Emission flame characteristics for cyclic combustion of liquid fuels

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Abstract. The paper considers issues related to the emissivity of the flame generated in the cylinder of a high-speed piston internal combustion engine and, in particular, diesel and the effect of soot particles formed during the combustion of motor fuel on this process. The factors determining this process are presented, the data of various researchers involved in these processes are analyzed. Data are presented that establish the relationship between the amount of soot particles formed and the emission characteristics of the flame, on which the thermal loading of the parts of the cylinder-piston group depends.

1. Introduction
In the combustion chamber of a reciprocating internal combustion engine, including diesel, when burning liquid fuels, a luminous flame is formed, the degree of emission of which determines the activity of heat transfer by radiation from the heat-absorbing surfaces of the combustion chamber. The emissivity of a flame in a cylinder of an engine depends, naturally, on its temperature, but the amount of soot particles formed and oxidized during combustion also makes an equally significant contribution to this process, that is, their concentration in a unit volume. Of course, the operating modes of the engine, the shape of the combustion chamber, and the type of fuel used also influence.

Despite the intense turbulent movement of gases in the combustion volume, for diesel engines, according to experts, heat transfer to the walls of the combustion chamber and further to the cooling system, due to radiation heat exchange, can reach half of the total heat transferred. Therefore, the control methods for these processes are extremely relevant and have not only theoretical value, but also purely practical, since without taking into account these processes it is impossible to design highly accelerated ICEs, primarily diesel engines [1-5].

To assess the emissivity of a flame, it is necessary to learn how to determine the temperature of a flame at a specific point or zone of combustion, and also to understand the processes leading to the formation of soot particles. On the basis of already known data, it can be said that pulsating combustion takes place with respect to the conditions characteristic of diesel cylinders when burning a cyclic dose of fuel injected into the combustion chamber through atomizer nozzles. It would be more correct to say even micropulsation, since the combustion process proceeds under conditions of changing average volumetric temperature and gas pressure, constantly changing gas composition and air excess ratio in a few thousandths of a second. At the same time, during the combustion process, an “instantaneous” change in the concentration of soot particles in the local volumes of the mixture occurs, on which, first of all, the radiation characteristics of the flame depend. But we must not forget that the radiation of
radicals arising as intermediate products of the combustion of hydrocarbon fuel will be superimposed on the radiation of oxidized soot particles [6-9].

2. Experimental

Of course, studying the local parameters of the workflow is very difficult from a scientific point of view and time-consuming with an experimental component. However, such studies are necessary because, as practice shows, the working cycle parameters averaged over the volume of the cylinder, obtained on the basis of processing indicator charts, do not allow one to correctly describe all in-cylinder processes. Therefore, studies of local temperatures, thermal radiation, determination of the optical properties and radiation characteristics of various particles and materials are carried out by leading universities and research centers both in our country and abroad: MSTU im. N.E. Bauman, MPEI, St. Petersburg State University, Kazan State Technical University named after A.N. Tupolev, Tomsk State University, Central Scientific Research Institute of Mechanical Engineering, Scientific Research Institute of Thermal Processes, Institute of Thermophysics SB RAS, NPO TsKTI named after Polzunova, Research Institute of Mechanics, Moscow State University, Institute of Physics, Academy of Sciences of Belarus, Institute of Technical Thermophysics, National Academy of Sciences of Ukraine and others [10-14].

The change in each parameter of the working fluid in the engine cylinder (pressure, temperature, concentration of fuel and oxidizer, concentration of solid particles, flame propagation velocity, etc.) is interconnected with the others on the one hand, and has its own characteristics on the other. For example, pressure equalization over the CC volume occurs almost instantly (for a 12,0/12,0 autotractor diesel engine and a rotational speed of 2500 rpm, the pressure equalization time is about $2 \times 10^{-4}$ s) and can be considered the same for any volume point cylinder [15-21].

On the other hand, there is evidence that the alignment of the temperature of the working fluid with the volume of the copolymer is much slower and the very first measurements by optical indexing showed that there are local temperatures in the ICE cylinder that differ from the temperature of the rest of the working fluid. This is due to the fact that the cause of temperature equalization in the engine cylinder is turbulent diffusion, while small-scale turbulence promotes local temperature equalization, and large-scale turbulence contributes to equalization throughout the cylinder volume. And it, in turn, depends on the frequency of growth, the shape and size of the CC, the organization and intensification of the movement of the air charge, etc [22-27].

The rate of fuel burnout also depends on various factors. Since the combustion of fuel is, first of all, a chemical reaction, depending on the temperature and concentration of fuel vapor. And the concentration of fuel vapor is clearly local in the volume of CC, especially in diesel engines.

Therefore, almost from the very beginning of the development of the ICE theory and research on heat transfer in CC, scientists talked about the use of multi-zone models for determining the temperature and concentration in the volume of the engine cylinder. The widespread use of such models began in the 70 thanks to the work of S. Patankar and B. Spalding.

As evidence, we can cite the work of the professor of Zurich Higher Technical School G. Eichelberg (1891-1972), published back in 1924.

Eichelberg showed that the averaged temperature over the cylinder volume cannot be used to estimate heat transfer in the internal combustion engine and introduced the concept of an averaged resulting temperature. Where in

$$T^* = T_{scp} + \kappa(T_{scp} - 273),$$

where $k = 0.6...0.8$ for four-stroke ICE.

$T_{scp}$ - the average temperature obtained by the indicator diagram.

At the same time, on the basis of experimental and calculated data, the value of the maximum instantaneous temperature in the intensive combustion zone for diesel engines reaches 3000 K, because...
In [5], to study the distribution of temperature field of the engine, the temperature of the working fluid in the CC volume was proved and, therefore, it was indicated that the volumetric average temperature can characterize the internal cylinder processes only to a first approximation [25]. The optical indication of the internal combustion engine showed that the temperature of the working fluid in the volume of the CC has a pronounced local character and it is the values of these temperatures that determine the radiation intensity in the CC. A flame spectrograms showed that micropulsation combustion occurs in the volume of the flare due to an instantaneous change in concentration, including soot particles.

Recent work on the optical display of ICE confirmed the correctness of the conclusions made earlier and obtained more accurate quantitative results for modern high-speed diesel engines.

So, according to the results of studies conducted at Altai State Technical University, the presence of zones differing in temperature and concentration was also established. In [5], to study the distribution of soot concentration and flame temperature in the cylinder, the optical indexing method using an optical quantum generator (OQG) as an external radiation source for measuring the soot concentration described in [15] was used.

Tractor diesel of the Vladimir Tractor Plant of dimensions 4CH 10,5/12,5 (D37E) and 1CH 13/14 (UK-2, Altaydizel JSC) was chosen as the objects of research.

The results of processing the experiment confirmed the assumption that the distribution of characteristics of the soot flame in the cylinder volume is significantly uneven: in the flame temperature, the difference was 600...700 K, in the soot concentration - in 10...15 times, in the concentration of nitrogen oxides - in 80...120 times, in the heat flux – 1,2...2,5 times [25]. And in [1] it was shown that at some moments the difference between the temperatures of the burned and unburnt zones can reach values of 1000... 500 K.

In CC engines, in addition to gaseous products of combustion, intermediate products are formed as a result of incomplete combustion of the fuel, which are either polyatomic radicals of hydrocarbon compounds or soot particles. The presence of such particles in the combustion products generally makes the medium emitting, absorbing and scattering. At the same time, such high-temperature heterogeneous combustion products have uneven continuous radiation. The intensity of thermal radiation of gas mixtures in the presence of soot particles can increase ten times. In this case, the radiation characteristics of the gas-solid particles system depend on the physical properties of the gas and particles, their size and temperature. At temperatures above 2500 K and pressures above 0,1 MPa, the radiation in the CC is determined mainly by the emission of solid particles and is not only solid, but similar to gray-body radiation [26].

For such processes, the Kirchhoff law is considered fair, i.e. it is assumed that the system at each moment of time is in a state of local thermodynamic equilibrium [27]. This assumption allows one to calculate the intrinsic radiation of reactive particles of fuel and combustion products by their temperature, emissivity and size. Heat transfer by radiation between radiation sources in a burning plume and the walls of the CC is considered in the general case as the propagation of electromagnetic waves in a turbid medium [27]. Radiation and absorption by gases occur according to the laws of propagation of electromagnetic radiation in a continuous medium. However, the presence of soot particles in the volume of the torch and the combustion products introduces distortions into the electromagnetic field that must be taken into account when evaluating the radiation of the torch.

To date, due to the extreme complexity of the processes of radiative heat transfer in the internal combustion engine, there is a method for calculating the radiant heat transfer in the internal combustion engine only for gasoline-powered external mixing engines, proposed by British scientists, and it is assumed that the combustion process occurs without the formation of soot particles, and heat transfer
by radiation is determined by the radiation intensity of polyatomic gases. As for ICE with direct fuel injection, for them these issues have not yet been fully studied due to the above reasons.

One of these reasons is the presence of soot particles in the diesel engine CC, and these particles have not only different concentrations in the cylinder volume, which is quite obvious for ICE with internal mixture formation, but also shape and size, due to the process of their formation and burning out.

When complying with diesel engines, when calculating radiation heat transfer, it is necessary to take into account a number of specific features related both to the cyclicity and non-stationarity of the process, and to the geometric parameters of the compressor and fuel flame. Depending on the intensity of turbulization of the air flow in the compressor station and the shape of the fuel jet injected by the nozzle, a concentration field of soot particles is formed. The presence of a certain duration of fuel injection, the polydisperse composition of the fuel droplets in the flare, the uncertainty of the coordinates of the centers of self-ignition, the turbulence of the intracylinder volume as a result of the movement of the piston and the fuel combustion process, the changing volume of the cylinder, the constantly changing concentration of soot particles and their dispersion composition practically exclude the possibility of directly calculating instantaneous local concentrations and dispersion composition of soot particles, which is necessary for calculating radiation heat exchange.

Studies of the development of the torch during fuel injection, carried out by various specialists, make it possible to reliably predict the shape of the torch, the dynamics of its change and the degree to which the torch fills the cylinder space. The main interest in this case is the time period from VMT up to $\varphi = 60...70^\circ$ p.c.v. after VMT This period of time is characterized by a relatively small volume of the overs- piston space, a high averaged temperature of the working fluid and, as a rule, high emissivity. With regard to automotive diesel engines, in practical calculations it is assumed that the inner cylinder space is uniformly filled with a radiator. As will be noted below, the presence of a cold near-wall layer of fuel does not significantly affect the calculation results [28].

![Figure 1. The nature of changes in the intensity of flame radiation along the angle p.c.v. and the change in the rate of heat release along the angle p.c.v. in nominal mode (b), $q_1$ - is the density of the radiant heat flux measured by the pyroelectric receiver.](image)

In [19], the following results of the measurement of flame radiation and heat evolution dynamics in a diesel cylinder are presented.

The quality of atomization of the fuel depends on its viscosity, pressure in the CC, the geometric parameters of the atomizer, the intensity of the fuel supply, etc. At the same time, there will always be fuel droplets in the torch volume, which differ both in size and in fractional composition. And since the dynamics of combustion and soot formation are mainly determined by these parameters, as well as by
the intensity of turbulization of the air flow in the compressor station, reliable data for calculating radiant heat transfer can be obtained only on the basis of their experimental determination.

According to the data given in [8], the rate of soot burnout can be estimated, for example, from the fact that the initially formed particles have a certain size and completely burn out by the end of the working stroke. The size of particles found in combustion products in diesel engines can be estimated at $(0,2 \ldots 1,0) \times 10^{-6}$ m. For an engine with a crankshaft speed of $1500 \text{ min}^{-1}$, the visible burning time is $(7\ldots8) \times 10^{-3}$ s, i.e. at a linear velocity of decreasing particle radius, the soot burnup rate can be estimated as $2,5 \times 10^{5} \ldots 1,25 \times 10^{4}$ m/s. If we take soot density $2 \times 10^{3}$ kg/m$^3$, then the average heat release rate on the soot surface will be $850\ldots4300$ W/m$^3$. Part of this energy is used to heat the combustion products, part is transferred to the environment by convection, part - by radiation. The approximate value of the heat capacity of the reaction products is estimated as the sum of the heat capacities of the components, for example, CO$_2$ and N$_2$. At the burnup rate adopted above, the heat capacity of the combustion products obtained per unit time from a unit of soot surface will be $16,2 \times 10^{5}$ W/(m$^2\cdot$K). In order to assess the intensity of convective heat transfer for the adopted conditions, the heat transfer coefficient $\alpha$ will be $2,5 \times 10^{4} \ldots 1,25 \times 10^{5}$ W/(m$^2\cdot$K).

Thus, at the accepted rate of soot particle burnup, only due to the convective heat transfer mechanism, all the energy released is discharged into the environment when the temperature of the soot particle is higher than the ambient temperature by less than 1 K. This allows us to further consider combustion products containing soot particles as homogeneous radiating, absorbing and scattering medium [29].

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. a layer adjacent to the walls of the cylinder and the CC. The thickness of this layer is 2...3 mm at the end of the expansion stroke [12]. Moreover, it was noted in [1] that soot particles near the wall have a lower temperature than in the core of the torch. Under these conditions, the combustion of soot particles is slowed down, so they cannot be any noticeable sources of heat. Based on this, it is concluded that the intensity of convective heat transfer in the ICE 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 cylinder volume.

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 particles and the indicatrix of radiation scattering by particles should also be known. These characteristics, in turn, depend on the physical nature of the particle material (the complex refractive index of the particle material), their size, concentration, shape and wavelength of the radiation. The most famous works devoted to solving the problem of finding the scattering and absorption indices for various particles include [6, 13, 14, etc.].

So, in [6], the size distribution of soot particles is given under various conditions (see figure 1). In this case, the distribution can be normal (curves 1 and 2), close to normal and asymmetric (curve 3).

In the same work, an analysis is given of the calculated results of the concentration of soot particles $Z$ depending on the particle size and mass fraction (see figure 2).

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

It should be borne in mind that in order to determine the emission characteristics of soot particles, reliable data are needed both on the concentration and size distribution of soot particles, and on their complex refractive index.

Moreover, the value of the complex refractive index changes with temperature, and this dependence is not exactly determined. The particle diameter also changes over time, the H/C ratio also changes, and this in turn affects the optical properties of soot particles.
3. Conclusion
Thus, based on the analysis of studies on the emissivity of the flame and heat transfer in the engine cylinder, we can conclude that they are significantly affected by the presence of solid soot particles in the flame. And their concentration, size and distribution over the volume of the cylinder depends on the parameters of the processes of injection, mixture formation and burnout during the expansion process. It should not be forgotten that part of the soot particles settles on the walls of the CC in the form of soot, which affects the radiation characteristics of the walls of the CC.

At the same time, there are no sufficiently accurate methods for calculating radiation heat transfer in high-speed automotive diesel engines due to the extremely short reaction time and the very large number of factors affecting it.

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