ISSN: 2520-6168 № 3 (134) / 2026 Vol. 134, № 3 / 2026

Техніка, енергетика, транспорт АПК

Technology, energy, agriculture transport AIC

UDC 621.436:665.75
DOI: 10.37128/2520-6168-2026-3-14

CALCULATED ASSESSMENT OF THE EFFECT OF INJECTOR HOLE CLOGGING ON FUEL DELIVERY

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This article examines changes in fuel delivery caused by partial blockage of the nozzle holes of the 171.1112010-50 injector equipped with the 6A1-20c2-50 nozzle for MTZ tractors. The study aims to assess the effect of a reduction in the unobstructed cross-sectional area of nozzle holes on fuel flow rate and to compare uniform and non-uniform clogging. The orifice flow equation and a geometric model of a uniform annular deposit layer are applied. The geometric parameters of the nozzle are taken from the manufacturer's data, while the pressure difference, fuel density, discharge coefficient and deposit thickness are specified as calculation inputs. This approach allows the effect of geometric blockage to be assessed at constant fuel properties, including those of a blend containing biofuel.

For a nozzle with five holes having an initial diameter of 0.32 mm, a uniform deposit layer 2–10 μm thick was found to reduce the unobstructed cross-sectional area of each hole by 2.48–12.11%. At a constant pressure difference, fuel density and discharge coefficient, the volumetric fuel flow rate decreases by the same percentages. At a pressure difference of 40 MPa, a density of 850 kg/m³ and a discharge coefficient of 0.75, the formation of a 10 μm deposit layer reduces the calculated mass of fuel flowing through all holes over 1 ms from 78.65 to 69.12 mg. Three clogging scenarios with a total flow rate equal to 90% of the initial value are compared: 10% area blockage in each hole, 50% in one hole, or 25% in two holes. The coefficients of variation of flow rates between the holes are 0, 22.22 and 13.61%, respectively. For initial diameters of 0.28, 0.32 and 0.36 mm and a deposit thickness of 10 μm, the relative fuel flow rates are 86.22, 87.89 and 89.20% of the flow rate through a clean hole of the corresponding diameter, respectively.

The results show that the same total fuel flow rate can be accompanied by different distributions of flow rates among individual nozzle holes. The practical significance of the findings lies in supporting the joint assessment of total fuel delivery and its uniformity among the jets when diagnosing multi-hole injectors. The effect of changes in the discharge coefficient on the calculation results is assessed: at 10% hole area blockage, varying the ratio of the discharge coefficient to its initial value from 0.90 to 1.10 yields a relative fuel flow rate of 81–99%. The numerical results are obtained using a steady-flow model under the specified conditions.

Keywords: *internal combustion engine; biofuel; biodiesel; fuel system; fuel supply system; petroleum products; fuel flow rate; injector; nozzle; clogging; discharge coefficient.*

Eq. 5. Fig. 3. Tabl. 3. Ref. 11.

1. Statement of the problem

The fuel system supplies fuel to the cylinders of a diesel internal combustion engine. Deposits in the nozzle holes change their unobstructed cross-sectional area and the fuel flow conditions. Assessing the uniformity of fuel delivery by a multi-hole injector requires consideration of both the total flow rate and the flow rates through individual nozzle holes. The same total amount of fuel delivered can be accompanied by different distributions among the jets. Such non-uniformity can impair mixture formation in the diesel engine cylinder even when the total fuel delivery per cycle meets the specified value. This may reduce combustion completeness and increase the engine's specific fuel consumption. Therefore, monitoring total delivery alone does not provide complete information about the uniformity of flow through the nozzle holes.

ANALYTICAL SUBSTANTIATION OF THE INFLUENCE OF PULSATION PARAMETERS AND TEAT LINER CHARACTERISTICS ON MILK FLOW INTENSITY © 2026 by Elchyn ALIIEV, Yevhenii NOSENKO is licensed under CC BY 4.0
Article received 13.07.26 Review completed 21.09.26 Article accepted 28.09.26 Article published 12.10.26

The fuel supply system may deliver blended fuel prepared from petroleum products and biofuel, including biodiesel. When assessing the flow rate, the effects of fuel properties and nozzle geometry must be distinguished. In this study, fuel density is specified as a constant calculation parameter without defining a particular blend composition, while the factor under investigation is the reduction in the unobstructed cross-sectional area of the nozzle holes. This formulation allows changes in the total flow rate to be compared with non-uniformity of fuel flow through individual holes.

2. Analysis of recent research and publications

S. A. Burlaka, O. O. Halushchak and Yu. V. Humeniuk [1] investigated the flow of emulsified fuel with alcohol additives in an injector nozzle. O. O. Halushchak et al. [2] examined the effect of the temperature of blended fuel components on engine operation. These studies highlight the need to specify fuel properties and delivery conditions when comparing calculations. In the present article, these factors are held constant to examine geometric blockage of the holes separately.

J. M. Desantes et al. [3] investigated the discharge coefficient of non-cavitating diesel nozzles and demonstrated its relationship with the flow regime. M. Sheykhvazayefi et al. [4] experimentally examined the effect of coking on spray characteristics. A. Butmarasri et al. [5] studied injector hole deposits, injection parameters and spray development. These studies confirm the need to consider hydrodynamic changes in addition to hole size.

Z. Stępień [6] systematized the factors governing the formation of external and internal deposits in diesel injectors and investigated their effects on diagnostic indicators of injector operation. These results provide a basis for distinguishing the causes of deposit formation from the consequences of nozzle passage blockage. D. P. Zhuravel et al. [7] describe the hydraulic principles of calculating liquid flow through orifices. These relationships form the basis of the fuel flow rate model used in the present study.

A. Birgel et al. [8] reviewed the effects of temperature, fuel composition and nozzle geometry on deposit formation. C. M. McGilvery et al. [9] used electron microscopy to investigate the structure and chemical composition of deposits inside injector passages, revealing their layered structure. These studies support the use of a uniform annular layer as a simplified calculation model; describing actual deposits requires their non-uniformity to be considered.

Source [10] specifies the injector application and the geometric parameters of the nozzle holes. These data are used to select the number of nozzle holes and their initial diameter. E. Alptekin and M. Canakci [11] investigated the density and viscosity of fuel blends. To assess the effect of reduced hole area separately, fuel density and the discharge coefficient are held constant in the calculations for Tables 2 and 3.

3. Purpose of the study

The aim of this study is to assess changes in fuel flow rate through the holes of the 6A1-20c2-50 nozzle of the 171.1112010-50 injector under partial cross-sectional blockage and to compare uniform and non-uniform clogging. To this end, changes in the unobstructed cross-sectional area of the holes are determined, relative fuel flow rates are calculated, and three blockage distributions among five holes are compared.

4. Results and discussion

Input conditions and calculation model.

The calculation considers the mechanical 171.1112010-50 injector equipped with the 6A1-20c2-50 nozzle, intended for the D-240 and D-243 engines of MTZ-80/82 tractors. According to [10], the nozzle has five holes with an initial diameter of 0.32 mm. The remaining input quantities are specified for the calculation (Table 1). The pressure difference of 40 MPa represents the difference between the inlet and outlet pressures of a nozzle hole and is not the injector opening pressure. Steady flow is assumed at constant fuel density, with the passages fully filled with fuel. The baseline calculations for Tables 2 and 3 use $C = C_0 = 0.75$; the effect of changes in the discharge coefficient C is considered separately. The model does not account for needle motion, fuel compressibility, cavitation, pressure fluctuations or heat transfer. The numerical results are obtained analytically. The volumetric flow rates q and Q_Σ represent the volumes of fuel flowing through one hole and through all holes per unit time, respectively. The fuel volume and mass reported below are determined for a 1 ms interval of steady flow, which is not equated to the duration of actual injection. Fuel delivery per cycle denotes the amount of fuel supplied to a cylinder during one operating cycle; it is not determined in this model. The injector is shown in Fig. 1.



Fig. 1. The 171.1112010-50 injector

Table 1

Nozzle parameters and calculation conditions

Parameter	Symbol	Value
Injector model [10]	—	171.1112010-50
Nozzle model [10]	—	6A1-20c2-50
Number of nozzle holes [10]	N	5
Initial hole diameter [10]	d_0	0.32 mm
Pressure difference	Δp	40 MPa
Fuel density	ρ	850 kg/m³
Discharge coefficient in baseline calculations (C = C_0)	C_0	0.75
Steady-flow interval	t	1 ms
Uniform deposit layer thickness	h	0; 2; 4; 6; 8; 10 μm

A density of 850 kg/m³ is specified as a calculation parameter without assigning a particular fuel blend composition or temperature. Density is held constant when comparing the clogging scenarios; the effect of the biofuel fraction is not investigated separately. To calculate the flow rate of a fuel of a different composition, its density at the operating temperature and pressure must be specified and the discharge coefficient refined. Determining the permissible contaminant content in fuel and injector service life is outside the scope of this study. The assumed deposit formation model is shown in Fig. 2.

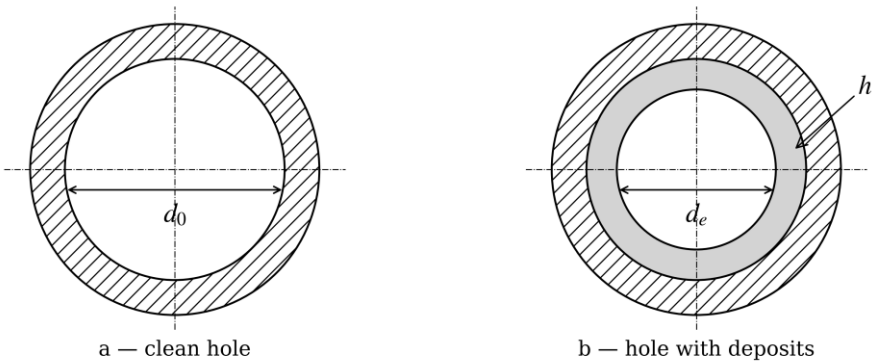


Fig. 2. Calculation model of a hole in the 6A1-20c2-50 nozzle:
d_0 – initial hole diameter; d_e – diameter of the unobstructed cross-section; h – deposit layer thickness

The model assumes that deposits form a uniform annular layer on the inner surface of the nozzle hole. The unobstructed cross-section therefore remains circular. Its diameter d_e and area A_e are determined as follows:

$$d_e = d_0 - 2h; \quad A_e = \frac{\pi d_e^2}{4} \tag{1}$$

where d_e is the diameter of the unobstructed cross-section of the nozzle hole after deposit formation, m; d_0 is the initial hole diameter, m; h is the thickness of the uniform deposit layer, m; A_e is the unobstructed cross-sectional area of the hole, m².

To calculate the area in SI units, the diameters and layer thickness must be entered in metres; the condition $0 \le h < d_0/2$ must be satisfied. With a non-uniform deposit distribution, the actual shape of the unobstructed cross-section may be non-circular. In this case, calculating the flow rate requires the unobstructed cross-sectional area and the discharge coefficient to be determined with allowance for the passage shape.

The blocked area fraction s and the volumetric flow rate q through one hole are expressed using the orifice flow equation [7]:

$$s = 1 - \frac{A_e}{A_0}; \quad q = CA_e\sqrt{\frac{2\Delta p}{\rho}} \tag{2}$$

where s is the fraction of the initial nozzle hole area that is blocked, dimensionless; A_e is the unobstructed cross-sectional area of the hole after deposit formation, m²; A_0 is the initial cross-sectional area of the clean hole, m²; q is the volumetric fuel flow rate through one hole, m³/s; C is the discharge coefficient, dimensionless; Δp is the pressure difference between the inlet and outlet of the nozzle hole, Pa; ρ is the fuel density, kg/m³.

The initial cross-sectional area is determined as $A_0 = \pi d_0^2/4$. A blockage of s = 0.10 denotes a 10% reduction in the unobstructed cross-sectional area relative to the initial area, rather than a 10% reduction in diameter. The coefficient C accounts for the deviation of actual flow from ideal flow [3].

With the same pressure difference across the nozzle hole and the same fuel density before and after deposit formation, the relative volumetric flow rate is determined as follows:

$$\frac{q}{q_0} = \frac{C}{C_0}(1 - s); \quad \frac{q}{q_0} = \left(1 - \frac{2h}{d_0}\right)^2 \ for\ C = C_0 \tag{3}$$

where q is the volumetric fuel flow rate through the hole with deposits, m³/s; q_0 is the volumetric fuel flow rate through the clean hole at the same pressure difference and fuel density, m³/s; C and C_0 are the discharge coefficients of the hole with deposits and the clean hole, respectively, dimensionless; s is the fraction of the initial hole area that is blocked, dimensionless; h is the thickness of the uniform deposit layer, m; d_0 is the initial hole diameter, m.

Thus, at a constant discharge coefficient, the relative reduction in volumetric fuel flow rate equals the relative reduction in the unobstructed cross-sectional area. The results in Tables 2 and 3 are obtained under this condition. The volume and mass of delivered fuel are determined for a specified steady-flow interval; these quantities do not account for the transient phases of actual injection.

Effect of deposit thickness on fuel delivery.

For a clean nozzle hole under the input conditions in Table 1, the volumetric fuel flow rate is $q_0 = 1.8505 \cdot 10^{-5}$ m³/s. The volume of fuel flowing through five nozzle holes over 1 ms is 92.52 mm³, and the corresponding mass is 78.65 mg. Table 2 presents the results for an equal deposit layer thickness in all holes. The fuel mass over the specified interval is determined as the product of the total volumetric flow rate, fuel density and flow duration.

Table 2

Fuel flow rate and delivered mass for an equal deposit thickness in all five holes

Thickness h, μm	Diameter d_e, mm	Hole area blockage, %	Relative fuel flow rate, %	Fuel mass over 1 ms, mg
0	0.320	0.00	100.00	78.65
2	0.316	2.48	97.52	76.69
4	0.312	4.94	95.06	74.76
6	0.308	7.36	92.64	72.86
8	0.304	9.75	90.25	70.98
10	0.300	12.11	87.89	69.12

The formation of a 2 μm deposit layer reduces the diameter of the unobstructed cross-section from 0.320 to 0.316 mm, and reduces its area and the volumetric fuel flow rate by 2.48%. At a layer thickness of 10 μm, the unobstructed diameter is 0.300 mm, and the fuel flow rate is 87.89% of that through a clean hole. The mass of fuel flowing through all five holes over 1 ms is 69.12 mg. The decrease in this mass relative to a nozzle without deposits is approximately 9.52 mg when calculated without intermediate rounding.

Additional calculations are performed for d_0 = 0.28, 0.32 and 0.36 mm to assess the effect of the initial nozzle hole diameter. The diameter of 0.32 mm corresponds to the selected nozzle, while 0.28 and 0.36 mm are used to compare the sensitivity of the flow rate to an equal deposit thickness. According to Eq. (3), when h = 10 μm and $C = C_0$, the fuel flow rates are 86.22, 87.89 and 89.20% of the flow rate through a clean hole of

the corresponding diameter, respectively. The dependence on deposit layer thickness is quadratic. For the same layer thickness, the relative reduction in unobstructed cross-sectional area and fuel flow rate is greater for a hole with a smaller initial diameter.

For an initial hole diameter d_0 = 0.32 mm and a constant discharge coefficient, a calculated 10% reduction in volumetric fuel flow rate corresponds to a uniform deposit layer thickness h = 8.21 μm. This value is obtained from Eq. (3) for q/q_0 = 0.90. It characterizes the assumed calculation conditions and does not establish an injector rejection criterion. Assessing a particular nozzle requires consideration of the actual deposit shape and discharge coefficient.

Uniform and non-uniform clogging.

To compare clogging distributions, equal initial diameters are assumed for all nozzle holes, together with the same fuel density and pressure difference. The total volumetric flow rate Q_Σ and its ratio to the initial total flow rate Nq_0 are determined as follows:

$$Q_\Sigma = \sum_{i=1}^{N} q_i; \quad \frac{Q_\Sigma}{Nq_0} = 1 - \frac{1}{N}\sum_{i=1}^{N} s_i \tag{4}$$

where Q_Σ is the total volumetric fuel flow rate through all nozzle holes, m³/s; q_i is the volumetric fuel flow rate through the i-th hole, m³/s; N is the number of nozzle holes, dimensionless; i is the hole index, from 1 to N; q_0 is the initial volumetric flow rate through one clean hole, m³/s; s_i is the fraction of the initial area of the i-th hole that is blocked, dimensionless.

The second relationship in Eq. (4) is valid when the discharge coefficient is the same for all holes and equals its initial value C_0. Under this condition, the total fuel flow rate depends on the sum of the blocked area fractions, but does not determine the distribution of flow rates among individual holes.

Non-uniformity of fuel flow rates among the nozzle holes is assessed using the coefficient of variation K_q, defined as the standard deviation of the flow rates through individual holes divided by their mean value and expressed as a percentage:

$$K_q = \frac{100\,\%}{\bar{q}} \sqrt{\frac{1}{N}\sum_{i=1}^{N}(q_i - \bar{q})^2} \tag{5}$$

where K_q is the coefficient of variation of volumetric fuel flow rates among the nozzle holes, expressed as a percentage; $\bar{q}$ is the mean volumetric fuel flow rate through one hole, m³/s; q_i is the volumetric fuel flow rate through the i-th hole, m³/s; N is the total number of nozzle holes, dimensionless; i is the hole index, from 1 to N.

The mean volumetric flow rate through one hole is $\bar{q} = Q_\Sigma/N$. The denominator of the expression under the square root uses the total number of nozzle holes N because the flow rate through every hole is included in the assessment of non-uniformity. The coefficient K_q is a dimensionless quantity expressed as a percentage. It characterizes differences in flow rates among holes, rather than measurement error or variability between repeated injections. When all holes have the same flow rate, K_q = 0.

Table 3

Distribution of hole area blockage and flow rate non-uniformity at the same total fuel flow rate

Scenario	Specified hole area blockage	Relative total flow rate, %	Coefficient of variation K_q, %
A	All 5 holes: 10% each	90.00	0.00
B	1 hole: 50%; others: 0%	90.00	22.22
C	2 holes: 25% each; others: 0%	90.00	13.61

In all three scenarios, the sum of the blocked area fractions s_i is 0.5, so the total fuel flow rate is 90% of its initial value. In Scenario A, the flow rate through each of the five holes is 90% of that through a clean hole. In Scenario B, the flow rate through one hole is 50% of the initial value, while the other four holes each retain 100%. In Scenario C, the flow rate through two holes is 75% each, while the other three holes each retain 100% (Fig. 3).

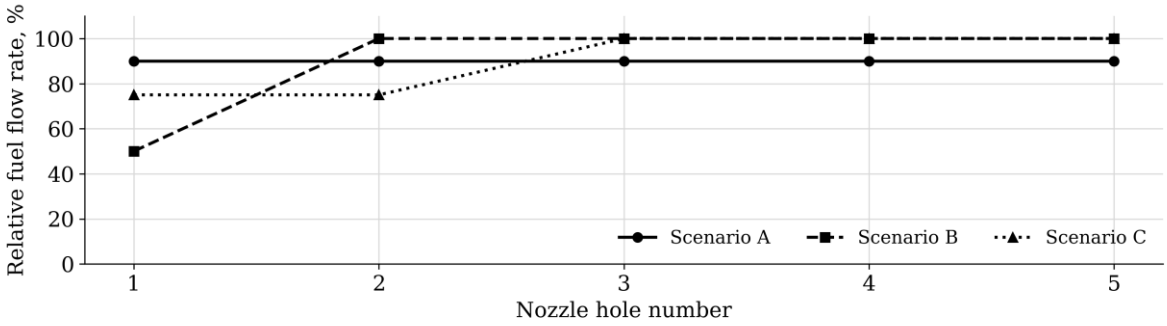


Fig. 3. Calculated distribution of relative fuel flow rates among nozzle holes for Scenarios A, B and C in Table 3

The coefficients of variation of fuel flow rates among the holes for Scenarios A, B and C are 0, 22.22 and 13.61%, respectively. Thus, the same 10% reduction in total fuel flow rate can be accompanied by different degrees of flow rate non-uniformity among the holes. The practical significance of this comparison lies in supporting the joint assessment of total fuel delivery and its distribution among the jets when diagnosing an injector. Experimental determination of this non-uniformity requires a method for separately assessing the amount of fuel in each jet.

Sensitivity to the discharge coefficient and scope of application.

To assess the effect of the discharge coefficient at a blocked area fraction s = 0.10, the ratios $C/C_0 = 0.90$, 1.00 and 1.10 are considered. According to Eq. (3), the corresponding volumetric fuel flow rates are 81, 90 and 99% of the initial flow rate through a clean hole. These scenarios illustrate the consequences of a decrease, no change and an increase in the discharge coefficient, but do not determine how it actually changes as deposits form. Therefore, assessing the flow rate solely from the unobstructed cross-sectional area requires justification of the assumed C value. For a particular nozzle, the discharge coefficient must be refined using the relationship between fuel flow rate and pressure difference at a known fuel density.

The model describes the effect of geometric blockage of nozzle holes on fuel flow rate under steady-flow conditions. It does not establish a relationship between deposit thickness, injector operating time and fuel contaminant content. Quantitative assessment of spray angle, droplet size, in-service fuel consumption, engine power and emissions requires additional measurements or models of the corresponding processes.

5. Conclusions

At a constant pressure difference between the inlet and outlet of a nozzle hole, fuel density and discharge coefficient, the ratio of the volumetric fuel flow rate through a hole with deposits to that through a clean hole equals the ratio of the corresponding unobstructed cross-sectional areas. For a uniform annular deposit layer, this ratio is $(1 - 2h/d_0)^2$, where h is the deposit layer thickness and d_0 is the initial nozzle hole diameter. The resulting relationship makes it possible to determine the relative reduction in flow rate for specified geometric parameters of the hole and deposits.

For the 6A1-20c2-50 nozzle of the 171.1112010-50 injector, which has five nozzle holes with an initial diameter of 0.32 mm, the formation of a uniform 10 μm deposit layer in each hole reduces the calculated total fuel flow rate by 12.11%. At a pressure difference of 40 MPa, a fuel density of 850 kg/m³ and a discharge coefficient of 0.75, the mass of fuel flowing through all holes during 1 ms of steady flow decreases from 78.65 to 69.12 mg.

At a total fuel flow rate equal to 90% of the initial value, different clogging distributions among five nozzle holes produce different degrees of flow non-uniformity. Area blockage of 10% in each hole, 50% in one hole or 25% in two holes corresponds to coefficients of variation of 0, 22.22 and 13.61%, respectively. The coefficient of variation is a dimensionless indicator expressed as a percentage. The results support the assessment of fuel distribution among individual jets alongside monitoring of total delivery when diagnosing multi-hole injectors.

At a blockage of 10% of the initial nozzle hole area, varying the ratio of the discharge coefficient of the fouled hole to its initial value from 0.90 to 1.10 changes the relative volumetric fuel flow rate from 81 to 99% of the initial flow rate through a clean hole. Therefore, applying the model to a particular nozzle requires refinement of the discharge coefficient using its flow characteristic. The results characterize steady flow and require verification under actual injection conditions.

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РОЗРАХУНКОВА ОЦІНКА ВПЛИВУ ЗАСМІЧЕННЯ ОТВОРІВ ФОРСУНКИ НА ПОДАЧУ ПАЛИВА

У статті розглянуто зміну подавання палива внаслідок часткового перекриття соплових отворів форсунки 171.1112010-50 із розпилювачем 6А1-20с2-50 для тракторів МТЗ. Мета дослідження – оцінити вплив зменшення площі вільного перерізу соплових отворів на витрату палива та порівняти рівномірне й нерівномірне засмічення. Застосовано рівняння витікання рідини через отвір і геометричну модель рівномірного кільцевого шару відкладень. Геометричні параметри розпилювача прийнято за даними виробника, а перепад тиску, густину палива, коефіцієнт витрати та товщину відкладень задано як вихідні умови розрахунку. Підхід дає змогу оцінити вплив геометричного перекриття отворів за незмінних властивостей палива, зокрема суміші, до складу якої входить біопаливо.

Для розпилювача з п'ятьма сопловими отворами початковим діаметром 0,32 мм установлено, що рівномірний шар відкладень завтовшки 2–10 мкм зменшує площу вільного перерізу кожного отвору на 2,48–12,11 %. За незмінних перепаду тиску, густини палива та коефіцієнта витрати об'ємна витрата палива зменшується на такі самі значення у відсотках. За перепаду тиску 40 МПа, густини 850 кг/м³ і коефіцієнта витрати 0,75 утворення шару відкладень завтовшки 10 мкм зменшує розрахункову масу палива, що витікає через усі отвори протягом 1 мс, з 78,65 до 69,12 мг. Зіставлено три варіанти засмічення, для яких сумарна витрата становить 90 % початкової: перекриття площі

кожного отвору на 10 %, одного отвору на 50 % або двох отворів на 25 %. Коефіцієнт варіації витрат між отворами становить відповідно 0; 22,22 та 13,61 %. За початкових діаметрів 0,28; 0,32 та 0,36 мм і товщини відкладень 10 мкм відносна витрата палива дорівнює відповідно 86,22; 87,89 та 89,20 % від витрати через чистий отвір відповідного діаметра.

Показано, що однакова сумарна витрата палива може супроводжуватися різним розподілом витрат між окремими сопловими отворами. Практичне значення результатів полягає в обґрунтуванні спільного оцінювання сумарного подавання палива та його рівномірності між струменями під час діагностування багатоотворових форсунок. Оцінено вплив зміни коефіцієнта витрати на результати розрахунку: за перекриття 10 % площі отвору зміна відношення коефіцієнта витрати до початкового значення від 0,90 до 1,10 відповідає відносній витраті палива від 81 до 99 %. Числові результати отримано для моделі усталеного витікання за заданих умов.

Ключові слова: *двигун внутрішнього згорання; біопаливо; біодизель; паливна система; система живлення; нафтопродукти; витрата палива; форсунка; розпилювач; засмічення; коефіцієнт витрати.*

Ф. 5. Рис. 3. Табл. 3. Літ. 11.

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