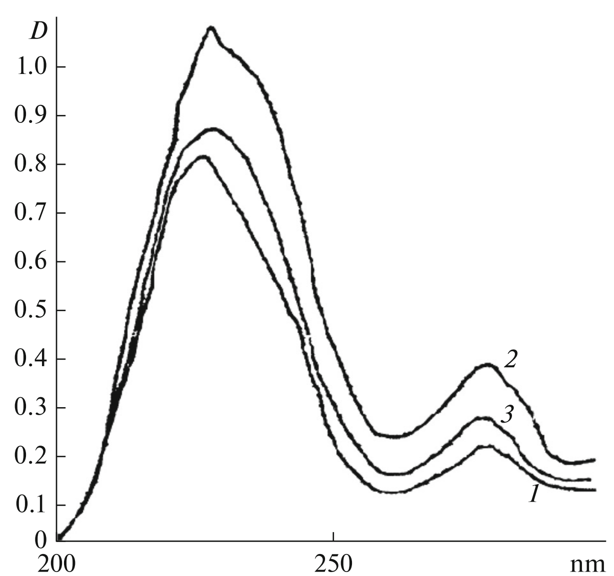

Fig. 3. Absorption spectra of plum juice depending on the wavelength.

• In the test sample versus the reference one, the aroma of wine is improved: it is pure, more developed, full, with flowery tones.

• The untreated (reference) wine material according to its indices of bottling stability is satisfactory in quality: the risk of appearance of microbiological milkiness (stability period) is up to 1 month.

• The treated (test) wine material according to its indices of bottling stability is good in quality: the period of resistance to microbiological milkiness is over 6 months.

• The electric pulse treatment does not affect significantly the physicochemical indices of the wine quality.

The effect of high-voltage pulses on the conservation of polyphenolic compounds in plum and cherry juices was also examined in this study.

During the study, three samples were prepared from each kind of fruit: sample 1 was a reference sample, which was not exposed to any treatment; sample 2 was exposed to thermal sterilization; sample 3 was treated using a pulsed electric field. The studies were performed by the method of measuring the optical density *D* of ethanol extracts of the juices (plum and cherry) on a spectrophotometer with a further plotting of the spectral curves (Figs. 3, 4).

Table 5. Results of analysis of the main physicochemical indices of red semidry wines treated with strong pulsed electric fields

Main physicochemical indices	Reference sample	Test sample
Ethanol, vol %	8.9	8.9
Reducing sugar, g/dm^3	1.8	1.8
Titrated acids, g/ dm^3	5.8	5.8
Volatile acids, g/dm^3	0.35	0.37
pH	2.8	3.0
Sulfurous acid, mg/dm^3:		
Free	15	17
Total	97	97
Iron, mg/dm^3	3	4
Facultative indices:		
Phenolic substances, mg/dm^3	1100	1100
Anthocyans, mg/dm^3	78	69
D_{420}	0.10	0.10
D_{520}	0.14	0.12
Intensity ($I = D_{420} + D_{520}$)	0.24	0.22
Tint ($T = 0420/0520$)	0.71	0.83
Malvidin diglucoside, mg/dm^3	6.8	7.0
Apple-milk fermentation	Did not proceed	Did not proceed
Total number of microorganisms, 1/cm^3	Over 38000	280

In all of the samples, the presence and amount of the oxidized forms of polyphenols were defined, which are a blend of the carboxylic acids and an insignificant quantity of quinones in the range of the wavelengths of 200–250 nm.

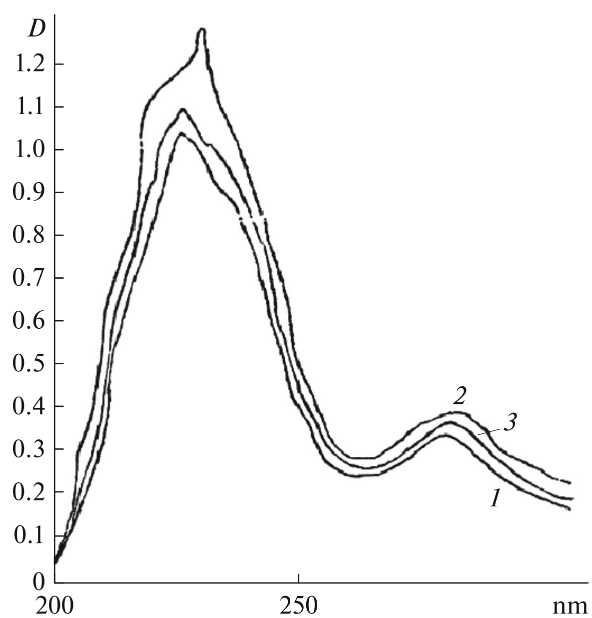

Fig. 4. Absorption spectra of extract of cherry juice depending on the wavelength.

The presented graphs of spectral density attest to the fact that the greatest number of oxidized forms of $D = 1.09$ in Fig. 3 (curve *2*) and $D = 1.30$ in Fig. 4 (curve *2*) are in the samples of the plum and cherry juices exposed to thermal sterilization. A considerably lower quantity of carboxylic acids, close to their amount in the control samples, is contained in the samples which were treated using high-voltage pulsed electric fields (Fig. 3, curve *3* and Fig. 4, curve *3*). This confirms the efficiency of the electric pulse method of treatment for conservation of polyphenolic complexes of fruits compared to thermal sterilization (pasteurization).

CONCLUSIONS

The results of experimental studies on inactivation of microorganisms in water-containing food products made it possible to propose the following concept of rational action (with minimal specific energy consumption) of a pulsed electric field during disinfecting high-voltage electric pulse treatment:

(1) Electric pulse treatment must be performed by pulses that ensure the highest degree of penetration of the field inside the cell. The following types of pulses satisfy these requirements: (a) pulses with a short front ($t \leqslant 20$ ns, where t_f is the duration of the pulse front for the characteristic dielectric permittivity and specific conductance of cytoplasm and the external membrane of a live cell (Table 1)) or (b) pulses with a frequency

spectrum that contains frequencies $f \geqslant 1.75 \times 10^7$ Hz [24]. In addition, these pulses must produce a maximal inactivating effect on the cytoplasmic membrane of the cells.

(2) The pulse duration t_i must be $t_i \geqslant 10^{-7}$ s = 100 ns. Note that the optimal pulse duration t_i is connected with the sizes of cells to be inactivated. The larger the characteristic size of the cells, the longer the duration. Moreover, the upper limit of the intensity amplitude of the external pulsed electric field is restricted by the breakdown intensity of the treated medium, which contains inactivated microorganisms, at the duration of pulses t_i that follow at a given frequency. Overly long pulses lead to an increase in the specific energy consumption at a similar inactivating effect [25, 26]. The field pulses with a long front ($t_f \geqslant 20$ ns) penetrate worse or do not penetrate at all inside the cell, which leads to a decrease or an absence of the effect of electric pulse treatment on the inside content of the cell [6].

(3) To reach a maximal inactivating effect, the treatment of a water-containing medium must be treated by pulses with minimum possible fronts and optimal duration (for microorganisms with characteristic sizes $r \sim 1$ μm, $t_{i.\,opt} \sim 0.1–1$ μs) at a maximum possible amplitude of intensity which does not result in breakdown of the medium. However, the highest temperature of the medium, which grows owing to the effect of the external electric field, must exceed somewhat the critical temperature, after which the inactivating effect sharply increases and becomes irreversible. It is noteworthy that the critical temperature is lower than the minimum temperature of thermal pasteurization, and the time of its maintenance in the treated product is substantially less than the time of thermal pasteurization.

(4) The high-voltage pulsed devices for the electron–ion treatment of water-containing food products must satisfy the following requirements:

(a) The high-voltage generators of pulsed voltages must ensure obtaining at a low-resistance (10–100 Ω) load pulses with the amplitude ⩾100 kV, front ⩽ 20 ns, frequency of pulse repetition ⩾100 Hz, and average load power of 50 kW and higher. Moreover, the generators must be easy to manufacture, i.e.:

—ensure a high rate of productivity of 1000 kg/h and more;

—have low specific energy consumption ⩽10 kW/m^3;

—have simple, reliable, and repairable construction and be safe in operation;

—be electromagnetically stable and compatible with other devices;

—have a high resource of $10^{10}–10^{11}$ pulses.

(b) The working chamber (a system of working chambers) as the most crucial element in the series of devices and systems of high-voltage pulsed devices must match up hardly compatible characteristics in the technological variant, i.e.:

—have maximally high, but less than the breakdown, operating intensities (⩾100 kV/cm and higher) of the electric field, close to uniform;

—sustain high voltages (⩾100 kV);

—have a high resource of ~10^{10} pulses and more;

—pass high pulsed currents (~10 kA and higher);

—sustain high average powers (50 kW and higher).

The working chambers can perform as flow-through or stationary.

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