THEORETICAL AND EXPERIMENTAL STUDY OF OPERATION OF THE TANK EQUIPMENT FOR ULTRASONIC PURIFICATION OF THE INTERNAL COMBUSTION ENGINE EXHAUST GASES

Adil Kadyrov[1], Aleksandr Ganyukov[1], Igor Pak[1], Bahtiyar Suleyev[1], Kyrmyzy Balabekova[2,*]

[1]Department of Transport Equipment and Logistics Systems, Karaganda Technical University, Karaganda, Kazakhstan
[2]Department of Transport, Transport Equipment and Technologies, L. N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan

*E-mail of corresponding author: 06_03_92@mail.ru

Resume

The article presents results of scientific and experimental studies of the authors on operation of the tank equipment for ultrasonic purification of exhaust gases of internal combustion engines designed to reduce environmental pollution.

The scheme of the experimental device implementing the principle of the tank equipment operation for ultrasonic cleaning of the motor vehicles exhaust gases is presented; the obtained experimental data of ultrasonic coagulation processes were processed and analyzed. Empirical relationships of the coagulation coefficient and its rate of change are derived from experimental data.

Article info
Received 5 November 2020
Accepted 14 December 2020
Online 7 May 2021

Keywords:
internal combustion engine,
exhausted gases,
tank equipment,
ultrasonic purification,
coagulation,
coagulation coefficient,
experiment

Available online: https://doi.org/10.26552/com.C.2021.3.B219-B226

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Motor vehicles are much more aggressive to the environment compared to other modes of the land transport. It is a powerful source of toxic substances. As the vehicle fleet increases, the level of harmful impact of motor vehicles on the environment increases intensively. Thus, while in the early 1980s the proportion of pollution introduced into the atmosphere by transport was on average equal to 20 %, it has now reached 50 % and continues to grow. For large cities and industrial centers, the share of motor transport in the total volume of pollution is much higher and reaches 70 % or more, which creates a serious environmental problem [1].

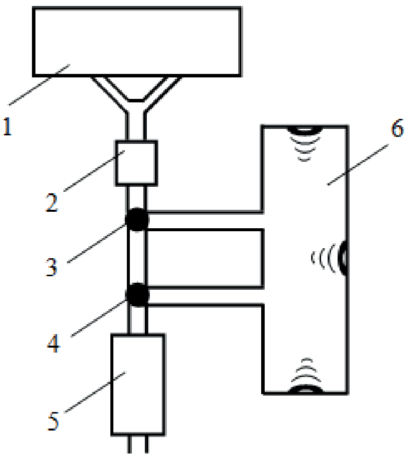
Solving environmental problems of transport requires development of the necessary mechanisms to protect the environment and adoption of scientifically based engineering and technical solutions to reduce the negative impact of transport facilities.

Reduction of harmful emissions of exhaust gases of internal combustion engine can be carried out by installation of various systems of neutralization and purification of exhaust gases operating on methods of liquid, thermal, catalytic neutralization, soot filters. A method for ultrasonic purification of exhaust gases is known. In order to reduce the concentration of toxic and polluting substances, it is proposed to equip motor vehicles with the tank equipment of cyclic action for ultrasonic purification of the motor vehicles exhaust gases, which is a tank with an ultrasonic generator and radiator mounted in it [2].

2 The tank equipment construction and principle of operation

During the development of equipment, the patents obtained by authors were used [3-4]. Diagram of connection of tank equipment for the ultrasonic purification of motor vehicles exhaust gases is shown in Figure 1.

The equipment operates in active and passive modes. In passive mode valves 3 and 4 pass exhaust gas from resonator 2 to muffler 5 bypassing the storage tank of equipment. During the engine warming-up, up-driving, acceleration or when the vehicle is driven to a stop, the device switches to the active mode - the inlet valve 3 is switched to the tank filling mode, the outlet valve of the device 4 closes the discharge from the storage tank and the gas is accumulated in the tank 6, that is, there is a temporary isolation of exhaust gases from emission into the atmosphere for the period



1 - engine; 2 - resonator; 3 - inlet valve; 4 - outlet valve;
5 - muffler; 6 - tank ultrasonic purifying equipment

Figure 1 *Scheme of installation of tank equipment of ultrasonic purification of motor vehicle exhaust gases.*

of a stop for some time, after starting driving. At the same moment the ultrasonic device is switched on and ultrasonic coagulation of soot particles occurs in the containers, accompanied by their weighting and settling. After a pre-determined period of time, for example, when the bus is starting from the stop by a sufficient distance or when a certain pressure is reached in the tank set by the critical filling mode, the exhaust valve opens and the purified exhaust gas is released through the muffler 5 and any filtering device into the atmosphere.

The time of tank filling, its volume and strength characteristics are determined in the work [5].

The coagulation process is accelerated by exposure to ultrasound, which has a dispersing effect on emulsions and liquid sols and coagulating effect on aerosols (smoke, fog, dust).

Efficiency of the coagulation process increases when a standing wave occurs. Standing waves are a particular case of interference; two identical waves spread in opposite directions.

Exhaust gas consists of particles of different sizes. Depending on their magnitude and frequency of oscillations, the particles can follow sound oscillations and coagulate.

The first process takes place at low oscillation frequencies. When the oscillation frequency increases, there is an optimal frequency segment at which particles of different magnitude have different amplitude, collide with each other and coagulate. This kind of coagulation is called ortho-kinetic. When frequency increases, coagulation becomes hydrodynamic and it is performed due to friction. This process is described by the Bjerknes equations [6-9].

The degree of particle participation in sound oscillations in the case of standing sound wave is related to frequency of oscillations, radius of a particle and viscosity of environment; it is described by the following ratio [6-8]:

$$\frac{U_{ch}}{U_g} = \frac{1}{\left[(4\pi\rho r^2 f/9\eta)^2 + 1\right]^{1/2}}, \tag{1}$$

where: U_{ch}, U_g are the amplitudes of the particle and gas oscillations respectively;
ρ - density of the particle;
r - the radius of the particle;
f - frequency of gas oscillations under action of ultrasound;
η - dynamic viscosity.

This equation is derived from the Stokes law [6-9] and reflects the hydrodynamic coagulation.

The amplitude ratio will be smaller the higher the frequency and greater the radius of the particles. Therefore, depending on the degree of particle participation in gas oscillations, the value r^2f is determined. It is accepted to define the coefficient of fascination by the expression:

$$Z = \frac{\rho r^2 f}{\eta}. \tag{2}$$

The coagulation process for this device is described by the following dependencies.

When the ultrasonic generator is switched on:
$t = 0; PV = \text{const}; P = \text{const}; V = \text{const}; \rho = \text{const}; m = m_0$, where t - time; P - pressure; V - volume; ρ - density; m - mass; m_0 - the initial mass.

During the ultrasonic generator operation:

$$t > 0; V = const; P = \tilde{P}(\rho, m); m = \tilde{m}(t).$$

Coagulation kinetics dependence, described by exponential dependence, is adopted as a coagulation model [10]:

$$n = n_0 \exp(-kt), \tag{3}$$

where n and n_0 are counting concentrations of gas

particles, respectively current at the initial moment;
k - coagulation coefficient.

Let it be assumed that the average concentration of gas and soot molecules is directly proportional to their masses and inversely proportional to the volume occupied. Then the total mass in the tank will be composed of the gas mass (m_G) and the soot mass (m_s):

$$m_0 = nm_G + (1-n)m_s. \tag{4}$$

From Equations (3) and (4), one obtains:

$$\frac{m_G}{V} = \frac{m_0}{V}e^{-kt}, \tag{5}$$

as:

$$m_s = m_0 - m_G,$$

then:

$$m_c = m_0 - m_0 e^{-kt} = m_0(1 - e^{-kt}). \tag{6}$$

The pressure depending on the mass is determined as $P = \frac{mg}{S}$ where S - square, taking into account the gas mass $P = \frac{m_0 e^{-kt}}{S}g$.

The density of gas and soot taking into account their volumes will be equal to $\rho_g = \frac{m_0 e^{-kt}}{V}; \rho_s = \frac{m_0(1-e^{-kt})}{V_c}$, respectively.

The value of the drag coefficient is determined by expression:

$$Z = \frac{m_0 e^{-kt} r^2 f}{\eta}. \tag{7}$$

From Equation (6), the coagulation coefficient is determined as:

$$k = -\frac{\ln\left(1 - \frac{m_c}{m_0}\right)}{t}. \tag{8}$$

The light transmission capacity of some volume of exhaust gas is directly dependent on the concentration of particulate matter contained therein, preferably soot, in a suspended state and it is due to the light absorption capacity of the particulate matter. The change in the light transmission capacity indicates the change in the soot concentration in the exhaust gas due to the deposition of soot particles on the bottom of the device.

The light absorption capacity can be estimated by the light flux absorption coefficient [2], determined as:

$$\beta_i = 1 - \alpha_i, \tag{9}$$

where α_i - is the degree of gas transparency α in the i-th time period determined by the ratio of illumination index E after gas injection into the i-th time period to illumination index prior to the gas injection.

$$\propto_i = \frac{E_i}{E_{ish}}, \tag{10}$$

where $i = 1 \ldots 10$.

Assuming that n and n_0 are counting concentrations of gas particles, respectively, they are current and at the initial moment are proportional to the light flux absorption degree β.

The coagulation coefficient is determined by formula:

$$k_i = -\frac{\ln\frac{\beta_i}{\beta_{i-1}}}{t}, \tag{11}$$

where $i = 1 \ldots 10$;
t - time interval between readings, $t = 60$ s.

Based on the hypothesis of close correlation between the coagulation and gas transparency degree, one equates Equations (8) and (11):

$$-\frac{\ln\left(1 - \frac{m_c}{m_0}\right)}{t} = -\frac{\ln\frac{\beta_i}{\beta_{i-1}}}{t}, \tag{12}$$

whence

$$m_c = m_0\left(1 - \frac{\beta_i}{\beta_{i-1}}\right), \tag{13}$$

or

$$m_c = m_0\left(1 - \frac{1-\alpha_i}{\alpha_{i-1}}\right) = m_0\left(1 - \frac{1 - \frac{E_i}{E_{ish}}}{1 - \frac{E_{i-1}}{E_{ish}}}\right). \tag{14}$$

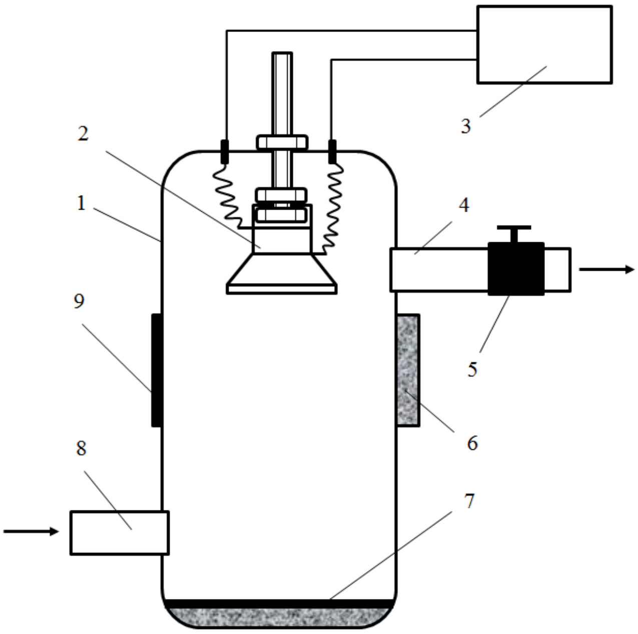
Thus, knowing the amount m_0 that can be determined from the volume of the tank and gas density, in order to determine the amount m_c, it is necessary to determine the ratio $\frac{\beta_i}{\beta_{i-1}}$ through the corresponding illumination values.

The device that detects this value is necessary, which is a transparent container, a light source, and an illumination sensor.

For experiments an experimental device was created for the ultrasonic purification of exhaust gases (Figure 2) consisting of a light-transmitting tank 1, an inlet 8 and an outlet 4 branch pipe with a valve 5, an ultrasonic radiator 2 and an ultrasonic generator 3, an ultrasonic wave reflector 7 [2].

The most effective frequencies of ultrasonic waves for the process of the soot particles coagulation of the internal combustion engines exhaust gases are in the frequency range from 15 to 30 kHz [6-7]; the frequency of ultrasonic generator of experimental device - 28 kHz, radiation power - 100 W.

The device is filled with exhaust gas through an inlet pipe 8, which in turn is connected to the exhaust pipe of the automobile. A faucet 5 is installed on the outlet branch pipe 4, which is closed after the installation is filled with exhaust gas. Under the action of ultrasonic waves, created by ultrasonic generator 3 and radiator



1 - light-transmitting tank; 2 - ultrasonic radiator; 3 - ultrasonic generator; 4 - outlet branch pipe; 5 - faucet; 6 - a light source; 7 - an ultrasonic wave reflector; 8 - inlet branch pipe; 9 - lux-meter.

Figure 2 *Experimental device for ultrasonic cleaning of exhaust gases*

Table 1 *The results of the experiments*

seconds	illumination index - E, lx		illumination change - ΔE, lx		transparency degree - α		degree of light flux absorption - β		coagulation coefficient - k	
	without ultrasound	with ultrasound	without ultrasound	with ultrasound	without ultrasound	with ultrasound	without ultrasound	with ultrasound	without ultrasound	with ultrasound
0	60	60			0.429	0.429	0.571	0.571		
60	66	80	5.64	20.00	0.469	0.571	0.531	0.429	0.0012	0.0048
120	70	90	4.82	9.91	0.503	0.642	0.497	0.358	0.0011	0.0030
180	73	95	2.18	5.18	0.519	0.679	0.481	0.321	0.0005	0.0018
240	76	101	3.00	5.64	0.540	0.719	0.460	0.281	0.0008	0.0022
300	77	105	1.00	4.45	0.547	0.751	0.453	0.249	0.0003	0.0020
360	79	109	2.27	3.73	0.564	0.778	0.436	0.222	0.0006	0.0019
420	80	113	0.91	3.64	0.570	0.804	0.430	0.196	0.0002	0.0021
480	82	116	2.55	3.00	0.588	0.825	0.412	0.175	0.0007	0.0019
540	84	118	1.27	2.45	0.597	0.843	0.403	0.157	0.0004	0.0018
600	85	120	0.91	1.64	0.604	0.855	0.396	0.145	0.0003	0.0013

2, processes of the soot particles coagulation are getting larger in exhaust gas, as a result of which soot particles are enlarged in size and mass and settle on the ultrasonic waves reflector's 7 surface. The purified exhaust gas is discharged to the atmosphere through the outlet branch pipe 4 after opening the faucet 5.

A lux-meter - 9 was used for the experiment. A light source - 6 was fixed on the opposite side. The entire structure was placed in a light-tight conduit to eliminate the effect of the external lighting change on results.

The experiments were carried out as follows. The device was filled with exhaust gas until the measured illumination decreased from 140 to 60 lx. The readings were taken at the frequency of 1 minute for 10 minutes without the ultrasonic generator being switched on and then a similar experiment was conducted with the ultrasonic generator turned on. The results of the experiments are shown in Table 1.

Graphs of the illumination index E (Figure 3), change of illumination ΔE (Figure 4) and coagulation coefficient - k dependences on the deposition time (Figure 5) are constructed.

Function of the coagulation coefficient dependence on time t is approximated according to the standard procedure described in [11] and [12]. The results are shown in Table 2.

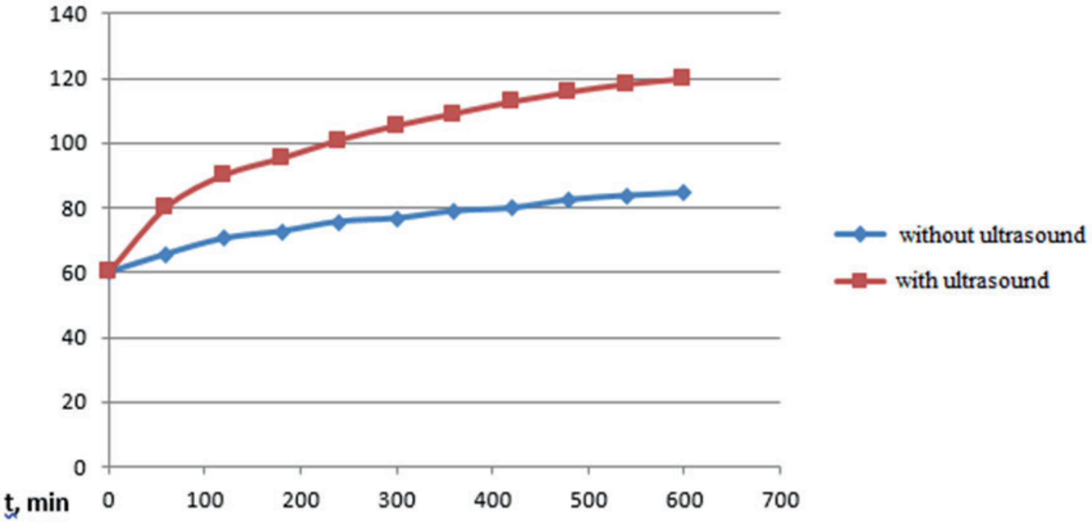


Figure 3 *Dependence of illumination index on deposition time*

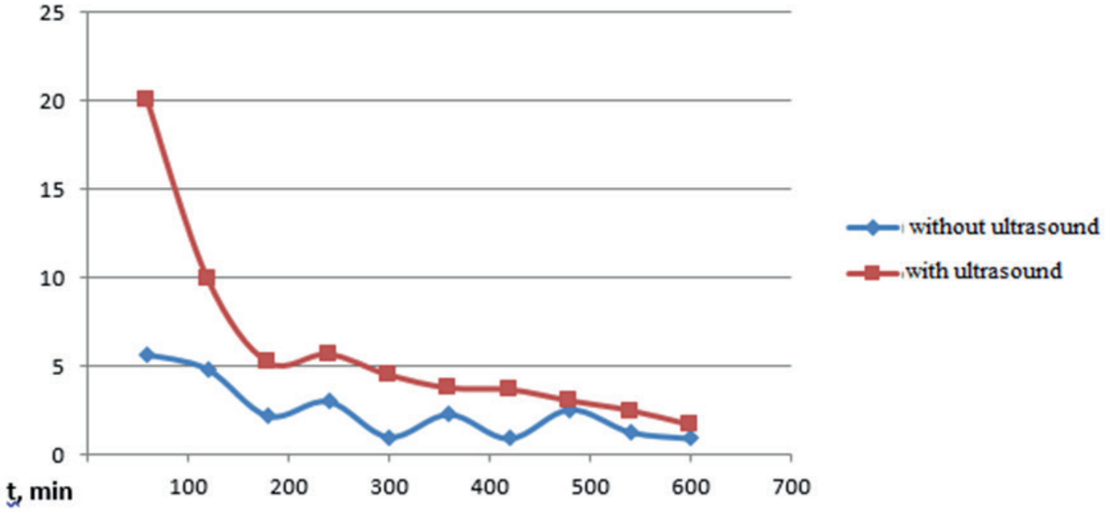


Figure 4 *Dependence of illumination index change on deposition time*

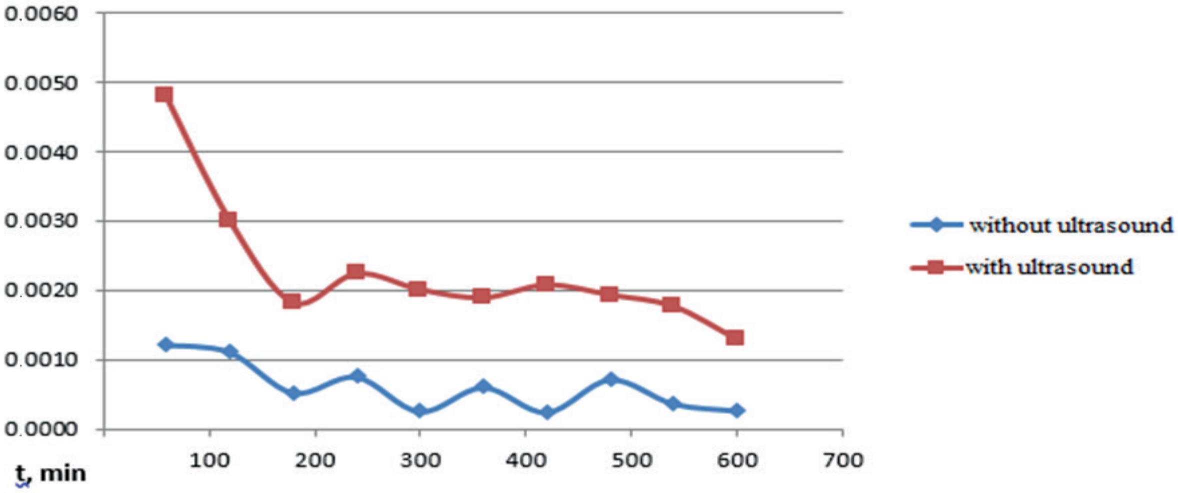


Figure 5 *Dependence of coagulation coefficient index on deposition time*

***Table 2** Results of approximation of the coagulation coefficient function of time*

regression	indicators	without ultrasound	with ultrasound
1	2	3	4
linear	dependence $k=f(t)*10^{-4}$	$k = -0.0136364t + 10.60$	$k = -0.0402020t + 36.0666667$
	linear pair correlation coefficient $k=f(t)*10^{-4}$	-0.7255863	-0.7429615
	determination coefficient	0.5264754	0.5519919
	average approximation error, %	45.4635773	19.6705412
quarter	dependence $k=f(t)*10^{-4}$	$k = 0.0000442t^2 - 0.0428030t + 14.10$	$k = 0.0001473t^2 - 0.1374242t + 47.7333333$
	correlation coefficient $k=f(t)*10^{-4}$	0.8086220	0.8501427
	determination coefficient	0.6538695	0.7227426
	average approximation error, %	38.3055195	18.8015330
cubic	dependence $k=f(t)*10^{-4}$	$k = -0.0000002t^3 + 0.0002223t^2 - 0.0920778t + 17.4333333$	$k = -0.0000012t^3 + 0.0012994t^2 - 0.4562322t + 69.3$
	correlation coefficient $k=f(t)*10^{-4}$ of $k=f(t)*10^{-4}$	0.8356506	0.9732228
	determination coefficient	0.6983119	0.9471627
	average approximation error, %	36.1394885	8.2440902
degree	dependence $k=f(t)*10^{-4}$	$k = 133.2196139t^{-0.5768993}$	$k = 232.5708630t^{-0.4255949}$
	correlation coefficient	0.8073428	0.9193806
	determination coefficient	0.6518023	0.8452607
	average approximation error, %	35.4446902	11.8821493
indicative	dependence $k=f(t)*10^{-4}$	$k = 10.6971362 \cdot 0.9978466^t$	$k = 35.5964301 \cdot 0.9984605^t$
	correlation coefficient	0.7491687	0.7698100
	determination coefficient	0.5612538	0.5926074
	average approximation error,%	39.7408550	15.9516601
logarithmic	dependence $k=f(t)*10^{-4}$	$k = 27.8815899 - 3.8848717 \cdot \ln t$	$k = 89.6447697 - 11.9255533 \cdot \ln t$
	correlation coefficient	0.8083030	0.8824176
	determination coefficient	0.6533538	0.7786609
	average approximation error, %	37.8721412	15.1343431
hyperbolic	dependence $k=f(t)*10^{-4}$	$k = \frac{3.2191661 + 590.1396602}{t}$	$k = \frac{12.8257622 + 2043.2255254}{t}$
	correlation coefficient of $k=f(t)*10^{-4}$	0.7987887	0.9605531
	determination coefficient	0.6380633	0.9226623
	average approximation error, %	40.1251236	10.3018760
exponential	dependence $k=f(t)*10^{-4}$	$k = e^{2.3699761 - 0.0021557t}$	$k = e^{3.5722454 - 0.0015407t}$
	correlation coefficient	0.7491687	0.7698100
	determination coefficient	0.5612538	0.5926074
	average approximation error, %	39.7408550	15.9516601

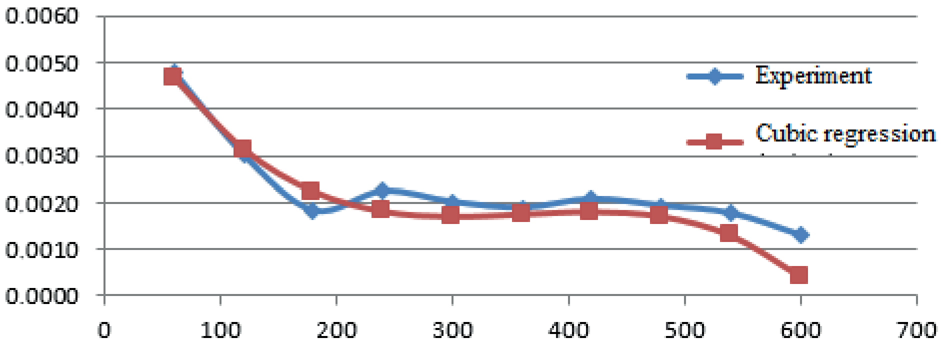


***Figure 6** Experimental and calculated graphs of coagulation coefficient dependence on time*

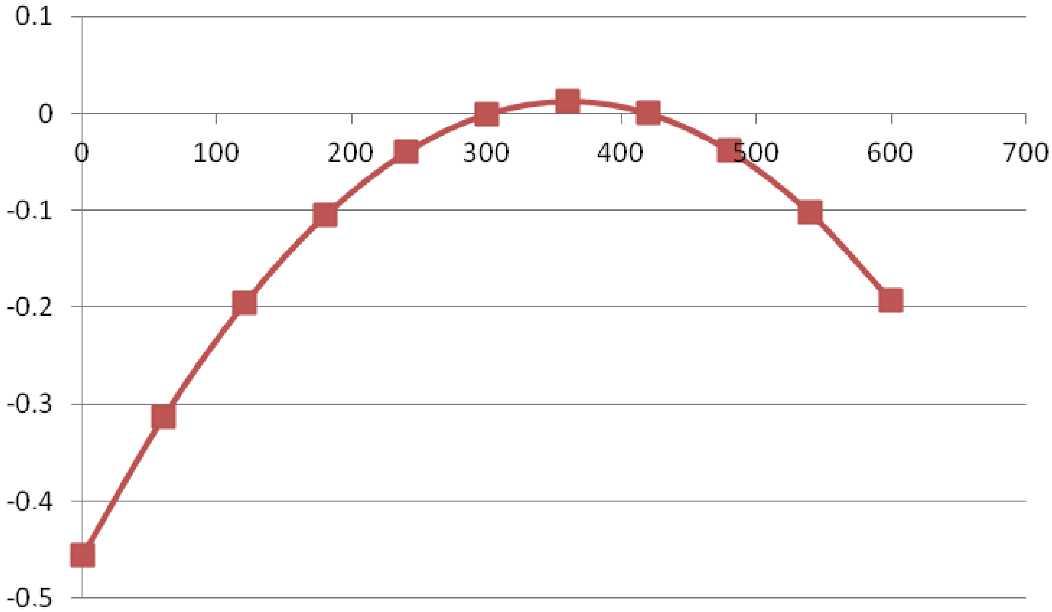


***Figure 7** Dependence of the coagulation coefficient change rate on time*

From analysis of Table 2 on the largest values of correlation coefficients, determinations and the smallest values of the average approximation error for the coagulation process using ultrasound, it is proposed to use the cubic regression equation:

$$\begin{gathered} k = (-0.0000012t^3 + 0.0012994t^2 - \\ -0.4562322t + 69.3)\cdot 10^{-4}. \end{gathered} \qquad (15)$$

Figure 6 shows graphs of dependencies *k (t)*, obtained from the experimental data and data calculated according to Equation (15).

Thus, the coagulation coefficient must be determined by Equation (15) and the soot mass by Equation (6).

The coagulation rate process is essential. Since Equation (15) has a significant determination factor, differentiation of the function is possible. Then, the coagulation rate was subjected to the following dependency:

$$\begin{gathered} \dot{k} = (-0.0000036t^2 + 0.0025988t - \\ -0 - 4562322)\cdot 10^{-4}. \end{gathered} \qquad (16)$$

Figure 7 shows a graph of the coagulation rate dependence on time.

3 Conclusions

The article confirms the possibility of using the exhaust gases in the isolation tank using ultrasonic generators. Using the assumptions that the average concentration of the gas molecules and soot particles is directly proportional to their masses and inversely proportional to their volumes, the ratio of these masses in the form of coagulation coefficient over time is obtained.

The assumption about close correlation between the coagulation and the degree of gas transparency was suggested, which made it possible to carry out the experiment based on determining the degrees of transparency and absorption of the light flux by the gas. The results of the experiment confirmed the analytical data.

The obtained results make it possible to use dependencies to determine the parameters and operation modes of the tank equipment for ultrasonic cleaning of motor vehicles exhaust gases depending on parameters of the ultrasonic generator and the tank volume by selection according to schedules.

Analytical and experimental studies make it possible to develop the methods of calculating the system of the tank equipment for ultrasonic cleaning of exhaust gases. This methodology includes dependencies for determining the parameters and operating modes of the system depending on parameters of the ultrasonic generator and the tank volume by selecting according to dependencies obtained in the article.

References

[1] EROKHOV, V. I. Toxicity of modern cars (methods and means of reducing harmful emissions to the atmosphere): textbook. Moscow: Forum: Infra-m, 2013. ISBN 978-5-911384-801-4.

[2] IBATOV, M. K., KADYROV, A. S., PAK, I. A., KADYROVA, I. A., ASKAROV, B. S. Results of experimental studies of operation of the tank equipment of ultrasonic purification of exhaust gases of motor vehicles (in Russian). *Ugol / Coal* [online]. 2020, **2**, p. 73-78. ISSN 0041-5790, eISSN 2412-8333. Available from: http://dx.doi.org/10.18796/0041-5790-2020-2-73-78

[3] IBATOV, M. K., KADYROV, A. S., BALABAYEV, O. T., ASKAROV, B. S., PAK, I. A. Device for ultrasonic purification of exhaust gases. Patent 3194 PK. 2018.

[4] IBATOV, M. K., KADYROV, A. S., PAK, I. A., ASKAROV; B. S. Device for exhaust gas isolation. *Bulletin*. 2012, **12**. ISSN 1609-1825.

[5] IBATOV, M. K., ALIYEV, S. B., BALABAYEV, O. T., ASKAROV, B. S. Main results of experimental studies of exhaust gas isolation of ICE of quarry locomotives. *Ugol / Coal* [online]. 2019, **7**, p. 28-30. ISSN 0041-5790, eISSN 2412-8333. Available from: http://dx.doi.org/10.18796/0041-5790-2019-7-28-30

[6] KHMELEV, V. N. Ultrasonic coagulation of aerosols. In: KHMELEV, V. N., SHALUNOV, A. V., SHALUNOVA, K. V., TSYGANOK, S. N., BARSUKOV, R. V., SLIVIN, A. N. (Eds.) Biysk: Biysk Institute of Technology, Altai State Technical University, 2010.

[7] BERGMAN, L. *Ultrasound and its applications in science and technology*. Moscow: Publishing House of Foreign Literature, 1957.

[8] BALDEV, R., RAJENDRAN, V., PALANICHAMI, P. *Applications of ultrasound*. Moscow: Technosphera, 2006. ISBN 5-94836-088-1.

[9] GALLEGO-JUAREZ, J. A., GRAFF, K. F. *Power ultrasonics: applications of high-intensity ultrasound*. 1. ed. Elsevier, 2014. ISBN 978-1-78242-028-6, eISBN 978-1-78242-036-1.

[10] KARDASHEV, G. A. *Fizicheskie metody intensifikatsii protsessov khimicheskoi tekhnologii / Physical methods of intensification of chemical technology processes* (in Russian). Moscow: Khimiya, 1990. ISBN 5-7245-0674-2.

[11] SHEROV, K. T., ALIKULOV, D. E. Control ruler for angles between planes of V-shaped guides. *Measurement Techniques* [online]. 2012, **55**(4), p. 397-399. ISSN 0543-1972, eISSN 1573-8906. Available from: https://doi.org/10.1007/s11018-012-9971-5

[12] SHEROV, K. T., SIKHIMBAYEV, M. R., NASAD, T. G., ABSADYKOV, B. N., IZOTOVA, A. S., OKIMBAYEVA, A. E., KUANOV, I. S. The research of the steel cutting blade reliability for thermo-frictional processing. *News of the National Academy of Sciences of the Republic of Kazakhstan. Series of Geology and Technical Sciences* [online]. 2020, **1**(439), p. 122-130. ISSN 2224-5278, eISSN 2518-170X. Available from: http://doi.org/10.32014/2020.2518-170X.15