DETERMINATION OF OPTIMAL PARAMETERS FOR ULTRASONIC CLEANING OF VEHICLE RADIATORS

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Resume

The research presented in this article was concerned with the efficiency of ultrasonic cleaning of vehicle radiators based on the cavitation phenomenon. A technique has been developed that takes into account the effect of the ultrasonic vibration amplitude and the time of exposure on the process of removing contaminants. The results of experimental studies are presented that confirm that increasing the exposure time contributes to increasing the washed scale mass and decreasing the time of liquid outflow. The developed regression model describes well the changes in the mass of washed scale, which is confirmed by a high coefficient of determination and correlation. The obtained results allow for optimizing the parameters of the ultrasonic cleaning process, increasing its efficiency and reducing the risk of damage to the structural elements of the radiator.

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1 Introduction

Present day vehicle engine cooling systems play the key role in maintaining the efficient and safe operation of a vehicle. Being the main element of such systems, radiators are subject to significant operational loads, which leads to the accumulation of various types of contaminants on the inner surfaces of the tubes. Scale, rust, oil and organic deposits prevent the normal heat exchange and can significantly reduce the efficiency of cooling. This in turn leads to engine overheating, increased fuel consumption and decreasing the service life of the cooling system. Therefore, the problem of cleaning radiators and maintaining them in optimal condition is relevant to ensure reliable operation of vehicles.

Traditional methods of cleaning radiators, such as mechanical and chemical cleaning, have a number of disadvantages. Mechanical cleaning damages the inner surfaces of the tubes, especially in narrow and hard-to-reach places. Chemical reagents in turn cause metal corrosion. For example, studies carried out by Said et al. prove that standard chemical methods compromise the design of the radiator and reduce their overall performance [1]. Studies carried out by Habeeb et al. also confirm that chemical compounds have a negative impact on aluminum radiators and lead to increased corrosion [2].

In addition, some reagents are difficult to completely remove from the system after the cleaning, which affects the durability of radiator materials. The use of aggressive chemicals requires careful handling and special disposal procedures, which increases the cleaning costs and creates potential risks for the environment. In this regard, the use of ultrasonic cavitation for cleaning radiator tubes is an optimal method.

Ultrasonic exposure is an effective cleaning method due to the phenomenon of cavitation. Bubbles that arise in the liquid under ultrasonic exposure collapse and generate hydrodynamic forces, reaching temperatures of up to 10,000 °C. This allows for the effective removal of scale and dirt from radiator tubes. A study carried out by Yamashita et al. shows that cavitation effects provide a multiple increase in the cleaning coefficient [3].

In previous studies [4-5], the theoretical and experimental foundations of the use of ultrasound for cleaning vehicle radiators were established, which confirmed its effectiveness due to cavitation processes. However, in those studies the effect of the key parameters of ultrasonic action on the cleaning efficiency indicators was not considered, in particular characteristics of the ultrasound effect on the mass of scale washed out. In this regard, the hypothesis of the study was the probability of increasing the mass of scale washed out of the radiator tubes due to changing the amplitude indicators and increasing the accumulated time of exposure to ultrasonic vibrations.

The goal of the study was to establish dependences that describe changing the mass of washed scale from the amplitude and accumulated time of exposure to ultrasonic vibrations.

To achieve the goal of the study, the following tasks were solved:

- analyzing the existing studies and establishing the degree of the parameters effect on the cavitation and cleaning processes;
- using the similarity theory and dimensional analysis, additional similarity criteria were obtained that allowed evaluating the cleaning efficiency;
- the design of the developed experimental bench for cleaning radiator tubes was improved;
- experimental studies were carried out on the stand;
- the obtained results were analyzed;
- a regression equation was obtained that described changing the mass of washed scale depending on the exposure time and the amplitude of ultrasonic vibrations;
- the optimal amplitude values were determined according to the obtained similarity criterion.

The scientific novelty lies in obtaining dependencies that allow studying the pattern and the efficiency of the ultrasonic cavitation process.

The practical significance of the study consists of the following:

- further development of an effective method of ultrasonic cleaning of radiators, ensuring the removal of dirt and scale without risk of damaging structural elements;
- reducing maintenance costs and extending the service life of radiators;
- the possibility of industrial application of the proposed technology for servicing vehicle radiators;
- improving the environmental safety of the technology of cleaning radiator tubes by eliminating aggressive chemicals.

2 Materials and methods

The results of studies by a number of well-known scientists in the field of ultrasonic cavitation cover the period of 1934-2020 (Figure 1) and contribute to more detailed understanding of the cavitation mechanism and establishment of the factors affecting the efficiency of cleaning (Table 1).

The analysis of the results of studies by scientists in this area made it possible to establish the key parameters that affect the cavitation process (Table 2).

Among the parameters considered, and according to the technical characteristics of the ultrasonic equipment operating at one frequency and power, as well as the conditions of the experimental studies, the most adjustable and fixed parameters that directly affect the cleaning result are the duration of ultrasound exposure and the amplitude of ultrasonic vibrations.

Despite the significant studies conducted in the previous works [4-5, 21-24] on ultrasonic cleaning of radiator tubes, the experimental technique had certain limitations that did not allow for complete determination of the optimal parameters of the cleaning process. In particular, insufficient attention was paid to the effect of such parameters as the cumulative effect of

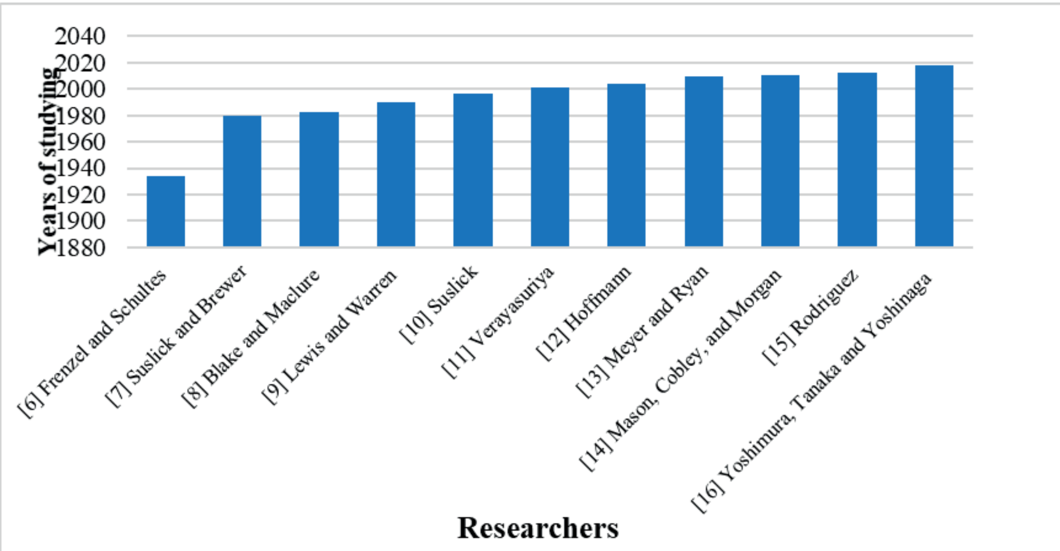


***Figure 1** The timeline of research in the field of ultrasonic cavitation*

Table 1 *Results of the scientists' studies the area of ultrasonic cavitation*

Researchers	Research area	Main results
Frenzel and Schultes	Low pressure high intensity ultrasound cavitation	It has been established that ultrasonic cavitation creates local zones with high temperatures and pressures, which improves cleaning due to microexplosions and mechanical action [6].
Suslick and Brewer	Chemical effects of cavitation	It has been found that the collapse of bubbles forms radicals (hydroxide and hydrogen), which destroy organic contaminants. The study is important for environmental cleaning technologies [7].
Blake and Maclure	Effect of pressure and fluid composition	The optimum pressure for cavitation is 1.5-2 bar. Carbon dioxide and oxygen enhance bubble stability and improve cleaning efficiency [8].
Lewis and Warren	Viscosity and chamber geometry	Using low-viscosity liquids and an optimized chamber improves cavitation and bubble collapse [9].
Suslick	Effect of ultrasound frequency	It has been shown that low frequencies (20-40 kHz) contribute to the formation of large bubbles, which increase the intensity of cleaning due to powerful collapse [10].
Verayasuriya	Effect of temperature on cavitation	It has been established that at the temperature of 30-60 °C, cleaning efficiency increases due to a decrease in the viscosity and density of the liquid. Adding gases also enhances the effect [11].
Hoffmann	Chemical additives to enhance cavitation	Adding hydrogen peroxide increases the formation of hydroxide radicals, which improves the destruction of organic contaminants [12].
Meyerand Ryan	Duration of ultrasonic action	Short sessions (about 10 minutes) are quite effective for cleaning, while longer sessions increase the risk of damaging materials [13].
Mason, Cobley, Graves and Morgan	Mechanical impact of cavitation on metal	Under certain conditions, cavitation can cause erosion of metal surfaces, which is important to consider when developing cavitation systems [14].
Rodriguez	Cavitation for water disinfection	A study showed that ultrasonic cavitation can effectively destroy bacteria and viruses in water without the use of chemicals, which opens up new possibilities for water purification [15].
Yoshimura, Tanaka and Yoshinaga	Effect of ultrasound power	Increasing the ultrasound power to 500 W improves the cleaning of metal parts from rust and oils without aggressive chemicals [16].

Table 2 *Key parameters that affect the process of cleaning the radiator tubes with ultrasound*

Parameter	Description
Ultrasound frequency	Low frequencies for removing dense dirt (scale, rust); high frequencies for delicate cleaning.
Amplitude of ultrasonic vibrations	High amplitude for dense dirt, but exceeding the value can damage the radiator tubes [17].
Power	High power increases the intensity of bubble collapse, which enhances cleaning; low power is suitable for delicate cleaning [18].
Duration of exposure	Long exposure allows removing stubborn dirt; short exposure is suitable for delicate cleaning, reducing the risk of tube wear.
Homogeneity of wave distribution	Uniform distribution of waves ensures effective cleaning of the entire surface, including hard-to-reach areas [19].
Temperature of ultrasonic transducer	Optimum temperature stabilizes the ultrasonic effect and increases the efficiency of cavitation, extending the service life of the equipment [20].

the time of ultrasound exposure and the amplitude of ultrasonic vibrations on the cleaning efficiency, which limited the understanding of their role in increasing the effectiveness of the cleaning process and preventing damage to the cleaned surface.

The time of ultrasound exposure is critically important, since increasing its duration contributes to a longer effect of cavitation bubbles on contaminants, which improves the removal of stubborn deposits. The amplitude of ultrasonic vibrations, in turn, determines the level of energy transferred to the bubbles and directly affects the intensity of their collapse, the release of energy in the form of microjets and shock waves, which increases their destructive effect on deposits. These parameters have the key impact on the main indicator of cleaning efficiency: the mass of removed contaminants. Optimization of these parameters can significantly increase the efficiency of the process, while minimizing the risk of damage to the cleaned surface. The absence of a detailed study of these factors limits the ability to fine-tune ultrasonic cleaning for different types of contaminants in radiator tubes.

In the previous studies, using the similarity theory and dimensional analysis methods, the criteria were determined by which the efficiency of tube cleaning by ultrasonic cavitation was assessed. However, the criteria obtained did not take into account the parameters of the mass of scale removed and the amplitude of ultrasonic waves. Therefore, the additional calculations of the similarity criteria were performed, taking into account the parameters of time, ultrasound amplitude and the mass of scale removed. According to the method of determining the similarity criteria, an equation was drawn up for the mass of scale removed dependence on the remaining parameters:

$$m = f(r, \rho, g, A, m, t). \tag{1}$$

From here follows the equation:

$$\varphi(r, \rho, g, A, m, t) = 0. \tag{2}$$

Then all the variables were transformed according to their dimensions in relation to three basic units of measurement: length L, mass M and time T (Table 3).

A detailed methodology of calculating the criteria is presented in the previous studies [5]. Based on this methodology, the calculation of similarity criteria was performed. The calculation results are shown in Table 4.

Then, the obtained criteria were transformed among themselves by means of a mutual relationship, as a result of which a single criterion was obtained.

$$k = \frac{m \cdot t}{r^{3/2}\sqrt{g}\,\rho A} \tag{3}$$

The physical meaning and significance of the obtained criterion is as follows. The obtained criterion reflects the balance between the time, geometric and energy characteristics of the ultrasonic cleaning process, indicating the efficiency of interaction of the system parameters. If the value of $k > 1$, that indicates that more time is required to remove contaminants, or the mass of contaminants is large relative to the geometry and energy characteristics of the system. This means that the system is not efficient enough, and optimization of such parameters as the ultrasound amplitude or the exposure time, is required. If $k < 1$, this indicates predominance of the effect of energy parameters, indicating high cleaning efficiency with relatively low time costs.

If $k = 1$, this indicates the balance of the system between the time, geometric and energy characteristics of the ultrasonic cleaning process. This means that the system operates with the optimal efficiency, where time and energy costs are in balance, and each of the parameters makes an equal contribution to the cleaning process. However, to confirm the optimality of the parameters by this criterion, experimental studies are required.

Thus, the application of the similarity theory method was justified for such complex processes as cavitation, since a complete mathematical analysis of the behavior

***Table 3** Dimension formulas for the main values of variables*

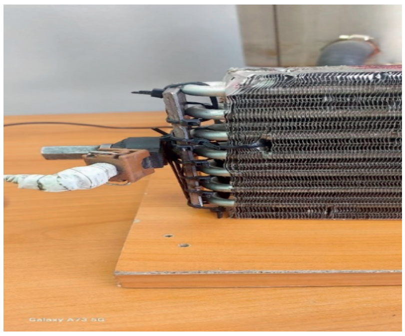
No.	Variable	Designation	Unit	Dimension formula
1	Tube radius	r	m	L
2	Tube length	l	m	L
3	Liquid density	ρ	kg/m^3	ML^{-3}
4	Gravity acceleration	g	m/s^2	LT^{-2}
5	Ultrasound exposure time	t	s	T
6	Ultrasound amplitude	A	m	L
7	Mass of scale washed out	m	kg	M

***Table 4** Results of calculating the criteria*

Parameter	Amplitude	Time	Mass
Methodology of calculating	$\pi_1 = r^{x_1}\rho^{y_1}g^{z_1}A^{-1}$ $\pi_1 = L^{x_1}\left(\frac{M}{L^3}\right)^{y_1}\left(\frac{L}{T^2}\right)^{z_1}(L)^{-1}$, $\pi_1 = L^{x_1-3y_1+z_1-1}M^{y_1}T^{-2z_1}$, $\begin{cases} x_1 - 3y_1 + z_1 - 1 = 0 \\ y_1 = 0 \\ -2z_1 = 0 \end{cases}$, $x_1 = 1, y_1 = 0, z_1 = 0.$	$\pi_2 = r^{x_2}\rho^{y_2}g^{z_2}t^{-1}$ $\pi_2 = L^{x_2}\left(\frac{M}{L^3}\right)^{y_2}\left(\frac{L}{T^2}\right)^{z_2}(T)^{-1}$, $\pi_2 = L^{x_2-3y_2+z_2-1}M^{y_2}T^{-2z_2-1}$, $\begin{cases} x_2 - 3y_2 + z_2 = 0 \\ y_2 = 0 \\ -2z_2 - 1 = 0 \end{cases}$, $x_2 = -1/2, y_2 = 0, z_2 = 1/2.$	$\pi_3 = r^{x_3}\rho^{y_3}g^{z_3}m^{-1}$ $\pi_3 = L^{x_3}\left(\frac{M}{L^3}\right)^{y_3}\left(\frac{L}{T^2}\right)^{z_3}(m)^{-1}$, $\pi_3 = L^{x_3-3y_3+z_3}M^{y_3-1}T^{-2z_3}$, $\begin{cases} x_3 - 3y_3 + z_3 = 0 \\ y_3 = 0 \\ -2z_3 = 0 \end{cases}$, $x_3 = 3, y_3 = 1, z_3 = 0.$
Criterion obtained	$\pi_1 = \frac{r}{A}$	$\pi_2 = \sqrt{\frac{r}{g}}t$	$\pi_3 = \frac{r^3\rho}{m}$

Figure 2 *Experimental bench for cleaning radiator tubes*

a) ultrasonic emitter



b) knock sensor

Figure 3 *Ultrasonic emitter and knock sensor placed on the radiator*

of cavitation bubbles is difficult due to the many factors affecting the process. Thanks to the criterion obtained, not only the cleaning process is described but the conditions for effective removal of contaminants, as well. The proposed criterion for the effectiveness of ultrasonic radiator cleaning can be applied to all the other types of radiators, such as, radiators of aviation and marine engines, heating and air conditioning systems, as well as the heat exchangers used in nuclear energy. All those systems are subject to contamination during operation, and the use of ultrasonic cavitation for their cleaning can significantly improve efficiency and extend service life without the risk of damaging the structural elements. At the same time, it is necessary to consider the specifics of each type of radiator, including parameters such as tube material, operating environment, and the level of contamination.

Then, experimental studies were carried out to determine the mass of washed scale depending on changing the time and amplitude parameters. The study was conducted on a more advanced experimental bench (Figure 2).

The main element of the bench was a heater radiator with operational deposits. To create an ultrasonic effect, a transmitter with the operating frequency of 40 kHz and power of 50 W was mounted and fixed on one of the ends of the radiator (Figure 3, a). On the opposite side of the radiator, a detonation sensor was placed to record the amplitude of ultrasonic vibrations (Figure 3, b).

An oscilloscope was used to monitor and to record the amplitude characteristics of the oscillations, and a circulation system supplied liquid through the radiator. The liquid temperature was maintained at 50 °C.

At the first stage, the radiator was filled with a liquid, and the initial parameters were recorded, including the mass and density of the liquid, as well as the time it took to flow through the radiator. Then, the ultrasonic emitter was turned on, and the initial value of the ultrasonic wave amplitude was recorded.

At the second stage of the experiment, the ultrasonic emitter was turned on, the effect of which was carried out over a specified time interval of 600 seconds. At the end of this time interval, the key parameters were measured: the time of liquid flow through the radiator, the mass of the liquid, the density of the liquid, the mass of the washed-out scale (calculated as the difference in the mass of the sediment before and after the effect). The procedure for ultrasound exposure and measurements was repeated three times with accumulation of the cleaning effect.

3 Results

The results of experiments are presented in Table 5.

The obtained experimental results indicate a gradual increase in the efficiency of radiator cleaning with each cycle of ultrasound exposure.

This approach allowed objective evaluating of the efficiency of ultrasound exposure, linking its parameters with the quality characteristics of the purified liquid and

Table 5 *Results of experimental studies*

Ultrasound action	Added time of exposure to ultrasound, s	Amplitude, m	Outflow time, s	Liquid mass, g	Liquid density, g/m^3	Mass of scale washed out, g
Before the ultrasound action	-	2.01	12.54	44.55	0.990000	0.00
With ultrasound action, f = 40 kHz	600	2.1	12.09	44.56	0.990222	0.01
	1200	2.26	11.39	44.6	0.991111	0.05
	1800	2.29	11.03	44.79	0.995333	0.24

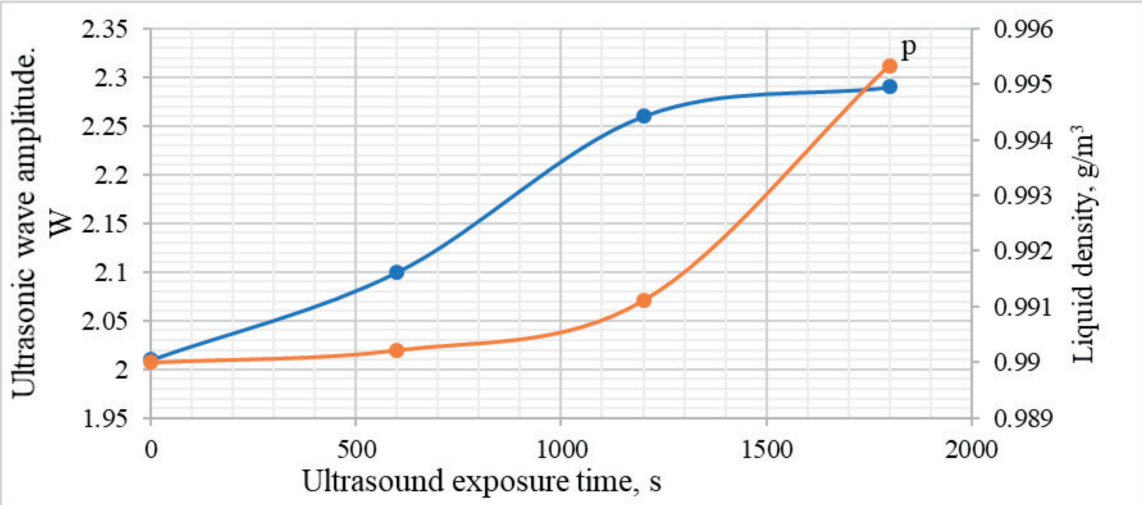


Figure 4 *Changing the ultrasound amplitude and liquid density with increasing the ultrasound exposure time*

the mass of contaminants removed from the radiator tubes.

Based on the obtained results of experimental studies, graphs of the parameters of ultrasound amplitude and liquid density dependence on the time of ultrasound exposure were constructed.

The graph in Figure 4 shows the amplitude increasing with increasing the cumulative effect of the ultrasound exposure time. This is due to increasing the efficiency of energy transfer from the emitter to the medium. Ultrasonic waves are reflected from the tube walls and create multiple reflections. As a result, the waves add up, which leads to increasing the amplitude of pressure and vibration in the liquid.

Increasing the amplitude when ultrasound affects the liquid in radiator tubes is caused not only by a combination of resonance, interference and cavitation effects but by the geometry of the tubes and changes in the properties of the liquid under the effect of ultrasonic waves, as well. Narrow and long radiator tubes act as waveguides focusing ultrasonic energy. This focusing leads to the concentration of energy and increasing the amplitude of sound pressure in a limited space.

Ultrasound creates acoustic flows in the liquid (the liquid movement under the effect of sound waves). These flows increase turbulence and the movement of bubbles, which leads to additional increasing the oscillations amplitude.

The graph also shows increasing of the liquid density with increasing the time of ultrasound exposure. This indicates that with each cycle of ultrasound exposure, the number of particles remaining in the liquid increases. This accumulation explains the gradual increasing of the density. When the density of a liquid increases, it means that the mass of liquid per unit volume also increases. The mass of the liquid has increased due to the inclusion of solid particles that were previously part of the contaminants. This indicates that ultrasound is successfully breaking down and dispersing contaminants.

According to the graph in Figure 5 the reduction in the time it takes for the liquid to flow through the radiator and the increase in the mass of scale washed out are interconnected and indicate the effectiveness of ultrasonic cleaning. When exposed to ultrasound, scale and deposits that previously partially blocked the passage of liquid through the radiator tubes are destroyed. Ultrasonic vibrations create cavitation bubbles that affect the contaminants, breaking them off and destroying them. With each cleaning cycle, these contaminants are gradually removed, which leads to increasing the diameter of the tubes and decreasing their hydraulic resistance. As a result, the flow of liquid

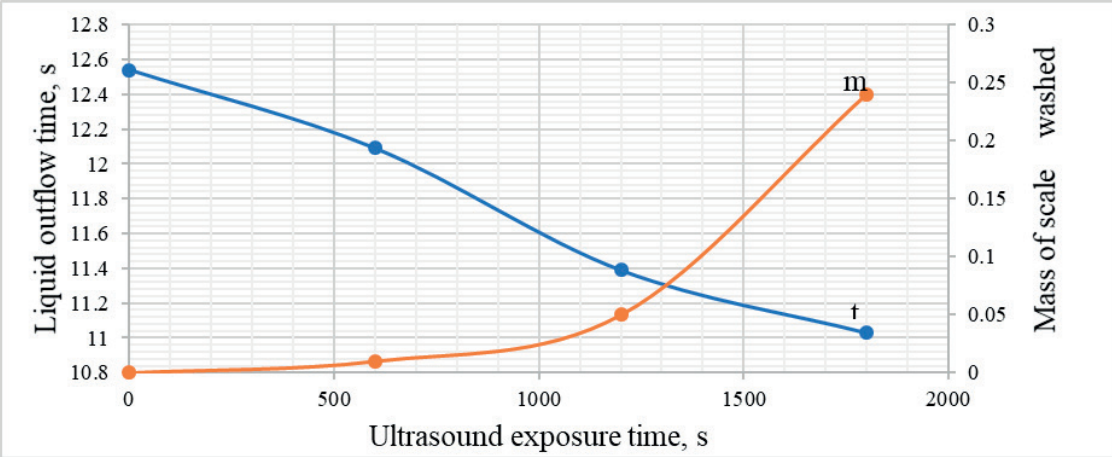


Figure 5 *Changing the liquid outflow time and the mass of scale washed out with increasing the ultrasound exposure time*

through the radiator becomes freer, which reduces its flow time.

At the same time, the mass of scale washed out increases, since each new cycle of ultrasonic action removes both the surface and deep layers of deposits. Ultrasound destroys the structure of contaminants, converting them into a finely dispersed state, which is then washed out of the system. This process has a cumulative effect: the longer the exposure, the more contaminants are removed. As a result, the mass of scale washed out increases linearly, reflecting the progressive cleaning of the radiator.

Thus, the reduction in the liquid outflow time and the increase in the mass of washed-out scale complements each other, demonstrating the effectiveness of ultrasonic cleaning. These changes demonstrate that ultrasound not only improves permeability of liquid through the radiator but also actively removes contaminants, improving the overall performance of the system.

Based on the results of experimental studies, a multivariate regression equation was compiled that described the change in the mass of washed-out scale from the time of ultrasound exposure and the amplitude of ultrasonic waves.

$$m = 8.88 \cdot 10^{-6}A^2 - 51.3 \cdot 10^{-6}At - \\ - 1.98 \cdot 10^{-6}A + 1.78 \cdot 10^{-7}t^2 + \\ + 986 \cdot 10^{-6}t + 3.99 \cdot 10^{-5} \quad (4)$$

The use of this type of regression is due to the fact that the dependent variable (m) is determined by several independent experimental variables A and t. Unlike the one-dimensional regression that considers the effect of only one of the factors, multivariate regression more accurately reflects complex relationships between variables, which is especially important for analyzing processes where the result depends on the interaction of several parameters.

The obtained value of the determination coefficient $(R^2 = 0.98)$ according to the regression equation shows that the multivariate regression model describes well the dependence of the mass of washed scale on the exposure time and the amplitude of ultrasonic waves. This means that the model is reliable for describing the cleaning process within these limits.

The obtained value of the correlation coefficient (r = 0.97) also indicates a strong linear relationship between the predicted model and the actual experimental values. This confirms that the model accurately describes changes in the scale mass with changes in time and amplitude. The approximation error shows that on average the regression model predictions deviate from the experimental data by 1.84%. This error rate is due to the small number of experimental runs, which limits the accuracy of the model. Therefore, to reduce the approximation error, it is necessary to increase the number of experimental runs.

Based on the obtained regression equation, the mass of washed scale was calculated (Table 6).

Then, a comparison was made between the experimental values and the calculated values from the regression equation for the mass of removed scale, taking into account the cumulative ultrasonic exposure time (Figure 6).

The graph in Figure 6 shows how accurately the regression model describes the process of ultrasonic radiator cleaning and how the experimental data compares to theoretical calculations.

Comparison to the regression equation shows that the calculated model matches the experimental data, with a small deviation. The deviation can be caused by the fact that experimental conditions, such as the heterogeneity of contaminants, or the dynamics of their removal, are not fully taken into account in the model.

The three-dimensional graph in Figure 7 also highlights the importance of the duration of ultrasound exposure: longer exposure allows removing not only the surface but the deeply embedded contaminants, as well. The increase in the mass of washed-out scale confirms that ultrasound successfully copes with the destruction

***Table 6** The calculated mass of washed out scale based on the regression equation*

Time (s)	Amplitude (m)	Mass based on the experimental results (g)	Mass based on the regression equation (g)
0	2.01	0.00	0.0320
600	2.10	0.01	0.0092
1200	2.26	0.05	0.0480
1800	2.29	0.24	0.2360

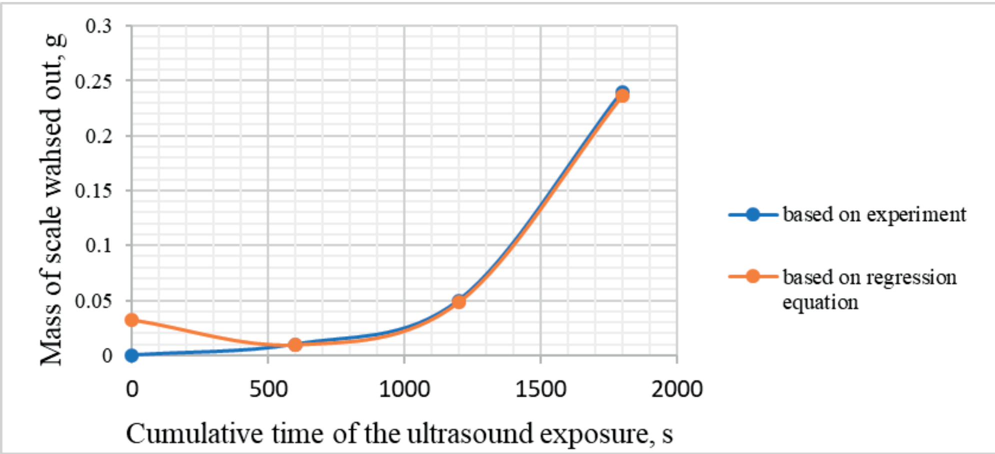


***Figure 6** Regression model for the process of radiator ultrasonic cleaning*

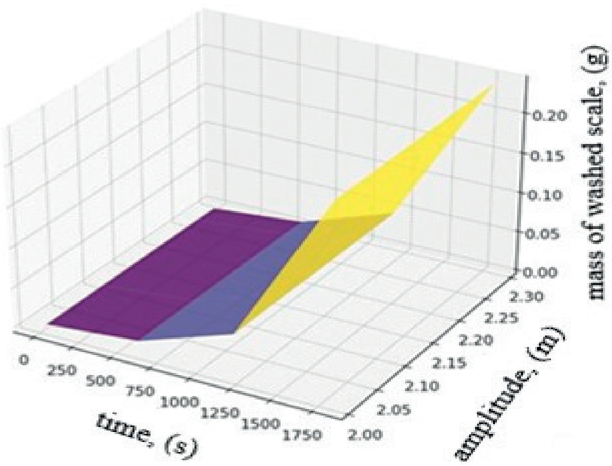


***Figure 7** The change in the mass of removed scale as a function of time and amplitude*

of various layers of deposits, and this is a key factor in increasing the efficiency of cleaning.

The lilac area in the graph is located between the purple and yellow zones and represents intermediate values of the mass of removed scale. This zone shows that the cleaning process is already actively underway, and the mass of removed contaminants is increasing, although it has not yet reached maximum values. The lilac area corresponds to moderate values of ultrasound exposure time and average amplitude of ultrasonic vibrations. It demonstrates the transitional stage of cleaning, when ultrasonic cavitation is already effectively affecting contaminants, but the time and energy of exposure are not yet sufficient to completely remove stubborn deposits. In this zone, deposits are partially destroyed, but the rate of their removal is lower than in the yellow zone, where the process reaches maximum intensity. Thus, the purple area shows how cleaning gradually gains efficiency as the time and amplitude of ultrasound increases, moving towards the yellow zone, where the greatest results are achieved.

On the whole, the graph demonstrates that the proposed regression model can be used to predict cleaning results, but its accuracy depends on the specifics of the contaminants and the experimental conditions.

Then a mathematical analysis of the regression equation was carried out, which made it possible to determine how changes in the amplitude (*A*) and the time (*t*) affect the mass of washed scale (*m*). Partial derivatives of the equation were determined, which made it possible to establish the rate of change in mass m with changes in *A* and *t*:

Partial derivatives of the regression equation are as follows:
by the amplitude:

$$\frac{dm}{dA} = -1.776 \cdot 10^{-5}A - \\ -0.000513t - 1.98 \cdot 10^{-6}, \tag{5}$$

by the time:

$$\frac{dm}{dt} = -0.000513A + 356 \cdot 10^{-7}t + 0.000986\,, \tag{6}$$

show that the amplitude reduces the mass of scale removed, especially at high values, and increasing the time always contributes to its growth.

Then, the critical points of the equations were determined, provided that $\frac{dm}{dA} = 0$ and $\frac{dm}{dt} = 0$. The solution of the two systems of equations is as follows:

$$\begin{cases} -1.776 \cdot 10^{-5}A - 0.000513t - 1.98 \cdot 10^{-6} = 0, \\ -0.000513A + 3.56 \cdot 10^{-7}t + 0.000986 = 0, \end{cases} \tag{7}$$

and it allowed obtaining the critical values of the parameters A = 1.92, t = –0.07, at which the change in the mass of washed-out scale m in terms of the amplitude (A) and the time (t) stops. However, the time cannot be negative in the physical sense, so there is no extremum of the function, and in the region t > 0 the function m = f(A,t) monotonically increases with the time t. This is also confirmed by the second derivative of the equations, which describes the nature of the critical point:
by the amplitude:

$$\frac{d^2m}{dA^2} = -1.776 \cdot 10^{-5}, \tag{8}$$

by the time:

$$\frac{d^2m}{dt^2} = 3.56 \cdot 10^{-7}, \tag{9}$$

by the amplitude and the time:

$$\frac{d^2m}{dAdt} = -0.000513A\,. \tag{10}$$

According to the calculated Hessian determinant H = $-2.63 \cdot 10^{-7}$, it is negative (H < 0), which indicates a saddle point. This means that the function behaves in different directions. With increasing the time (t), the mass of washed-out scale (m) increases, and with increasing the amplitude (A), the mass (m) decreases. This means that an increase in time (t) always contributes to an increase in the mass of washed-out scale, and the amplitude value A should not go beyond the boundary values of its negative impact.

Therefore, to optimize the cleaning process, the amplitude A and the time *t* should be selected so as to take into account their combined effect, namely, to increase *t* so that the mass grows and to control A to avoid its excessive decrease.

Then, according to the established criterion k, which describes how efficiently the cleaning system uses its energy resources, the optimal amplitude values are determined, which must be adjusted for different degrees of contamination by the mass of washed out scale.

$$k = \frac{m \cdot t}{r^{3/2}\sqrt{g}\,\rho A} \rightarrow A = \frac{m \cdot t}{r^{3/2}\sqrt{g}\,\rho k} \tag{11}$$

where *k* = 1, since its value indicates the balance of the cleaning system between the time, geometric and energy characteristics of the ultrasonic cavitation process. This confirms that the time and energy costs are balanced, and each parameter makes an equal contribution to the cleaning efficiency.

Table 7 *Results of calculating the amplitude optimal values*

No.	Scale mass, kg	Time, s	Radiator tube radius, m	Cooling liquid density, kg/m^3	Optimal amplitude, 10^{-3}m
1	0.005	600	0.005	1070	2.56
2	0.01				5.12
3	0.015				7.68
4	0.02				10.24
5	0.025				12.79
6	0.03				15.35
7	0.035				17.91
8	0.04				20.47
9	0.045				23.03
10	0.05				25.59

During the standard ultrasonic cleaning, the mass of the removed scale varies from 5 to 50 grams, which is determined by the degree of contamination of the tubes. Modern aluminum radiators are characterized by a standard tube radius in the range from 2 to 5 mm. The ultrasound exposure time in the experiments was 600 seconds. The average density of the coolant used in radiators with antifreeze is about 1070 kg/m^3. The results of calculating the optimal amplitude values are presented in Table 7.

The obtained amplitude values allow for carrying out further studies and obtaining more accurate results on the degree of radiator tubes cleaning by ultrasonic cavitation.

4 Conclusion

Based on the studies carried out, the high efficiency of ultrasonic cleaning of vehicle radiators due to the cavitation phenomenon has been proven. The results of experimental studies have shown that increasing the ultrasound exposure time leads to a significant increase in the mass of washed-out scale, improved liquid characteristics and reducing the flow time.

The developed regression model confirmed a strong relationship between the process parameters, such as the amplitude and the exposure time, with the cleaning efficiency indicators. The resulting regression model makes it possible to establish the quantitative dependences between the process parameters, which provides predicting the cleaning results under various conditions. It has been established that the exposure time has a positive effect on the cleaning results, while increasing the amplitude requires precise optimization to prevent a negative effect. The identified saddle point in the parameter system emphasizes the need to balance the amplitude and the exposure time to achieve the maximum cleaning efficiency. According to the obtained criterion, the optimal values of the ultrasonic vibration amplitude were determined depending on the values of the washed-out scale mass. The optimum amplitude values were determined at k = 1, demonstrating the optimum balance of the system between the time, geometric and energy characteristics of the ultrasonic cleaning process. The obtained results confirm that the use of ultrasound can significantly improve the operational characteristics of radiators, reducing their maintenance costs and increasing their service life. The practical significance of the results lies in the development of an ultrasonic cleaning technique that ensures the removal of contaminants without the risk of damaging the radiator structural elements, as well as in the possibility of its industrial application.

Future research in this field may focus on studying the effect of ultrasonic frequency on cleaning efficiency. Investigating different frequency ranges will help determine the optimal parameters for removing specific contaminants while minimizing potential destructive effects on radiator materials. Optimizing cavitation parameters is another important area, as the power of ultrasonic exposure and the characteristics of cavitation bubbles directly influence the cleaning quality. Computer modelling of these processes will help predict the conditions under which cavitation is most effective.

Additionally, it is important to consider the influence of radiator geometry on the propagation of ultrasonic waves. Research can focus on analyzing the shape of tubes and their ability to transmit ultrasonic vibrations, allowing the method to be adapted to radiators of various configurations. Another key aspect is the durability of radiators after the regular ultrasonic exposure. Studies should assess the long-term effects of ultrasonic vibrations on radiator materials and determine the economic efficiency of this method compared to traditional mechanical and chemical cleaning techniques. These future research directions would not only enhance the effectiveness of ultrasonic cleaning but would expand its applications, as well, making the radiator cleaning process safer, more cost-effective, and more versatile.

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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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