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Formation and impact of soil particles on flame radiation in the cylinder of diesel while working on gas-motor fuel

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Abstract. The article deals with the formation of soot particles in the cylinder of a high-speed diesel engine with turbocharging when operating on gas engine fuel (compressed natural gas). It is shown that the main source of data on the processes occurring in the engine cylinder is the indicator diagram. But the data obtained with its help is often not enough to answer a number of questions regarding the characteristics of the course of intra-cylinder processes. As an example, one can cite the problem of studying the formation of harmful substances in an engine cylinder during fuel combustion, such as soot (C), the mechanism of the chemical kinetics of the formation of which has not yet been explicitly solved. The article presents the spectral effective cross-sections of the absorption of soot particles, depending on the optical properties and dispersion, spectral and integral absorption coefficients of soot particles, depending on the angle of rotation of the crankshaft.

1. Introduction

The intensity of combustion of fuel, which determines the nature and dynamics of heat release, depends on the physical and chemical processes occurring in the reaction zone. And the conditions in which these reactions occur, especially in engines with internal mixture formation, undoubtedly have a pronounced dependence on the location of the local volume of the combustion chamber in question.

Another interesting, important, but little studied process, is the process of radiative heat transfer in the combustion chamber of a diesel engine. The complexity of studying this phenomenon is due to the presence in the combustion chamber of the diesel engine of a large number of soot particles of different shapes and sizes, whose emissivity significantly exceeds the emissivity of gases, and the processes of formation and, accordingly, burnout of these particles have a clearly expressed local character. And to calculate the processes of formation and burning out of soot, relying solely on the indicator diagram can only be in the first approximation.

For the combustion chambers of diesel engines in calculating radiation heat transfer, it is necessary to take into account a list of the features of the working process associated with the cyclicity and instability of the working process, and with the geometrical parameters of the combustion chamber and the fuel flare. Depending on the intensity of the turbulence of the air charge in the combustion chamber and the parameters of the top jet spray injected by the injector, a volume of gases containing soot particles is formed. The presence of a certain duration of fuel supply, the different sizes of droplets in the torch, the set of accidental spontaneous ignition points, the turbulence of the air charge in the cylinder as a result of the movement of the piston and burning of the fuel, the varying volume of the cylinder, the continuously changing amount of soot particles and their dimensions practically reduce zero possibility of direct calculation of the amount of soot particles in the local volume and

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their dimensions, which is required for calculations of radiative heat transfer in the combustion chamber.

The processes of injection and spraying of fuel have been studied in sufficient detail. Knowing the fuel supply law, the injection pressure, the diameter of the spray holes, the physical and chemical properties of the fuel, the conditions in the combustion chamber can be determined with sufficient accuracy for further calculations to determine the size, shape and process of the fuel-air jet development. It is common knowledge that the main part of the combustion and heat release process is completed in 50...60o r.c. after TDC. It is during this period that the main amount of fuel burns in the volume of the combustion chamber when the piston is near TDC, the pressure and temperature of the gases in the engine cylinder reach the maximum values, as well as the concentration of soot particles. This, in turn, leads to the fact that the emissivity of the flame is high.

2. Experimental

A feature of the processes of formation and burnup of soot particles in the cylinder of the engine with internal mixture formation is a significant heterogeneity in the composition of the fuel-air mixture in the combustion chamber and its large temperature unevenness. That is, the processes of soot formation and further oxidation of solid particles are of a local or band nature and depend on a number of factors, although the stages or phases of these processes can be formulated as follows.

Phase I is the phase of predominantly soot formation. The beginning of the formation of soot particles coincides with the onset of visible combustion and the active release of heat in the engine cylinder during the combustion of the fuel supplied for the ELV.

Phase II is the phase of simultaneous formation and oxidation of particles, lasting until reaching the greatest saturation. This phase corresponds to a second maximum of the soot emission rate, whose position lags behind the second maximum of the heat release rate. At this moment, the diffusion combustion of the main portion of the fuel takes place in the cylinder. The combustion process takes up most of the combustion chamber, and the temperature of the working fluid reaches its maximum values. The processes of formation and oxidation of soot particles come at comparable rates, but the quantitative mass yield of soot exceeds the amount of burnt soot, and the rate of the final process remains positive, causing an increase in the number of soot particles to their peak values.

Phase III is the phase of preferential oxidation of soot particles, which lasts until the opening of the exhaust valves. This phase corresponds to a third maximum of the rate of soot emission, which assumes negative values, since it characterizes the reduction of the containment in the cylinder. The process of combustion by this time has ended, and only the burning of individual sections of unburned soot occurs. The formation of soot is also almost complete, and the burning out of the remaining soot from the second phase continues. The more time allowed for the burning of soot, the less it remains in the cylinder at the time of release [1].

The quality of spraying of fuel depends on its viscosity, pressure in the compressor, geometric parameters of the atomizer, fuel delivery intensity, etc. At the same time in the volume of the torch there will always be a drop of fuel, differing in both size and fractional composition. And since the dynamics of combustion and soot formation is determined mainly by these parameters, and also by the intensity of the turbulence of the air flow in the CS, reliable data for calculating radiative heat transfer can be obtained only on the basis of their experimental determination.

According to the data given in [2], the burning rate of soot can be estimated, for example, from the fact that the initially formed particles have a certain size, and at the end of the working stroke they completely burn out. The particle size found in combustion products in diesel engines can be estimated at $(0.2...1.0) \times 10^{-6}$ m. For an engine with a crankshaft rotation speed of 1500 min^{-1}, the visible burning time is $(7...8)\times10^{-3}$ s, i.e. at a linear rate of reduction of the particle radius, the burning rate of the soot can be estimated at $2.5\times10^{-5}...1.25\times10^{-4}$ m/s. If the density of carbon black is 2×10^{3} kg/m^3, then the average heat release rate on the surface of the soot is 850...4300 W/m^3. Part of this energy goes to the heating of combustion products, some are transferred to the environment by convection, some by radiation. The approximate value of the heat capacity of the reaction products is estimated as the sum of the specific heats of the components, for example, CO_2 and N_2. With the burn-up rate adopted above, the heat capacity of the combustion products produced per unit time from a unit of the soot surface is 16.2×10^3 W/(m$^2\times$K). In order to estimate the intensity of convective heat transfer for the adopted conditions, the heat transfer coefficient α will be $2.5\times10^4 ... 1.25\times10^5$ W/(m$^2\times$K).

Thus, with the accepted burn-up rate of the soot particles, only due to the mechanism of conductive heat exchange, all energy released is discharged into the environment when the temperature of the soot particle of the ambient temperature exceeds the temperature by less than 1 K. This allows us to further consider the combustion products, containing soot particles, as a homogeneous radiating, absorbing and scattering medium [3].

At the same time, soot particles are located not only in the volume of the cylinder, but also in the so-called boundary layer, i.e. layer adjacent to the walls of the cylinder and CC. The thickness of this layer is 2...3 mm at the end of the expansion cycle. It was noted in [4] that near the wall, soot particles have a lower temperature than in the core of the torch. Under these conditions, combustion of the soot particles is slowed down, so they can not be any appreciable sources of heat release. On the basis of this, it is concluded that the intensity of convective heat transfer in the cylinder is determined by the flow conditions and the state of the gas in the immediate vicinity of the wall, while the intensity of radiant heat transfer depends on the concentration and temperature of the combustion products, including soot particles, in the volume of the cylinder .

To determine the intensity of radiative heat transfer in a medium containing suspended particles, in addition to the boundary conditions, the spectral absorption and scattering coefficients of the particles and the scattering indicatrix of the radiation on the particles must also be known. These characteristics, in turn, depend on the physical nature of the substance of the particles (the complex refractive index of the particle material), their dimensions, concentration, shape and wavelength of radiation. The most famous papers devoted to the solution of the problem of finding scattering and absorption indices on various particles include works [5].

Thus, in [5] the distribution of soot particles in size is given under different conditions (Figure 1). In this case, the distribution can be normal (curves 1 and 2), close to normal and asymmetric (curve 3).

In the same paper, an analysis is given of the calculated results for the concentration of soot particles Z as a function of particle size and mass fraction (Figure 2).

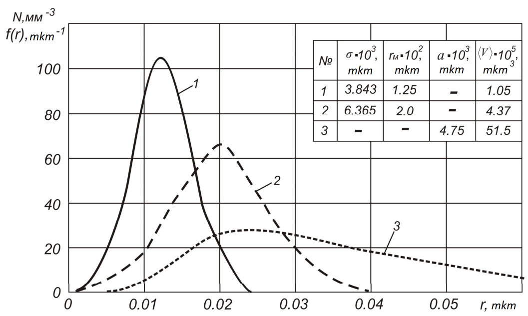


Figure 1. Distribution of soot particles by size.

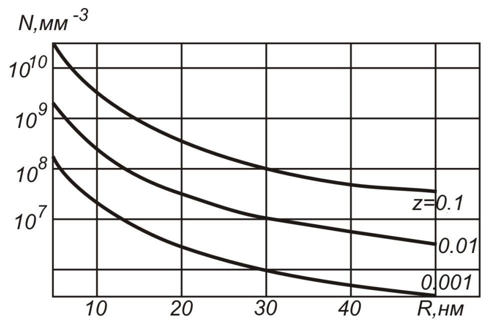


Figure 2. Concentrations of soot particles Z depending on the particle size and mass fraction.

An analysis of the results shows that a decrease in particle size leads to a sharp increase in their concentration.

Using these and other results, it is possible to determine the scattering and absorption indices of the emission of a cloud of soot particles. At the same time, analytical solutions are obtained only for particles of simple and regular geometric shapes, for example spheres.

In practical calculations of heat transfer by radiation in the combustion engine, the characteristics of the medium are usually used on the average along the length of the beam, while the emitting capacity of the torch is calculated from $a_v = 1 - \exp\left(\frac{N}{V}\frac{\pi d^2}{4}\vartheta_v \alpha\right)$, where d is the effective particle diameter. It should be borne in mind that to determine the emission characteristics of soot particles, reliable data are required as to the concentration and distribution of soot particles in size, and their complex refractive index.

In this case, the value of the complex refractive index varies with the temperature change, and this dependence is not exactly determined. The diameter of the particles also changes with time, and the H / C ratio also changes, and this in turn affects the optical properties of soot particles.

At the same time, there are no sufficiently accurate methods for calculating radiative heat transfer in fast-moving autotractor diesels due to the extremely short reaction time and a very large number of factors affecting it.

To determine the radiative characteristics of the sooty flame, it is necessary to know the optical properties of the solid particles on which the refractive index of the medium depends:

$$m = n_1 - n_2 \cdot i. \tag{1}$$

The rate of propagation of radiation in a gaseous medium depends on this index. The absorption index of the medium n_2 determines the decrease in the amplitude of the electromagnetic oscillations caused by the absorption in the medium. These optical constants n_1 and n_2 depend on a number of parameters of the substance in which the radiation is propagated, such as the temperature of the substance, the wavelength of the radiation, the presence of suspended particles or a homogeneous gas medium, etc.

The optical constants n_1 and n_2 for carbon blacks typical for combustion chambers of diesel engines, depending on the temperature and the ratio of H/C for different wavelengths are shown in Figure 1.

If we consider a single carbon black particle, which has the form of a ball of a certain radius r, through which the radiation wave passes, then part of the energy of this electromagnetic wave will be absorbed by the particle, and some will be scattered. When studying the indices of individual particles, the following parameters are used: the effective cross sections for attenuation, scattering and absorption are determined by the Equations:

$$\sigma_{att} = \pi r^2 K_{att}(m,\rho), \quad \sigma_{sc} = \pi r^2 K_{sc}(m,\rho), \qquad \sigma_{abs} = \sigma_{att} - \sigma_{sc}, \tag{2}$$

where K_{att} and K_{sc} are the dimensionless attenuation and scattering efficiency factors, which depend on the parameters m and $\rho = 2\pi r / \lambda$.

The values of K_{att} and K_{sc} are written in terms of the relations:

$$K_{att} = \frac{4}{\rho^2}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}(a_n + b_n), \qquad K_{abs}(m,\rho) = \frac{2}{\rho^2}\sum_{n=1}^{\infty}(2n+1)\left(|a_n|^2 + |b_n|^2\right), \tag{3}$$

where a_n and b_n are the amplitudes of the n-th electric and n-th magnetic waves, respectively (the Mi coefficients).

When electromagnetic radiation is propagated in a substance that is solid particles of the same particle size and composition in the amount of N in a single volume suspended in the gas, it is necessary to consider the characteristics of a single volume rather than an individual particle. It is characterized by spectral coefficients of attenuation, scattering and absorption:

$$\kappa_\lambda = N \cdot \sigma_{att}, \qquad \beta_\lambda = N \cdot \sigma_{sc}, \qquad \alpha_\lambda = N \cdot \sigma_{abs}. \tag{4}$$

In this case, the value of N can be expressed in terms of the mass concentration of soot particles C_m:

$$N = \frac{3C_m}{4\pi\rho r^3}, \tag{5}$$

where ρ is the particle density (for carbon black $\rho = 1.9$ g/cm^3).

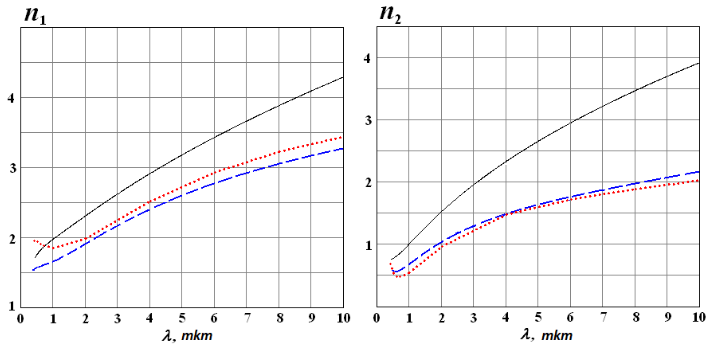


Figure 3. Dependence of optical constants and black carbon on the wavelength, where ——— at H/C=0, T = 2250 K [6]; •••• at H/C=0.07…0.22, T = 1700 K [7], — — at H/C=0.217, T = 293 K [6].

For conditions corresponding to the conditions for the formation of soot particles in the engine cylinder, the presence of particles of different sizes is characteristic, that is, it is no longer a monodisperse but a polydisperse medium. In this case, the following dependencies should be considered:

$$\sigma_{att} = \int_0^{\infty} \pi r^2 K_{att}(r) \cdot f(r) \cdot dr \,, \; \sigma_{sc} = \int_0^{\infty} \pi r^2 K_{sc}(r) \cdot f(r) \cdot dr \,, \qquad \sigma_{abs} = \sigma_{att} - \sigma_{sc} \,. \quad (6)$$

$$\kappa_\lambda = N \cdot \int_0^{\infty} \pi r^2 K_{att}(r) \cdot f(r) \cdot dr, \; \beta_\lambda = N \cdot \int_0^{\infty} \pi r^2 K_{sc}(r) \cdot f(r) \cdot dr, \; \alpha_\lambda = N \cdot \int_0^{\infty} \pi r^2 K_{abs}(r) \cdot f(r) \cdot dr. \quad (7)$$

Then the value of N is defined as:

$$N = \frac{3C_m}{4\pi\rho \int_0^{\infty} r^3 f(r) dr} \,. \quad (8)$$

3. Results of Researches

For the practical application of this technique for studying the radiative characteristics of matter, we studied the working process of a high-speed diesel engine with a turbocharger of the dimension 4FP 11.0/12.5 when operating both on diesel fuel and on gas engine fuel. As a calculation, we considered the nominal operating mode of the diesel engine.

The distribution of soot particles in the exhaust gases in size is described by the distribution function:

$$f(r) = \frac{4r^2}{\sqrt{\pi} r_m^3} e^{-\left(\frac{r}{r_m}\right)^2} \,. \quad (9)$$

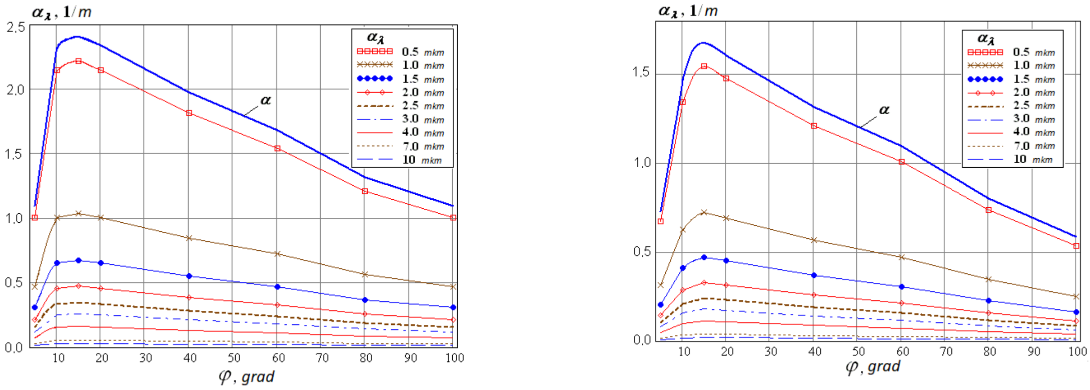
We established the dependence of the radiative properties of soot particles on their optical parameters and the particle size. The results of the calculation of the characteristics of individual soot particles are presented using data on optical constants for both particle systems of the same size and for polydisperse systems in the wavelength range 0.5...10 mm.

Further, the dependence of the radiation characteristics of the final volume on the angle of rotation of the crankshaft during the operation of the diesel engine on diesel fuel and compressed natural gas was investigated. Table 1 shows the change in the mass concentration of soot particles in the diesel and gas diesel cylinder at different angles of rotation of the crankshaft (s.q.v.).

Table 1. Dependence of the mass concentration of soot in the cylinder of a diesel engine and gas diesel engine of the dimension 4FP 11.0/12.5, depending on the change in the angle of the pc.

	s.q.v. φ, [°]							
	5	10	15	20	40	60	80	100
Mass concentration C_m, g/m^3 (diesel)	0.15	0.32	0.33	0.32	0.27	0.23	0.18	0.15
Mass concentration C_m, g/m^3 (gas diesel engine)	0.10	0.20	0.23	0.22	0.18	0.15	0.11	0.08

For a system of soot particles characterized by the presence of particles of different sizes, the largest value of the spectral (α_λ) and integral (α) absorption coefficients is observed at an angle φ = 15°s.q.v. (Figure 4*a*). The values increase with decreasing wavelength from 10 mkm to 0.5 mkm. For a gas-diesel engine, the dependence for is the same, although the numerical values are reduced by 30...47% (Figure 4*b*).



a b

Figure 4. Spectral and integral absorption coefficients of soot particles as a function of the angle of the pcc, where a is diesel process; b is gas-diesel process.

4. Conclusion

The results of the calculations made it possible to determine the radiation characteristics of soot particles, depending on their optical properties and dimensions. The calculated values of the radiation characteristics of soot black by optical constants at T = 293...2250 K lead to a discrepancy of the results up to 45%, which indicates the influence of the temperature of the medium on these processes.

The use of a monodisperse system in the calculations instead of a polydisperse system leads to a difference of up to 8% in the presence of PXEO. At the RHICH level, with a similar replacement, the results may differ by more than 2 times. The conducted comparison of PXEO with respect to the diesel engine and gas diesel engine 4FP 11.0/12.5 at different angles of rotation of the crankshaft is necessary for further estimation of the share of heat exchange by radiation when switching to gas engine fuel. This will allow to determine the working and technical characteristics of diesel engines working on alternative fuels.

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