JUSTIFICATION OF THE METHOD OF VEHICLE ENGINE RADIATOR ULTRASONIC CLEANING

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Resume

The article presents theoretical and experimental results on ultrasonic cleaning of a vehicle radiator. Criterion relationships between ultrasound energy, kinetic energy of the liquid, and shock wave energy were established, enabling the evaluation of cavitation energy efficiency and cleaning effectiveness. Experimental confirmation was obtained using a developed full-size bench. Using the developed full-size bench, the numerical values of parameters were obtained that made it possible to calculate the values of energies involved in the cavitation process, the ratio of which allows evaluating the effectiveness of washing the radiator from scale. The cavitation coefficient of erosion efficiency was established, proving the effectiveness of ultrasonic cleaning. Results confirm the applicability of this method for cleaning the vehicle radiators.

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1 Introduction

The internal combustion engine (ICE) is the main part of a vehicle that combines a lot of integrated systems and ensures their proper operation, however, the operation of the internal combustion engine results in air pollution due to exhaust gases. The failure of almost any system involved in the engine operation leads to increased formation of harmful and toxic substances in the processed gases, which, in turn, has an impact on the environment, harms human health and contributes to the development of serious diseases [1-3]. One of the main components of the internal combustion engine is the cooling system that removes excess heat from the engine elements and maintains the optimal operating temperature.

If the operating temperature in the cooling system is disrupted, this leads to the overheating of the engine that subsequently causes irreversible consequences in violating its technical condition, performance and failure of the other systems involved in the operation of the internal combustion engine [4].

This in turn leads to increased air pollution and the risk of various diseases.

In general, the cooling system malfunctions account for about 25-30% of all the internal combustion engine failures. One of the main malfunctions of the cooling system is its overheating. Overheating can be caused for various reasons. The most common cause of this malfunction is the formation of scale on the system elements. The appearance of scale depends on various factors, such as: untimely vehicle maintenance, oil getting into the antifreeze, radiator tightness, quality of detergents, rust formation on the internal surfaces of the system and the effect of decomposition products of antifreeze components. The combination of these factors leads to the scale depositing on the elements of the cooling system, in particular on the walls of the cooling jacket, which contributes to decreasing the heat transfer between the system parts and subsequent clogging of thin channels and tubes of vehicle radiators [5].

The radiator, being one of the main elements of the internal combustion engine cooling system, consists of thin-walled tubes through which the coolant flows. This component ensures the required operating temperature of the engine coolant, while giving off the excess heat to the flow of oncoming air.

Radiators are descaled using mechanical and chemical methods. The mechanical cleaning method is characterized by high labor intensity and the accompanying large expenditure of time and money on the cleaning process. During the mechanical cleaning, radiator tubes are often damaged and become unusable [6].

The chemical method for descaling radiators involves flushing with distilled water and adding various chemical agents. Radiators made from different metals, such as aluminum, brass, copper, or galvanized steel, are subject to different risks when using such methods.

Aluminum radiators are particularly vulnerable to corrosion caused by acidic or alkaline cleaning agents. Incorrect chemical selection can lead to damage to aluminum surfaces, formation of holes, and leaks.

While the copper and brass radiators are more resistant to corrosion, they can also suffer from aggressive chemicals, which may cause copper leaching and solder degradation. Acids can destroy the zinc coating on galvanized steel, leading to corrosion of the steel base.

Copper, with its excellent thermal conductivity, is an effective material for radiators as it helps to dissipate engine heat more quickly. However, aluminum radiators are lighter and less costly to manufacture, making them the preferred choice for modern vehicles.

As a result, it can be concluded that chemical methods for cleaning radiators have significant disadvantages, including high physical and time costs for the cleaning process and a destructive impact on the radiator's functional condition.

In this regard, we propose the use of an ultrasonic cleaning method for descaling the radiator tubes. Under the influence of ultrasound, the speed and level of liquid movement inside the radiator are significantly increased, facilitating its penetration into the internal surface of the scale buildup [7].

In industry and mechanical engineering, there are widely used methods to achieve various purposes using ultrasonic impact, for example, cleaning, welding, flaw detection, machining and cutting. In recent years, a number of successful studies have been carried out to reduce the harm of exhaust gases and to analyze their impact [8-11]. New methods of cleaning the exhaust gases and vehicle radiators by cavitation and coagulation using ultrasonic impact are being considered [12-13].

The cleaning process is characterized by the joint manifestation of various nonlinear effects that arise in the liquid when they are affected by ultrasonic vibrations. In particular, when cleaning radiator tubes with ultrasound, the cavitation effect is observed that arises from the energy of the ultrasonic wave and depends on changing the parameters of the intensity and pressure of the shock waves. Under the effect of cavitation, in the liquid cavitation bubbles form that collapse near the contaminants and destroy the scale layer and the other deposits [14].

In general, the ultrasonic method does not require significant use of manual labor and the other mechanical effects from the outside, thereby greatly simplifying the cleaning process.

In connection with the above, the proposed method of cleaning the vehicle radiator from the scale is relevant.

The research hypothesis is the probability of cleaning the radiator using the ultrasonic impact.

The purpose of the study is to establish the dependences that determine the mode and efficiency of the ultrasonic cleaning process for radiators of internal combustion engines.

To achieve the goal of the study, the following tasks were solved: the physical essence of the cavitation process was considered; criterion energy dependences were obtained that allowed evaluating the energy efficiency of the cavitation process when cleaning the radiator with ultrasound; an experimental bench for radiator cleaning was developed and the results were analyzed; the cavitation coefficient of erosion activity was obtained, the numerical value of which confirmed the effectiveness of radiator cleaning by ultrasound.

The scientific novelty lies in obtaining dependences that allow designing the technology of cleaning radiators with ultrasound.

The practical significance lies in obtaining calculated dependences and the algorithm of the cleaning process.

2 Materials and methods

The physical essence of the process of cleaning radiator tubes by cavitation is as follows. Cavitation refers to the formation of pulsating bubbles filled with gas in a liquid. In an ultrasonic wave, during the half-periods of rarefaction, cavitation bubbles appear that collapse sharply after moving to the region of increased pressure generating strong hydrodynamic disturbances in the liquid and intense radiation of acoustic waves. At the same time, destruction of the surfaces of solid bodies adjacent to the cavitating liquid occurs in the liquid.

The general picture of the process of cavitation formation in the liquid is presented in the following form. The liquid is exposed to low-intensity ultrasonic vibrations. It is known that an ultrasonic wave passing through the liquid forms compression zones and rarefaction zones changing places in each half-cycle of the wave and characterized by the appearance of alternating pressure. As the intensity of ultrasound increases, the violation of the liquid homogeneity is observed. In the rarefaction phase (low pressure), emission of dissolved gases begins in the weakest places with formation of one long-lived bubble. In this case, the resulting bubble oscillates linearly with the ultrasound frequency relative to its equilibrium radius R. It is obvious that the maximum amplitude A will be observed in bubbles resonant for a given frequency f, therefore, in the compression phase, under the effect of increased pressure and surface tension forces, the bubble collapses. Further increasing of the intensity leads to violation of the linearity of the bubble walls vibrations. The stage of stable cavitation begins, in which the bubble itself becomes a source of ultrasonic vibrations. In this regard, waves, microcurrents and electrical discharges appear on its surface. When the intensity value reaches more than I >2.5 W/cm^2, the stage of unstable cavitation occurs that is characterized by the formation of rapidly growing gas bubbles that, in the compression phase, instantly contract in volume and collapse [15].

At the moment of collapse, the pressure and temperature of the gas reach significant values (according to some sources, up to 100 MPa and 10,000 ^{0}C). After the bubbles collapse, a spherical shock wave propagates in the surrounding liquid and quickly decays in space. The collapse means the following phenomenon: decreasing the radius R of the bubble to the minimum value R_{min} or decreasing the radius of the cavity, that is, its deformation and disintegration into several bubbles [16].

A review of publications and patents on the research topic demonstrates that ultrasonic cleaning, due to the phenomenon of cavitation, is an effective and environmentally friendly method for cleaning vehicle radiators from rust and other contaminants. Authors of [17] discussed approaches to optimizing ultrasonic cleaning for different types of contaminants, including rust, and the importance of ultrasonic wave frequency in enhancing the cleaning process's efficiency.

Kamar et al. described the process of cleaning the heat exchangers in [18]. They explained in detail how ultrasonic cavitation helps remove deposits and scale, while also increasing heat transfer efficiency. Patent US4705054A, titled "Ultrasonic Radiator Cleaning System," describes a cleaning system using ultrasound, specifically designed for heat exchangers and vehicle radiators. The patent covers the design of ultrasonic baths used for effectively removing contaminants [19].

Additionally, patent US20120291657A1, "Ultrasonic Cleaning Apparatus," describes an ultrasonic device for cleaning various surfaces, including vehicle parts. The system uses acoustic cavitation in liquids to clean rust and other contaminants [20].

Acoustic cavitation in liquids initiates various physical and chemical phenomena, such as sonoluminescence (glow of liquids); chemical effects (sound-chemical reactions); dispersion (grinding solid particles in the liquid), emulsification (mixing and homogenizing immiscible liquids) and mechanical erosion (destruction of surfaces) [21].

Mechanical erosion leads to destruction and cleaning of the interacting surface due to the formation of the cavitation region based on two characteristic manifestations of cavitation: shock waves and cumulative jets formed during the collapse of cavitation bubbles. Cumulative streams destroy the surface of a solid body due to the kinetic energy of the liquid. Small particles of a solid body, the dimensions of which are commensurate with the cross section of the cumulative jets, are carried away by them and make an additional contribution to the process of destruction of solid particles in the liquid [22].

Some of the energy of the primary sound field is spent for forming the cavitation region. At the stage of formation of the cavitation region, the field energy is spent for the appearance and growth of cavitation bubbles. The primary energy cannot be spent only for the formation of cavitation, since if the value of the primary energy of the sound field is lower than the energy spent for formation of cavitation $E<E_{cav}$, then the duration of the cavitation process will immediately stop. Consequently, part of this energy is given back when the bubbles collapse in various forms, primarily in the form of shock waves capable of producing mechanical erosion, which is effective in ultrasonic cleaning processes. Thus, the ratio of the energy spent for the formation of cavitation to the total energy of the primary sound field gives the parameter of the coefficient of cavitation utilization of acoustic energy, the value of which should not be greater than 1 $x<1$:

$$x = \frac{E_{cav}}{E}, \tag{1}$$

where E_{cav} is the energy spent for forming cavitation; E is the total energy of the primary sound field.

If to denote the energy emitted in the form of shock waves by E_m and to relate it to the energy of the primary sound field, then their ratio will give the parameter that evaluates the measure of the erosive activity of cavitation or the cavitation coefficient of erosive efficiency:

$$\varepsilon = \frac{E_m}{E}, \tag{2}$$

where E_m is the energy given in the form of shock waves.

By definition, it is clear that the value of the parameter ε should not be greater than $\varepsilon < 1$. However, the closer the value of ε is to 1, the higher the erosive activity of the cavitation process.

It is known that for the appearance of mechanical erosion it is necessary that the values of the resulting mechanical stresses exceed their threshold values. Mechanical stresses are aimed at weakening the adhesion forces of the surfaces of the cleaned bodies interacting with the liquid, which lead to their subsequent separation and displacement from the surface during the cleaning process. Mechanical stresses are determined by the pressure of the shock wave. If the pressure of the shock wave exceeds the threshold stress values, then this can cause mechanical destruction (erosion), in which case the total volume of destruction will be proportional to the coefficient ε.

Currently, there is no satisfactory model of the cavitation region that adequately describes its behavior and the action of the individual cavitation bubble belonging to it. After all, the behavior of the cavitation region depends on many phenomena and factors that are completely impossible to take into account. In this case, the method of similarity theory and the dimensional analysis was used, since it is very effective in the analysis of complex processes, the mathematical description of which is difficult to form. In addition, this method allows establishing the characteristic and convenient parameters that determine the main effects and modes of the processes. At the same time, the combination of this method with thea general qualitative analysis of the mechanism of physical phenomena can be a fruitful theoretical method of research in a number of cases.

In accordance with the provisions of the method of similarity theory and dimensional analysis [23], the following fundamental variables were considered, taking into account the main factors of the cavitation region and allowing one to set parameters describing the process of ultrasonic radiator cleaning: the tube radius *(r),* the tube length *(l),* the section layer *(Δ)*, the fluid density *(ρ),* the gravitational acceleration *(g),* the ultrasonic exposure time *(t),* the ultrasonic wave intensity *(I),* and the shock wave pressure *(P).* As a result, eight fundamental variables were obtained that depend on the shock wave pressure, the functional relationship of which can be written in the following form:

$$P = f(r, l, \Delta, \rho, g, t, I). \tag{3}$$

From here there follows such an equation:

$$\varphi\left(r, l, \Delta, \rho, g, I, \frac{P}{t}\right) = 0. \tag{4}$$

Then, the resulting variables are transformed by expressing their dimension in relation to three basic units of measurement: length *L,* mass *M* and time *T* (Table 1).

It is assumed that the number of basic dimensionless parameters through which all n variables can be expressed is equal to m. According to the resulting equation (Equation (4)), the number of variables is equal to n = 7, and the number of basic units of measurement is equal to k=3, in accordance with the ϖ-theorem, the number of basic dimensionless parameters will be equal to: $m = n - k = 7 - 3 = 4$. Therefore, the following equation is obtained:

$$\pi = \varphi(\pi_1, \pi_2, \pi_3, \pi_4). \tag{5}$$

From here there follows the equation:

$$\varphi(\pi_1, \pi_2, \pi_3, \pi_4) = 0, \tag{6}$$

where $\pi_1, \pi_2, \pi_3, \pi_4$ are dimensionless parameters that are determined as follows.

From n variables, three are selected, with independent dimensions, including three basic units (length *L*, mass *M* and time *T*); let this be the radius *(r)* of the radiator tube, the density of the liquid *(ρ)* and the acceleration of gravity *(g).*

Then, the dimensionless parameters π_1, π_2, π_3 and π_4 were defined. The selected three variables (*r, ρ, g*) were included in each of the ϖ-terms, the remaining variables, namely: $\Delta, I, l, \frac{P}{t}$, were then, one at a time, included in the previously formed ϖ-terms with three main variables. The exponents of the three main variables that determine the dimensionless parameters are unknown, therefore they are denoted as *x, y* and *z.* The exponents of the remaining variables are accepted equal to -1. As a result, the relations for ϖ - terms will have the following form:

$$\pi_1 = r^{x1}\rho^{y1}g^{z1}\Delta^{-1}; \tag{7}$$

$$\pi_2 = r^{x2}\rho^{y2}g^{z2}I^{-1}; \tag{8}$$

$$\pi_3 = r^{x3}\rho^{y3}g^{z3}l^{-1}; \tag{9}$$

$$\pi_4 = r^{x4}\rho^{y4}g^{z4}\left(\frac{P}{t}\right)^{-1}. \tag{10}$$

The variables included in the ϖ-terms can be expressed in terms of basic dimensions. Since these terms are dimensionless, the exponents of each of the main dimensions must be equal to zero. As a result, for each of the ϖ-terms, three independent equations can be constructed (one for each dimension), which relate the exponents of the variables included in them. Solving the resulting system of equations makes it possible to

***Table 1** List of dimensional formulas for the basic variable values*

N	Variable	Designation	Unit	Dimensional formula
1	Tube radius	*r*	m	L
2	Tube length	*l*	M	L
3	Parcel layer	Δ	M	L
4	Liquid density	*ρ*	kg/m^3	ML^{-3}
5	Acceleration of gravity	*g*	m/s^2	LT^{-2}
6	Ultrasound exposure time	*t*	S	T
7	Ultrasonic wave intensity	*I*	W/m^2	M T^{-3}
8	Shock wave pressure	*P*	Pa	ML^{-1} T^{-2}

find the numerical values of the unknown exponents *x, y* and *z*. As a result, each of the ϖ-terms is defined in the form of a formula composed of specific quantities to the appropriate degree.

Then, the dimension equation for the first π -terms is composed:

$$\pi_1 = L^{x1}\left(\frac{M}{L^3}\right)^{y1}\left(\frac{L}{T^2}\right)^{z1}(L)^{-1}. \tag{11}$$

The exponents with the same bases are then added:

$$\pi_1 = L^{x1-3y1+z1-1}L^{y1}M^{-2z1}. \tag{12}$$

For the dimension π_1 to be equal to one, it is necessary to equate all the exponents to zero:

$$\begin{cases} x_1 - 3y_1 + z_1 - 1 = 0 \\ \quad - y_1 = 0 \\ \quad - 2z_1 = 0. \end{cases} \tag{13}$$

The system of algebraic equations contains three unknown quantities x_1, y_1, and z_1. By solving this system of equations it is found that $x_1 = 1$, $y_1 = 1$ and $z_1 = 1$.

Substituting these values of exponents into the first π_1 term, there is obtained the first dimensionless parameter:

$$\pi_1 = \frac{r}{\Delta}. \tag{14}$$

The similar calculation is then performed for the remaining ϖ-terms and the second, third and fourth dimensionless parameters are obtained:

$$\pi_2 = \frac{\rho rg\sqrt{rg}}{I}; \tag{15}$$

$$\pi_3 = \frac{r}{l}; \tag{16}$$

$$\pi_4 = \frac{\rho tg\sqrt{rg}}{P}. \tag{17}$$

Substituting the resulting ϖ-terms into Equation (4), the four dimensionless parameters are obtained:

$$\varphi\left(\frac{r}{\Delta}, \frac{\rho rg\sqrt{rg}}{I}, \frac{r}{l}, \frac{\rho rg\sqrt{rg}}{P}\right) = 0. \tag{18}$$

The equation for π_1 is then solved, where $\frac{r}{\Delta}$ to the left side of the equation $\frac{r}{\Delta}$ is derived. Then, the dimensionless parameters of the second, third and fourth ϖ-terms are reduced and a single criterion is obtained. Thus, one can write equation (18) in the following form:

$$\frac{r}{\Delta} = \varphi\left(\frac{Pl}{It}\right). \tag{19}$$

As mentioned earlier, mechanical stresses are determined by the the shock wave pressure. It should be understood as the force applied to the upper layer of liquid, causing displacement of the layers, namely the shear stress of the inner surface (scale) of the radiator tube relative to its cross-sectional area. Therefore, the pressure can be converted as the ratio of force to area:

$$P = F_p/S, \tag{20}$$

where F_p is the force conditioned by the shock wave pressure on the surface considered;
S is the cross-section area of the radiator tube.

Substituting this expression instead of P the following criterion is obtained as a result:

$$k_2 = \frac{F_p l}{SIt}. \tag{21}$$

It should also be noted that the intensity of ultrasonic vibrations is the amount of energy passing through the unit cross-sectional area of the radiator tube during the unit time of exposure to ultrasound. Therefore, it can be concluded that the product of area, ultrasound intensity and time gives the ultrasound energy parameter E_u. The product of the force, caused by the shock wave pressure, by the length of the radiator tube characterizes the work occurring inside the radiator's tube, which can be conditionally equated to the energy given off in the form of shock waves E_m. The energy of the shock wave contributes to formation of the mechanical stress on the scale area and leads to its subsequent separation from the inner surface of the tube. Then, the criterion obtained will have the following form:

$$k_2 = \frac{E_m}{E_u}. \tag{22}$$

The ultrasonic energy characterizes the total energy of the primary sound field that includes the energy spent for the formation of the cavitation process and the energy released in the form of shock waves.

Thus, the fundamental variables, which were selected, were reduced into dimensionless parameters and transformed into two similarity criteria:

$$k_1 = \frac{r}{\Delta}; \tag{23}$$

$$k_2 = \frac{E_m}{E_u}. \tag{24}$$

The first criterion k_1 characterizes the ratio of the geometric parameter of the radiator tube, namely the radius of the tube to the thickness of the scale. The second criterion k_2 characterizes the erosive efficiency of the cavitation process by the ratio of the energy released in the form of shock waves to the energy of the ultrasonic emitter.

Taking into account the law of conservation of momentum in a closed region, Borgnis derived an approximate theorem according to which it is believed that during the propagation of an acoustic wave, the energy of the sound field spent on the formation of cavitation E_{cav} is equal to the kinetic energy of the fluid flow E_{kin},:

$$E_{cav} = E_{kin} . \quad (25)$$

In addition, based on the approximate Borgnis theory, it is possible to determine the force due to the pressure of the ultrasonic wave through the force due to the energy of the sound field:

$$F = F_p + F_{kin} , \quad (26)$$

where F is the force caused by the energy of the sound field;
F_p is the force caused by the shock wave pressure on the surface considered;
F_{kin} is the force of the liquid flow kinetic energy.
It follows that

$$F_p = F - F_{kin} . \quad (27)$$

Having transformed equation (27) through the ultrasound energy and kinetic energy, one ultimately obtains the following equation, which allows to determine the force F_p caused by the the shock wave pressure:

$$F_p l = E_u - E_{kin} ; \quad (28)$$

$$F_p = \frac{E_u - E_{kin}}{l} , \quad (29)$$

where l is the radiator tube length.

From the obtained k_2 criterion is known that the product of the force caused by the shock wave pressure and the length of the radiator tube gives the energy released in the form of shock waves, $E_m = F_p l$.

The values of energy indicators, in particular the kinetic energy of the liquid in the radiator tube, were determined experimentally. For this purpose, the values of the parameters of mass and the liquid outflow from the radiator tube were set. To carry out the relevant experimental studies, a full-size test bench for ultrasonic cleaning of vehicle radiators was developed.

The bench is a setup (Figure 1) designed for cleaning radiators. It consists of the following elements: interior heater radiator 1, ultrasonic emitter 2; axial fan 3; circulation pump with heating element 4; filter 5; liquid reservoir 6; temperature control devices 7; rubber pipes 8.

The procedure of the experiment was as follows. At the preparatory stage, the setup for ultrasonic cleaning of radiators was assembled and connected. Then, the bench was filled with clean water and the parameters of this water were determined. At subsequent stages, water was heated to 50 °C. Next, ultrasound was applied to the radiator within various time intervals (600, 1200 and 1800 seconds), and then the liquid parameters (volume, mass, density and flow time) were determined. The final stage included saturation of water with air before exposure to ultrasound and analyzing the experimental results.

3 Results

According to the plan and procedure of the experiment, appropriate experimental studies were carried out, the results of which are presented in Table 2.

Based on the results of experimental studies (Table 2), calculations were carried out to determine the rate of fluid outflow, based on the parameters of the volume and time of fluid outflow. The following parameters were also determined by calculation: kinetic energy of the liquid, ultrasound energy and energy released in the form of shock waves. The calculation results are presented in Table 3.

Based on the calculation results, a graph of changing the parameters of mass and fluid flow rate was obtained,

1- interior heater radiator; 2 - ultrasonic emitter; 3 - axial fan; 4 - circulation pump with heating element; 5 - filter; 6 - liquid reservoir; 7 - temperature control devices; 8 - rubber pipes

Figure 1 *Mounting the emitter on the interior heater radiator*

***Table 2** Experimental study results*

Measured parameter	Unit	Exposure time, s.			
		0	600	1200	1800
Liquid volume (V)	ml	45	45	45	45
Liquid mass (m)	g	44.57	44.60	44.63	44.69
Liquid density (ρ)	g/cm^3	0.9904	0.9911	0.9917	0.9931
Effusion time (t)	s	9.93 s/l	9.73 s/l	9.22 s/l	9.20 s/l

***Table 3** Results of calculations*

Calculated parameter	Unit	Exposure time, s.			
		0	600	1200	1800
Effusion time, (ϑ)	Milliliter per second (ml/s)	100.7	102.7	108.45	108.69
Kinetic energy of the liquid flow, (E_{kin})	J	225.98 μJ	235.2 μJ	262.45 μJ	263.97 μJ
Ultrasound energy (E_u), (emitter power 50 W)	J	0	30 kJ	60 kJ	90 kJ
Energy given in the form of shock waves, (E_m)	J	-225.98 μJ	29 kJ	59kJ	89kJ

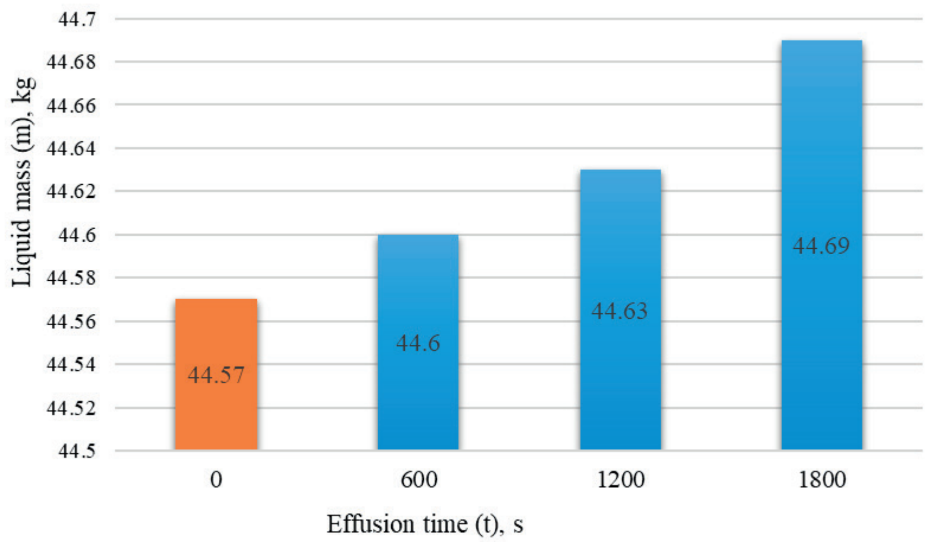

***Figure 2** Changing the liquid mass (m) depending on the time of exposure to ultrasound (t)*

as well as the graph of changing the energy versus the time of exposure to ultrasound, Figures 2 and 3, respectively.

From the dependences in Figures 2 and 3 it follows that with increasing the time of exposure to ultrasound, the mass and flow rate of liquid with scale increase compared to the mass and flow rate of the original liquid (not exposed to ultrasound). This is explained by the fact that a large amount of energy is formed in the liquid after exposure to ultrasound that is spent for formation of the cavitation process and leads to the washing of scale from the radiator tubes.

From Table 3 it follows that with increasing the time of exposure to ultrasound, the energy of the liquid increases. This increase in energy leads to the more efficient removal of contaminants from the radiator tubes and improved cleaning efficiency.

According to calculations, based on the obtained energy indicators, the numerical values of the coefficient of cavitation use of acoustic energy and the cavitation coefficient of erosion efficiency were calculated.

The coefficient of cavitation use of acoustic energy is determined as follows:

$$x = \frac{E_{cav}}{E} = \frac{E_{kin}}{E_u};$$
$$x_1 = 0;$$
$$x_2 = \frac{235.2 \cdot 10^{-6}}{30 \cdot 10^3} = 0.0078 \cdot 10^{-6}; \qquad (30)$$
$$x_3 = \frac{262.45 \cdot 10^{-6}}{60 \cdot 10^3} = 0.00437 \cdot 10^{-6};$$
$$x_3 = \frac{263.97 \cdot 10^{-6}}{390 \cdot 10^3} = 0.00293 \cdot 10^{-6}.$$

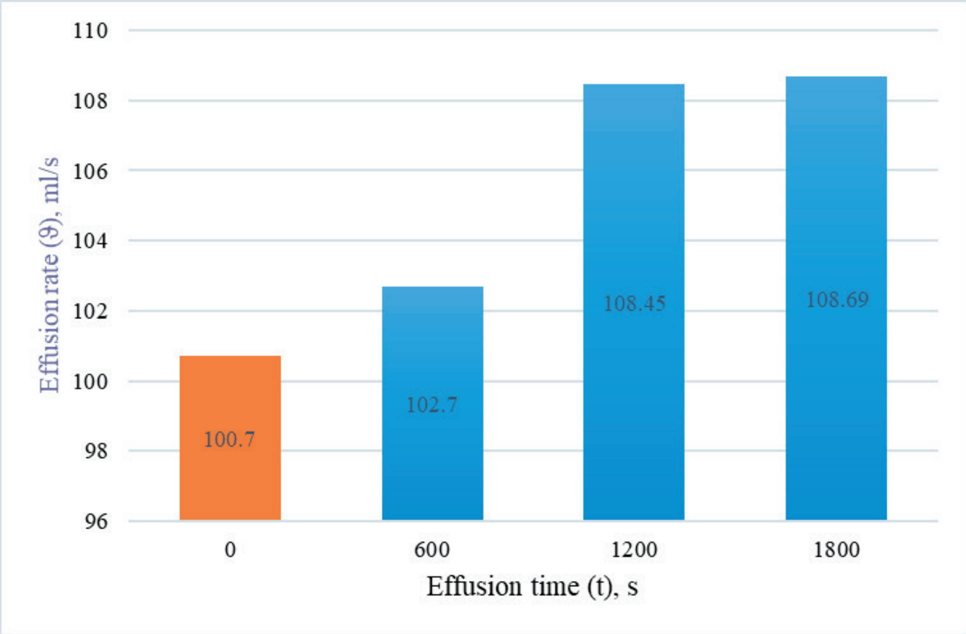

Figure 3 *Changing the effusion rate (ϑ) depending on the time of exposure to ultrasound (t)*

The cavitation coefficient of the erosion efficiency is determined as:

$$\varepsilon = \frac{E_m}{E} = \frac{E_m}{E_u};$$
$$\varepsilon_1 = \frac{29}{30} = 0.96;$$
$$\varepsilon_2 = \frac{59}{60} = 0.98; \tag{31}$$
$$\varepsilon_2 = \frac{89}{90} = 0.99.$$

Thus, the average cavitation coefficient of erosion efficiency is 0.98, thereby satisfying the condition $\varepsilon < 1$ and proving the effectiveness of ultrasonic radiator cleaning.

4 Conclusion

Based on the results of the study, the hypothesis about the possibility of determining dependences that allows assessing the effectiveness of radiator cleaning with ultrasound was confirmed.

Using the method of similarity theory and the dimensional analysis, criterion dependences were obtained that theoretically made it possible to consider the energy consumption for radiator cleaning and the erosive activity of the cavitation effect.

An experimental bench was developed, the purpose of which was to obtain numerical indicators of parameters that made it possible to calculate the energy consumed during the process of flushing the radiator from scale.

As a criterion proving the effectiveness of radiator cleaning with ultrasound, the cavitation coefficient of erosion efficiency was established, the numerical value of which confirmed the high effectiveness of ultrasonic cleaning.

The results obtained made it possible to prove scientific and practical significance of developing a methodology of calculating the parameters of the technological process of a radiator maintenance.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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