# Semitransparent ceramic heat-insulation of eco-friendly Low-Heat-Rejection diesel

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**Abstract**. Efficiency of diesel has been studied using well-known types of the ceramic heat-insulating HICs- or thermal barrier TBCs-coatings. This problem is relevant for a high-speed diesel combustion chamber in which an intensive radiant component (near IR) reaches ~50% within total thermal flux. Therefore, in their works the authors had been offering new concept of study these materials as semitransparent SHICs-, STBCs-coatings. On the Mie scattering theory, the effect of selection of the specific structural composition and porosity of coatings on the variation of their optical parameters is considered. Conducted spectrophotometric modeling of the volume-absorbed radiant energy by the coating had determined their acceptable temperature field. For rig testings, a coated piston using selected SHIC (PSZ-ceramic $ZrO_2+8\%Y_2O_3$) with a calculated optimum temperature gradient was chosen. A single cylinder experimental tractor diesel was used. At rotation frequency $n > 2800$ rpm, the heat losses were no more than 0.2 MW/m$^2$. Executed testings showed ~2-3% lower specific fuel consumption in contrast to the diesel with an uncoated piston. Effective power and drive torque were ~2-5% greater. The authors have substantiated the growth the efficiency of this Low-Heat-Rejection (LHR) diesel due to the known effect of soot deposition gasification at high speed. Then unpolluted semitransparent ceramic thermal insulation forms the required thermoradiation fields and temperature profiles and can affect regulation of heat losses and a reduction of primarily nitrogen dioxide generation.

## 1. Introduction

This paper examines an already recognized method of efficiency increasing for Low-Heat-Rejection (LHR) diesel using well-known ceramic heat-insulating HICs- or thermal barrier TBCs-coatings which have been applied from the 70s of the last century in Russia [1-10] and abroad [13- 32]. But when suggesting that, the reducing toxicity of exhaust gases can be achieved using these ceramic coatings as a semitransparent one, taking into account their specific optical properties and formation of

a predetermined absorption regime of penetrating thermoradiation for control and management temperature of the exposed surface [7-10].

This problem is relevant for a diesel engine with a combustion chamber (CC), in which there is an intensive radiant (near-IR) component up to ~50% within total thermal flux [33-36]. Then these so called semitransparent coatings (SHICs or STBCs) can ensure the required heat rejection and controlled generation rate of exhaust gases (primarily nitrogen dioxide), caused by formation of specific temperature fields in their subsurface zones.

Extensive research of a quasi-adiabatic engine with using of heat-insulating coatings has been suspended since the end of the 20th century [1-3, 14-17]. In the authors' opinion, it was connected with an unresolved problem of effect of the radiant penetrating component (generated by red-hot soot particles) of total thermal flux falling on the heat-insulating coating, which can be semitransparent (see Fig. 1). Most well-known ceramic coatings based on oxides ($Al_2O_3$, $SiO_2$, $Zr_2O_3$) are semitransparent [7-10, 17, 36-38].
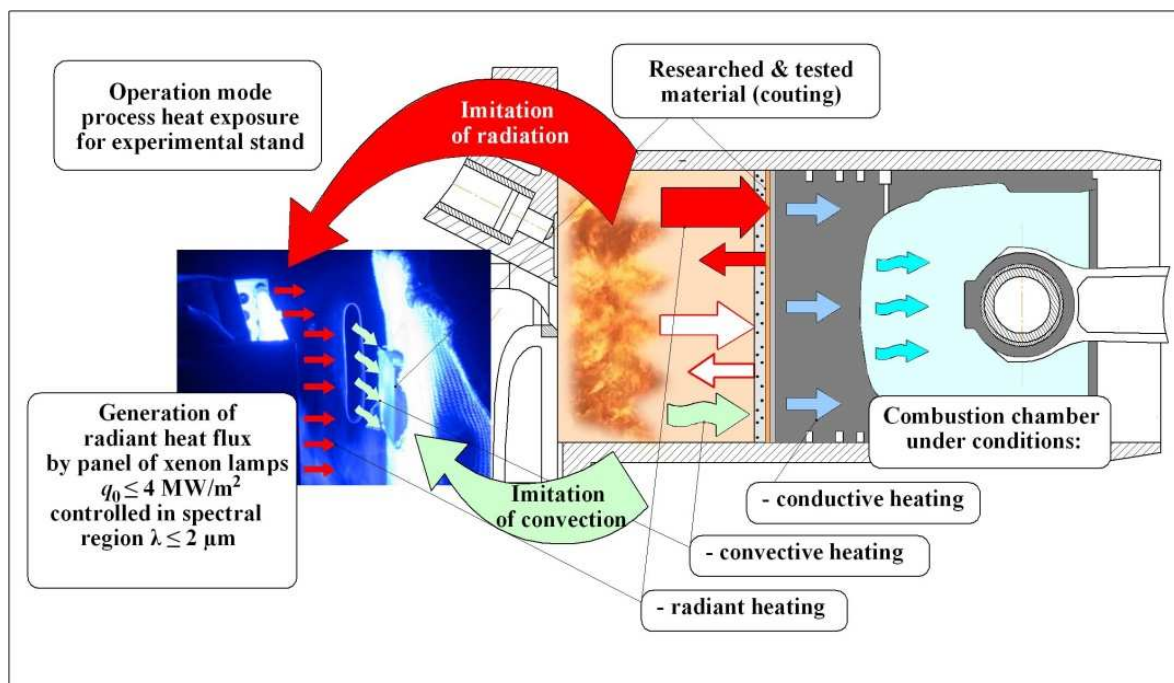


**Figure 1.** Block diagram of convective and radiant heat transfer inside diesel combustion chamber with opportunity of physical modeling using radiative-and-convective cycling simulator [11, 12].

Earlier used traditional heat-insulating coatings were considered as opaque for IR radiation. This was true only for some coatings, for example, based on $Si_3N_4$, SiC [4, 20-22]. Otherwise above-mentioned assertion will be erroneous and there is an incorrect analysis of complex heat transfer in the coated combustion chamber (CC).

Even the latest developments of thermal protection for LHR diesel engines still do not take into account the presence of the radiant component inside the combustion chamber and the optical properties of its ceramic coatings [4-6, 18-32]

But semitransparent coatings could be also considered as opaque because of the imperfection of the plasma-spraying technology, which causes the appearance of highly absorbent metallic particles of the plasmatron electrodes inside the coating.

All the opaque materials cause an increase of temperature on their irradiated surface due to high surface absorption of radiation within near IR. This effect had resulted to impermissible overheating of

the inner surface of the heat insulated CC' walls and intensive generation of the most toxic nitrogen oxides.

The temperature increase of the walls was noticed and indicated by the first publications [15-17], classical monographs [3, 18] and many subsequent current researches. But the main reason of surface overheating was not noticed - the possible surface absorption of thermoradiation by highly absorbing coatings of CC walls.

Nowadays numerous publications and special thematic reviews indicate the trend of extraordinary growing interest in application and study of ceramic TBCs (HICs) during the last 10 years [4-6, 13, 19-32]. This was due to progress and improving deposition technologies with a predetermined porosity and structural composition.

The authors of one of the reviews confirm the start of intensive development of TBCs by the global automotive industry [25]: "Research for decreasing costs and consumed fuel in internal combustion engines and technological innovation studies have been continuing. Engine efficiency improvement efforts via constructional modifications are increased today; for instance, parallel to development of advanced technology ceramics, ceramic coating applications in internal combustion engines grow rapidly".

As a rule, researchers only are citing [29, 30] the publications of the authors of this work. The fact of the need to analyse "semitransparent characteristics of ceramics" is indicated, but their own methodology of radiant-conductive heat transfer has not been corrected.

The studies of ceramic coatings for internal combustion engines in automotive industry are actually the result of implementation of earlier researches characteristics of radiant and convective ablative thermal protection for aerospace aircrafts started in 1960-70s [39-43].

Numerous R&D of TBCs were carried out using a classical apparatus of radiative transfer in semitransparent materials. But until now these developments have not been applied for investigation of non-destructible protective heat-insulating coatings in the auto industry [3-6, 13-32]. In aerospace industry, applying semitransparent ceramic for turbine elements was a logical continuation of investigation materials with a predetermined destruction threshold under continuous exposure of penetrating thermoradiation [44-47].

The term "Thermal Barrier Coating" came to the automotive industry from the aerospace terminology. Such heat-insulating materials are used to create a combustion chamber for adiabatic engines or their elements. At the same time, the first developers pointed out the need to study the role of radiation components in the combine exchange inside CC [1, 15-18]. Thus, in spite of the legendary developments of ceramic ICE in previous decades, many modern automotive engineers have not yet involved analysis of thermoradiation processes in their current researches [1, 3-6, 13, 18-32].

## 2. Physical and mathematical simulation of radiant and heat conductivity transfer

The engine researches show that if the temperature of combustion chamber' inner walls becomes 2 times higher, the value of the heat transfer coefficient increases 5 times. Then the heat exchange in the boundary layer of the combustion chamber (CC) wall begins to intensify [1-3, 18]. This is because the flame (combustion source) at high surface temperatures is moving closer to the wall, causing a rise of the temperature gradient since the distance from the source to the wall is decreasing.

In this connection, the studying of heat exchange of semitransparent heat-insulating coatings (SHICs) focuses on research of the influence of its thermal regime on the temperature of the inner surface of combustion chamber walls and the heat transfer through these coatings. The methodology of analysis of radiant heat exchange and theoretical evolutions of temperature profiles based on calculated thermoradiation fields inside coating layer are presented in the authors' works [7-10]. In this paper, new boundary conditions and thermal characteristics, obtained during conducted rig tests, were used for theoretical calculations of temperature fields in semitransparent coatings.

A one-dimensional optical two-layer model of semitransparent coating of the SHIC protecting metal substrate with surface reflection was used (see Fig. 1).

The diagram also presents the experimental radiative-and-convective cycling simulator allowing one to imitate a complex heat transfer inside the combustion chamber at an radiant flux of up to ~5 MW/m$^2$ (with several simulators) within a wavelength range of 0.3-2 µm in one-dimensional approximation for significant areas of internal CC walls (up to hundreds of square centimeters) [11, 12]. In these works, authors have solved the main problem of creation of laboratory set up with a broadband radiation source. This simulator's component includes high-intensity discharge xenon lamps, which is capable to generate the modelled impure radiation spectrum which is close to the continuous spectrum of radiation of red-hot soot particles in the typical combustion chamber (CC).

Partially yttria stabilized zirconia (PSZ) is the currently preferred coating for applications in CC diesel and turbines [4, 6-10, 13, 19-32, 36, 37, 44-47]. This coating has two import properties among semitransparent ceramics with low thermal conductivity: the most high thermal expansion coefficient and a good erosion resistance.

Substances PSZ ($ZrO_2$+3-8% $Y_2O_3$) were used to produce flat tablets of various thickness intended for optical measurements of reflection (transmittance) coefficients for evaluation scattering and absorption indexes [7, 8]. It is a purified granular powder with white colour in the visible range. This substance has a transparency window up to 4 µm with a stable reflection coefficient of 0.7-0.9 for thick layers [8, 38]. This material was applied for plasma spraying and forming:

- homogeneous plane ceramic layer (thickness up to 0.5 mm) of semitransparent coating for spectrophotometric measurements [8] and
- same layer deposited on the piston surface of the tested tractor diesel.

Therefore, in addition to heat conduction by lattice waves (phonons), inside semitransparent coating (SHIC), heat is also transferred by a radiative component (photons) which becomes increasingly important at elevated temperatures. Thus, the total energy transfer through the coating increases above the heat transfer caused by solid heat conduction alone.

Penetrating radiation certainly reduces the efficiency of thermal barrier characteristics of semitransparent coatings and degrades the insulating ability of SHIC. But the effect of their own surface heat reradiation causes a decrease of surface temperature and allows displacing a temperature maximum from a surface semitransparent material into the depth of a SHIC-coating with the expansion of the subsurface zone of volumetric radiant heating.

Thus, the simulated optical properties of the coating will determine the temperature field. Experimental modeling of optical parameters is carried out using spectrophotometric measurements of control flat ceramic samples of different thicknesses.

Using the Mie scattering theory, the given optical parameters will be determined by the selection of the specific structural composition and the porosity of the coatings [8].

Thus, technological structuring can ensure control and management of thermal conditions, form an acceptable temperature gradient, temperature regime of the coatings surface and gas in the combustion chamber [7-10, 44-47].

The opaque materials represent a model in which radiation of red-hot soot particles inside the combustion chamber does not penetrate through its exposed surface. This radiation is mainly absorbed by the combustion chamber (CC) walls surface with the exception of insignificant surface scattering and a small surface reflection by the Fresnel law. In this work, the surface reflection coefficient of the irradiated opaque ceramics was assumed to be equal to $R_{op} = R_S = 20\%$ for the heat-insulating coating HIC [8, 10, 37, 38]. An opaque HIC-coating is examined as a material with the same known thermal physical characteristics as the semitransparent SHIC-coating.

## 3. Numerically simulated temporal temperature of heat-insulating coatings under the action of a radiant-convective monopulse

For rig testings, samples of semitransparent SHIC-coatings were selected with the best form of calculated temperature profiles due to volumetric subsurface overheating and reduced surface temperature of determined specific optical properties of ceramic coatings (See Fig. 2). Powder PSZ-

ceramics based on $ZrO_2+8\%Y_2O_3$ had the optimal optical characteristics based on experimental measurement with the help of a serial spectrophotometer.

Selected ceramic powder was used both to make the control of flat samples and to spray on the piston surface using plasma technology.

These coatings were semitransparent ceramics with insignificant absorption ($\kappa = 14$ m$^{-1}$) and a high scattering ($\sigma = 2400$ m$^{-1}$) in the near infrared region of the spectrum. The reflection coefficients are ~ 40% for thin (0.5 mm) and ~ 90% for thick layers.

To analyze the difference in the temperature profiles of opaque HIC- and SHIC-coatings for the diesel combustion chamber (CC), these are the following interaction conditions (close to the heat characteristics of diesel during rig tests): the model total thermal flux is $q_0 = 1.8$ MW/m$^2$, fraction of radiant component is ~ 50%. The middle temperature in the CC gas volume was constant, $T_A(t) = 800$ K. The coefficient of turbulent heat exchange is $\alpha_T = 3000$ MW/(m$^2\cdot$K). Initial temperature is $T_0 = 500$ K.

Figure 2 shows the calculated temperature profiles inside thick layers of polluted opaque (line 2) and rectified semitransparent (3) PSZ-ceramic coatings, soot deposition (1) and uncoated metal wall (4) under conditions of constant heat pulse of radiant and convective action on the internal walls of the diesel combustion chamber.
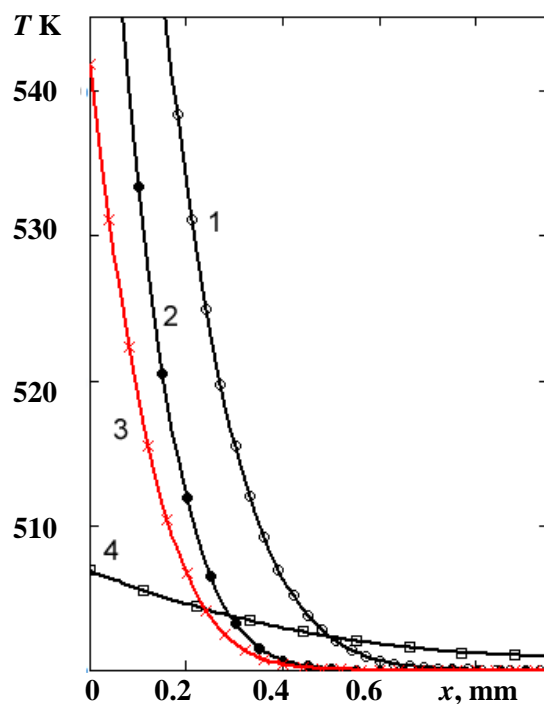


**Figure 2.** Numerically simulated temporal temperature in subsurface zone of heat insulation of combustion chamber exposed by radiant-convective monopulse at $t = 0.01$ s of primary fuel combustion tact for following layers:

- soot deposition (line 1),
- PSZ-ceramic coatings with equal thermophysical parameters and different absorption indexes
  - $\kappa \gg 14$ m$^{-1}$ (opaque ceramic, line 2) and
  - $\kappa = 14$ m$^{-1}$ (semitransparent ceramic with scattering index $\sigma = 2400$ m$^{-1}$, line 3).

Unprotected metal wall - line 4.
Back surfaces of coatings with thickness $H = 1$ mm are heat insulated.

The application of opaque coatings and soot deposition increases the temperature of the piston head surface by 100-200 K (see Fig. 2, lines 1, 2) stimulating the generation of nitrogen oxides and often with an undesirable regime of convective-radiation heat transfer inside CC. Under these conditions, the ceramic coating can be destroyed due to a large forming subsurface temperature gradient.

Thus, the thermal regime of the semitransparent coating (see Fig. 2, line 3) is more suitable and can be controlled by changing only the optical parameters due to the specific structuring, for example, the selection of the prevailing orientation for the scattering particles inside the ceramic layer [8, 40, 44-46]. In this case, the coefficient of thermal conductivity remains practically unchanged.

Proposed physical modeling of the optimal SHIC structure should contribute to the required thermal regulation of the CC' gas atmosphere, preventing its overheating and better self-ignition of the fuel.

**4. Numerically simulated temporal temperature of heat-insulating semitransparent SHIC- and opaque HIC-coatings at steady state**

Let us take the model conditions for the internal surface of the combustion chamber (CC) wall of a high-speed diesel during simulation of harmonic characteristics at rotational speed $n$ = 3000 rpm to be as follows: total thermal flux is ~ 1.8 MW/m$^2$ at the "hot" phase of 10 ms ("cold" phase of 30 ms) with fraction of radiant component of ~ 50% which varies from 0 up to 0.9 MW/m$^2$ during 2 ms [2, 3] (in a short wavelength diapason of 0.8-2 µm); direct heat loss through coated piston $q_w(t)$ changes up to 0.20 MW/m$^2$ at the "hot" phase. Gas temperature in CC volume changes from 330K to 2000K; oscillation amplitude of the heat turbulent transfer coefficient varies from 70 to 2000 W/(m$^2$·K); gas emissivity is 0.2 - 0.6. The heated top layer of the coating surface is considered as a black body with its own radiation in a long wavelength diapason of 2-5 µm.

Duration of cyclic times changing of the specified characteristics was obtained according to conditions of an optimum temperature regime of the exposed moving piston with a SHIC-coating during complex radiant heat exchange inside CC of high speed tractor engine TMZ-450D (see Fig. 1, 3, Table 1).
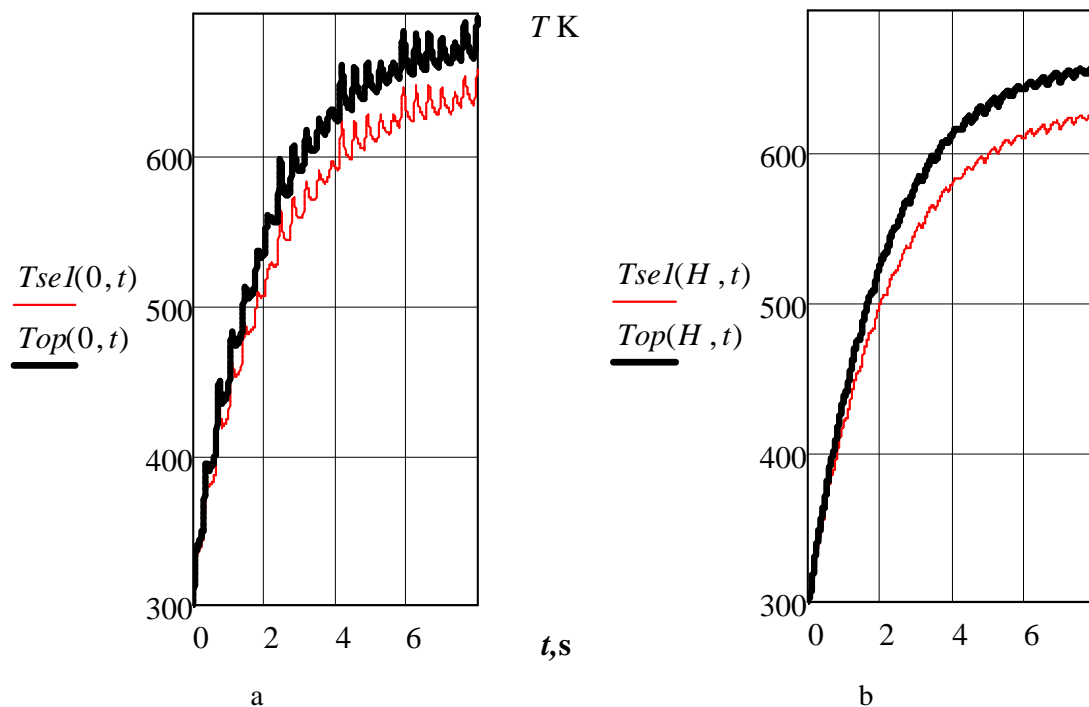


**Figure 3.** Cyclic temporal temperature variations $T(x,t)$ for the front (exposed) (a) and back (b) surfaces of the 0.5 mm ceramic top layer for optical parameters of the following coatings:
- opaque HIC-coating (surface heating at $R_S$ = 20%) with temperature distributions $T_{op}(0,t)$, $T_{op}(H,t)$;
- semitransparent SHIC-coating (volumetric subsurface heating with absorption index $\kappa$ = 14 m$^{-1}$ and scattering one $\sigma$ = 2400 m$^{-1}$) with temperature distributions of $T_{se1}(0,t)$, $T_{se1}(H,t)$.

A surface of oxidized metal substrate has reflection coefficient $R_{me}$ = 90%. The malty cycle of piston movement is at $n$=3000 rpm.

The temperature distributions in semitransparent layers with different optical models are simulated for the boundary conditions of the internal surface of the CC wall.

For example, the highest temperature of the front (exposed) surface of semitransparent

coating could be reached at $T_{se}(0, t) \sim 680K$ with transmissivity coefficient $\tau_{se} \sim 79$ % (absorption $\kappa = 10$ m$^{-1}$ and scattering $\sigma = 1000$ m$^{-1}$ indexes) and substrate reflection $R_{me} = 10\%$.

But changing of the SHIC structure allows one to decrease transmissivity $\tau_{se}$ up to 56 % (with higher scattering of $\sigma = 3000$ m$^{-1}$) and this surface temperature becomes lower, $T_{se}(0, t) \sim 660K$.

When increasing of substrate reflection $R_{me}$ up to 90%, there is the same result of $\sim 660K$ for SHIC and its temperature (on the back side of the coating) can be lower, $T_{se}(H,t) \sim 615K$, in comparison to temperature $T_{op}(H,t) \sim 655K$ for opaque coating.

When all radiant and heat fluxes are absorbed on the front surface of opaque HIC-coatings, then there is a high temperature gradient for opaque coatings in comparison to semitransparent SHIC-coatings.

The smaller absorption and the higher scattering of SHIC cause a decrease of the surface temperature of these SHIC-coatings in comparison with the opaque one, near 20–30 degree lower during one cycle (1$^{st}$ strike of combustion) of piston movement.

**Table 1.** The main performance characteristics, design and energy parameters of single-cylinder experimental diesel engine TMZ-450D (Russian production) [9]

| Characteristics of the engine | Physical dimensions | Numerical value or description |
|---|---|---|
| Location of cylinders | - | Vertical |
| Piston distance / Cylinder diameter | mm | 80/85 |
| Piston-swept volume | dm$^3$ | 0.454 |
| Compressive ratio | - | 20 |
| Rated speed | min$^{-1}$ | 3000 |
| Indicated power | kW | 8.0 |
| Specific fuel consumption at rated conditions | g/ (kW·h) | < 280 |

Optical models of such SHIC-coatings have the following characteristics: reflection of the semi-infinite layer is $\sim 80 \div 90\%$, absorption is $\kappa \sim 10$ m$^{-1}$ and scattering is $\sigma \sim 100\text{-}1000$ m$^{-1}$, indexes at emittance coefficient are $\sim 0.98$ in near IR (for such coatings as a black body in the middle IR diapason of $\sim 2\text{-}5$ µm ).

Increasing the scattering of semitransparent coatings 10 times leads to reducing temperatures on a surface and in the subsurface area of SHIC of about $\Delta T \sim 2\text{ -}3$ K for action of the 1$^{st}$ heat monopulse.

These results agree with data on temperature regimes of ceramic thermal barrier TBC-coatings for aircraft engines [44, 45].

For steady state conditions, the overheating of the surface of opaque coatings also exceeds the corresponding value for semitransparent coatings.

Figure 3 shows the temporal temperature variation for the front (exposed) and back surfaces of the 0.5 mm top layer for opaque $T_{op}$ and semitransparent $T_{se1}$ coatings with optical model $\kappa = 14$ m$^{-1}$, $\sigma = 2400$ m$^{-1}$ covering the reflecting layer of metal substrate $R_{ms} = 90\%$. Peak temperatures of SHIC keeps a value of $T_S \sim 650K$.

For opaque coating, the surface temperature is by $\sim 50$ K higher during the steady state.

On a back surface of coatings, temperatures are stabilized during achievement of 660 K for an opaque HIC-coating and 620 K for the semitransparent SHIC-coating. One should note the dependence of temperature maximum appearance on the back side of SHIC when decreasing the substrate reflection coefficient.

The steady state of the thermal regime is reached for 6-8 s.

The simulation of temperature regimes shows essential dependence on radiating heat fluxes for semitransparent coatings. It allows predicting optimal regimes of the operation for the LHR diesel before development and production of the coated combustion chamber using heat-insulating PSZ-ceramics.

**5. Experimental results of rig tests of high-speed tractor engine with piston coated PSZ-ceramics**
In this work, the influence of the selected piston' heat-insulating semitransparent coating (rectified PSZ-ceramic based on $ZrO_2+8\%Y_2O_3$ with highly reflective and weakly absorbing qualities in near IR) on reduction heat losses was evaluated with help of rig testings of the combustion chamber of high-speed single cylinder tractor engine diesel TMZ-450D (Table 1).

It is well-known that the heat-insulating surface of the piston or other CC elements contributes to:
•   growth of the intensity of combustion near the top dead centre, where the maximum pressure and temperature at the end of compression are reached;
•   increase of the brightness and temperature of the flame in the initial phase of combustion and shortening of the time of the combustion process.

The mechanical and fuel-energy characteristics of CC with a heat-insulated piston were determined in comparison with an unprotected piston (see Fig. 4).



|        a        |        b        |

**Figure 4.** Unprotected piston (a) and protected one (b) by semitransparent PSZ- ceramics.

Figure 5 shows that when using semitransparent heat insulation, the maximum value for heat rejection $q_w(\varphi)$ almost equidistantly decreases by 10% vs the crankshaft angle within the range from 20 to 80 degrees in comparison with the traditional diesel CC without heat insulating inserts.

Heat rejection from the working medium in the absence of semitransparent thermal insulation occurs in a wider range of CRA changing up to 80° during the combustion process. But SHICs application allows showing the effect of the regeneracy of useful heat accumulated inside coated walls. During the expansion stroke, the accumulated heat from the subsurface zone of this coating can be returned back to the diesel CC, i.e. it additionally turns into a useful work.

Some heat-energy and fuel characteristics of the unprotected piston and coated one of high-speed tractor engine TMZ-450D have been shown in Figures 5-7.

The rig test of this diesel with the use of semitransparent thermal insulation based on zirconium oxide with yttrium showed that the best results are obtained with high engine speeds from ~2800 to ~3400 rpm.

This is because combustion of fuel occurs almost completely near the top centre compression stroke since the surface temperature of the coated piston is higher than that for the unprotected one in CC. It will promote more favourable conditions of spontaneous fuel ignition and reduction of its combustion time. Thus, efficiency of the given operating regime of typical diesel tractor engine can be managed and controlled when using SHIC with optimal selected optical parameters in a wide range of their changes with negligible varying of thermophysical parameters.

Conducted standard rig testing of the diesel allowed one to estimate the heat losses of up to 0.2 MW/m$^2$ through the coated piston (see Fig. 5).

The hourly fuel consumption was determined by the weight method and was calculated based on measurements of time and expenditure of the fuel dose. Experimental test showed a 2-3% lower specific fuel consumption (see Fig. 6); ~2-5% greater power and turning moment (see Fig. 7) on a single cylinder experimental diesel at $n > 2800$ rpm, and it is due to the application of semitransparent ceramic coating.

The maximum pressure of the diesel cycle was increased by 3% at decreasing of the exhaust gases temperature up to 7%. This shows improvements in the diesel's working process, especially in the expansion cycle, where fuel energy turns into useful work.

The principle of the obtained results was confirmed in a number of works, including the paper of G. Woschni "Heat Insulation of Combustion Chamber Walls – a Measure to Decrease the Fuel Consumption of IC Engines" (1987) [15].

The data obtained from the tractor diesel testings with the coated piston by SHIC allowed qualitatively confirming volumetric overheating based on the predicted above calculated temperature distributions in SHIC-coatings, as well as a model version of the application of a completely opaque coating using the example of a polluted semitransparent coating and soot deposition (see Fig. 2, 3).

In Figure 8, the model of forming and removal of soot deposition is presented for a heat-insulated combustion chamber using semitransparent PSZ-ceramics (with a selected structure and optical parameters) for operating modes of a single-cylinder experimental engine at various speeds of rotation: 0 rpm - initial moment (*a*); in the process of the speed increasing (*b, c, d*).
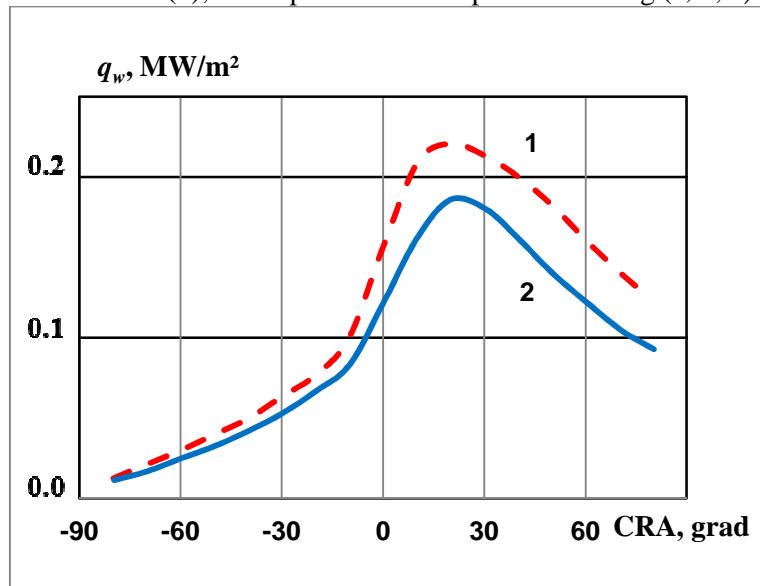


**Figure 5.** Heat losses $q_w$ through the uncoated (1) piston head and coated (2) one with semitransparent heat-insulating ceramic coating vs crankshaft rotation angle (CRA) for high-speed tractor engine TMZ-450D (Russian production).

In the process of fuel combustion, the internal surface of CC is polluted with soot deposition (see Fig. 8, *b, c*). In this case, the advantages of applying semitransparent coatings in comparison with opaque ones disappear. But with the increase of diesel engine speed, soot can begin to be gasified intensively (see Fig. 8, *d*) [3].

The conducted ring testings confirmed the prospects of using semitransparent SHIC-coatings to increase the efficiency of the diesel and possibility of the surface temperature regulation for irradiated ceramic insulation when controlling the nitrogen dioxide generation.

## 6. Conclusion

The experimental research of heat-insulated elements of the diesel combustion chamber and theoretical evolutions of thermoradiative and temperature fields allow one to predict reasonably the advantages of the application of semitransparent heat-insulating coatings which can ensure:

(1) volumetric absorption of penetrating thermal radiation in near IR (as fraction of total heat flux) inside the subsurface zone of semitransparent heat-insulating SHICs- or thermal barrier STBCs-coatings;

(2) accumulation of penetrating and absorbed thermoradiation in a near-IR during a combustion process and it will promote the thermal regeneration effect during other strokes of piston moving;
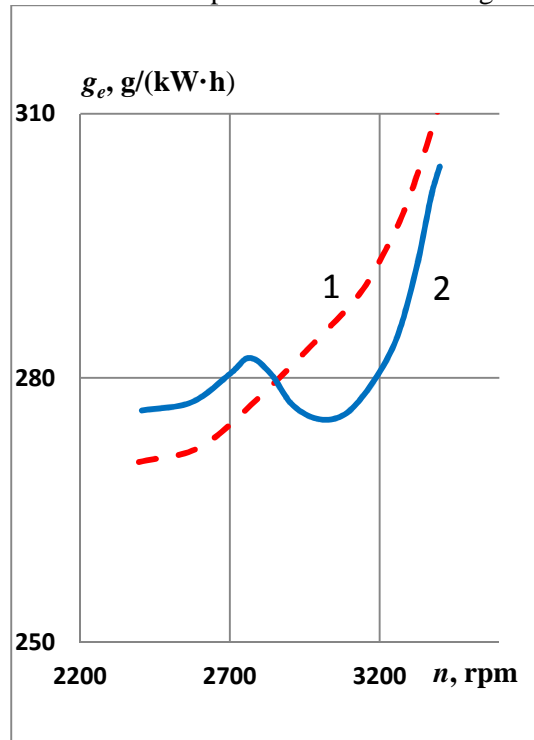


**Figure 6.** Experimentally measured values of specific fuel consumption $g_e$ depending on diesel speed $n$ during rig testings (see explanations in Fig. 5).
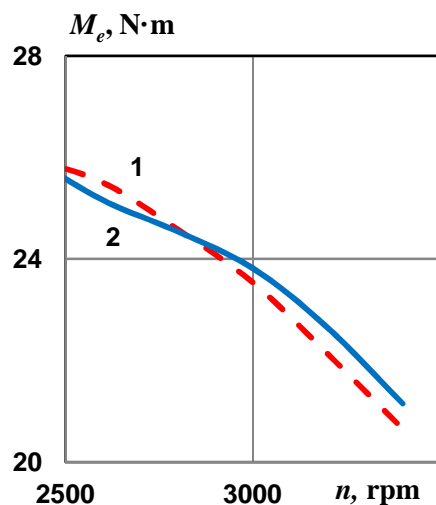


**Figure 7.** Turning moment $M_e$ depending on diesel speed $n$ during rig testings (see explanations in Fig. 5).

(3) formation of subsurface temperature maximum and low temperature gradient inside exposed semitransparent heat-insulating (thermal barrier) materials and coatings at combine radiant-convective heat exchange;

(4) thermal cooling of a heat-insulated metallic wall (substrate) taking into account the conductive heat removal to the irradiated surface of coating, its own reradiation in the long wavelength (2-5 µm) range and volume reflection in the short wavelength (0.8-2 µm) range;

(5) thermoregulation of the internal heat insulated surface of the combustion chamber based on modeling optical properties (reflection – transmissivity or absorption - scattering) for SHIC-coatings;

(6) simulation of surface temperature for the piston head with semitransparent SHIC-coatings (in contrast to the use of opaque HIC-coatings) causing the possibility of the reduction of $NO_x$ generation which will determine improved management by temperatures of the diesel combustion-exhaust system;

(7) controlling surface temperature of the coated piston using semitransparent SHIC-coatings with layer thickness of ~ 0.5 mm and following optical characteristics: reflection coefficient is ~ 70÷90% for the semi-infinite layer, absorption is $\kappa$~1-20 m$^{-1}$ and scattering $\sigma$ ~ 100-1000 m$^{-1}$ indexes (in the short-wave region); emittance coefficient is ε ~0.98 (in the long-wave region);

(8) regulated thermal stresses and the damage threshold based on the selection of optical parameters of coatings due to variation of the structure, changing distribution of absorbed thermal radiation and formation of the desired temperature profile;
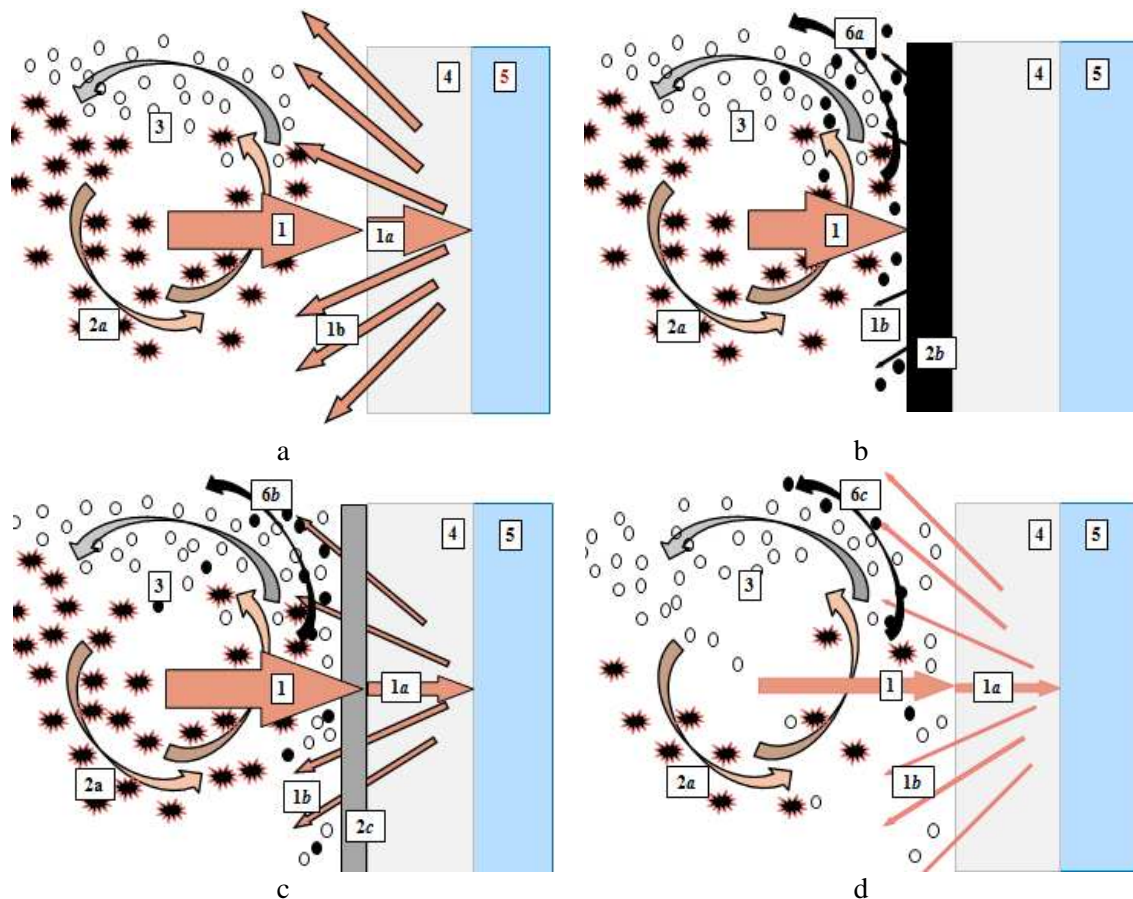


**Figure 8.** Model of forming and removal of soot deposition for a heat-insulated combustion chamber (using PSZ-ceramics) for operating modes of a Low-Heat-Rejection (LHR) diesel at various speeds of rotation at initial moment (a) and for processes of the speed increasing up to *n* = 2800 rpm (b, c) and more 2800 rpm (d):

1   - radiant component of the total heat flux in the near infrared wavelength range with the absorbed (1*a*) and reflected (1*b*) fluxes;

2   - flow of individual red-hot particles (2*a*) and a soot deposition (2*b*, 2*c*) above ceramic coating;

3   - flow of gasified carbon molecules;

4   - heat-insulating semitransparent coating;

5   - metal substrate;

6   - generation of nitrogen oxides molecules with maximum (6*a,* b) and negligible (6*b*, c; 6*c*, d) concentrations at high and low temperatures of the heated surface respectively for opaque (2*b*, b) and semitransparent (2*c*, c) soot deposition or its absence (d) above the SHIC-coating.

(9) standard rig testing confirmed the effectiveness of the combustion chamber of the high-speed diesel engine with the coated piston head using the PSZ-ceramic (with selected composition of $ZrO_2+8\%Y_2O_3$) layer produced by a plasma-spraying technology;

(10) heat losses do not exceed the value of ~ 0.2 MW/m$^2$ through the coated piston;

(11) improving characteristics of the LHR diesel at $n > 2800$ rpm: ~2-3% lower specific fuel consumption; ~2-5% greater effective power and drive torque in comparison with the uncoated piston

(12) physical modeling of the optimal SHIC-coatings' structure should contribute to the required thermal regulation gas atmosphere of the combustion chamber, preventing its overheating and better self-ignition of the fuel.

The authors have substantiated the growth of the efficiency of LHR diesel with increasing rotational speed by the effect of soot gasification, causing the changing of the coating' transparency and possibility of a wide range of variation scattering and absorption values due to structure modeling.

The opportunity is shown for the structure of the coating as an intellectual material able to monitor thermoradiative and temperature fields inside ceramic heat insulation for control of heat losses and formation exhaust gasses.

An application of the innovative ceramic with an adjustable structure as semitransparent heat-insulating SHICs-coatings (thermal barrier STBCs-coatings) for a new generation of diesel will promote increase efficiency engines with control of nitrogen dioxide generation.

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