Diesel operation efficiency improvement based on modelling of fuel carburetion process

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Summary. Modeling of the droplet motion kinetics in the cylinder of the engine from the moment of the fuel injection rate to its falling on the parts of the cylinder-piston group taking into account the peculiarities of the temperature influences and acquired kinetic energy for finding out the influence of the carburetion conditions on the operational features of the engine in relation to the geometric characteristics of the cylinder-piston group is considered.
Key words: diesel, structure, fuel, drop, carburetion.

INTRODUCTION

The investigation performed within the scope of this work deals with the improving of carburetion and air-fuel mixture combustion processes and allows making conclusions on the occurence of several contradictions concerning the description of intra-cylinder processes [1,5,12,15,17,18]. Certain physical and chemical processes, which are, in our opinion, significant, are not accounted for taking into consideration their unconditional complexity and multiple-factor character in the known developments of theoretical models. Thereupon, these approaches result in certain discrepancies between theory and practice.

This discrepancy can be seen in a multi-zone model of internal combustion engine operation [7,9] which is based on the equation systems set up by the law of conservation of energy and mass as well as Clapeyron-Mendeleev equation:

$$\frac{d(mu)}{d\tau}=\frac{dQ_x}{d\tau}-\frac{dQ_w}{d\tau}-P_c\frac{dV_z}{d\tau}+h_{vp}\frac{dm_{vp}}{d\tau}-h_{vyp}\frac{dm_{vyp}}{d\tau}, \quad (1)$$

$$\frac{dm}{d\tau}=\frac{dm_{vp}}{d\tau}-\frac{dm_{vyp}}{d\tau}, \quad (2)$$

$$\frac{dP_c}{d\tau}=\frac{mR}{V_z}\frac{dT_z}{d\tau}+\frac{mT_z}{V_z}\frac{dR}{d\tau}+\frac{RT_z}{V_z}\frac{dm}{d\tau}-\frac{RT_z m}{V_z^2}\frac{dV_z}{d\tau}, \quad (3)$$

where:

m - total mass of the working substance (air-fuel – combustion products) in the zone kg,

u - work performed by the working substance J/kg,

Q_x - energy received from the fuel combustion J,

Q_w - energy consumed for evaporating the droplet and heating the working substance J,

P_c - pressure in the cylinder of the engine Pa,

V_z - volume of the zone at the instant time τ m3,

h_{vp} - enthalpy of the working substance coming into the zone J/kg,

m_{vp} - mass of the working substance coming into the zone kg,

h_{vyp} - enthalpy of the working substance leaving the zone J/kg,

m_{vyp} - mass of the working substance leaving the zone kg,

R - gas constant of the working substance J/(kgK),

T_z - tempera of the zone K.

This model accounts little for the kinetics of the mass change of the fuel coming into the cylinder of the engine. The specification of the injected fuel ratio for each zone is required to solve the system. And further, a priori, there is an assumption that the carburetion meets the requirements of the volumetric process, that is the heat transfer is effected from the air charge in the combustion chamber on the micro-particles of the fuel evenly sprayed throughout it.

The specified conditions do not conform to the results concerning the formation of the air-fuel mixture received by the known researchers like N.F. Razleitsev [19], B.I. Sreznevskiy [22], A.S. Lyshevksiy [13], Kitamura T. [8] and others.

The work, thereby, sets a task to determine the kinetics of the droplet motion in the cylinder of the engine from the moment of the fuel injection to the moment of its falling on the parts of the cylinder-piston group taking into consideration thermal effect and gained kinetic energy. The consideration of such task is thought actual as it allows defining the level of influence of carburetion conditions on the operational characteristics of the engine depending on the geometrical features of the cylinder-piston group.

We find it possible to consider several variants of distributing the fuel in the cylinder taking into account a great amount of the components contained in the low-volatility fuel [3, 10, 21]. The droplets of the fuel evaporate partially not reaching the piston or the cylinder walls and thus provide carburetion, at the same time, the heavy fractions (asphaltens, paraphines) do not evaporate and reach the surface of the piston and the cylinder absorbing the heat not only from gases but from the combustion chamber as well and only then they evaporate providing film carburetion. The process of their thermal decomposition is undoubtedly observed as well.

The processes of carburetion and, further, the processes of combustion in the cylinder of the engine are influenced by structural features of the injector and its location, diameter of the orifices of the atomizer, dimensions, physical and chemical properties of the material of the cylinder-piston group as well as operational parameters of the engine: pressure of the fuel injection, temperature of the fuel, pressure of the boost, temperature and humidity of the air, fractional composition of the fuel, temperature of the cooling liquid and oil, engine load. The fuel injection advance angle and valve timing appear essential.

When the fuel jet moves, the air flow appears and it is caught by the fuel jet, the speed of the jet reduces due to the friction as the air medium resists the movement. Vortices appear on the surface of the jet, they are the main means of air retract and provision of the jet aeration. It results in the expansion of the fuel jet surface, the lateral section increases and its moving mass flow grows. Thus, the fuel jet expansion angle depends on air density, fuel viscosity, diameter of the nozzle orifice, speed of the fuel discharge, the shape of the nozzle and cleanness of its inner side and can be considered by the scheme represented on Fig.1.

The influence of the main structural and operational parameters on the fuel jet expansion angle is, in our opinion, to the fullest extent possible described in the following works [6, 13, 14, 23]. The expression is recommended for calculating the fuel jet expansion angle based on the analysis of the investigations:

$$tg\beta = C_{\text{ras}} \, \text{Re}_{\text{ras}}^{\;0,5} \, Fr^{0,125} \left(\frac{\rho_{\text{v}}}{\rho_k} \right), \tag{4}$$

where:

β - the fuel jet expansion angle, degrees,

C_{ras} - dimensionless coefficient characterizing the shape, dimensions and surface finish of the atomizer as well as the initial or the main segment of the jet,

$\text{Re}_{\text{ras}} = \dfrac{d_c v_{\text{n}} \rho_{\text{k}}}{\mu_{\text{k}}}$ - Reynolds number,

d_c - diameter of the nozzle orifice m;

v_{n} - initial speed of the jet m/s,

ρ_k - fuel density kg/m^3,

μ_k - coefficient of the dynamic fuel viscosity Pa·s,

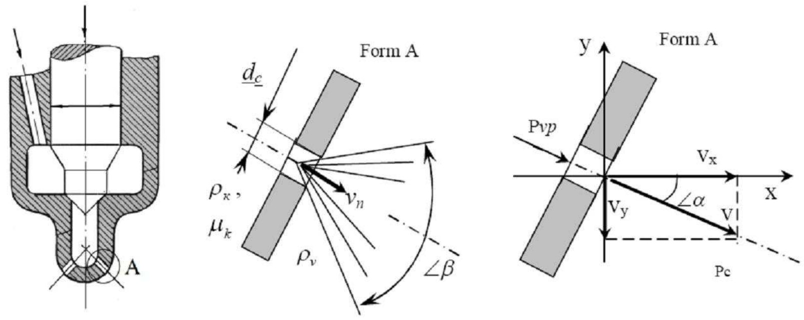
$Fr = \dfrac{v_{\text{n}}^2}{g d_c}$ - Froude number,

ρ_{v} - air density kg/m^3,

g - acceleration of gravity m/s^2.

The initial speed of the jet through the nozzle of the atomizer can be expressed the following way [2]:

$$v_{\text{n}} = \varphi \sqrt{\frac{2(P_{\text{vp}} - P_c)}{\rho_k}} \,. \tag{5}$$



a b c

Fig.1. The scheme of normal atomizer construction and fuel discharge: a – general arrangement of the normal atomizer, b – the scheme for calculating the jet expansion angle, c – the scheme for calculating the speed of the jet

Providing that ρ_k=const and after differentiating the equation (5) we get the following:

$$\frac{dv_n}{d\tau_{\mathrm{vp}}} = \varphi\sqrt{\frac{1}{2\rho_k}}\left(A\cdot\frac{dP_{\mathrm{vp}}}{d\tau_{\mathrm{vp}}} - A\cdot\frac{dP_c}{d\tau_{\mathrm{vp}}}\right), \quad (6)$$

where:

τ_{vp} - time since the beginning of the fuel injection s,

φ - dimensionless coefficient of discharge through the atomizer depending on the shape of the orifice:

$$A = \frac{1}{\sqrt{(P_{\mathrm{vp}} - P_c)}};$$

P_{vp} - pressure of the injection in the inner chamber of the atomizer MPa,

P_c - pressure in the engine cylinder MPa.

The speed of the droplet depending on the direction of the fuel jet (fig. 1-c) equals:

$$v = \sqrt{v_x^{\ 2} + v_y^{\ 2}}, \quad (7)$$

where:

v - the speed of the droplet motion m/s,

v_x, v_y - velocity vectors along the axis m/s.

Taking into consideration that the motion equation accounting the resistance of the medium equals:

$$v_x = v_n\sin\alpha + (g - \frac{kv_x^{\ 2}}{2})\tau,\ v_y = v_n\cos\alpha - \frac{kv_y^{\ 2}}{2}\tau, \quad (8)$$

where:

α - the deviation angle of the jet direction relative to the horizontal plane degrees:

$k = \frac{C\rho_{\mathrm{v}}F_{\mathrm{k}}}{m_{\mathrm{k}}}$ - generalized coefficient of the medium resistance m^{-1},

F_{k} - frontal area of the droplet m^2,

m_{k} - mass of the droplet kg,

C – dimensionless aerodynamic resistance coefficient,

τ - motion time s.

The aerodynamic resistance coefficient is usually taken for a spherical droplet which simplifies the calculation greatly. The dependence of determining the aerodynamic resistance coefficient is the following [16]:

$$C = \frac{24}{\mathrm{Re}} + \frac{3{,}6}{\mathrm{Re}^{0{,}317}} \text{ where } \mathrm{Re} = 0\ldots700, \quad (9)$$

$$C = 0{,}46 \text{ where } \mathrm{Re} > 700, \quad (10)$$

where:

$\mathrm{Re} = \frac{d_k v\rho_{\mathrm{v}}}{\mu_{\mathrm{v}}}$ - Reynolds number,

d_k - diameter of the droplet m,

μ_{v} - coefficient of the air dynamic viscosity Pa·s.

Considering that such assumption to some extent does not correspond to the physical representation of the process as, when flying (especially at high velocity rates), the droplet deforms and deviates from the spherical form considerably [11], we defined the aerodynamic resistance taking into account the shape coefficient k_{dn}:

$$\mathrm{k_{dn}} = \frac{d_{\mathrm{ek}}^2}{d_k^2}, \quad (11)$$

where:

d_{ek} - volumetric diameter of the droplet m,

d_k - mean diameter of the droplet of the current discharge velocity m.

According to the results of research [4]:

$$d_k = d_c 2{,}88 Lp^{-0{,}0733} We^{-0{,}24} \left(\frac{0{,}25}{d_c} \right)^{0{,}7}, \quad (12)$$

where:

$Lp = \frac{\sigma_k \rho_k d_c}{\mu_k^2}$ - Laplace number,

σ_k - coefficient of the superficial tension of the droplet kg/s^2,

$We = \frac{v^2 \rho_k d_c}{\sigma_k}$ - Weber number.

$$d_{\text{ek}} = 1{,}96 We^{-0{,}04} d_k \,. \quad (13)$$

After converting the expression (8) into the root equation we get:

$$v_x = \frac{-1 + \sqrt{1 + 2k\tau(v_n \sin\alpha + g\tau)}}{k\tau}, \quad (14)$$

$$v_y = \frac{-1 + \sqrt{1 + 2k\tau v_n \cos\alpha}}{k\tau}. \quad (15)$$

We have the equation of jet flow velocity change after substituting (14-15) into (7) and differentiating:

$$\frac{dv}{d\tau} = \frac{\frac{(-1+B)(2kv_n\cos\alpha + 2\tau v_n \cos\alpha \frac{dk}{d\tau})}{B}}{2k\tau\sqrt{(-1+B)^2 + (-1+G)^2}} + \frac{\frac{(2kg\tau + 2k(H))(-1+G)}{G}}{2k\tau\sqrt{(-1+B)^2 + (-1+G)^2}} - \frac{\sqrt{(-1+B)^2 + (-1+G)^2}}{\tau^2 k} - \frac{\sqrt{(-1+B)^2 + (-1+G)^2}}{\tau k^2} \frac{dk}{d\tau} \quad (16)$$

where: $B = \sqrt{1 + 2k\tau v_n \cos\alpha}$,

$G = \sqrt{1 + 2k\tau(v_n \sin\alpha + g\tau)}$,

$H = g\tau + v_n \sin\alpha + 2\tau \, dk(J)$,

$J = 10\tau + v_n \sin\alpha$.

Define the limits of the drop motion along the axis:

$$\int_{\tau_{\text{vp}}}^{\tau_k} v_x d\tau \le R_k \,, \quad (17)$$

where:

R_k - horizontal distance from the atomizer to the walls of the cylinder.

$$\int_{\tau_{\text{п vp}}}^{\tau} v_y d\tau \le \frac{\int_{\tau_{\text{п vp}}}^{\tau} dV}{\pi R^2} \quad \text{where } \tau \le \tau_{\text{vmt}}, \quad (18)$$

where:

$\tau_{\text{п vp}}$ - time of the start of the injection s,

V - volume of the cylinder involved in the process m^3,

R - radius of the cylinder m,

τ_{vmt} - time when the piston reaches the top dead center C.

$$\int_{\tau_{\text{vmt}}}^{\tau} v_y d\tau \le \frac{\int_{\tau_{\text{vmt}}}^{\tau} dV}{\pi R^2} \quad \text{where } \tau > \tau_{\text{vmt}}. \quad (19)$$

The conditions of carburetion process character are defined. If condition (11) as well as (12) or (13) are met, then we observe the volumetric carburetion, if the conditions are not met, we observe film carburetion.

When the droplet flies, it is effected by the processes of heat and mass transfer, evaporation mostly. Research of the evaporation of separate droplets of the combustible fluid in the flow was conducted experimentally by B. I. Sreznevskiy [22] and theoretically by D. S. Maxwell [14]. That is why we can use the dependence shown in [20] for determining the volumetric flow rate of the liquid droplet evaporation:

$$\frac{dV_k}{d\tau} = \frac{1}{K_{\text{vap}} 4\sqrt{\pi}} \sqrt{F_k^n - \frac{\tau}{K_{\text{vap}}}}, \quad (20)$$

where:

V_k - volume of the droplet evaporated m^3,

F_k^n - area of the fuel droplet surface m^2,

K_{vap} - evaporation constant of the fuel s/m^2.

The influence of the temperature and air velocity on the evaporation constant of the diesel oil (fig. 2-a) and heavy fuel oil M40 (fig. 2-b) was investigated experimentally by the authors of the works [20]. Grounding on these research we determined the empirical dependences of calculating the evaporation constant for the temperature limits in the combustion chamber for diesel oil (21) and heavy fuel oil M40 (22):

$$\frac{1}{K_{vap.}^{d.}} = 0{,}115v + 0{,}0032T_{\text{v}} - 1{,}2926,$$

$$550\text{ K} \le T_{\text{v}} \le 2000\text{ K}, \quad (21)$$

$$\frac{1}{K^{f.o.}_{vap.}} = 0{,}163v + 0{,}0028T_{\text{v}} - 1{,}763\,,$$

$$650\ \text{K} \le T_{\text{v}} \le 2000\ \text{K}, \tag{22}$$

where:

$K^{d.}_{vap.}$ - evaporation constant of the diesel oil c/m^2,

$K^{f.o.}_{vap.}$ -evaporation constant of the heavy fuel oil c/m^2,

T_{v} - air temperature, K.

It should be noted that the empirical coefficient before the variables in the expression (21) have dimensions: for 0,115 - [*m*]; 0,0032 - m^2/(*cK*)]; 1,2926 - [*m*^{2}/*s*], the same dimensions are in the dependence (22) as well.

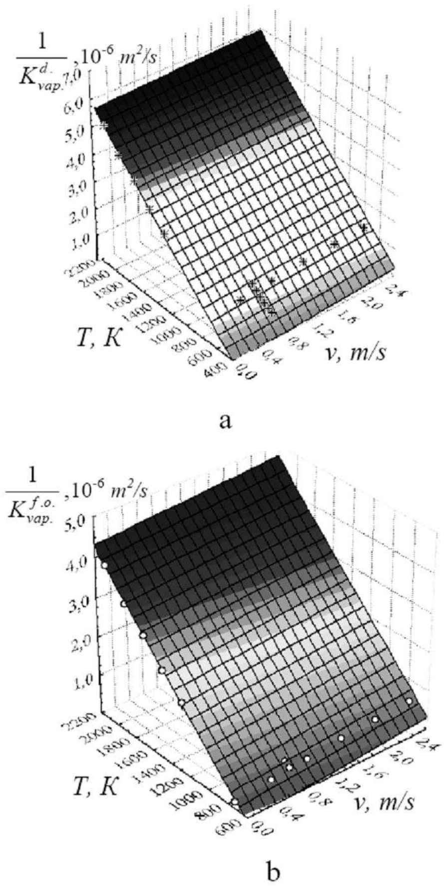


Fig. 2. The influence of the air temperature and velocity on the evaporation constant: a – of diesel oil (∗ - experimental data); b – heavy fuel oil M40 (○ -experimental data

Thus, the change of the droplet diameter in the motion process is defined from the expression:

$$\frac{d(d_{ek})}{d\tau} = 2\frac{\sqrt[3]{\dfrac{3dV_k}{4\pi}}}{d\tau}\,. \tag{23}$$

CONCLUSIONS

Grounding on the research performed it can be said that calculating of the volumetric flow rate of the fuel drop evaporation can be done by the expression (20) at the same time taking into account the change of its diameter by the expression (23) and the change in the drop motion velocity by the expression (16).

Using the simple comparison it is easy to see that in the expressions (1-3) the mass of the working substance can be defined with accounting for the dynamics of temperature influences, acquired kinetic energy and the character of carburetion processes.

The approaches on calculation the kinetics of the droplet shown in the present work permit to detail the methods of calculation of the operating processes in diesel engines taking into account structural and operational factors.

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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ РАБОТЫ ДИЗЕЛЯ НА ОСНОВАНИИ МОДЕЛИРОВАНИЯ ПРОЦЕССА СМЕСЕОБРАЗОВАНИЯ ТОПЛИВА

Иван Берестовой, Галина Айнагоз,
Михаил Берестовой

Аннотация. Рассматривается моделирование кинетики движения капли в цилиндре двигателя, от момента впрыска цикловой подачи топлива до ее падения на детали цилиндропоршневой группы, с учетом особенностей температурных воздействий и приобретенной кинетической энергии с целью влияния условий смесеобразования на технико-эксплуатационные характеристики работы двигателя в зависимости от геометрических характеристик цилиндропоршневой группы.

Ключевые слова: дизель, топливо, смесеобразование, капля, конструкция.