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Theoretical and Experimental Analysis of Ultrasonic Cleaning of Internal Combustion Engine Radiators with the Development of Practical Recommendations

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Abstract. The article presents the results of studies on ultrasonic cleaning of radiators in internal combustion engine cooling systems. The aim of the research is to identify the dependencies affecting the efficiency of ultrasonic cleaning of internal combustion engine radiators, as well as to develop recommendations for further research. Using the theory of similarity and dimensional analysis, critical dependencies were established, allowing for the determination of the energy efficiency of the cavitation process and the assessment of the cleaning effectiveness of the radiator using ultrasound. The obtained theoretical dependencies were experimentally validated, and their numerical values were determined. Based on these recommendations, a flowchart was developed that outlines the sequence of the radiator tube cleaning process using ultrasound, taking into account improvements in design and changes in the testing methodology.

Keywords: car, internal combustion engine, cooling system, radiator, cavitation, similarity theory and dimensional analysis.

Introduction

Cleaning the cooling systems of internal combustion engines remains a relevant task, especially when vehicles are operated in conditions that promote the formation of scale and contamination. It is known that traditional cleaning methods, such as mechanical and chemical approaches, have a number of drawbacks. Mechanical methods can lead to damage to the tubes and other radiator components. Chemical compounds do not always provide complete cleaning and also damage the radiators due to their corrosive effects.

Ultrasonic treatment, based on the phenomenon of cavitation, generates microscopic bubbles in the liquid that release high energy in the form of shockwaves and microjets when they collapse. This process effectively removes scale and other contaminants from the internal surfaces of radiator tubes without damaging their structure. Unlike mechanical methods, ultrasound penetrates difficult-to-reach areas, such as tube bends and small channels, ensuring a more uniform and thorough cleaning.

Ultrasonic cleaning is also environmentally friendly, as it does not require the use of aggressive chemical reagents, and the process can be adjusted to minimize the impact on radiator materials. By regulating the parameters of ultrasonic treatment, the method can be adapted to different types of radiators and contamination levels, ensuring high cleaning efficiency without the risk of damage.

The hypothesis of the study is the probability of radiator cleaning through ultrasonic treatment.

The aim of the study is to establish the dependencies that determine the effectiveness of the ultrasonic cleaning process for internal combustion engine radiators and to develop recommendations for further research.

To achieve the research goal, the following tasks were addressed: the physical essence of the cavitation process was considered; critical dependencies were derived to evaluate the energy efficiency of the cavitation process when cleaning radiators with ultrasound; an analysis of existing results was conducted, and recommendations were made for improving the experimental setup for radiator cleaning.

The scientific novelty lies in obtaining dependencies that allow evaluating the efficiency of radiator cleaning with ultrasound.

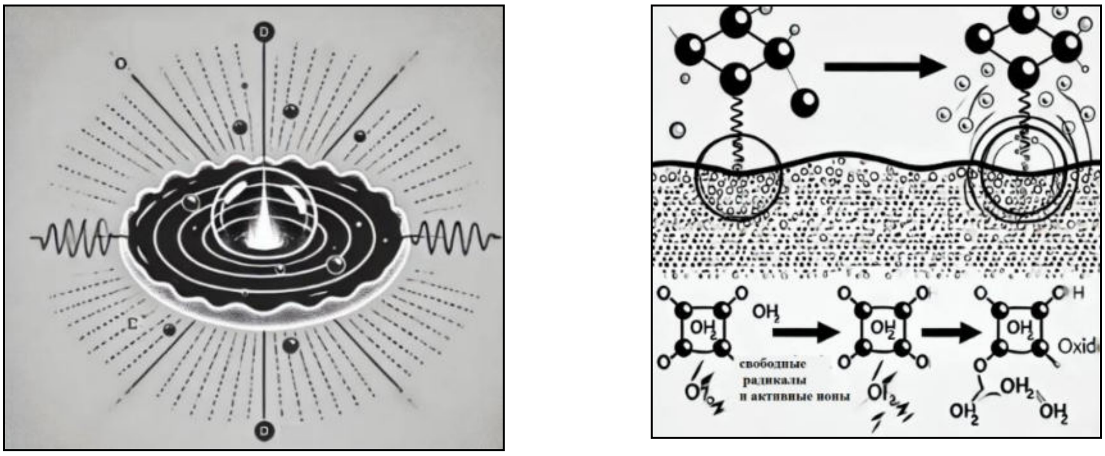
The practical significance of the research lies in the development of recommendations and standard protocols that will improve the conduct of experimental studies and ensure reliable results. The implementation of this method in auto repair and service enterprises will increase the availability and effectiveness of innovative radiator cleaning methods, contributing to an increase in their durability and reliability.

1. Materials and methods

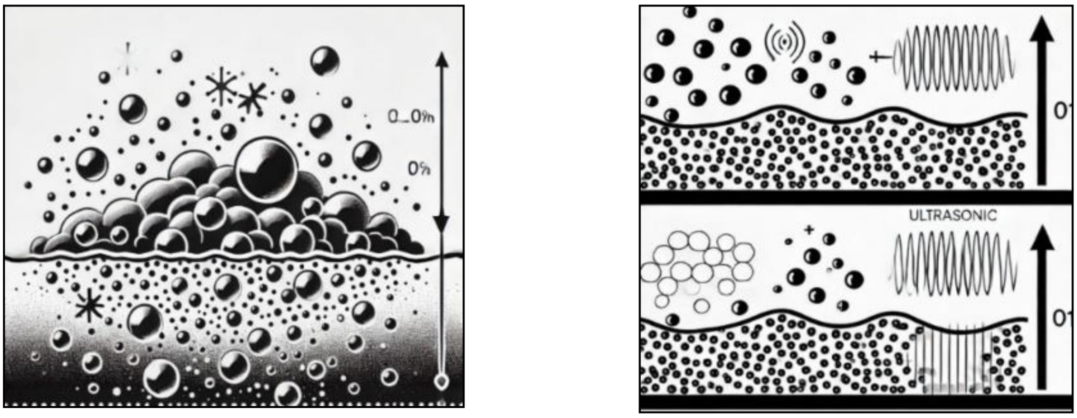
Cavitation is the process of formation, growth, and collapse of gas or vapor bubbles in a liquid, occurring due to significant pressure fluctuations, such as those induced by ultrasound waves or the movement of objects like propellers and turbines.

The main stages of cavitation include bubble formation under conditions of low pressure, their growth by capturing surrounding gas and accumulating energy, and then rapid collapse due to compression. During the cavitation process, chemically active radicals, such as hydroxyl (•OH) and hydrogen (•H) radicals, are also formed, which interact with contaminants, breaking down their structure. This effect is particularly useful for cleaning wastewater and exhaust gases, where the radicals initiate the decomposition of organic substances, enhancing the efficiency of the cleaning process [1-4].

Acoustic cavitation in liquids also triggers various physicochemical phenomena, such as sonoluminescence (the emission of light by liquids), sono-chemical reactions (the chemical effects of cavitation), dispersion (the grinding of solid particles in a liquid), emulsification (mixing and homogenization of immiscible liquids), and mechanical erosion (surface destruction), as shown in Figure 1 [5-8].



sonoluminescence sonoreactions



dispergating emulsionizing

Fig. 1. – Physical and chemical phenomena of the cavitation process

Sonoreactions (chemical effects of cavitation) are chemical processes initiated by the collapse of cavitation bubbles in a liquid with releasing significant energy. This process leads to the formation of free radicals and active ions, which promotes oxidation, reduction and decomposition reactions of molecules. Dispergating (grinding of solid particles) is the process of mechanical destruction of solid particles in a liquid under the impact of cavitation. Collapsing bubbles provide intense forces that crush particles and agglomerates. Dispergating is used in the production of paints, pharmaceuticals and in the other industries where the homogeneity of particles is important [9-12]. Emulsionizing (homogenization of immiscible liquids) is the process of forming stable emulsions, where ultrasound allows mixing liquids (for example, oil and water), forming small drops and ensuring uniform distribution of phases. It is used in the food, cosmetic and pharmaceutical industries.

Mechanical erosion (surface destruction) is the process of destruction of solid material surfaces as a result of ultrasonic cavitation. When cavitation bubbles collapse on the surface of a solid material, they generate powerful shock waves and microjets that destroy the surface of the material. This process can be used to clean surfaces from dirt and scale, as well as in metalworking processes [13-16].

A number of mathematical dependencies are used to describe and quantify these processes, each of which reflects certain aspects of cavitation dynamics

The Rayleigh-Plesset equation is used to describe cavitation, which models the change in the bubble radius R(t) over time under the influence of such factors as density, surface tension and viscosity of the liquid. When the bubble collapses, the pressure inside it increases adiabatically, and its maximum value P_{max} can be expressed through the initial radius R_0 and the minimum radius R_{min}:

$$P_{max} = P_0 \left(\frac{R_0}{R_{min}}\right)^3, \qquad (1)$$

where P_{max} is maximal pressure innnnnsude the bubble at the momment of collapse;

P_0 is the initial (static) pressure of the liquid;

R_0 is the initial radius of the bubble;

R_{min} is the minimum radius of the bubble at the moment of collapse.

Energy E released at the moment of the bubble collapse is calculated as work done on a volume from R to R_{min}:

$$E \approx \int_{R_{min}}^{R_0} P(r) \cdot 4\pi r^2 dr, \tag{2}$$

where P(r) is pressure inside the bubble as the function of the radius;

r is the current radius of the bubble [17-18].

The cavitation number σ determines the tendency of a liquid to cavitation and reflects the relationship between the external pressure and the saturated vapor pressure of the liquid:

$$\sigma = \frac{P_\infty - P_\vartheta}{\frac{1}{2}\rho\vartheta^2}. \tag{3}$$

The ultrasound frequency also affects the bubble dynamics: at the resonant frequency, the oscillation amplitude is maximum, which leads to stronger cavitation effects and erosive action. The radius of the resonant bubble R_{res} at a given ultrasound frequency is expressed as:

$$\sigma = \frac{P_\infty - P_\vartheta}{\frac{1}{2}\rho\vartheta^2}, \tag{4}$$

where σ is the cavitation number, a dimensionless parameter indicating the liquid tendency to cavitation;

P_∞ is pressure in the liquid far from the bubble;

P_ϑ is the saturated vapor pressure of the liquid (depends on the liquid temperature;

ρ is the liquid density;

ϑ is the rate flow of the liquid.

$$\varepsilon = \frac{E_m}{E_y}, \tag{5}$$

where E_m is the energy released in the form of shock waves at the moment if the bubble collapse;

E_y is the ultrasonic impact energy [19-22].

Thus, regulating the ultrasound frequency and pressure parameters allows enhancing cavitation effects and increasing erosive activity, which contributes to effective cleaning.

Currently, there is no universal model that can accurately describe the process of ultrasonic cavitation in radiator tubes. This is due to the high complexity of the phenomenon, which is influenced by many factors. Cavitation is a complex nonlinear process that depends on parameters such as the intensity and frequency of ultrasound waves, the shape and size of the tubes, the characteristics of the working liquid, and the duration of exposure. Taking all these variables into account within a single model proves to be extremely difficult.

Due to these challenges, the method of similarity theory and dimensional analysis was applied. This method allows reducing the number of variables affecting the process and identifying dimensionless criteria that describe the main patterns. The similarity theory approach is particularly effective when analyzing complex processes for which constructing a mathematical model is challenging. The application of this approach enables the identification of key parameters affecting the cleaning process and allows for an assessment of their impact on cleaning efficiency. The physical meaning and significance of the obtained similarity criteria are presented in Table 1.

Based on the physical meaning and values of the criteria, the following conclusions can be drawn:

- criterion k1 helps determine the optimal tube radius or assess the allowable thickness of the contaminant layer for effective cleaning.
- criterion k_2 evaluates the efficiency of energy transfer into the liquid and enables adjustments to the power of the ultrasonic emitter.
- criterion k_3 determines the efficiency of utilizing the liquid volume and system energy for contaminant removal, as well as the relationship between the liquid's characteristics, system geometry, and the mass of contaminants removed.

Table 1. The physical meaning and significance of the obtained similarity criteria

Criterion	Physical Meaning	Value
$k_1 = \frac{r}{\Delta}$	Characterizes the influence of tube geometry and contaminant layer thickness on the penetration of ultrasonic waves to contaminants.	Indicates that the tube radius significantly exceeds the thickness of the contaminant layer, promoting effective ultrasonic wave penetration. The cleaning process becomes more localized and intensive.
		Indicates that the contaminant layer thickness is large relative to the tube radius, making ultrasonic wave penetration more challenging and reducing cleaning efficiency. Additional measures, such as increasing power or duration of ultrasonic exposure, are required.
$k_2 = \frac{E_м}{E_y}$	Evaluates the efficiency of converting ultrasonic energy into cavitation effects through the energy transferred to shock waves.	A significant portion of ultrasonic energy is efficiently converted into shock waves. This indicates high energy efficiency of the system and an intense cavitation process, leading to active contaminant removal.
		Only a small fraction of ultrasonic energy is used to generate shock waves, indicating energy losses or insufficient power. The system requires improvements to enhance efficiency.
$k_3 = \frac{m}{r^2 \rho l}$	Indicates the relative efficiency of contaminant removal from the tube.	The volume of liquid involved in the process is significantly larger than the mass of contaminants removed. This may indicate low cleaning efficiency, as only a small amount of contamination was removed relative to the liquid volume.
		Low values of the criterion indicate high cleaning efficiency: a significant amount of contamination is removed even with a small liquid volume.

The combined analysis of all criteria allows for a detailed evaluation of the balance between energy consumption, tube geometry, and the mass of contaminants removed. The dimensionless criteria derived using the similarity theory provide essential relationships for assessing the efficiency of cavitation processes, which is crucial for understanding the mechanical impact of ultrasonic vibrations on contaminants.

Thus, the application of the similarity theory was justified for such complex processes as cavitation, as a complete mathematical analysis of cavitation bubble behavior is challenging due to the numerous factors influencing the process. The derived criteria not only describe the cleaning process but also define the conditions for effective contaminant removal.

2. Analysis and Discussion

An analysis of the results from experimental studies presented in the works of K.A. Sinelnikov has been conducted, where a method for cleaning car radiator tubes using cavitation generated by ultrasound waves is proposed [23-26]. As part of the dissertation work, an experimental setup for radiator tube cleaning was developed, and the process of conducting experiments aimed at evaluating the effectiveness of ultrasonic cleaning was described (Figure 2).

Fig. 2. – Experimental Setup for Ultrasonic Cleaning of Automotive Radiators

The experiment followed these steps:

1. Preparation Stage: The experimental setup was assembled and connected. The test bench was then filled with clean water, and its initial parameters were measured.
2. Heating Stage: The water was heated to 50°C;
3. Ultrasonic Treatment: Ultrasonic exposure was applied to the radiator for three different time intervals: 600, 1200, and 1800 seconds;
4. Parameter Measurement: After each treatment, key parameters of the liquid were measured, including volume, mass, and outflow time;
5. Final Stage: The water was aerated (saturated with air) before ultrasonic exposure, and the experimental results were analyzed [25,26].

The results of the study demonstrate that ultrasonic treatment effectively removes scale and contaminants from the walls of radiator tubes, positively impacting the performance of the cooling system and extending its service life (Table 2).

Table 2. Results of Experimental Studies

Exposure time (s)	Liquid mass (g)	Density (g/cm³)	Drain time (s)	Drain speed (ml/s)
0	44,57	0,9904	9,93	100,7
600	44,60	0,9911	9,73	102,7
1200	44,63	0,9917	9,22	108,45
1800	44,69	0,9931	9,20	108,69

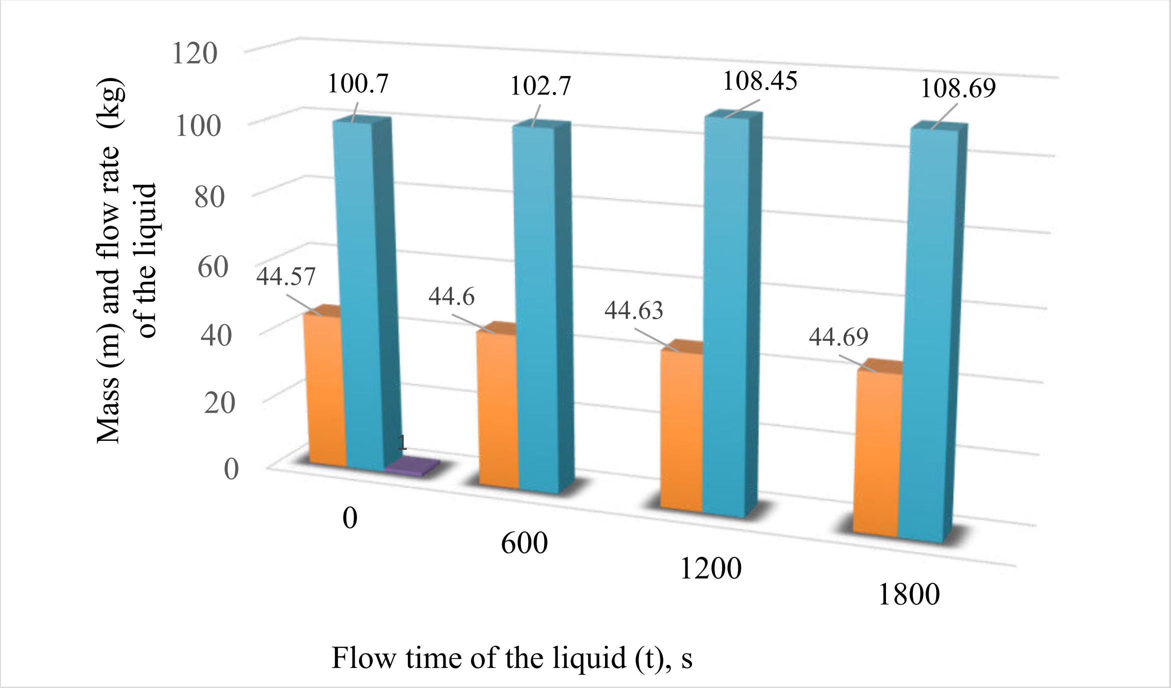


Fig. 3. – Changing the mass and the flow rate of liquid (ϑ)
Depending on the time of exposure to ultrasound (t)

In Figure 3, it can be observed that as the duration of ultrasonic exposure increases, both the mass and outflow rate of the liquid with removed scale increase compared to the initial parameters of untreated liquid. This phenomenon is explained by the significant amount of energy transferred to the liquid through ultrasonic waves, which induces cavitation.

As a result, microbubbles form, and their collapse generates powerful microjets. These microjets effectively clean the inner walls of radiator tubes from scale, contributing to the increase in both mass and outflow rate of the liquid. Ultrasonic exposure thus not only enhances the cleaning of the radiator but also improves the fluid's flow properties by removing deposits, as evidenced by the increase in measurable parameters.

Based on the experimental results, an assessment of the efficiency of the ultrasonic cavitation process was conducted using the derived criteria listed in Table 3.

Table 3. Results of Criteria Calculations

Exposure time (s)	E_{kin} (μJ)	E_u (kJ)	E_m (kJ)	k_2	k_3
0	225,98	0	-225,98	-	-
600	235,2	30	29	0,96	0,3
1200	262,45	60	59	0,98	0,295
1800	263,97	90	89	0,99	0,286

The numerical values of the criteria indicate high cleaning efficiency: even with a minimal liquid volume, a significant amount of contaminants was removed, confirming the effectiveness of ultrasonic waves on contaminated radiator tube surfaces.

Although K.A. Sinelnikov's dissertation involved substantial research on ultrasonic cleaning of radiator tubes, certain limitations in the experimental methodology may have affected the accuracy of the results.

We conducted an analysis of K.A. Sinelnikov's dissertation, addressing unexplored aspects and developing recommendations and suggestions for further research. The results of this analysis are presented in Table 4.

Table 4. Analysis Results, Recommendations, and Suggestions

Unexplored Aspects of the Dissertation	Recommendations and Suggestions
Lack of analysis of the influence of the ultrasonic emitter's position on the uniformity of cavitation along the entire length of the radiator tubes.	Conduct studies with different emitter positions to evaluate the uniformity of cavitation and its impact on cleaning efficiency.
Insufficient detail in controlling the saturation of the liquid with air, which could have affected the intensity of cavitation.	Implement a system for controlling the saturation of the liquid with air to ensure the stability of cavitation along the entire length of the tubes.
Lack of description regarding the accuracy of maintaining the liquid temperature during the experiments.	Utilize precise liquid temperature control systems and record temperature variations to analyze their impact on the process.
Insufficient attention to the types of contaminants (scale, organic deposits), which require different cavitation intensities.	Investigate the impact of different types of contaminants on cleaning efficiency and determine the optimal cavitation parameters for each type.
Lack of cavitation level control to ensure stable experimental conditions.	Develop a methodology for real-time cavitation level monitoring to ensure the reproducibility of experiments.
Insufficient analysis of the impact of ultrasonic exposure time and vibration amplitude on the cleaning process and the mass of removed contaminants.	Study the influence of ultrasonic exposure time and vibration amplitude on the dynamics of cavitation and the mechanism of contaminant removal, as well as determine their optimal values for various conditions.

According to the analysis of the research results presented in Table 4, it was determined that one of the key factors influencing the effectiveness of ultrasonic cleaning is the optimal placement of the emitter and the method of water supply [31]. It is hypothesized that using an ultrasonic emitter with directed action from bottom to top, combined with water supplied by a pump, can significantly enhance the efficiency of the process.

The proposed placement and method of liquid supply offer several important advantages. Firstly, this configuration allows cavitation bubbles to rise upward, effectively interacting with contaminants along the entire length of the radiator tubes. The bubbles accumulate at contaminated areas and, upon collapsing, destroy scale and other deposits, ensuring thorough and uniform cleaning. The pumped water supply further enhances this process by creating a turbulent flow that evenly distributes the liquid and saturates it with air, promoting the formation of cavitation bubbles. A continuous water flow also maintains a stable liquid temperature, enabling more intense cavitation, especially at elevated temperatures. All these factors together ensure effective breakdown and removal of contaminants, making the cleaning process more environmentally friendly and cost-effective by reducing the need for chemical agents and mechanical cleaning. Based on the above, the gas cleaning process on the experimental setup is presented, which will be carried out according to the flowchart in Figure 4.

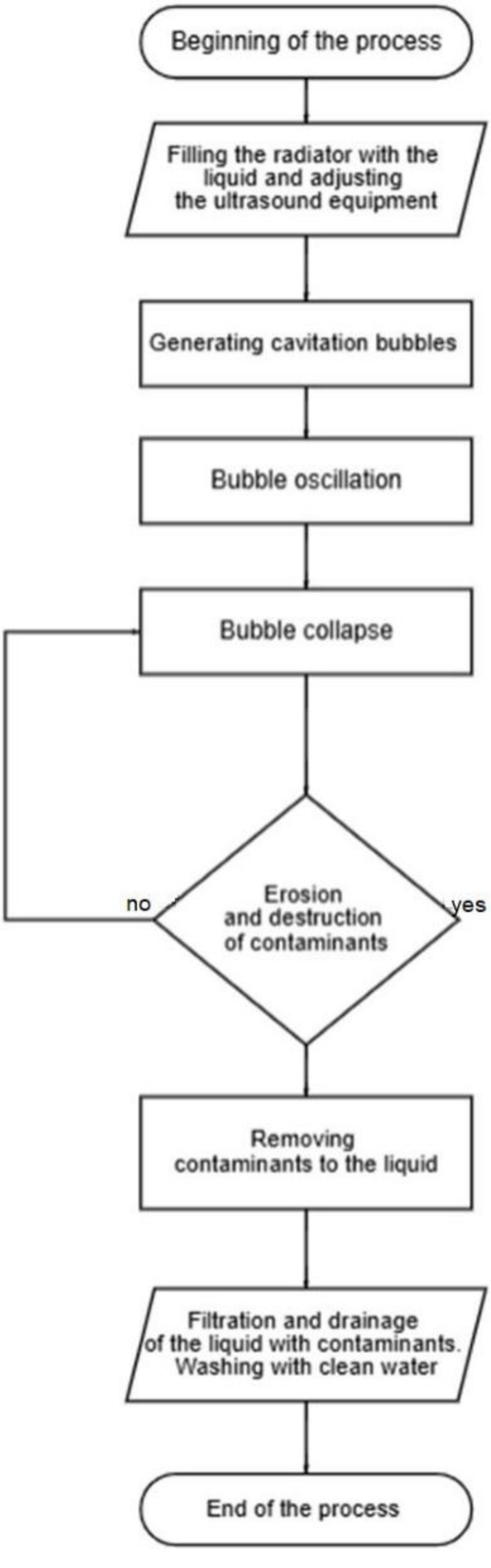


Fig. 4. – Stages of cleaning the radiator tubes with ultrasound

The proposed flowchart visually represents the ultrasonic cleaning process for radiators, highlighting key stages and the sequence of actions to achieve maximum efficiency. The diagram simplifies the understanding of the process, making it more accessible for analysis and practical implementation. It clearly outlines the critical parameters that need to be considered for effective radiator cleaning.

Conclusion

The conducted analysis confirms that ultrasonic cavitation has significant potential for effective and safe cleaning of car radiator tubes. The main advantage of ultrasonic cleaning lies in its ability to break down contaminants at the molecular level through microjets and shockwaves generated by the collapse of cavitation bubbles. This process allows the removal of even the most stubborn deposits deeply embedded in the tube walls, without causing significant mechanical impact on the radiator material. As a result, the risk of tube damage is reduced, which is especially important for car radiators, where the strength and durability of the structure are crucial for the stable operation of the engine cooling system.

Unlike existing studies, future work will focus on detailed control of parameters such as the position of the ultrasonic emitter and the stability of air saturation in the liquid, to achieve uniform cleaning along the entire length of the tubes. It is expected that these improvements will enhance the repeatability of results, allow for more precise control of the cavitation process, and increase the overall reliability of the method.

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