Development of a semitransparent ceramic heat-insulation for an eco-friendly combustion chamber of 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 intensive radiant component (near IR) reaches ~50% within total thermal flux. Therefore, in their papers the authors offered 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 coated piston using selected SHIC (PSZ-ceramic ZrO$_2$+8%Y$_2$O$_3$) with a calculated optimum temperature gradient was chosen. A single cylinder experimental tractor diesel was used. At rotation frequency $n \geq 2800$ rpm the heat losses were no more than 0.2 MW/m$^2$. Executed testings showed ~2-3% lower specific fuel consumption in contrast the diesel with 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 reduction of primarily nitrogen dioxide generation.

1. Introduction
This paper examines 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 1970s of last century in Russia [1-10] and abroad [13-32]. But the authors suggest the reducing toxicity of exhaust gases can be achieved when using these ceramic coatings as semitransparent one taking into account their specific optical properties and formation 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 combustion chamber (CC) in which 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.

Since the end of the 20th century, extensive research of quasi-adiabatic engine with using of heat-insulating coatings has been suspended since the end of the 20th century [1-3, 14-17]. In our opinion, it was connected with unresolved problem of effect of radiant penetrating component (generated by red-hot soot particles) of total thermal flux falling on the heat-insulating coating, which can be semitransparent (see figure 1). Most well-known ceramic coatings based on oxides (Al₂O₃, SiO₂, Zr₂O₃) are semitransparent [7-10, 17, 36-38].

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

Earlier used traditional heat-insulating coatings were considered as opaque for IR radiation. This was true only for some coatings, for example, based on Si₃N₄, SiC [4, 20-22]. Otherwise the assertion will be erroneous and incorrect analysis of complex heat transfer in the coated combustion chamber (CC) would be conducted.

Even the latest developments in the field of thermal protection for LHR diesel engines still do not take into account the radiant component inside the combustion chamber and the optical properties of its ceramic coatings [4-6, 18-32].
But semitransparent coatings could be considered as opaque also 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 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 it was indicated by the first publications [15-
18], classical monographs [4, 18] and many recent researches. Eventual surface absorption of
thermoradiation by highly absorbing coatings of CC walls is the primary reason for overheating which
was not noticed.

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

The authors of one of the reviews confirm commencement of TBCs intensive development of by
global carmakers [25]: “Research to decrease costs and fuel consumption in internal combustion
engines and technological innovation studies continue. Today, researchers work hard to improve
engine efficiency via constructional modifications. For instance, alongside with development of
advanced technology ceramics, ceramic coating applications in ICEs are taking place”.

Usually, researchers are citing only the publications of the authors of this paper [29, 30]. Need to
analyse “semitransparent characteristics of ceramics” - is emphasized, but their own methodology of
radiant-conductive heat transfer has not been corrected.

The studies of ceramic coatings for ICEs in automotive industry are actually the result of earlier
researches of 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 classical apparatus of radiative transfer in
semitransparent materials. But until now these developments have not been applied for research 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 research
of materials with a predetermined destruction threshold under continuous exposure of penetrating
thermoradiation [44-47].

The term “Thermal Barrier Coating (TBC)” came to the automotive industry from the aerospace
terminology. Such heat-insulating materials were used to design combustion chamber (CC) 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 ICEs in previous decades many automotive engineers have not yet
involved analysis of thermoradiation processes in their current researches [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 fivefold. 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.

As such, the studying 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. Methodology of analysis of
radiant heat exchange and theoretical evolutions of temperature profiles based on calculated
thermoradiation fields inside coating layer are presented in our papers [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.

One-dimensional optical two-layer model of semitransparent coating SHIC protecting metal substrate with surface reflection was used (see figure 1).

The diagram also presents the experimental radiative-and-convective cycling simulator. It allows to imitate a complex heat transfer inside the combustion chamber at an radiant flux up to ~5 MW/m² (with several simulators). Within wavelength range 0.3-2 µm in one-dimensional approximation for large areas of internal CC walls (up to hundreds of square centimeters) [11, 12]. In these papers authors have solved the main problem of creation of laboratory set up with broadband radiation source. This simulator’ component includes high-intensity discharge xenon lamps, which is capable to generate the modelled impure radiation spectrum 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]. Among semitransparent ceramics with low thermal conductivity the coating has two import properties: the most high thermal expansion coefficient and a good erosion resistance.

A substances PSZ (ZrO_2+3-8%Y₂O₃) 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 0.7-0.9 for thick layers [8, 38]. This material was used 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.

So, alongside to heat conduction by lattice waves (phonons), inside semitransparent SHIC-coating heat is also transferred by a radiative component (photons). They become increasingly important at elevated temperatures. Thus, the total energy transfer through the coating exceeds the heat transfer caused by solid heat conduction alone.

Certainly, penetrating radiation reduces the efficiency of thermal barrier characteristics of semitransparent coatings and degrades SHIC insulating ability. 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 would 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 would be determined by the selection of the specific structural composition and the porosity of the coatings [8]. 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 model in which radiation of red-hot soot particles inside 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 paper the surface reflection coefficient of the irradiated opaque ceramic was assumed to be equal $R_{op} = R_s = 20\%$ for the heat-insulating HIC-coating [8, 10, 37, 38]. An opaque HIC-coating is seen 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 with best form of calculated temperature profiles due to volumetric subsurface overheating and reduced surface temperature determined specific optical properties of ceramic coatings were selected (see figure 2). Powder PSZ-ceramic based on ZrO$_2$+8%Y$_2$O$_3$ had the optimal optical characteristics experimental measurement with a serial spectrophotometer.

The ceramic powder was used to make check 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 $\sim 40\%$ for thin (0.5 mm) and $\sim 90\%$ for thick layers.

Difference in the temperature profiles of opaque HIC- and SHIC-coatings analysis for the diesel combustion chamber (CC) was conducted under the following interaction conditions (close to the heat characteristics of bench tests): the model total thermal flux $q_0 = 1.8$ MW/m$^2$, fraction of radiant component $\sim 50\%$. The middle temperature in the CC gas volume was constant $T_A(t) = 800$ K. Turbulent heat exchange ratio is $\alpha_T = 3000$ MW/(m$^2$·K). Initial temperature $T_0 = 500$ K.

Figure 2 shows the calculated temperature profiles in side 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.

![Temperature Profiles](image)

**Figure 2.** Numerically simulated temporal temperature in subsurface zone of heat insulation of combustion chamber exposed by radiant-convective monopulse during at $t = 0.01$ s of primary fuel combustion tact for the following layers:
- soot deposition (line 1);
- PSZ-ceramic coatings with equal thermophysical parameters and different absorption indexes
  - $\kappa >> 14$ 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 is heat insulated.

The usage of opaque coatings and soot deposition increases the temperature of the piston head surface by 100-200 K (see figure 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 figure 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 the prevailing orientation for the scattering particles inside the ceramic layer [8, 40, 44-
46]. In this case, coefficient of thermal conductivity seems to remain 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 more active fuel self-
ignition.

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

We use the standard conditions of ring testings for internal surface of the high-speed diesel combustion chamber (CC) wall. At harmonic characteristics simulation at rotational speed of \( n = 3000 \) rpm they are to be the following: total thermal flux \( \sim 1.8 \text{ MW/m}^2 \) at the “hot” phase 10 ms (“cold” phase 30 ms) with fraction of radiant component \( \sim 50\% \) which varies from 0 up to 0.9 MW/m\(^2\) during 2 ms [2, 3] (in short wavelength diapason 0.8-2 \( \mu \)m); 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 heat turbulent transfer coefficient varies from 70 to 2000 W/(m\(^2\)·K); gas emissivity 0.2 - 0.6. Heated top layer of coating surface considered as black body with own radiation in long wavelength diapason 2-5 \( \mu \)m.

Duration of cyclic changes of values of the characteristics is achieved for a moving piston with SHIC-coating at complex radiant heat exchange inside CC of high-speed tractor engine TMZ-450D (see table 1, figure 1, 3).

![Figure 3](image-url)

**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 \( T_{\text{op}}(0,t) \), \( T_{\text{op}}(H,t) \);
- semitransparent SHIC-coating (volumetric subsurface heating at absorption index \( \kappa = 14 \) m\(^{-1}\) and scattering one \( \sigma = 2400 \) m\(^{-1}\)) with temperature distributions - \( T_{\text{se1}}(0,t) \), \( T_{\text{se1}}(H,t) \).

A surface of oxidized metal substrate has reflection coefficient \( R_{\text{me}} = 90\% \). Malty cycle of piston movement at \( n=3000 \) rpm.
The temperature distributions in semitransparent layers with different optical models are simulated for the boundary conditions of internal surface of CC wall.

For example, the highest temperature of front (exposed) surface of semitransparent coating could be reached \( T_{se}(0, t) \sim 680\text{K} \) with transmissivity coefficient \( \tau_{se} \sim 79 \% \) (absorption \( \kappa = 10 \text{m}^{-1} \) and scattering \( \sigma = 1000 \text{m}^{-1} \) indexes) and substrate reflection \( R_{me}=10\% \).

But changing of SHIC-coating structure allows to decrees transmissivity \( \tau_{se} \) up to 56 \% (at more high scattering \( \sigma = 3000 \text{m}^{-1} \)) and this surface temperature becomes lower \( T_{se}(0, t) \sim 660\text{K} \).

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

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

| 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 | g/ (kW·h) | < 280                       |

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

Increasing of scattering of semitransparent coatings in 10 times leads to reducing temperatures on a surface and in subsurface area of SHIC about \( \delta T \sim 2 \text{-} 3 \text{K} \) for action of 1st 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 surface of opaque coatings also exceeds the corresponding value for semitransparent coatings.

Figure 3 show temporal temperature variation for the front (exposed) and back surfaces of the 0.5 mm top layer for opaque \( T_{op} \) and semitransparent \( T_{se} \) coatings with optical model \( \kappa =14 \text{m}^{-1}, \sigma = 2400 \text{m}^{-1} \) covering reflecting layer of metal substrate \( R_{me} = 90\% \).

Peak temperatures of SHIC-coating keeps a value \( T_S \sim 650\text{K} \).

For opaque coating the surface temperature by \( \sim 50 \text{K} \) is higher during steady state.

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

On a back surface of coatings temperature are stabilized at achievement 660 K for an opaque HIC-coating and 620 K for the semitransparent SHIC-coating.

It should be noted dependence of temperature maximum appearance on the back side of SHIC at decreasing of substrate reflection coefficient.
The simulation of temperature regimes shows essential dependence from radiating heat fluxes for semitransparent coatings. It allows predicting optimal regimes of the operation for LHR diesel before development and production of coated combustion chamber using heat-insulating PSZ-ceramic.

5. Experimental results of rig tests of high-speed tractor engine with piston coated PSZ-ceramic

Let us consider practical application of semitransparent materials for heat insulation of CC piston using a single cylinder experimental diesel engine TMZ-450D (see figure 4, table 1).

The main objective of this research is standard rig testing and confirmation of the effectiveness of high-speed diesel engine combustion chamber (CC) with coated piston head using rectified PSZ-ceramic layer produced by a plasma-spraying technology.

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 the brightness and temperature of the flame in the initial phase of combustion and shorten the time of the combustion process.

In this paper, the influence of selected piston's heat-insulating coating (PSZ-ceramic based on ZrO₂ + 8% Y2O₃ with highly reflective and weakly absorbing in near IR) on heat losses reduction was evaluated through ring tests of high-speed tractor engine diesel combustion chamber.

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

![Figure 4. Picture of unprotected (a) piston and protected one (b) by semitransparent PSZ-ceramic.](image)

The figure 5 shows usage of semitransparent heat insulation decreases the maximum value for heat rejection \( q_w(\phi) \) almost equidistantly by 10% depending upon the crankshaft angle within range from 20 to 80 degrees in comparison with the traditional diesel CC without heat insulating inserts.

The CC combustion intensity with coated piston can be regulated using semitransparent coatings with selected structure for volumetric absorption of penetrating radiant energy. This effect takes place at transmittance coefficient \( \tau_{se} \sim 66\% \) for the coating with absorption \( \kappa = 14 \text{ m}^{-1} \) and scattering \( \sigma = 2400 \text{ m}^{-1} \) indexes which theoretically determined the temperature profile with the minimum temperature gradient.

As noted above, the modeled structure of the plasma coating was produced via required optical parameters using spectrophotometric control method.

Thus, the desired temperature profile for the CC heat-insulated walls with a predetermined subsurface temperature gradient will be selected by the forming thermoradiation and temperature field inside the appropriate structural composition of SHIC for coated piston or other CC elements.
Heat rejection from the working environment in the absence of semitransparent thermal insulation occurs in a wider range of CRA changing up to 80° at 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 (Russian production) are shown on figures 5-7.

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, that combustion of fuel occurs almost completely near the top centre compression stroke, since the surface temperature of the coated piston is higher than for 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 at use SHIC with optimal selected optical parameters in a wide range of their changes at negligible varying of thermophysical parameters.

Conducted standard rig testing of the diesel allowed to estimate the heat losses up to 0.2 MW/m² through coated piston (see figure 5).

![Figure 5](image_url)

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

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 2-3% lower specific fuel consumption (see figure 6); ~2-5% greater power and turning moment (see figure 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 paper 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 a coated piston by SHIC allowed confirm volumetric overheating qualitatively based on the predicted above calculated temperature distributions in this coating as well as provide a model version of the application of a completely opaque coating (based on a polluted semitransparent coating and soot deposition sample) (see figures 2, 3).

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

In figure 8, the model of forming and removal of soot deposition is presented for a heat-insulated combustion chamber using semitransparent PSZ-ceramic (with 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).

In the process of fuel combustion, the internal surface of CC is polluted with soot deposition (see figure 8, (b), (c)). In this case, the advantages of applying semitransparent SHIC-coatings in comparison with opaque HIC-coating disappear. But with the increase of diesel engine speed, soot can begin to be gasified intensively (see figure 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 at control the nitrogen dioxide generation.
6. Conclusion
Experimental researches of heat-insulated elements of the diesel combustion chamber (CC) and theoretical evolutions of thermoradiative and temperature fields allow to make a case for the advantages of the semitransparent heat-insulating coatings application which can ensure:

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

2. accumulation of penetrating and absorbed thermoradiation at a combustion process and it will promote the thermal regeneration effect during other strokes of piston moving;

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

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

7. controlling surface temperature of coated piston using semitransparent the SHIC-coatings with layer thickness ~ 0.5 mm and following optical characteristics: reflection coefficient ~ 70-90% for semi-infinite layer, absorption κ~ 1-20 m⁻¹ and scattering σ~ 100-1000 m⁻¹ indexes (in the short-wave region); emittance coefficient 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 desired temperature profile;

9. standard rig testing confirmed of the effectiveness of combustion chamber of high-speed diesel engine with coated piston head using PSZ-ceramic (with selected composition ZrO₂+8%Y₂O₃) layer produced by a plasma-spraying technology

10. heat losses do not exceed value ~ 0.2 MW/m² through coated piston;
(11) improving characteristics of the LHR diesel at \( n > 2800 \) rpm: \( \sim 2-3\% \) lower specific fuel consumption; \( \sim 2-5\% \) greater effective power and drive torque in comparison with uncoated piston

(12) physical modeling of the optimal SHIC-coating’ 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 made the case for rise in the efficiency of LHR diesel with increasing rotational speed due to of soot gasification. This brought about the changes of the coating’ transparency and possibility of wide range of variation scattering and absorption values and structure modeling.

The opportunity of reconstructing the structure of the coating as “smart material” to monitor thermoradiative and temperature fields inside ceramic heat insulation for control heat losses and formation exhaust gasses is shown.

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

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 2800 rpm (b), (c) and more this value (d):

1 - radiant component of the total heat flux in the near infrared wavelength range with the absorbed \((1a)\) and reflected \((1b)\) fluxes;
2 - flow of individual red-hot particles \((2a)\) and a soot deposition \((2b, 2c)\) above ceramic
coating;  
3 - flow of gasified carbon molecules;  
4 - heat-insulating semitransparent coating;  
5 - metal substrate;  
6 - generation of nitrogen oxides molecules with a maximum (6a, b) and a negligible (6b,  
c; 6c, d) concentrations at high and low temperatures of heated surface respectively for  
opaque (2b, b) and semitransparent (2c, c) soot deposition or its absence (d) above SHIC-  
coating.

References
[1] Kostin A K 1979 Thermal Stress of Internal Combustion Engines (Moscow: Russ Publ Mech  
Eng) p 231  
[2] Bazhaykin A N 1992 Characteristics of ignition and combustion of fuel jets in heat-insulated  
combustion chamber Journal of Engine Building 4 pp 23-8  
[3] Kavtaradze R Z 2001 Local Heat Transfer in the Piston Engines (Moscow: Bauman Moscow  
State Technical University) p 592  
[4] Kavtaradze R Z, Onishchenko D O, Zelentsov A A, Kadyrov S M and Arypzhano M M 2011  
Calculus-experimental study of influence of thermal insulation piston and cylinder liner for  
generation nitric oxides in combustion products high-speed diesel Herald of the Bauman  
MSTU, Ser. Mech. Eng. 4 pp 83–102  
[5] Dudareva N Yu, Kal’shchikov R V, Dombrovskii O P and Butusov I A 2015 Experimentally  
studied thermal piston-head state of the ICE with a thermal layer formed by micro-arc  
oxidation method Nauka i Obrazovanie. MGTU im. N.E. Bauman (Electronic Materials) 05  
pp115–125  
[6] Onishchenko D O, Pankratov S A and Smirnov A Yu 2016 Effect of the partial heat insulation  
of the d. e. combustion chamber on heat transfer into the cooling system Herald of the  
Bauman MSTU, ser. Mech. Eng. 3 pp 81–89  
[7] Merzlikin V, Timonin V, Gutierrez O M and Sidorov O 2007 New selectively absorbing and  
scattering heat-insulating coatings of the combustion chamber for LHR Diesel SAE  
Technical Paper 2007-01-1755  
[8] Merzlikin V, Sidorov O, Cheranev S and Antonakopoulos N 2011 Optimal spectral optical and  
thermo radiating characteristics of semitransparent heat-insulating coatings for Low-Heat-  
Rejection diesel engines Proc. 11th Int. Conference on Engines and Vehicle ICE2011 (Capri  
– Naples) Book of abstracts 41  
[9] Gutierrez O M 2007 Reduction of heat losses and thermal stress of diesels using  
semitransparent ceramic coatings (Moscow: Extended abstract of PhD dissertation, Moscow  
State Technical University “MAMI”) p 28  
[10] Merzlikin V G, Parshina S A, Garnova V Yu, Bystrov A V, Makarov A R and Khudyakov S V  
2017 Rig test of diesel combustion chamber with piston coated optically simulated  
semitransparent PSZ-ceramic Proc. 13th Int. Conference on Engines and Vehicle ICE2017  
(Capri - Naples) 2017-24-0129  
[11] Merzlikin V G, Tovstonog V A, Eliseev V N 2014 Thermal Energy Radiator RF Patent  
2,529,894  
[12] Eliseev V N and Tovstonog V A 2013 Evaluation of possibility of using tubular gas-discharge  
radiation sources for simulating thermal regimes of large-size space structures Herald of the  
Bauman Moscow State Tech. Uni., Ser. Mech. Eng. 2 pp 111-16  
[13] Uchida N and Osada H 2017 A new insulation concept for heavy-duty diesel engines to reduce  
heat loss from the wall Proc. 13th Int. Conference on Engines and Vehicle ICE2017 (Capri  
– Naples) 2017-24-0161
[14] Annand W J D 1963 Heat transfer in the cylinders of the reciprocating Internal Combustion Engines Proc. Inst. Mech. Engin 177 973-990
[15] Woschni G, Spindler W and Kolesa K 1987 Heat insulation of combustion chamber walls – a measure to decrease the fuel consumption of IC Engines SAE International Paper 870339
[16] Morel T and et al. 1989 Heat transfer in a cooled and an insulated diesel engine SAE Technical Paper 890572
[17] Ogury T and Inaba S 1972 Radiant heat transfer in diesel engines SAE Technical Paper 720023
[18] Rakopoulos C D and Giakoumis E G 2009 Diesel engine transient operation. principles of operation and simulation analysis (Springer-Verlag London Limited) p 390
[19] Azadi M A 2013 A review of the effects on diesel engine performance and components lifetime Int. J. of Autom. Eng. 3 pp 305-317
[20] Das D, Majumdar G, Sen R S and Ghosh B B 2013 Evaluation of combustion and emission characteristics on diesel engine with varying thickness of PSZ coated piston crown Int. J. of Innovative Research in Sci., Eng. and Tech. 2 (10)
[21] Ramu P and Saravanan C G 2009 Effects of ZrO2-Al2O3 and SiC coating on diesel engine to study the combustion and emission characteristics SAE International Paper 2009-01-1435
[22] Sankar V 2014 Thermal barrier coatings material selection, method of preparation and applications – a review Int. J. Mech. Eng. & Rob. Res. 510-517
[23] Domakonda V K and Puli R K 2012 Application of thermal barrier coatings in diesel engines: a review Energy and Power 2(1) pp 9-17
[24] Kosaka H, Wakisaka Y, Nomura Y, Hotta Y, Koike M, Nakakita K and Kawaguchi A 2013 Concept of “Temperature Swing Heat Insulation” in combustion chamber walls, and appropriate thermo-physical properties for heat insulation coat SAE Int. J. Engines 6 (1) 142-149
[25] Ciniviz M, Salman M S, Canl E, Köse H and Solmaz Ö 2012 Ceramic coating applications and research fields for ICES”, Ceramic Coatings – App. in Engineering 195-234
[26] Bovo M, 2014 Principles of heat transfer in Internal Combustion Engines from a modeling standpoint (Gothenburg: PhD Diss., Dep. of Appl. Mech., Chalmers Uni. of Tech) p 37
[27] Blomqvist Ch 2014 Thermal Barrier Coatings for Diesel Engine Exhaust Application (Karlstad: Master’s degree in Eng. Sc. & Mech. Eng., Karlstads Univ.) p 73
[28] Mohan B 2015 Performance and emission optimization of CIDI Engine through various fuel injection strategies (Singapore: PhD Diss., National Uni. of Singapore) p 250
[29] Hoffman M A, Lawler B J, Filipi Z S, Güralp O A and Paul M N 2014 Development of a device for the nondestructive thermal diffusivity determination of combustion chamber deposits and thin coatings J. Heat Transfer 136 7
[30] Dubouil R 2012 Simulation study of heat transfers in a motor electric hybrid powertrain thermics (Nantes: Ecole Centrale de Nantes) p 266
[31] Carmona D D V 2014 Thermal barrier coatings for efficient combustion (Stockholm: Master’s Degree in Materials Sc. & Eng., School of Ind. Eng. & Manag., KTN Campus) p 96
[32] Güralp O A 2008 The effect of combustion chamber deposits on heat transfer and combustion in a homogeneous charge compression ignition engine (Michigan: PhD Diss., Uni. of Michigan, Dep. of Mech. Eng.) p 107
[33] Chirkov A A 1962 About the level of scientific research of heat transfer in internal combustion engines Bulletin of Mechanical Engineering (Yaroslavl: Yaroslavl Ins. of Technology) 6 pp112-124
[34] Ryabov D I and Sviridov U B 1958 Research of some features of burning sprayed fuels. News of Academy of Sciences of the USSR OTN
[35] Pflaum W 1961 Die Warmeubertragung bei dieselmaschinen mit unci ohne auflagung Motor Technische Zeitung 3 pp 570-574
[36] Dannecker R, Noll B, Hase M, Krebs W, Schildmacher K.-U, Koch R. and Aigner M 2007
Impact of radiation on the wall heat load at a test bench gas turbine combustion chamber: measurements and CFD simulation Am. Soc. of Mech. Eng. (ASME), Proc. of Turbo Expo. Power for Land, Sea, and Air (Montreal) vol 4 parts A & B GT2007-27148 1311-1321

[37] Makino T, Kunitomo T, Sakai I and H. Kinoshita 1984 Heat Transfer. Jpn. Res. 13 33-36

[38] Novitski L A 1980 Optical properties of materials in low temperatures (Moscow: Mashinostrojenye) p 243

[39] Avduevskiy V S 1972 Fundamentals of the flight theory of space vehicles (Moscow: Publ. “Mashinostroenie”) p 345

[40] Tovstonog V A 1993 The evaluation of fireproof properties of light-scattering coatings High Temp. 31(4) 202–208

[41] Boeringer J C and Spindler R J 1963 Radiant heating of semitransparent materials AAIA Journal 1(1) pp 84-88

[42] Viskanta R and Grosh R J 1961 Heat transfer in a thermal radiation, in absorbing and scattering medium Int. Development in Heat Transfer (New York: ASME) part IV pp 820-828

[43] Howe J T, Green M J and Weston K C 1973 Thermal protection by subliming volumetric reflective materials in convective and intensive radiant environments, AAIA J. 11(7)

[44] Siegel R 1996 Internal radiation effects in zirconia thermal barrier coatings AIAA J. Thermophysics Heat Trans. 10(4) pp 707-709

[45] Manara J, Arduini-Schuster M, Rötzler-Scheibe H-J and Schulz U 2009 Infrared-optical properties and heat transfer coefficients of semitransparent thermal barrier coatings Surface and Coatings Technology 203(8) pp 1059-1068

[46] Wang L, Eldridge J I and Guo S M 2014 Comparison of different models for the determination of the absorption and scattering coefficients of TBCs Acta Materialia 64 pp 402-410

[47] Karaoglanli A C, Ogawa K, Türk A and Ozdemir I 2013 Thermal shock and cycling behavior of thermal barrier coatings (TBCs) used in gas turbines Progress in Gas Turbine Performance, ed E Benini chapter 10 p 268