Analysis of environmental performance of a turbocharged diesel engine operating on natural gas

M I Araslanov
Department of thermal engines, automobiles and tractors, Vyatka State Agricultural Academy, 610017, Kirov, October prospect, 133, Russian Federation

E-mail Rossokhin.dvs@mail.ru

Abstract. In the process of fuel oxidation, various harmful substances are formed in the compression ignition engine (CIE) cylinder, including nitrogen compounds and soot. The presence of these components, and especially soot, has a decisive role in the processes of thermal radiation of the flame, local heat transfer in the CC, the degree of blackness of the flame, the thermal stress of the piston and cylinder cover. Under the conditions of non-stationary processes, it is necessary to solve local problems by determining the concentration of these substances, taking into account the uneven distribution of fuel, the non-stationary local thermal conditions and the various state of aggregation of the components of the medium. The presence of soot leads to the formation of soot, which leads to disruption of heat transfer processes between the functioning fluid and the cylinder cover and the piston bottom, that is, the conditions in the boundary layer. The concentrations of these substances depending on the operating parameters of the CIE are considered, recommendations are made on the practical use of compressed natural gas in a tractor CIE.

1. Introduction
The problem of pollution of the air basin with the exhaust gas (EG) of vehicles is especially acute in megacities, where the number of cars reaches high values when operating vehicles in confined spaces, such as warehouses, workshops, and production facilities. And the problem of reducing the negative impact of road transport on the environment requires an early solution. One of the most harmful components of EG is nitrogen compounds and soot particles (SP). Nitrogen compounds cause severe damage to the lung tissue and lead to respiratory diseases. SP are dangerous not only by themselves, but because of their ability to adsorb carcinogenic PAH on their surface. They, in turn, accumulate in the body, can cause mutations in the development of cells and cancer. To achieve a significant reduction in these substances in EG only by optimizing the functioning process of CIE, in particular CIE, is no longer possible. Therefore, you have to look for new ways to solve this problem. One of such ways is the full or partial replacement of petroleum CIE fuel with compressed natural gas [1-9].

Issues related to the formation of soot in a cylinder are not only important from an environmental point of view, but are also closely related to studies of heat transfer processes in a CC. SP suspended in the cylinder volume directly affect the emissivity and absorption capacity of the medium in which they are located, primarily thermal energy. Due to the presence of SP in the cylinder, the medium located there becomes multicomponent, since solid is added to its gaseous and liquid components. The volume and pressure of this medium is constantly changing, as is the thermal condition. The sizes of the resulting
SP vary over a wide range; after the coagulation and agglomeration processes, secondary soot formations can reach sizes up to 10 microns. And this is already comparable in size to the scale of small turbulent pulsations and dynamic gas flows. Although the formation of such large structures occurs either at the end of the oxidation process, or already at the exit of the cylinder. Most particles are several nanometers in size. Such particle sizes allow them to move freely in the boundary dynamic layer [7-16].

2. Experimental

Another aspect of the soot formation process in the CIE cylinder is the formation of soot on the heat-absorbing surfaces of the cylinder and the CC, which, of course, affects the surface thermal condition, heat transfer between the surface and deeper layers. The presence of SP in the volume of the gas medium critically affects the emissivity of the flame, that is, the fraction of radiant heat transfer that occurs in the CC. Of course, this is also due to the uneven concentration of the air-fuel mixture and the oxidizing agent with respect to local CS volumes, local unsteadiness of the oxidation processes of the functioning fluid, and also the fraction of radiant and convective heat transfer in the final CC volume under consideration. These parameters will determine the values of local non-stationary densities of convective heat flow on the surface of the cylinder head and piston head with compressor. These values, in turn, are also constantly changing due to the uneven distribution of oxygen and fuel over the volume of CC. And the use of natural gas as a fuel makes it possible to make a gas air-fuel medium in a compressor station more homogeneous both in composition and thermal condition [17-25].

Figure 1 shows how the content of nitrogen compounds and soot in the EG changes depending on the value of the installation angle of advancing fuel injection at nominal conditions. In one figure, the data for work on the CIE process and gas-diesel are combined. The concentration of nitrogen compounds was determined using a continuous automatic gas analysis system, and the content of SP was determined using a smoke meter by passing the EG through a special filter and then determining the amount of SP deposited on it by the optical method.

When a hydrocarbon fuel is burned, the EG of an ICE always contains solid carbon in a dispersed state (carbon black). CIE soot is not pure carbon and contains hydrogen, oxygen, volatile, ash, coke compounds. The specific surface area of soot is significant and can reach 300 m$^2$/g. Therefore, the oxidation of hydrocarbon fuels leads to an increase in the fraction of radiation in the total heat transfer, which significantly increases the thermal stress of the walls of the CC of a CIE and reduces their resource.

![Figure 1. The content in the EG of a turbocharged CIE 4CHN 11.0/12.5 nitrogen compounds NOx and soot C, depending on the installation of the high-voltage circuit at n=2400min$^{-1}$ and $p_e = 0.84$ MPa: - CIE; - - - - - gas CIE.](image)
a gas-CIE, this value is practically independent of the value of the high-voltage switch. The main conclusion that can be drawn by analyzing this graph is that CNG is most effective for reducing exhaust smoke [36-42].

Figure 2 shows the results of studies of the content of these components, depending on the CIE load at a constant crankshaft speed of 2400 min⁻¹.

![Figure 2](image)

**Figure 2.** The content in the EG of a turbocharged CIE 4CHN 11.0/12.5 NOₓ and soot C, depending on the load change at Θᵥpr = 11° and n = 2400 min⁻¹: - CIE; - - - - - gas CIE.

The greater the load the CIE runs on, the more nitrogen compounds are contained in its EG. The main mechanism of their formation depends on the thermal condition of the gases in the cylinder. The higher it is, the more nitrogen molecules react with oxygen molecules, forming new compounds. But here, the use of CNG can reduce the content of nitrogen compounds in EG, especially at high load conditions [43-51].

With the content of soot depending on the load, the picture develops similarly. The more fuel we supply, the smaller the excess air coefficient becomes and the higher the oxygen deficiency necessary for the complete oxidation of fuel compounds. As a result, the smokiness of the EG increases, since soot is the product of fuel oxidation. We get completely different smoke indicators when functioning on CNG. The simpler chemical formula of the gas combined with a large coefficient of excess air provides almost zero smoke in the entire range of load changes. Even at the highest loads, soot practically does not form; more precisely, the soot formed has time to oxidize and burn in the cylinder [52-58].

Finally, the third step of our research was to study the effect on the content of nitrogen compounds and soot in the EG of the crankshaft speed, the results of which are presented in figure 3.

We analyzed the content of the components under consideration when changing the rotational speed from 1200 to 2500 rpm at full fuel supply. With increasing speed decreases the time devoted to the formation of nitrogen compounds, therefore, their content decreases. At the same time, when functioning on CNG, their content is lower in the entire range of rotation frequencies [59-63].

![Figure 3](image)

**Figure 3.** The content in the EG of a turbocharged CIE 4CHN 11.0/12.5 nitrogen oxides NOₓ and soot C, depending on the speed at Θᵥpr = 11° p.k.v.: - CIE; - - - - - gas CIE.

Based on the data on the carbon black content in the cylinder, knowing their size and density, we can determine the mass of carbon black particles formed in the CC in order to assess the degree of their
influence on dynamic gas flows. In the calculations, the assumption is made that the SP move at a speed equal to the speed of the air flow in which they are located. In addition, they have a thermal condition equal to the thermal condition of the surrounding gas. Therefore, the turbulent flow swirling in the CC of a CIE can be considered homogeneous and inextricable. But from the point of view of the optical density of the medium in which SP are weighed, the indicators vary greatly. First of all, this refers to the transparency of the medium, to scattering, the degree of blackness of the medium in the CC. In further calculations, it is assumed that the gray body, which is the functioning mixture in the CIE, has a constant attenuation coefficient and, accordingly, a constant emissivity. It should be remembered that the thermal condition of the functioning fluid is constantly changing, as well as its chemical composition.

3. Conclusion
Thus, it was found that the presence of SP in the volume of the functioning fluid fundamentally affects the formation of radiant local heat fluxes on the surfaces of the CC and the radiation distribution of heat on all surfaces surrounding the burning functioning fluid, whether it be the walls of the cylinders, the walls of the CC, or the head of the cylinder block. An increase in the concentration of SP leads to an increase in the degree of blackness of the flame and high local thermal conditions. If these zones are located far from the walls of the CC, then when passing through the absorbing medium this flow will weaken somewhat due to scattering. If they are in the boundary layer, then there will be a local thermal load on the heat-absorbing surface. The use of CNG allows to smooth out such irregularities, which means to reduce thermal deformations and stresses that arise during the operation of the CIE.

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