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COMPARATIVE STUDY OF KNOWN FORMULAS FOR THE CONVERSION OF OPACITY INDICATORS OF EXHAUST GAS OF DIESEL ENGINES AS AN ENVIRONMENTAL HAZARD FACTOR

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Relevance of research. Nowadays, in Ukraine there are legally established standards for indicators of the toxicity of exhaust gases (EG) of reciprocating internal combustion engines (RICE) of motor vehicles (MV), in particular, the specific effective mass hourly emission of solid particles (SP) with the flow of EG of the g_{ePM} engine in g/(kW·h)) [1–5]. At the same time, the g_{ePM} value itself is obtained by relating the value of the mass hourly emission of SP with the flow of EG G_{PM} in g/h to the value of the effective power of the RICE N_e in kW. Obtaining the value of Ne and the values of its instrumental absolute and relative errors is not a difficult task. The main difficulty in obtaining the values of g_{ePM} as a legally standardized indicator of the environmental friendliness of a reciprocating internal combustion engine according to the pollutant with the highest value of the relative aggressiveness indicator is in obtaining the values of the G_{PM} value. As it is known from the basic provisions of the scientific discipline «Metrology», no measurements can be performed with absolute accuracy, but only with some error [4], which should also be taken into account when planning experimental or computational studies.

Normative requirements [5] for such an indicator of EG toxicity of reciprocating internal combustion engines of various purposes also establish a method of experimentally obtaining G_{PM} values – gravimetric [1–5]. However, due to the well-known circumstances characteristic of our country, calculation formulas of various types have become widespread, the most known of which is the formula of Prof. Ihor Parsadanov (NTU «KhPI»), described in the monograph [3]. This calculation formula, unlike its alternatives, takes into account not only the opacity of EG (in particular, the attenuation coefficient of the luminous flux N_D (in %), determined with a opacity-meter [6]), but also the toxicity of EG (in particular, the volumetric concentration of unburned hydrocarbons in EG C_{CH} (in ppm), determined using a gas analyzer [7]) and on the basis of these two independent variables it allows to obtain the value of G_{PM} (in kg/(kW·h)). At the same time, this formula contains two more independent variables – the values of mass hourly consumption of fuel G_{fuel} and air G_{air} of the RICE (in kg/h). The analysis of the scientific and technical literature on the topic of the use of calculation formulas did not reveal the method of assessing their accuracy and its results. There is also an analysis of the quantitative and qualitative aspects of the accuracy of obtaining G_{PM} values by the gravimetric method.

Another unresolved issue in the application of any calculation formula is the choice of units of measurement of EG opacity indicators and corresponding measuring equipment (ME), namely opacity-meters of various designs. Different indicators of

EG opacity with their corresponding units of measurement are related to each other according to non-linear laws, and direct use in a certain calculation formula of alternative base indicators of EG opacity is impossible. Such questions arise in practice in the following cases. 1) Selection of the type and model of the ME when equipping the motor stand of a newly created or modernized laboratory. 2) Bench motor studies of a reciprocating internal combustion engine – separately or as part of an vehicle – in a laboratory already equipped with a certain type of ME, which gives alternative indicators of opacity of EG. 3) Criteria-based assessment of the fuel-ecological perfection of the RICE of vehicle in the presence of a ready-made set of initial data obtained by other researchers, among which there are only alternative indicators of EG opacity. In connection with the above considerations, there is also the question of the influence of the type of units of measurement of EG opacity indicators on the quantitative and qualitative aspects of the instrumental accuracy of the calculation formulas, which determines its relevance.

The aim of the study. Creation of a methodology for calculating the values of the instrumental error of obtaining the values of the mass hourly emission of PM with the EG flow of a RICE of the vehicle, obtained when using a known conversion formula, taking into account the type of EG opacity index. **The Object of the study**. Instrumental accuracy of the calculation formula of Prof. Ihor Parsadanov. **The Subject of the study**. The influence of the type of EG opacity index with its inherent units of measurement on the instrumental accuracy of the selected calculation formula.

The analysis of the nomenclature of known recalculation formulas.

The recalculation formula, suggested by Prof. Ihor Parsadanov and described in the monograph [3], obtained as the data result analysis of the certification testing of the auto tractor diesel SMD-31 on the Ricardo motor stand, equipped with the full-flow dilution tunnel, is presented as the formula (1.1).

$$G_{PM} = \left(2{,}3\cdot10^{-3}\cdot N_D + 5\cdot10^{-5}\cdot N_D^2 + 0{,}145\cdot\frac{C_{CnHm}\cdot4{,}78\cdot10^{-7}\cdot\left(G_{air}+G_{fuel}\right)}{0{,}7734\cdot G_{air}+0{,}7239\cdot G_{fuel}} + 0{,}33\cdot\left(\frac{C_{CnHm}\cdot4{,}78\cdot10^{-7}\cdot\left(G_{air}+G_{fuel}\right)}{0{,}7734\cdot G_{air}+0{,}7239\cdot G_{fuel}}\right)^2\right)\times\frac{\left(0{,}7734\cdot G_{air}+0{,}7239\cdot G_{fuel}\right)}{1000}, \text{ kg/hr.} \quad (1.1)$$

The recalculation formula MIRA (The Motor Industry Research Association) is presented as a set of formulas (1.2)–(1.4) [4].

$$N = 100\cdot\left(1-\exp\left(-\varepsilon\cdot l\cdot C\right)\right), \text{ \%;} \quad (1.2)$$

$$C_C = \ln\left(1-N/100\right)/\left(\varepsilon\cdot l\right), \text{ g/m}^3; \quad (1.3)$$

$$\varepsilon = 3\cdot d_A^2/\left(2\cdot\rho\cdot d_v^3\right), \text{ m}^2\text{/g;} \quad (1.4)$$

where C_C is PM concentration, g/m^3; $\varepsilon \approx 6{,}82$ m^2/g is specific light transmission coefficient; $\rho \approx 1$ g/m^3 is PM density; $d_A \approx 0{,}1\cdot10^{-6}$ m is PM equivalent projection diameter; $d_v \approx 0{,}13\cdot10^{-6}$ m is PM equivalent volume diameter.

A.C. Alkidas's recalculation formula is presented by formula (1.5) [4], where *BSU* (*BSN*) is EG opacity on Bosch (Bosch Soot Units or Number) scale.

$$C_C = 565\cdot\left(\ln\left(\frac{10}{10-BSU}\right)\right)^{1{,}206}, \text{ mg/m}^3; \quad (1.5)$$

G.G. Muntean's recalculation formula is presented by formula (1.6) [4].

$$C_C = (-184 \cdot BSU - 727{,}5) \cdot \log(1 - BSU/10), \text{ mg/m}^3. \quad (1.6)$$

The analysis of the known indexes of exhaust gases opacity

The EG opacity is most often characterized by the value of light flux attenuation coefficient N (further in this study marked as N_D) [4] is determined by the formulas (1.7) and (1.8), where τ is transmittance coefficient; I and I_0 are light flux through the EG sample released form the light source and obtained at the light receiver, lm. According to the definition, the values N and K are related to each other by the formula [4] (1.9), at L = 0,43 m [4]. The correlation between the EG opacity units of measure by Harritage HSN (Harritage Soot Number) scale and Bosch BSU scale is described by the formula (1.10) [4].

$$N = 100 - \tau, \%; \quad (1.7)$$

$$\tau = I / I_0 \cdot 100, \%; \quad (1.8)$$

$$K = -\ln(1 - N/100)/L, \text{ m}^{-1}. \quad (1.9)$$

$$HSN = -2{,}64 \cdot 10^{-4} \cdot BSU^2 + 0{,}111642\, BSU - 1{,}023 \cdot 10^{-3}. \quad (1.10)$$

The information about correlation between different indicators of opacity if EG is summarized in Fig. 1, where the correlation between the alternative EG opacity indicators and the base indicator by the data from the source [4] is presented.

Dependency graphs in Fig. 1 are described by polynomials by the method of least squares, which coefficients are summarized in Table 1, for the indicator R^2 for those polynomials rates 0,999-1,0, so the polynomials obtained can be used as alternative to the formulas (1.2)-(1.6), (1.10).

Table 1 – Coefficients of the approximating polynomials of the EG opacity indicators dependences of diesel RICE with each other [4]

Coefficient	a_4	$\times 10^x$	a_3	$\times 10^x$	a_2	$\times 10^x$	a_1	$\times 10^x$
	$N_D = f(K)$, a_0 = 0 %, R^2 = 1,0							
un. meas.	%·m^4		%·m^3		%·m^2		%·m	
value	–4,985	–2	9,863	–1	–8,681	0	4,266	1
	$N_D = f(BSU)$, a_0 = 0 %, R^2 = 1,0							
un. meas.	%/BSU^4		%/BSU^3		%/BSU^2		%/BSU	
value	–1,169	–1	1,219	0	–2,471	0	1,082	1
	$N_D = f(C_C)$, a_0 = 0 %, R^2 = 0,999							
un. meas.	%/(mg/m^3)^4		%/(mg/m^3)^3		%/(mg/m^3)^2		%/(mg/m^3)	
value	–1,932	–10	4,381	–7	–4,350	–4	2,773	–1
	$N_D = f(HSN)$, a_0 = 0 %, R^2 = 1,0							
un. meas.	%/HSN^4		%/HSN^3		%/HSN^2		%/HSN	
value	0	0	0	0	0	0	1,0	0
	$K = f(N_D)$, a_0 = 0 1/m, R^2 = 0,999							
un. meas.	1/(m·%^{4})		1/(m·%^{3})		1/(m·%^{2})		1/(m·%)	
value	1,475	–7	–1,731	–5	8,534	–4	1,433	–2
	$BSU = f(N_D)$, a_0 = 0 BSU, R^2 = 0,999							
un. meas.	BSU/%^{4}		BSU/%^{3}		BSU/%^{2}		BSU/%	
value	0	0	7,562	–6	–1,301	–3	1,242	–1
	$C_C = f(N_D)$, a_0 = 0 mg/m^3, R^2 = 0,999							
un. meas.	mg/(m^3·%^{4})		mg/(m·%^{3})		mg/(m^3·%^{2})		mg/(m^3·%^{1})	
value	1,954	–5	–2,351	–3	1,333	–1	2,074	0
	$HSN = f(N_D)$, a_0 = 0 HSN, R^2 = 1,0							
un. meas.	HSN/%^{4}		HSN/%^{3}		HSN/%^{2}		HSN/%	
value	0	0	0	0	0	0	1,0	0

Data contained in table 1 allow us to suggest formulas for describing graphs in Fig. 1 in the form of the 4th degree as a uniform alternative to various formulas (1.2)-(1.6), (1.10), partial derivatives for the formula (1.1) are much easier to obtain.

Conclusions. The analysis of the mathematical apparatuses of known recalculation formulas and the nomenclature of the most widely used EG opacity indicators of RICE has been carried out. Dependences of the values of the EG opacity indicators on each other are described by polynomials by the method of least squares which are much more useful for further computational studies.

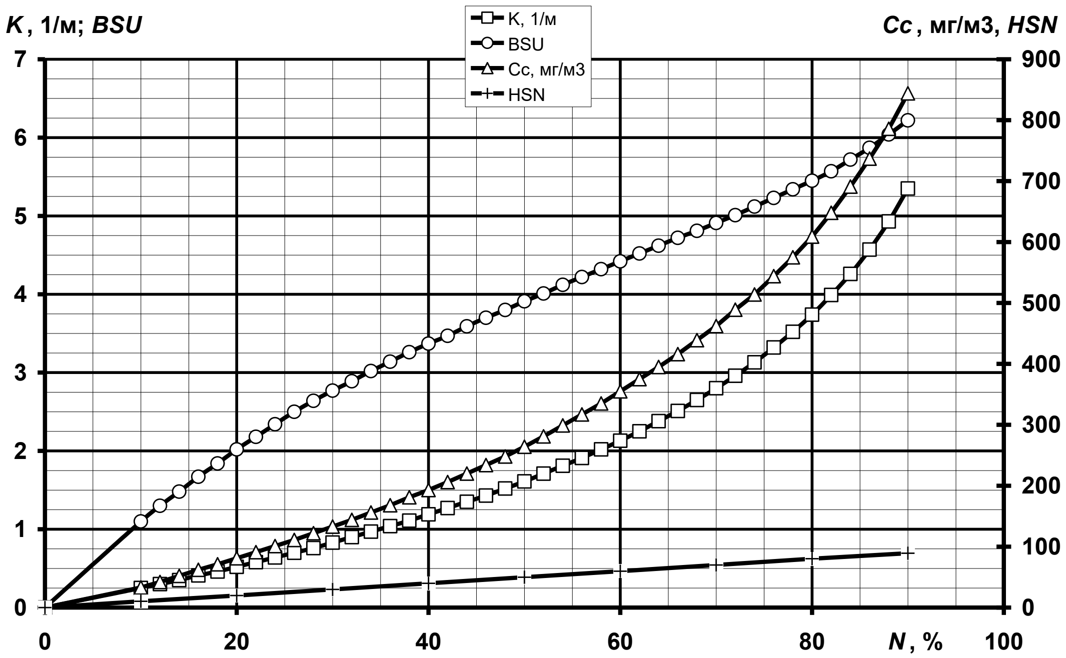

Figure 1 – Correlation between alternative EG opacity indicators of diesel RICE and the base indicator on the data [4]

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