Feature comparison regeneration particulate filter with the catalytic coating and the use of oxidation catalyst

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Summary. The paper presents the results of computational and theoretical research of passive regeneration particle filter diesel engine. According to the results of the analysis are reasonable prospects of application of the direct and indirect path burnout soot into the layer filter element under passive regeneration of the diesel particle filter.

Keywords: diesel particle filter, regeneration, soot.

INTRODUCTION

The important objective at the currently is to reduce the amount of harmful emissions with exhaust gases vehicles. Exhaust gases contain a lot of harmful substances, the most significant of which are nitrogen oxides, particulate matter (PM), carbon monoxide, hydrocarbons, sulfur compounds. Particulate matter is one of the main components of the diesel vehicles emissions. Analysis of the composition of exhaust gases is made by the method of determining the reduced mass of the harmful release, showed that the fraction of PM is more than 40% of the total exhaust emissions of diesel vehicles operating in Ukraine [28]. Particulate matters have the broad range of negative impacts on the environment and human, including contribute to the emergence of cancerous diseases [26]. Implementation of the existing and promising standards for emissions of PM diesel vehicles only by the impact on the operating process engine is almost impossible. For this to need the trapping PM with diesel particulate filters (DPF) that are installed into the engine exhaust system. The most simple, effective and reliable are mechanical DPF’s, where the trapping of PM is the porous layer of the filtering material. However, under the exploitation of DPF there is the problem with filling the filter material of the PM, which precipitously reduces the operating time of filter and impairs the effective performance of the diesel engine [5, 9]. Therefore, ensuring the regeneration of particulate filters is the actual problem, the solution to which will enable their widespread introduction in exploitation.

MATERIALS AND METHODS

There are different ways of regeneration DPF [20], among which the most simple and reliable seems thermal regeneration. Its essence lies in the fact that, under the temperature exhaust gases above 550 °C with PM begin to burnout at the expense of residual oxygen, always contained into exhaust gases diesel engines. However, under operation diesel vehicle such temperature exhaust gases
not achieved or reached not long, that does not provide self-regeneration DPF. Therefore, to implement the regeneration DPF using different ways of the exhaust gases heating to the required temperature or ways of lowering the temperature of the beginning burnout soot.

Thermal or catalytic burnout soot under regeneration DPF is possible direct \((C + O_2)\) or indirect \((C + NO_2)\) paths. It is believed that the regeneration of the DPF for both paths are based on assumptions of the kinetic behavior of the process of burnout soot into the layer filter element according to the law of the Arrhenius [1, 10, 16]. The kinetic equation is the basis of the material balance of the flow of reactants. Depending on the availability of experimental and calculated data kinetic parameters are presented in the form of modified the temperature dependence of the soot burning rate:

\[
k(T) = k_0 T^b e^{-E_a/RT},
\]

(1)

where: \(k(T)\) – reaction rate constant, \(m/s\) (1/s for gas-phase reactions), \(k_{0,th}\) – pre-exponential factor Arrhenius, \(m/(s \cdot K^b)\) (1/(s \cdot K^b) for gas-phase reactions), \(T\) – thermodynamic temperature, \(K\), \(b\) – exponent at \(T\), usually is accepted 0.5 or minus 0.5, \(E_a\) – activation energy, \(J/mol\), \(R\) – universal gas constant, \(J/(mol \cdot K)\).

The factor \(k_0 T^b\) depends on the temperature is much weaker exponent, therefore it is taken as constant, and equation (1) are as follows:

\[
k(T) = k_0 e^{-E_a/RT},
\]

(2)

where: \(k_0\) has a rank of \(k(T)\).

Recently, a lot of research is devoted to the regeneration of the DPF, which under the organization of the process burnout soot into the layer filter element occurs on indirect \((C + NO_2)\) path with the use of diesel oxidative converter (DOC) [2, 7, 14, 15, 24]. In international publications occurs mainly experimental material obtained in the laboratory or move trials, which confirms the applicability of this method for neutralization exhaust gases diesel engines.

In this paper was performed computational and theoretical research of regeneration DPF for two cases: direct burnout diesel soot – catalytic oxidation of soot at the expense of residual oxygen exhaust gases and indirect – oxidation soot with nitrogen dioxide obtained by the oxidation of nitrogen oxide in DOC. It is obvious that on the process of regeneration DPF affects the mode of the operation diesel engine and kinetic constants soot burning rate.

The purpose of this research was to compare the specific soot burning rates for direct and indirect paths at the temperature exhaust gases typical for catalytic oxidation of soot, as well as to assess the possibility of the regeneration DPF for direct path burnout soot under operation of the diesel engine.

RESULTS, DISCUSSION

These types of burnout soot filter element DPF need to be assessed the position of the possibility of their application in real conditions regeneration. To do this made the comparative analysis of the above regeneration paths.

Quantitative characteristics of diesel engines equipped DPF with continuous regeneration (CRT), which applies indirect path burnout soot. Consider the example of the running tests of the bus in the Central part of the city (Fig. 1). Use fuel with ultra-low sulfur (27 ppm) significantly improves the operation of DOC for CH and CO in comparison with fuel with low sulfur content (247 ppm), and the reduction of emissions of PM happens by reducing the fraction of sulfates in their composition.

The use of CRT improves DOC and reduces emissions of PM, which is determined by the efficiency of the operation DPF and the quantity of the burnt soot. The use of CRT impairs the efficiency of the diesel engine, increases the emissions of CO\(_2\) and NO\(_x\) which is a disadvantage.

On the soot oxidation of NO\(_2\) affects the amount of soot into exhaust gases and filter element, concentration of NO\(_x\) and temperature of exhaust gases and the filter
element. The concentration of NO$_2$ into the exhaust gases of the diesel engine KAMAZ-740M is 2300-240 ppm, that with under significant filling DPF not enough for regeneration through the low soot oxidation rate and low concentration of NO$_2$. At the temperature above 250 °C is possible soot oxidation at stoichiometric ratio NO$_2$/C or excess NO$_2$. For DPF of a volume of 12,5 l with the total amount soot of 0,05 kg under gas flow of 920-206 kg/h formed the mass ratio NO$_2$/C from 0,00035 to 0,000064. Stoichiometric mass ratio NO$_2$/C is 3,83. At low concentrations of the NO$_2$ into DPF and taking into account the developed surface of the soot to wait for high oxidation rate of the accumulated soot is not possible.

The application of the scheme C + NO$_2$ for the regeneration of DPF in some cases not justified for a number of reasons. According to the data of the running tests (see Fig. 1) the total emission of nitrogen oxides is not reduced, and even slightly increase. It is adversely affects the total exhaust gases emissions of diesel engine because oxides of nitrogen have the greatest contribution in total toxicity of exhaust gases.

The Johnson Matthey Company suggested the path burnout soot particulate filter in two stages (Fig. 2). In front of the diesel particulate filter to the exhaust gases flow is set oxidation catalyst, whose main function is the oxidation of NO, which is contained in the exhaust gases, to the formation of NO$_2$. The short distance from DOC is installed DPF with filter element of the cellular structure, in which the soot trapping and its oxidation of NO$_2$ according to the thermal mechanism.

![Fig. 1. Emission of pollutants according to the results of the test bus in the city centre, equipped with a diesel engine 1999 DDC Series 50 volume of 8,5 l and power of 275 hp[14]](image)

Into the exhaust gases of the diesel engine KAMAZ-740M ratio NO$_2$/C is from 18 to 93 that exceeds the stoichiometric and with the growth of load and engine speed this ratio decreases. This means that local burnout soot into the volume of exhaust gases and accumulated soot layer possible due to the appearance of the area depletion (with NO$_2$/C ≥ 3,83), where at a certain temperature oxidation occurs soot.

Stoichiometric mass ratio O$_2$/C under the burnout soot for the oxygen mechanism is 2,67. In operation conditions of CRT concentration of the O$_2$ varies in the range 6-18 % by volume. The ratio O$_2$/C for residence time of exhaust gases into the filter up to the moment of the beginning regeneration is 0,03-0,01.

![Fig. 2. The scheme of the CRT: 1 – diesel oxidation catalyst, 2 – diesel particulate filter](image)

According to the data of the Johnson Matthey company requirements to the operation of this system CRT there is:

1. Proportion (over 50 %) of engine modes that provide heat of exhaust gases more than 250 °C,
2. The ratio of NO$_x$/PM in the diesel exhaust gases should be 20:1 and higher,
3. The maximum sulfur content in the diesel fuel pets at the level of 50 ppm (by mass).

Such strong requirements for the application of DPF in the operation conditions of the diesel engine can be the disadvantage. In addition, this design of DPF needs about
two times more space than a conventional of DPF, and possible oxidation reaction of NO to NO\(_2\) with the high sulfur content in diesel fuel that limited the scope of the method.

The mechanism of the soot indirect oxidation in the system CRT is divided into two stages [3, 8, 22, 23, 27]. The first stages in DOC (Fig. 2) are oxidized CO, CH and NO according to the following reactions:

\[
\begin{align*}
2\text{CO} + \text{O}_2 & \xrightarrow{\text{n}} 2\text{CO}_2, \\
\text{C}_n\text{H}_m + \left(\frac{n + m}{4}\right)\text{O}_2 & \xrightarrow{\text{Pt}} n\text{CO}_2 + \frac{m}{2}\text{H}_2\text{O}, \\
2\text{NO} + \text{O}_2 & \xrightarrow{\text{Pt}} 2\text{NO}_2. 
\end{align*}
\]

In the second stage of the soot oxidation by restoring NO\(_2\) to NO:

\[
\text{C + 2NO}_2 \rightarrow \text{CO}_2 + 2\text{NO},
\]

\[
\text{C + NO}_2 \rightarrow \text{CO} + \text{NO},
\]

\[
\text{NO}_2 + \text{NO}_2 \xrightarrow{\text{Pt}} 2\text{O}_2 + \text{NO} + \text{NO}. 
\]

Decrease in particle diameter according to the summary mechanism (Eq. 6) and (Eq. 7) in [22] is empirically described using a modified form of Arrhenius expression to account for variable NO\(_2\) concentrations given as:

\[
\dot{D}_p = -A_{\text{soot}}T^{1/2}e^{-\frac{47100}{RT}}[\text{NO}_2]^n, 
\]

where: \(\dot{D}_p\) – rate of decrease of particle diameter with time, nm/s, \(A_{\text{soot}}\) – frequency factor, \(A_{\text{soot}}=2.4\times10^{-14}\ \text{nm}\cdot\text{cm}^3/(\text{K}^{1/2}\cdot\text{s}\cdot\text{molecule})\), \([\text{NO}_2]\) – concentration of NO\(_2\), molecules/cm\(^3\), \(n = 1\) – order of reaction in [22] was not determined.

Scheme burnout diesel soot in DPF with the catalytic coating on the basis of copper is shown in Fig. 3.

Copper is the transitional metal and has two main valence states. The literary sources it is known that when heated in air copper oxidizes to CuO and Cu\(_2\)O oxides [4]. In the temperatures of 200-375 °C the copper to air oxidized to black copper oxide (II) CuO (decomposition temperature of 1026 °C to Cu\(_2\)O [13]). At high temperatures occurs two-layer oxide. The surface layer consists of black copper oxide (II) CuO, and the inside is made of red copper oxide (I) Cu\(_2\)O (melting point of 1235 °C [13]). At high temperature oxidation (1000 °C or more) of copper metal, when values of the oxygen partial pressure about 13,3 kPa or less oxide CuO is not formed, and the only product of the reaction is the oxide of Cu\(_2\)O [6]. The existence region of CuO in the air lies in the temperature of 250-1000 °C, and with decreasing the partial pressure of the O\(_2\) this interval is decreases. When the partial pressure of O\(_2\) less of 0,133 Pa and temperature less than 700 °C with the total oxidation rate of copper is very low. Also in the [6, 12] notes that the oxide CuO is formed at the further oxidation of Cu\(_2\)O. There is a certain critical thickness of the layer Cu\(_2\)O on the metal surface above which formation oxide of CuO possible.

Fig. 3. Scheme burnout soot on the surface of catalytic coating, which includes oxide CuO

Oxidation of copper nanopowders when heated in air investigated in [11]. At the linear heat in the air of copper nanopowders samples with a large fraction of the small fraction oxidized with the clearly the staging of Cu→Cu\(_2\)O→CuO. On the first stage rate proportional to the fraction of small fraction particles. For the second stage of the clearly dependence rate on dispersion is not detected. With the growing proportion of particles big fraction in the sample of staging process.
oxidation becomes less expressive as well as for roughly dispersed copper powder (average size is 40 \( \mu m \)) staging is also not expressed.

According to [4] oxide CuO detects oxidizing properties. The copper oxide (II) oxidizes carbon to \( CO_2 \) and hydrogen to \( H_2O \) when heated with various organic substances as well as copper oxide (II) restored to copper metal. The author of this paper provides the mechanism of catalytic burnout in the following form:

\[
\begin{align*}
2CuO + C & \xrightleftharpoons{\text{stage recovery}} 2Cu + CO_2, \\
CuO + C & \xrightarrow{\text{stage oxidation}} Cu + CO, \\
CuO + CO & \xrightarrow{\text{decomposition stage}} Cu + CO_2, \\
2Cu_2O + C & \xrightarrow{\text{kinetic regime}} 4Cu + CO_2, \\
Cu_2O + C & \xrightarrow{\text{kinetic regime}} 2Cu + CO, \\
Cu_2O + CO & \xrightarrow{\text{kinetic regime}} 2Cu + CO_2,
\end{align*}
\]

Chromium oxide \( Cr_2O_3 \) is refractory substance green, manifests amphoteric properties, insoluble in water and many solvents, slightly soluble in all acid and alkali, persistent in the air [4, 13]. Oxide \( Cr_2O_3 \) contributes to the development of the inner surface of the active component and the increase of the catalyst thermal stability [25], also not restored to the metal Cr when interacting with reducing agents: C, CO, \( H_2 \).

For soot burning rate according to the summary mechanism \( C + O_2 \) for catalyst with \( CuO \) in [19] applied the Arrhenius equation:

\[
k_{\text{cat}}(T) = 80.4e^{-82308/(RT)}.
\]

The diffusion process can influence the burnout soot in DPF. Soot burning rate of the kinetic equation Arrhenius decreases faster at decrease of temperature than the diffusion rate. It is therefore possible to assume that at temperatures 300-1000 °C and small sizes of soot particles the burning process occurs in the kinetic region. This assumption requires an assessment depending on the conditions and features of the filter element. Mechanisms of catalytic burnout soot differ because of the diversity catalytic systems used for DPF. For example, platinum promotes the oxidation of soot at the temperature about 450-500 °C and the mechanism its oxidation consists in the adsorption of oxygen molecules on the catalyst surface, dissociation and interaction with carbon on the periphery soot particles.

Usually for path \( C + O_2 \) assumes kinetic regime burnout soot on the Arrhenius law. Kinetic equations are the basis of the material balance of the reactants flow. Their views are in classical (Eq. 2) or modified (Eq. 1) form depending on the availability of data kinetic parameters. The estimates or experimental investigation of the kinetic regime burnout soot in filter is absent.

The influence of the gas-phase reaction:

\[
2CO + O_2 \rightarrow 2CO_2,
\]

on the chemism burnout soot were checked using the criterion Semenov (Se). It is defined as the ratio of the oxygen flow into the reaction of burnout \( CO \), to its diffusion flow [18]:

\[
Se = \frac{\sqrt{kD}}{a_{\text{dif}}},
\]

where: \( k \) – constant velocity of gas-phase reaction burnout of \( CO \), 1/s, \( D \) – diffusion
coefficient, $m^2/s$, $a_{\text{dif}}$ – coefficient of diffusion mass transfer, $m/s$.

For soot particles, which are in the free volume of the granular filter element, the criterion of $S_e$ in the range of temperatures and velocities of the flow exhaust gases significantly less than the limit $S_e = 0.4$ (Fig. 4). In this case burnout CO near the particles considers not need. In the layer of granular filter element at the temperature of $960 \, ^\circ\text{C}$ and more to show excess limit of $S_e$ for speeds of exhaust gases $0.1 \, \text{m/s}$ or less. For the conditions of catalytic thermal regeneration of the filter element, the affect of gas-phase reaction on the material flows the surface of the soot particles and grains not be considered and assume that this reaction is observed only on the surface of oxidative catalyst or in the volume of the exhaust gases.

But the interaction of soot with $\text{CO}_2$ and $\text{H}_2\text{O}$ can be not taken into account when the kinetic mode burnout carbon. This is determined by diffuse-chemical criterion of similarity [18]:

$$\text{Nu}_{\text{ch}} = \frac{k_1 + k_2}{a_{\text{dif}}},$$

where: $k_1, k_2$ – rate constants reactions of (Eq. 25) and (Eq. 26). Kinetic burning mode is determined by the value criterion of 0.1 or less.

Role of surface reactions burnout soot:

$$C + \text{CO}_2 \rightarrow 2\text{CO},$$

$$C + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2,$$

significantly manifested under diffusion combustion, where the integral rate of carbon oxidation according to the reactions has approximately the first order as well as for the reactions:

$$C + \text{O}_2 \rightarrow \text{CO}_2,$$

$$2\text{C} + \text{O}_2 \rightarrow 2\text{CO}.$$

Burnout soot in the free volume of the filter element and on the surface of grains runs in the kinetic region in the whole range of temperatures and velocities of exhaust gases (Fig. 5). Excess can be considered insignificant, because if the value of $\text{Nu}_{\text{ch}}$ of
more than 100 do not take into account kinetic burning. In this case, burnout proceeds in the diffusion region.

Soot burning rate depends on the operation mode of the diesel engine, which is characterized by the engine speed and its power. These indicators determine the temperature exhaust gases and also the concentration of nitrogen oxides and residual oxygen in them. To account for the operation modes and operation conditions of the diesel engine were used the data of the 13-mode diesel engine test of KAMAZ-740 (Table 1).

Table 1. The data of the 13-mode diesel engine test of KAMAZ-740

<table>
<thead>
<tr>
<th>Mode</th>
<th>Engine speed, min⁻¹</th>
<th>Load, %</th>
<th>Engine power, kW</th>
<th>Fuel flow, kg/h</th>
<th>Air flow, kg/h</th>
<th>Concentration NO₂, ppm</th>
<th>PM, g/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600</td>
<td>0</td>
<td>0</td>
<td>0.13</td>
<td>205</td>
<td>240</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>1400</td>
<td>10</td>
<td>9.1</td>
<td>4.7</td>
<td>492</td>
<td>340</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>1400</td>
<td>25</td>
<td>23.1</td>
<td>6.9</td>
<td>487</td>
<td>300</td>
<td>5.2</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>50</td>
<td>46.8</td>
<td>10.9</td>
<td>483</td>
<td>1350</td>
<td>8.9</td>
</tr>
<tr>
<td>5</td>
<td>1400</td>
<td>75</td>
<td>71.4</td>
<td>15.4</td>
<td>478</td>
<td>2200</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>1400</td>
<td>100</td>
<td>94.4</td>
<td>20</td>
<td>471</td>
<td>2300</td>
<td>94</td>
</tr>
<tr>
<td>7</td>
<td>600</td>
<td>0</td>
<td>1.3</td>
<td>207</td>
<td>250</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2600</td>
<td>100</td>
<td>157.5</td>
<td>36.4</td>
<td>890</td>
<td>700</td>
<td>200</td>
</tr>
<tr>
<td>9</td>
<td>2600</td>
<td>75</td>
<td>118.2</td>
<td>28.6</td>
<td>892</td>
<td>1300</td>
<td>145</td>
</tr>
<tr>
<td>10</td>
<td>2600</td>
<td>50</td>
<td>79.2</td>
<td>21.1</td>
<td>892</td>
<td>900</td>
<td>32</td>
</tr>
<tr>
<td>11</td>
<td>2600</td>
<td>25</td>
<td>40.3</td>
<td>14.3</td>
<td>891</td>
<td>520</td>
<td>17</td>
</tr>
<tr>
<td>12</td>
<td>2600</td>
<td>10</td>
<td>15.6</td>
<td>10.7</td>
<td>886</td>
<td>370</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>600</td>
<td>0</td>
<td>1.3</td>
<td>205</td>
<td>270</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

For the analysis of the soot burning rate resulted equation (Eq. 20) in the form equation (Eq. 9). After transformations for soot particles with a density of 2000 kg/m³ were the following equation:

\[ D_{p,cat} = 4.02 \times 10^7 e^{-829308/(RT)} [O_2], \]  (28)

where: \( D_{p,cat} \) – rate of decrease of particle diameter with time, nm/s, \([O_2]\) – concentration residual of O₂, kg/m³.

The concentration residual of O₂ is determined by the equation:

\[ [O_2] = \frac{\mu O_2 r_{O_2} P}{RT}, \]  (29)

where: \( \mu O_2 \) – molar mass of O₂, kg/mol, \( r_{O_2} \) – volume fraction residual of O₂ in the exhaust gases, m³/m³, \( P \) – absolute pressure, Pa.

Volume fraction residual of O₂ in the exhaust gases is determined with fuel factor Bunte by the equation

\[ r_{O_2} = \frac{0.21(\alpha - 1)(0.79 + \beta)}{\alpha(0.79 + \beta) - 0.21\beta}, \]  (30)

where: \( \alpha \) – excess air ratio, \( \beta \) – fuel factor Bunte.

Excess air ratio is calculated by the equation:

\[ \alpha = \frac{G_{air}}{14.33G_{fuel}}, \]  (31)

where: \( G_{air} \) – air flow, kg/h, \( G_{fuel} \) – fuel flow, kg/h.

Fuel factor Bunte is calculated by the equation [18]:

\[ \beta = \frac{2.37(H - 0.125O)}{C}, \]  (32)

where: H, O, C – mass fraction of hydrogen, oxygen and carbon in the fuel, accordingly, accept for diesel fuel: H = 0.126, O = 0.004, C = 0.87.

The concentration of NO₂ for (Eq. 9) is calculated by the equation:

\[ [NO_2] = \frac{r_{NO_2} P}{kT}, \]  (33)

where: \( r_{NO_2} \) – volume fraction residual of NO₂ in the exhaust gases, ppm, \( P \) – absolute pressure, Pa, \( k = 1.38 \times 10^{-23} \) J/K – Boltzmann constant.

For the test conditions of diesel engine according to (Eq. 9), (Eq. 28)-(Eq. 33) calculated rate of burning soot particles (Table 2). Is assumed that the concentration of NO₂ is 50 % of the total concentration of NOₓ in the exhaust gases at the temperature of 300-350 °C [22].

Due to low the exhaust gas temperature (less than 250 °C) on modes 1-3, 7 and 11-13 burnout soot does not occur to both paths.
Modes of the diesel engine operation of 4-6 and 8-10 are favorable for burnout soot by temperature (Fig. 6). At modes of 4-6 of soot burning rate by the direct path less of 1,3-3,5 in times than the indirect path, conversely, at the modes of 8-10 – more in 1,3-5,6 in times.

Table 2. The rate of direct (Eq. 28) and indirect (Eq. 9) burning of soot particles for the test conditions diesel engine of KAMAZ-740M

<table>
<thead>
<tr>
<th>Mode</th>
<th>Ex. gases T, °C</th>
<th>Excess air ratio</th>
<th>[O₂], kg/m³</th>
<th>[NO₂], 1/cm³</th>
<th>( \dot{D}_p ), nm/s</th>
<th>( \dot{D}_{p,cat} ), nm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>11.00</td>
<td>0.191</td>
<td>2.24E+15</td>
<td>0.00059</td>
<td>0.00009</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>7.31</td>
<td>0.160</td>
<td>2.82E+15</td>
<td>0.00398</td>
<td>0.00126</td>
</tr>
<tr>
<td>3</td>
<td>217</td>
<td>4.93</td>
<td>0.133</td>
<td>2.25E+15</td>
<td>0.01137</td>
<td>0.00900</td>
</tr>
<tr>
<td>4</td>
<td>260</td>
<td>3.09</td>
<td>0.104</td>
<td>9.30E+15</td>
<td>0.12473</td>
<td>0.03585</td>
</tr>
<tr>
<td>5</td>
<td>320</td>
<td>2.17</td>
<td>0.074</td>
<td>1.36E+16</td>
<td>0.56486</td>
<td>0.16792</td>
</tr>
<tr>
<td>6</td>
<td>470</td>
<td>1.64</td>
<td>0.043</td>
<td>1.14E+16</td>
<td>3.62988</td>
<td>2.83530</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>11.11</td>
<td>0.190</td>
<td>2.34E+15</td>
<td>0.00061</td>
<td>0.00009</td>
</tr>
<tr>
<td>8</td>
<td>590</td>
<td>1.71</td>
<td>0.039</td>
<td>2.98E+15</td>
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</tr>
<tr>
<td>9</td>
<td>420</td>
<td>2.18</td>
<td>0.064</td>
<td>6.89E+15</td>
<td>1.22552</td>
<td>1.60485</td>
</tr>
<tr>
<td>10</td>
<td>330</td>
<td>2.95</td>
<td>0.090</td>
<td>5.48E+15</td>
<td>0.26849</td>
<td>0.26745</td>
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<tr>
<td>11</td>
<td>230</td>
<td>4.35</td>
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<td>3.80E+15</td>
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<tr>
<td>12</td>
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<td>5.78</td>
<td>0.147</td>
<td>2.95E+15</td>
<td>0.00681</td>
<td>0.00266</td>
</tr>
<tr>
<td>13</td>
<td>120</td>
<td>11.00</td>
<td>0.189</td>
<td>2.52E+15</td>
<td>0.00066</td>
<td>0.00009</td>
</tr>
</tbody>
</table>

Fig. 6. Soot burning rate on the operation modes of 4-6, 8-10 (Table 2) of diesel engine

For the temperature of exhaust gases close to 250-300 °C are expected high degree regeneration of DPF with the catalytic coating according to the scheme C + O₂ in comparison with the system of CRT. Despite the high soot oxidation rate of NO₂ on modes of partial loads, the degree regeneration is higher for soot oxidation with oxygen. For example, in mode \( n = 1400 \text{ min}^{-1} \) NO₂ weight is 0,15 g/s, PM – 0.94 g/s and the O₂ – 21,6 g/s. Soot oxidation rate on the oxygen path is less than 3,5 times, but the amount of oxygen is sufficient to oxidize the soot stream and in the filter element. This evaluation shows that the system CRT cannot ensure the operation of DPF when it is completely filled. In such case, the necessary force regeneration [21], which contradicts the idea of self-regeneration. The advantage of catalytic oxidation of soot on the scheme C + O₂ is the possibility of using the oxide catalysts, which are cheaper catalysts on the base of noble metals (Pt, Pd, Au), and organize a comprehensive neutralization of toxic components of exhaust gases diesel engines. In addition, a decrease in emission standards of nitrogen oxides to the level Euro 5 entails a decrease in the soot burning rate. The system CRT is intended for to operate in conditions of ultra low content of sulfur in the diesel fuel (50 ppm by mass) due to the use of DOC with the catalytic coating containing Pt. The quality of diesel fuel for the system CRT must comply with standards Euro 4 or Euro 5 that narrows the application of this system in Ukraine.

CONCLUSIONS

1. Assessment of diffuse-chemical criterion by (Eq. 27) showed the practical possibility of use of the kinetic dependences for the description of the regeneration process material balance into granular filter element excluding oxygen diffusion near the reaction surface of soot.

2. For satisfactory operation of system CRT are desired high content of nitrogen oxides into the exhaust gases. It is the downside.

3. Regeneration for the path C + NO₂ depends not only on the diesel operation mode, but also the operation DOC. The DOC failure will lead to excessive filling of DPF and the inability to vehicle operation without forced
regeneration. It is contradicts the concept of system CRT.

4. Requiring ultra low content of sulfur in diesel fuel limits the application of system CRT in Ukraine, on the contrary regeneration for the path C + O₂ less demanding to the quality of diesel fuel.

5. In the temperature range of 250-350 °C soot burning rate profitable direct path than indirect and conditions for the self-regeneration of DPF is favorable.

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СРАВНЕНИЕ ВОЗМОЖНОСТЕЙ РЕГЕНЕРАЦИИ САЖЕВОГО ФИЛЬТРА С КАТАЛИТИЧЕСКИМ ПОКРЫТИЕМ И ПРИМЕНЕНИЕМ ОКИСЛИТЕЛЬНОГО НЕЙТРАЛИЗАТОРА

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Аннотация. В статье представлены результаты расчетно-теоретических исследований пассивной регенерации дизельного сажевого фильтра. На основе анализа рассмотрены перспективы применения прямого и непрямого типа выгорания сажи в слое фильтрующего элемента при пассивной регенерации сажевого фильтра.

Ключевые слова: дизельный сажевой фильтр, регенерация, сажа.