Features of heat transfer by radiation in a diesel combustion chamber when operating on gas engine fuel

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Abstract. The use of compressed natural gas as automotive fuel in automotive diesel engines allows solving a number of problems that cannot be overcome when working on traditional diesel fuel. First of all, this is a problem of reducing dependence on oil fuel, since the cost of the latter is steadily increasing due to the depletion of oil reserves. Secondly, the use of natural gas can significantly reduce emissions of harmful substances from exhaust gases. First of all, this applies to soot particles. But it is precisely this fact that has a key influence on the fraction of heat transmitted by radiation from the working fluid, since it is the soot particles that affect the radiation characteristics of the flame. The paper discusses exactly how this happens, quantitative indicators of radiation heat transfer are given.

1. Introduction
The intensity of fuel combustion, which determines the nature and dynamics of heat generation, depends on the physical and chemical processes occurring in the reaction zone. And the conditions in which these reactions take place, especially in engines with internal mixture formation, undoubtedly bear a pronounced dependence on the location of the considered local volume of the combustion chamber.

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

2. Experimental
According to the data given in [8], the soot burnout rate can be estimated, for example, from the fact that the initially formed particles have a certain size, and by the end of the working stroke they burn out completely. The size of particles detected 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 \((7...8)\times 10^{-3}\) s, i.e. at a linear rate of reduction of the particle radius, the soot burnout rate can be estimated as \(2.5\times 10^{-5}...1.25\times 10^{-3}\) m/s. If we assume the density of soot is \(2\times 10^{3}\) kg/m\(^3\), then the average heat release rate on the surface of soot will be 850...4300 W/m\(^3\). Some of this energy is used to heat the combustion products, some is transferred to the environment by convection,
and some by radiation. The approximate value of the heat capacity of the reaction products is estimated as the sum of the specific heat capacities of the components, for example, CO₂ and N₂. At the burnout rate adopted above, the heat capacity of the combustion products obtained per unit time per unit of soot surface will be 16.2 × 10³ W/(m² K). At the same time, to estimate the intensity of convective heat transfer for the accepted conditions, the heat transfer coefficient α will be 2.5 · 10⁴...1.25 · 10⁵ W/(m² K).

To determine the intensity of radiative heat transfer in a medium containing suspended particles, in addition to the boundary conditions, the spectral coefficients of absorption and scattering by particles and the indicatrix of radiation scattering on particles must also be known. These characteristics, in turn, depend on the physical nature of the matter of the particles (the complex refractive index of the particle material), their size, concentration, shape and wavelength of the radiation.

Taking into account the studies on the mechanisms of soot formation during combustion of hydrocarbon fuels, the results of which today are beyond doubt, we assume that the formation of the main mass of soot particles occurs through a radical chain process and the main ways of soot formation in the cylinder CNG is a low-temperature phenyl mechanism (LTPM) (prevailing in the core of the torch and a temperature less than 1500 K) and a high-temperature acetylene mechanism (HTAM) (having in the leading edge and a temperature of over 1500 K) [3, 4].

Soot formation occurs predominantly in the core of the ignition DT jet as a result of thermal and oxidative pyrolysis of fuel under conditions of an oxidizer lack, where the concentration of fuel is high and the local excess air ratio is below the “soot formation threshold”. At the initial stage and in the core of the plume, the dominant mechanism of soot formation is NTFM. The rapid expansion of the flame front causes an increase in the amount of fuel burning in this front through a diffusion mechanism, and, consequently, a corresponding increase in the mass yield of soot. In conditions of increased charge turbulization, the bulk of the soot produced is removed from the flame to zones with relatively low temperature and an excess of oxidant. Oxidation of soot particles begins in these zones, but due to the low temperature the oxidation processes are slow and cannot compete with the processes of soot formation, therefore the mass concentration of soot in the cylinder increases rapidly.

It can also be assumed that the reaction rate is finite and proportional to the concentration of the gas reactant. In addition, it is possible to take into account the matter supply to the surface of the particle due to diffusion. It can also be assumed that the interaction of carbon with oxygen occurs not only on the outer surface of the particle, but also in volume, that is, it is necessary to take into account the supply of the substance to the inner surface of the particle are shown in figure 1.

![Figure 1](image.png)

Figure 1. The distribution of soot particles by size in the cylinder of a diesel engine and the number of soot particles per unit volume n = 2400 min⁻¹ ℓ p_c = 0.84 MPa.

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

\[ a_v = 1 - \exp \left( \frac{N \pi d^2}{V} \frac{\alpha}{2} \right) \]

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:

\[ m = n_1 - n_2 i. \] (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 waves pass, 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:

\[ \sigma_{att} = \pi r^2 K_{att} (m, \rho), \quad \sigma_{sc} = \pi r^2 K_{sc} (m, \rho), \quad \sigma_{abs} = \sigma_{att} - \sigma_{sc}, \] (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:

\[ K_{att} = \frac{4}{\rho^2} \sum_{n=1}^{\infty} (2n+1) \Re(a_n + b_n), \quad K_{abs} (m, \rho) = \frac{2}{\rho^2} \sum_{n=1}^{\infty} (2n+1) \left( |a_n|^2 + |b_n|^2 \right), \] (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 are shown in figure 2. It is characterized by spectral coefficients of attenuation, scattering and absorption:

\[ \kappa = N \cdot \sigma_{att}, \quad \beta = N \cdot \sigma_{sc}, \quad \alpha = N \cdot \sigma_{abs}. \] (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 \( \rho \) is the particle density (for carbon black \( \rho = 1.9 \) g/cm\(^3\)).

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:

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

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

Then the value of \( N \) is defined as:
\[ N = \frac{3C_m}{4\pi \rho \int_0^\infty r^3 f(r) dr}. \tag{8} \]

3. Conclusion
Studies have shown that the replacement of traditional petroleum diesel fuel with compressed natural gas has significantly reduced the content of soot particles in the exhaust gases. This became possible due to a more complete combustion of the fuel-air mixture in the combustion chamber of a diesel engine under conditions of a sufficient amount of oxygen. Due to this, the radiation of the flame has significantly decreased, and, consequently, the thermal load on the parts directly in contact with the flame. At the same time, the amount of soot that accumulates on the walls of the combustion chamber, piston bottom and valves will also decrease, which will also positively affect the engine.

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