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Establishment of the Reynolds Criterion for Ultrasonic Cleaning of Exhaust Gases of Internal Combustion Engines

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Abstract. *In the article, the authors establish the Reynolds criterion for the use of ultrasonic cleaning of exhaust gases of internal combustion engines in order to reduce their toxicity. To conduct the experiment, we have developed an experimental full-size ultrasound stand. The scheme of the stand is described, the results of calculations of criteria and experiment are given. The obtained data will determine the dependence of the coagulation rate on the criteria and will make it possible to compile a regression equation necessary for practical calculations. Through the application of similarity theory and dimensional analysis, three similarity criteria have been calculated that will simplify the multivariate experimental study. The resulting experimental plan allows us to determine the effectiveness of the coagulation process, which is accelerated by ultrasound. The results of the experiment confirm the hypothesis of reducing the toxicity of exhaust gases of motor transport.*

Keywords: *automobile, internal combustion engine, ultrasonic cleaning, exhaust gases, coagulation, Reynolds criterion, experiment, toxicity of gases, ultrasonic stand, experiment plan, ultrasonic generator, ultrasonic emitter, ultrasonic muffler, air pollution.*

Introduction

Cars are the main source of urban air pollution. Pollution occurs due to the emission of exhaust gases into the atmosphere. Car mufflers are designed to reduce the harm of this process.

Reduction of toxic emissions in modern mufflers is carried out by means of cleaning and neutralization of exhaust gases that operate on motor vehicles, devices operating on absorption, thermocatalytic methods, and thermal afterburning have become widespread [1].

We propose an ultrasonic method for cleaning exhaust gases, due to the coagulation of its part in the muffler. Studied patients and research in this area, for example, the use of a four-wave resonator. The difference between our proposal is in the placement of the ultrasonic emitter in the muffler [2, 8].

The hypothesis of our study is to increase the efficiency of exhaust gas cleaning and the obtained similarity criteria, which allow us to draw up an experimental plan, to simplify the process of processing data from an experimental study.

The aim of the study is to obtain similarity criteria and conduct an experimental study.

The tasks of the study included the definition of criteria, the development of experimental stands, the conduct of experiments, and the processing of the results.

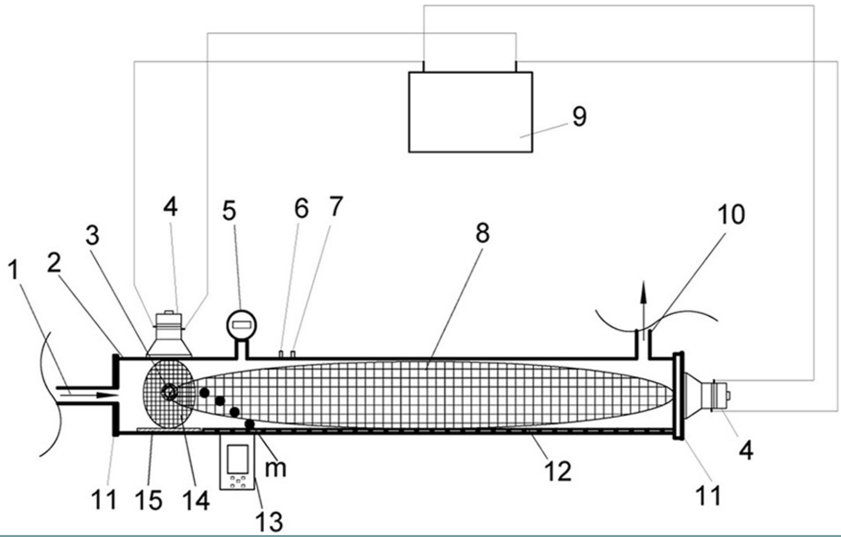
Materials and methods

To achieve the set goals, a full-scale experiment was carried out on a developed laboratory full-size stand (Figures 1-2). During the experiment, at the first stage, the criteria were determined allowing to reduce the number of experiments, at the second stage the experiment was carried out [2].

A diagram of an experimental ultrasonic muffler is shown in Figure 2.

The experimental metal ultrasonic muffler consists of a steel tube with a diameter of 108 mm and a length of 2000 mm. An ultrasonic equipment is installed in the muffler housing, consisting of an ultrasonic generator 9, two ultrasonic emitters 4 and a reflector of ultrasonic waves 15, a digital USB microscope Mikmed 2.0 3 with a magnification factor of 20 to 200x with the possibility of photo and video recording at a resolution of 1920 × 1080 pixels, a sensor temperature 6 and hygrometer 7 transmitting information to thermometer-hygrometer 13, electronic pressure gauge 5.

Figure 1 – Experimental metal ultrasonic muffler



1 – inlet pipe; 2 – housing of the ultrasonic muffler; 3 – electron microscope MIKMED 2.0; 4 – ultrasonic emitter; 5 – electronic pressure gauge; 6 – temperature sensor; 7 – moisture meter; 8 – area of influence of longitudinal ultrasonic waves; 9 – ultrasonic generator; 10 – outlet branch pipe; 11 – side flange; 12 – place of collection of soot; 13 – thermometer-hygrometer; 14 – area of influence of transverse ultrasonic waves; 15 – reflector; m – mass of gas particles

Figure 2 – Diagram of an experimental ultrasonic muffler

To determine the qualitative and quantitative composition of the exhaust gas mixture, a Bosch FSA 740 gas analyzer was used. An ultrasonic generator manufactured by «TOCOOL», China was used. The input voltage is 220 volts, with the power of the emitters – 50 watts, the frequency of generating ultrasonic waves is 40 kHz. To study the internal processes of the ultrasonic muffler, a Mikmed 2.0 USB microscope was installed in the housing, intended for quality control and testing of industrial objects.

The experimental study was carried out as follows:

- the tests were carried out without turning on and turning on the ultrasonic equipment for 1 minute each;

- the study was carried out at 1000, 1200, 1500 rpm crankshaft revolutions per minute. Used car VW Passat B3, engine capacity 1800 cc. see, the brand of fuel is gasoline.

- after 60 seconds, when the muffler was operating without ultrasound and with ultrasonic action, the gas analyzer readings were taken.

The spent exhaust gas was supplied to the ultrasonic muffler through the inlet pipe 1 at a pressure that depends on the crankshaft speed. In the muffler, with the ultrasonic equipment turned on, ultrasonic waves were applied to the exhaust gas in the longitudinal directions. In the muffler, ultrasonic intensification of coagulation processes and cleaning of exhaust gases took place due to the sedimentation of enlarged particles of exhaust gas at the place where soot 12 was collected. The cleaned exhaust gas was discharged through the outlet pipe 10.

During the operation of the ultrasonic muffler, the readings of the gas analyzer, hygrometer were taken, and photo and video recording of the processes taking place inside the muffler was made. Photo and video recording was carried out inside the ultrasonic muffler using a Mikmed 2.0 digital microscope, with the possibility of magnification from 20 to 200x at a maximum resolution of 1920 × 1080 pixels (photographs are not shown because of an unclear image during transfer).

Results

The method of the theory of similarity is used along with the method of dimensional analysis, since both methods are considered as one whole and is a single research system. For the correct application of the method of the theory of similarity and analysis of dimensions in the study, it is necessary to know the nature and number of fundamental variables. Fundamental variables are understood as a quantity that affects the experiment and changes independently of other variables. Accordingly, the following variables were considered that have an effect on the ultrasonic cleaning process: engine speed (n), the vibration amplitude of the ultrasonic wave (A), particle mass (m), gravity acceleration (g), particle settling time (t), ultrasonic pressure waves (P), kinematic viscosity (ν), particle diameter (d). As a result, we got eight fundamental variables, depending on the settling time of particles, the dependence of which can be written in the following form, formula (1):

$$t \sim (n, A, m, g, P, v, d). \quad (1)$$

Then, according to Buckingham's theorem, the resulting functional relationship can be expressed in terms of dimensionless combinations. Buckingham's theorem says: «If any equation is homogeneous with respect to dimensions, then it can be transformed to a relation containing a set of dimensionless combinations of quantities». To do this, we express the dimension of the variables in relation to three basic units: length L, mass M, and time θ. For the main values, the dimension formulas were given in table 1 [3-11].

Designation Unit of measurement Formula of dimension.

Let us now assume that the following relationship exists between these quantities, formula (2):

$$t = \varphi[n^{\alpha}, A^{\beta}, m^{\gamma}, g^{d}, P^{e}, v^{k}, d^{p}]. \quad (2)$$

Let's put dimension formulas taken from the table in place of dimension symbols, formula (3):

$$\theta = [(\theta^{-1})^{\alpha}, L^{\beta}, M^{\gamma}, (L\theta^{-2})^{d}, (ML^{-1}\theta^{-2})^{e}, (L^{2}\theta^{-1})^{k}, L^{p}]. \quad (3)$$

For this equation to be homogeneous with respect to uniformities, the following relations between the exponents, formulas (4), (5), (6) must be satisfied:

$$\text{for } L\!: 0 = \beta + d - e + 2k + p. \quad (4)$$

$$\text{for } M\!: 0 = \gamma + e, \quad (5)$$

$$\text{for } \theta\!: 1 = -\alpha - 2d - 2e - k. \quad (6)$$

We have three equations with seven unknowns. Let us simplify them by transforming them as follows: $\beta = e - d - 2k - p$, $\gamma = -e$, $\alpha = -2d - 2e - k - 1$. Substituting these ratios for exponents into formula (2), we obtain formula (7):

$$t = (n^{(-2d-2e-k-1)}, A^{(e-d-2k-p)}, m^{(-e)}, g^{d}, p^{e}, v^{k}, d^{p}). \quad (7)$$

Combining terms with the same exponents, it is easy to make dimensionless combinations, formula (8).

$$\left[\left(\frac{g}{n^{2}A}\right)^{d}, \left(\frac{AP}{n^{2}m}\right)^{e}, \left(\frac{v}{nA^{2}}\right)^{k}, \left(\frac{d}{A}\right)^{p}\right] = tn. \quad (8)$$

Table 1 – List of dimension formulas for the main values of variables

No.	Name variable	Designation	Unit of measurement	Formula of dimension
1	Engine speed	n	rpm	θ^{-1}
2	Amplitude of vibration of an ultrasonic wave	A	m	L
3	Particle mass	m	kg	M
4	Acceleration of gravity	g	m/s^2	$L\,\theta^{-2}$
5	Particle settling time	t	s	θ
6	Ultrasonic wave pressure	P	$Pa = N/m^2$	$M\,L^{-1}\,\theta^{-2}$
7	Kinematic viscosity	v	m/s^2	$L^2\,\theta^{-1}$
8	Particle diameter	d	m	L

The eight initial variables of the problem give five dimensionless combinations. The resulting number of criteria is confirmed by the so-called «pi-theorem». According to the theorem: «if there is an unambiguous relationship between n physical quantities, for the description of which k basic units are used, then the relationship between $(n-k)$ dimensionless combinations made up of these quantities corresponds». In our case, eight physical quantities were considered, three basic units were chosen and, according to this, five dimensionless combinations were obtained. Applying the method of the theory of similarity and the analysis of dimensions, we passed from ordinary physical quantities to quantities of a complex type, thus we easily made progress in solving the problem.

As a result, the fundamental variables were reduced and transformed into three similarity criteria, formulas (9), (10), (11).

$$\frac{g}{n^2 d} = k_1, \quad (9)$$

$$\frac{Pd}{n^2 m} = k_2, \quad (10)$$

$$\frac{v}{nAd} = k_3. \quad (11)$$

The obtained similarity criteria make it possible to draw up an experimental plan. To simplify the processing of the data obtained from the experiments of the experiment, the interval for changing the criteria is selected in accordance with the scale from +1 (upper level) to –1 (lower level). Since the criteria are considered between two levels, the experimental design has eight experiments and corresponds to the multivariate experimental design 23. In this regard, the experimental design matrix has the following form (Table 2).

The geometric interpretation of this plan is cubic. To build a graphical image of the plan, it is necessary to determine the average, maximum, minimum values of the criteria corresponding to the coordinates of the cube.

The coordinates of the center of the cube are the average value of the similarity criteria, formulas (12), (13), (14):

Table 2 – Design of the experiment matrix 2^3

Experiment numbers	x_1	x_2	x_3	y
1	–1	–1	+1	y_1
2	–1	+1	–1	y_2
3	+1	–1	–1	y_3
4	+1	+1	+1	y_4
5	–1	–1	–1	y_5
6	–1	+1	+1	y_6
7	+1	–1	+1	y_7
8	+1	+1	–1	y_8

$$\frac{g}{n_{cp}^2 d_{cp}} = k_{1cp}, \quad (12)$$

$$\frac{P_{cp} d_{cp}}{n_{cp}^2 m_{cp}} = k_{2cp}, \quad (13)$$

$$\frac{v_{cp}}{n_{cp} A_{cp} d_{cp}} = k_{3cp}. \quad (14)$$

We find the minimum and maximum values of the dimensionless quantities, formulas (15), (16), (17), (18), (19), (20):

$$\frac{g}{n_{\max}^2 d_{\max}} = k_{1\min}, \quad (15)$$

$$\frac{P_{\min} d_{\min}}{n_{\max}^2 m_{\max}} = k_{2\min}, \quad (16)$$

$$\frac{v_{\min}}{n_{\max} A_{\max} d_{\max}} = k_{3\min}, \quad (17)$$

$$\frac{g}{n_{\min}^2 d_{\min}} = k_{1\max}, \quad (18)$$

$$\frac{P_{\max} d_{\max}}{n_{\min}^2 m_{\min}} = k_{2\max}, \quad (19)$$

$$\frac{v_{\max}}{n_{\min} A_{\min} d_{\min}} = k_{3\max}. \quad (20)$$

Based on these data, we construct the coordinates of the vertices of the cube, formulas (21), (22), (23), (24), (25), (26), (27), (28).

$$1.\ (k_{1\max}, k_{2\min}, k_{3\min}), \quad (21)$$

$$2.\ (k_{1\min}, k_{2\min}, k_{3\min}), \quad (22)$$

$$3.\ (k_{1\min}, k_{2\max}, k_{3\min}), \quad (23)$$

$$4.\ (k_{1\max}, k_{2\max}, k_{3\min}), \quad (24)$$

$$5.\ (k_{1\max}, k_{2\min}, k_{3\max}), \quad (25)$$

$$6.\ (k_{1\min}, k_{2\min}, k_{3\max}), \quad (26)$$

$$7.\ (k_{1\min}, k_{2\max}, k_{3\max}), \quad (27)$$

$$8.\ (k_{1\max}, k_{2\max}, k_{3\max}). \quad (28)$$

The geometric interpretation of the full factorial experiment 2^3 is a cube, the coordinates of the vertices of which are set by the conditions of the experiments (Figure 3).

Table 3 shows the data of the conducted field experiment.

As can be seen from Table 3, the CO content decreased by 13.3%, which confirms the hypothesis of a decrease in the toxicity of exhaust gases due to the use of ultrasonic equipment in a car muffler.

Conclusion

The data obtained will determine the dependence of the rate of coagulation on the criterion k_1, k_2, k_3 and will make it possible to draw up the regression equation necessary for practical calculations.

Through the application of similarity theory and dimensional analysis, three similarity criteria were obtained, which give us the following advantages:

- firstly, the number of variables influencing the experiment has decreased;

- secondly, the experiment will be influenced not by individual factors of quantities, but by its entire complex as three criteria of similarity, that is, the internal connections of quantities will appear more clearly.

- thirdly, on the basis of the similarity criteria obtained, it was established that eight experiments were carried out, a plan for a multifactorial experiment 23 was chosen, and a method of experimental research was developed.

The experimental design allows to determine the effectiveness of the application of the coagulation process, which is accelerated under the action of ultrasound on the developed full-size stand.

Experimental results have been obtained that confirm the hypothesis of a decrease in the toxicity of exhaust gases from motor vehicles.

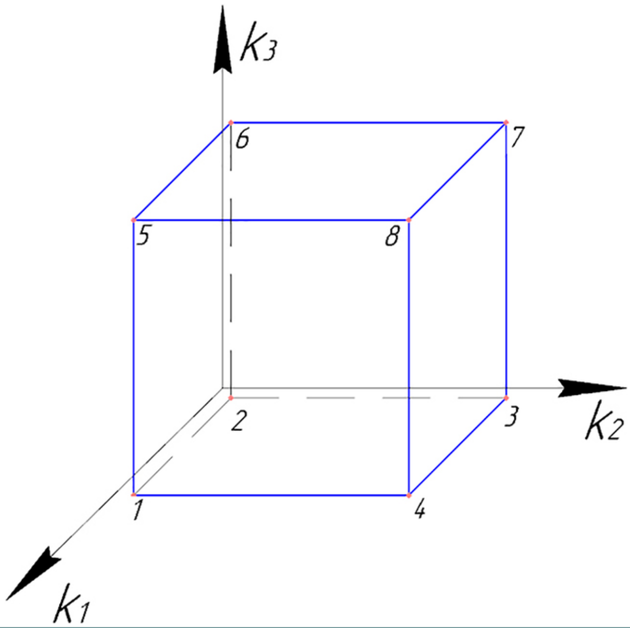


Figure 3 – Geometric interpretation of a full factorial experiment 2^3

Table 3 – Readings of the Bosch FSA 740 gas analyzer

Muffler operation	Rotation frequency (rpm)	Moisture (%)	O_2, (%)	CO_2, (%)	HC, (ppm)	CO, (%)	Measurement time (sec)
Without ultrasound	1000	48	9,11	7,78	67	0,3	60
With ultrasound (1 transverse emitter)	1000	50	8,83	8,38	68	0,264	60
Without ultrasound	1200	51	8,75	7,54	68	0,302	60
With ultrasound (1 transverse emitter)	1200	51	8,73	7,62	70	0,297	60
Without ultrasound	1500	57	8,23	6,69	69	0,326	60
With ultrasound (1 transverse emitter)	1500	58	7,98	6,72	71	0,324	60

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Іштен жану қозғалтқыштардың пайдаланылған газдарын ультрадыбыстық тазарту үшін Рейнольдс өлшемін белгілеу

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Аңдатпа. *Мақалада авторлар іштен жану қозғалтқыштардың улы газдар зиянын төмендету үшін ультрадыбыстық тазартуда Рейнольдс өлшемін қолдану жүргізілді. Эксперимент жүргізу үшін біз эксперименттік толық өлшемді ультрадыбыстық стенд жасадық. Стендтің схемасы сипатталған, критерийлер мен эксперименттің нәтижелері келтірілген. Алынған мәліметтер коагуляция жылдамдығының критерийлерге тәуелділігін анықтайды және практикалық есептеулер үшін қажетті регрессия теңдеуін құруға мүмкіндік береді. Ұқсастық теориясы мен өлшемдік талдауды қолдану арқылы көп өлшемді эксперименталды зерттеуді жеңілдететін үш ұқсастық критерийі есептелді. Алынған эксперимент жоспары әзірленген толық өлшемді стендте ультрадыбыстың әсерінен жеделдетілетін коагуляция процесінің тиімділігін анықтауға мүмкіндік береді. Эксперимент нәтижелері автомобиль көлігінен шығатын газдардың уыттылығын төмендету туралы гипотезаны растайды.*

Кілт сөздер: *автомобиль, іштен жану қозғалтқышы, ультрадыбыстық тазарту, пайдаланылған газдар, коагуляция, Рейнольдс критериі, эксперимент, газдың уыттылығы, ультрадыбыстық стенд, эксперимент жоспары, ультрадыбыстық генератор, ультрадыбыстық сәулелендіргіш, ультрадыбыстық сөндіргіш, ауаның ластануы.*

Установление критерия Рейнольдса для ультразвуковой очистки выхлопных газов двигателей внутреннего сгорания

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Аннотация. *В статье авторами производится установление критерия Рейнольдса для применения ультразвуковой очистки выхлопных газов двигателей внутреннего сгорания с целью уменьшения их токсичности. Для проведения эксперимента нами разработан экспериментальный полноразмерный ультразвуковой стенд. Описана схема стенда, приведены результаты расчетов критериев и эксперимента. Полученные данные будут определять зависимости скорости коагуляции от критериев и позволят составить уравнение регрессии, необходимых для практических расчетов. Благодаря применению теории подобия и анализа размерностей рассчитаны три критерия подобия, которые упростят проведение многофакторного экспериментального исследования. Полученный план эксперимента позволяет определить эффективность применения процесса коагуляции, который ускоряется под действием ультразвука. Результаты эксперимента подтверждают гипотезу об уменьшении токсичности выхлопных газов автомобильного транспорта.*

Ключевые слова: *автомобиль, двигатель внутреннего сгорания, ультразвуковая очистка, выхлопные газы, коагулирование, критерий Рейнольдса, эксперимент, токсичность газов, ультразвуковой стенд, план эксперимента, ультразвуковой генератор, ультразвуковой излучатель, ультразвуковой глушитель, загрязнение воздуха.*

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