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SEMITRANSPARENT CERAMICS FOR HEAT-INSULATING COVERS OF THE COMBUSTION CHAMBER

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Theoretical study of the semitransparent heat-insulating coatings used for the combustion chamber (CC) of reciprocating engines is made. These coatings will provide the thermal regime at generation in combustion chamber until 50% radiant component heat flow.

Model of the samples of porous ceramic materials, were offered as heat-insulating coatings. They are based on powders of zirconium, silicon, aluminum oxide which have transparent bands over the range of radiation wavelengths of the inflamed gas mixture in the combustion chamber of high-speed diesel engines. The radiant - conductive theory of subsurface heat of semitransparent coatings combustion chamber walls under the action of intensive radiant and convection heat flow is discussed. Results of simulation have shown that there is a subsurface temperature maximum inside ceramics under intensive visual and short-range infrared radiation. This allows providing an optimum temperature mode in the CC. This will limit the formation of toxic gases and may increase the efficiency of the internal combustion engine.

Introduction

Object of research are heat-insulating covers applied in the combustion chambers of diesel engines. This cover provides regulation of the thermal regime due to selective absorption radiant components of the thermal flow by the gas mixture combustion during the operation of the internal combustion engine. The theory of radiant-conductive subsurface heating of the combustion chamber wall is presented at the influence of intensive radiant component heating. It is the new point of view on radiant heat transfer processes in heat-insulating covers as light-scattering and faintly absorption medium. It has been shown as a functional communication between albedo of the ceramic layer and its scattering and absorption indexes. It has allowed to offer simple optical models for thick ceramics and directly to calculate the absorbed radiant energy function depending on absorption and scattering indexes. It has been used real thermal physical characteristics of the ceramics on the basis silicon oxide. At the analysis of optical properties, the absorption indexes for porous ceramics are presented by known experimentally measured of monolithic powder. But scattering indexes values of various kinds of a porous ceramics have been considered as modeling.

Analysis of the thermal radiation effects in semitransparent ceramics as heat-insulating or thermal barrier coatings is made.

Ceramic parts and coatings are needed to withstand high temperatures and to reduce an external heat reject in the advanced high-speed diesel engines.

In hot environments, such as in the combustion chambers of these engines, infrared and visible radiation can penetrate into some ceramics and heat them internally.

From numerical simulations follows that the intensive short-wave radiation flux is able to create the subsurface temperature maximum even under small external temperatures including temperatures under zero [3,9]. That is why the temperature in the surface increases its value more slowly than the heated inner layers. It leads to formation of subsurface temperature maximum and may be subsurface fusion and sublimation.

The internal temperatures depend of the radiating effects combined with heat conduction, and of the convection and radiation in the boundary zone of the material.

Since inflamed gas mixture temperatures are high until 1500-2000 K, its radiant emission can be large from them and this radiation can penetrate into semitransparent parts and coatings of CC. This must be included in the heat transfer analysis of the combustion chambers walls.

Transient and steady-state behaviors are both important. During a transient stage, radiant penetration provides more rapid internal heating than conduction alone. The temperature distributions are usually considerably different than for steady-state conditions; this can produce transient thermal stresses.

Therefore in the given research was studied the heating up of the ceramic as a heat-insulating coatings, and have been considered models as thin layers, and real models as thick layers with thickness equals to 1 mm.

Modern analytical and numerical methods allow predicting transient temperatures and heat flows in translucent materials.

A transient processes analysis was done for plane thin and thick layers from:

1) a traditional opaque materials [1, 2]: iron - materials of combustion chamber wall, and its heat-insulating coatings from the industrial ceramic, the sample on the basis of chemically no rectified powder, for example oxide zirconium,

2) an advanced semitransparent and scattering materials [4-6, 8 - 9] from the ceramic sample on the basis of chemically rectified typical powder: ZrO_2 (partial stabilized zircon with yttrium), SiO_2 , Al_2O_3 .

Model description

As have shown researches of last 10-15 years an essential fraction of radiant components up to 50% takes place in chambers of combustion of high-speed diesel engines [1, 2, 10].
It was caused by local combustion of soot particles at temperatures 1500K - 2500K with characteristic wave length of radiation equal to 1-3 µm.

In general, the generation of a short-wave radiation flow q_o can occur in visible and near infra red-ranges of wavelength $\lambda = 0.3\text{-}5$ µm.
Thus, it is necessary to examine radiating heat exchange between the combustion chamber walls and the heat insulating coating.

Then takes place two types of thermal fluxes: radiant and convective (fig.1).

This flux on the wall of the combustion chamber defines superficial and volumetric radiating heating of the insulating heat coverings and walls.

The equations of heat conductivity and radiation were solved in common in one-dimensional approximation [5]. Optical parameters were introduced in two-flux optical model [5, 9]. The profiles of temperature and the temperatures on frontal and back surfaces, and also the maximum temperature sub-surface volume for semitransparent materials (tab. 2) have been calculated.

In known researches [2] of diesel engines for achievement of high efficiency heat insulating coatings are used in the combustion chambers.

With rare exception [4, 7], but materials of these coverings it was not considered as translucent. Besides process plasma deposition for the heat insulating covers leads to essential pollution of a ceramic layer by absorbing particles of metal of electrodes. Therefore considered industrial ceramic heat insulating covers are opaque on the optical properties in a short-wave range.

That is why in experimental development heat insulating coatings absorbed all thermal flux on the surface. It considerably reduced a heat-conducting rejection, the temperature of the internal surface up to 900 K. But there was not raise of efficiency, and it was slightly. At the same time the raise of nitrous oxides was higher. In consequence in 1990 the research and development the combustion chambers of diesel engines has been stopped practically.

In the articles used by authors [4, 9] the mathematical and theoretical models will allow to give the forecast of development of new types of heat insulating coatings. In these coverings the profile of temperature can be changed due to displacement of the maximum of the temperature in the sub surface-area (fig. 2, tab. 2).

The specified thermal regimen could be reached for porous ceramics while exist scattering with the short-wave radiation. While the part of the radiant component ξ_R is higher, the temperature of the subsurface heating it is also higher (fig. 3). The maximal temperature changes from 830 K to 1300 K in the rise of ξ_R from 21 % up to 50 % with increase in depth of the radiant volumetric heating about 3 mm up to 6 mm.

For thick translucent samples displacement of the temperature profile can reach centimeters. It is determined by a ratio of parameters, these are: absorption and scattering. As have shown technological development [3, 5], as a rule, value of absorption is a constant value conditioned by initial industrial raw material. Therefore only dispersion can be changed due to modeling structural structure of ceramics (the size of the porous), and also the determinate fractional structure of inorganic powders (fig.4). On the graphic clearly that the maximum of temperature changes from 1300 K up to 1800 K with reduction of scattering in 10 times with rise of depth about 5 mm up to 10 mm.

Thus, application of translucent coverings promotes essential reduction of superficial temperature of the heat insulating covers, and also in the boundary zone with the metal wall of the combustion chamber (tab 2, fig 2). The uncovered metal wall with thickness of 1 cm for the period of heating 1 hour changes the correspondent temperatures with about 714 K up to 694 K. Its shelter of opaque ceramics (traditionally used industrial samples) allows keeping the back side of the metal wall at initial reference temperature 500 K for theoretically used thick layer of ceramics. For practical applications with a millimetric layer the gain will be 77 degrees already on the frontal surface of the metal wall.

In case of deposition of the translucent covering (tab. 2, 3-rd line) on the basis of rectified zirconium oxide the superficial and volumetric temperature decreases on 200 degrees. These results correspond to thick heat-shielding coverings which can be used in the space industry.

For creation of real and practical heat insulating coverings we shall consider a layer of 1 mm and a combustion time of its heating in a hot phase of the volume in the combustion chamber in time 1 millisecond [2]. From tab. 2 follows, that application of a translucent covering gives a gain in comparison with opaque up to 10 degrees. These data are agreed with estimations [8] which have been received at creation of heat-shielding coverings for cases of flying object.

At operation of diesel engines it is important to estimate the regimen of temperature of the wall in the combustion chamber at the cyclic heating during hot (1 millisecond) and cold (3 millisecond) phases (figs 6 and 7). The variant for the period of the movement of the piston in the combustion chamber for 4 milliseconds of millimetric thickness without heat rejection has been calculated. Upon termination of one cycle excess of temperature in the surface of an opaque covering in comparison with translucent will make 8 degrees after a hot phase. The absorbed energy in both cases approximately is identical, since on small thickness processes of heat conductivity are essential. But depth of heating in the scattering material also is more than at opaque coverings (it was obviously observed on big thickness of modeling samples, figs. 2, tab. 2). After the end of a cold phase the difference in temperature makes not less than 2 degrees.

This depth of heating up is a modeling parameter. It depends on the optical parameters determined by the nature of initial substance and its structural composition. Then value of the maximum of temperature and its coordinate can be predicted, and the demanded structure of a covering can be provided corresponding to the technologies of its manufacturing.

Conclusions

Distinctive feature developed of the new translucent heat insulating coverings is their ability to accumulate radiant heat flux from the full thermal flux in the CC. Even with a high part of a radiating flux the temperature on the surface can remain stability due to raise of the penetrating radiation, its subsequent sub-surface absorption and if it is necessary its reject:

1. Out of the external border of the combustion chamber by conductivity.
2. Back to the internal CC volume , in the regime of a cold phase by development of engines with regenerative effect (one among of development directions of Low-Heat- Rejection Diesel Engines).

For first time was possible to estimate a non-stationary temperature profile in a ceramic covers as the semitransparent medium at modeling external conditions of "a hot phase" of high-speed diesel engines at convective -radiant heating.

At use of a semitransparent ceramic layer 1 mm thickness with a absorption indexes in an interval of 1- 5 m^{-1} and a scattering indexes in an interval of 10-100 m^{-1} subsurface temperature may be exceed the temperature on the surface wall of the combustion chamber l00-400 degrees at the depth up to 1 cm.

Thus, the picked up thermal regimen of the heat insulating coverings will provide necessary temperatures of the internal surface wall and the volume of air fuel mixture and therefore can influence in the rice of the efficiency and in the concentration of formed toxic gases.

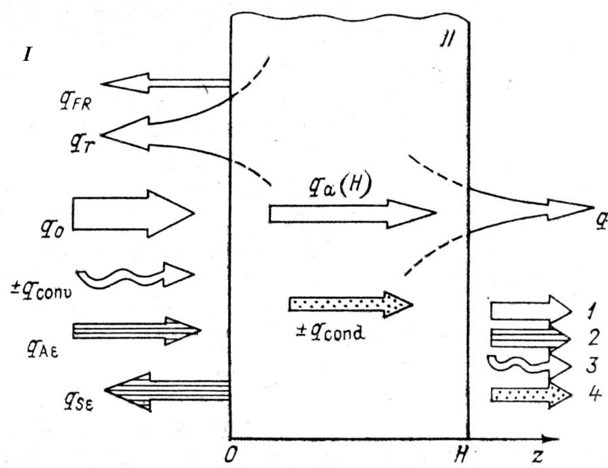

Fig.1. Physical model of the balance of energy in the volume (I) and in the boundary wall (II) of the combustion chamber (CC) in the high speed diesel engines

1. Radiant flux of local volumes of an inflammable gas mixture and its interaction with the thermal insulating coatings of the walls in the combustion chamber:

q_{fr} – the reflected flux from irradiated border (Fresnel),

q_r, q_α , q_τ – the reflected, absorbed and penetrated heat fluxes of short-wave radiation conditioned with the possible dispersion of the heat insulating covers (tab. 1);

2. Radiant long-wave ($\lambda > 5\mu m$) heat fluxes $q_{A\varepsilon}$, $q_{S\varepsilon}$, where:

$q_{A\varepsilon}$ – heat flux of own radiation of hot gases (air fuel mixture) at temperature $T_A > 800K$,

$q_{S\varepsilon}$ – heat flux of own radiation of a heated up wall of the combustion chamber;

3. Convective thermal flux q_{conv}, from hot gases with a heat transfer coefficient (B) up to 3000 Вт/м^2.

4. Conductive thermal flux $q_{cond.}$

Then the full heat flux will be $q_{in} = q_o + q_{A\varepsilon} + q_{conv.}$

This flux on the wall of the combustion chamber defines superficial and volumetric radiating heating of the insulating heat coverings and walls.

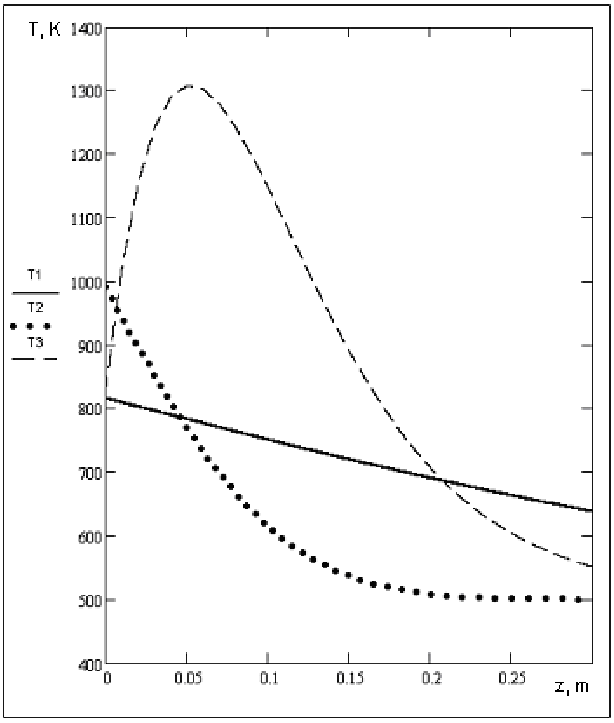

Fig. 2. Distribution of temperature in a flat thick layer of the combustion chamber in the diesel engines at the influence of convective and radiating fluxes q_{in} = 1,9 МВт/м^2 with a radiant component ξ_R = 50 %. Time of heating 1 hour. (without heat rejection on back border) for the following materials:

· T1 - metal wall (Fe) without covering with boundary factor of reflection Fresnel R =0.9,

·T2 - thick layer of a heat-insulating coating from opaque ceramics with boundary factor of reflection Fresnel$R$ =0.4 (industrial sample on the basis of chemically no rectified powder of stabilized oxide zirconium),

· T3 - a thick layer a thermal barrier coating from translucent ceramics (the model of the sample on the basis of chemically rectify powder stabilized oxide zirconium with a parameter of absorption æ = 1 m^{-1}and a parameter of scattering σ = 100 m^{-1} альбедо A = 87 %).

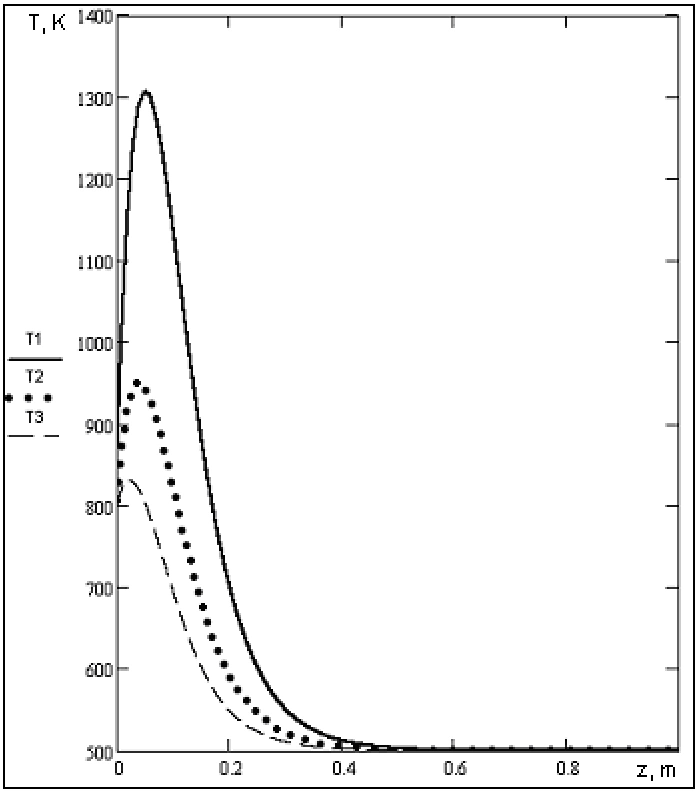

Fig. 3. Distributions of temperature in a flat thick layer of a heat-insulating coating of the combustion chamber in the diesel engine at the influence of a heat flux q_{in} = 1.9 MВт/м^2 with different radiating components during 1hour heating. (without a heat rejection on back border) for curves:

T1 - ξ_R = 50 %, T2 - ξ_R = 32 %, T3 - ξ_R = 21 %.

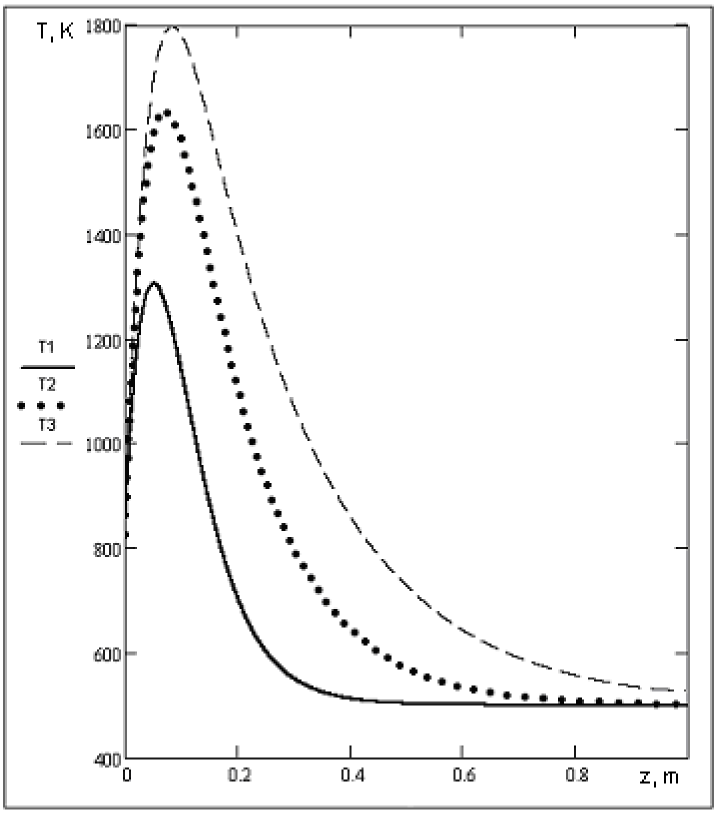

Fig. 4. Distribution of temperature in a flat thick layer of a translucent heat-insulating coating in the walls of the combustion chamber in the high speed diesel engines at influence of a thermal flux q_{in} = 1,9 MВт/м^2 with a radiating component ξ_R = 50 %. Time of heating: 1 hour. With a heat rejection on back border η_{out} = 0 for materials with an identical parameter of absorption æ = 1 m^{-1} and following values of indexes of scattering and albedo:

- T1 – σ = 100 m^{-1} , A = 86 % ,
- T2 - σ = 25 m^{-1} , A = 75 % ,
- T3 - σ = 10 m^{-1} , A = 64 % ,

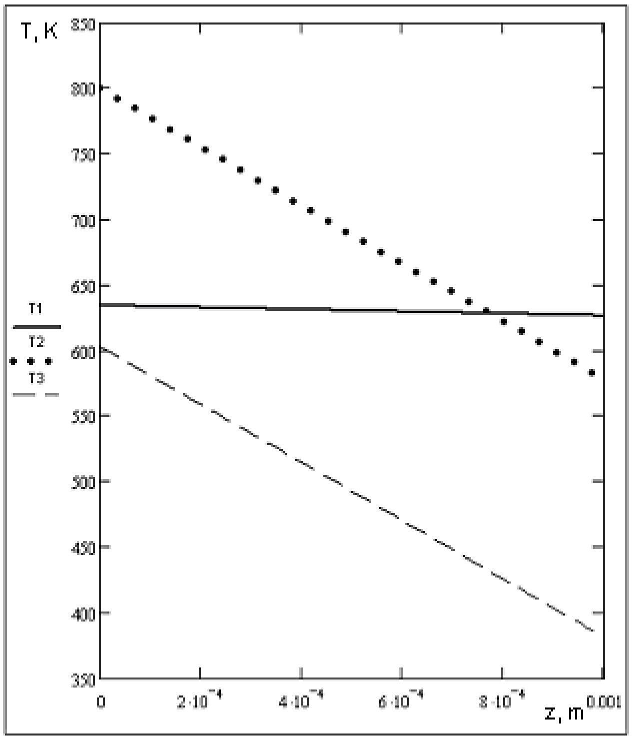

Fig. 5. Distribution of temperature in a flat thin layer (1 mm) in a heat-insulating coating in the combustion chamber walls in the high speed diesel engines at influence of a thermal flux q_{in} = 1,9 МВт/м^2, ξ_R = 50 %. Time of heating 1 hour, with a heat rejection on back border η_{out} = 30 % for following materials:

- T1-metal (Fe),
- T2 - opaque ceramics with boundary Fresnel factor of reflection,
- *R* =0.4 the industrial sample of the heat-insulating coating is on the basis of no chemically rectified powder of stabilized oxide zirconium,
- T3 - translucent ceramic with a parameter of absorption æ = 1 m^{-1} and a index of scattering σ = 100 m^{-1}, альбедо 87 % (the model of the sample on the basis of chemically rectified powder stabilized oxide zirconium).

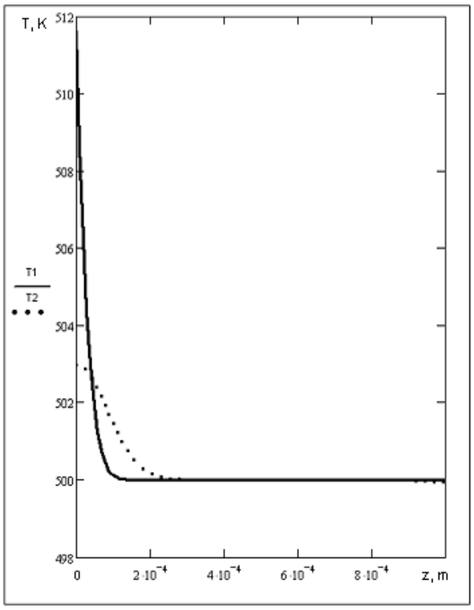

Fig. 6. Distribution of temperature in a flat thin layer 1mm in a heat-insulating coating in the hot (curve T1, time 0.001s with, q_{in} = 1,9 MВт/м^2, ξ_R = 50 %, η_{out} = 0) and cold (curve T2, time 0.003s) phases for translucent ceramics on the basis of chemically rectified powder of stabilized oxide zirconium (tab.2).

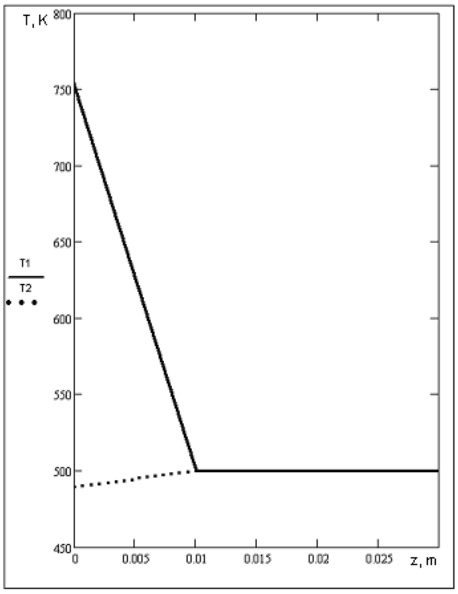

Fig. 7. Distribution of temperature in a flat thick layer in a heat-insulating coating in the walls of the combustion chamber during hot and cold phases (initial data on fig. 6)

Table 1

Thermophysical and optical ** characteristics of the heat insulating coatings of combustion chambers

<table>
<tr><th rowspan="3">№</th><th rowspan="3">Thermal barrier coating Material</th><th rowspan="3" colspan="2">Fresnel Reflectance λ=0.3-6 мкм</th><th colspan="3">Albedo</th><th colspan="3">Emissivity</th><th rowspan="3">Density, Kg / m^3</th><th rowspan="3">Specific heat capacity, J / Kg K</th><th rowspan="3">Thermal conductivity, W / m-K</th></tr>
<tr><th colspan="6">Length wave, µm</th></tr>
<tr><th>0.3-1.0</th><th>1-5</th><th>5-10</th><th>0.3-1.0</th><th>1-5.0</th><th>10</th></tr>
<tr><td>1</td><td>Opaque material Iron.</td><td colspan="2">40-90%</td><td>0</td><td>0</td><td>0.6-0.8</td><td>0.6-0.1</td><td>0.6-0.1</td><td></td><td>7870</td><td>440</td><td>76.2</td></tr>
<tr><td>2</td><td>Opaque heat insulating coating (the industrial sample on the basis of chemically no clean powder of stabilized oxide zirconium).</td><td colspan="2">10-40%</td><td>0</td><td>0</td><td>0.8-0.9</td><td>0.9-0.6</td><td>>0.9</td><td>0.9</td><td>6030</td><td>450</td><td>2.7</td></tr>
<tr><td rowspan="3">3</td><td rowspan="3">Semitransparent heat insulating coating from translucent ceramics (the model of the sample on the basis of chemically clean powder).</td><td>*ZrO_2</td><td>0.1</td><td>0.8</td><td>0.8-0.9</td><td>0.8-0.9</td><td>0.2</td><td>0.1</td><td>0.8</td><td>6030</td><td>450</td><td>2.7</td></tr>
<tr><td>SiO2</td><td>0.04-0.08</td><td>0.9-0.99</td><td>0.1</td><td>0.2</td><td>0.1</td><td>0.93</td><td>0.88</td><td>2200</td><td>700</td><td>1.4-2</td></tr>
<tr><td>Al_2O_3</td><td>0.1</td><td>0.9-0.96</td><td>0.7-0.8</td><td>0.8-0.9</td><td>0,1</td><td>0.3-0.2</td><td>0.2-0.1</td><td>3984</td><td>755</td><td>33</td></tr>
</table>

- *As PSZ (partial stabilized zircon with yttrium)
- ** Novitski L. A. Optical properties of materials in low temperatures. Mashinostroyenye. 1980. Pag. 243.

Table 2.

Calculated temperatures (T, K) of combustion chamber walls of the high-speed diesel engines with

various heat-insulating coatings (HIC), q_0 = 1.9 МВт / м^2, ξ_R = 50 %,. T_A = 800К, T_o = 500К.

Materials of the wall		Internal surface CC	T_{max} /z,(м)	External surface HIC	External surface CC wall /z,(м)
Metallics walls without heat –insulating coating.	Thin layer with out heat reject t = 1 h	714	714	-	694/ 0.01
Opaque heat-insulating coatings from the industrial ceramic sample (Item 2, tabl. 1)	Thick layer with out heat reject t = 1 h	991	991/ 0	500	<500
	*Thin layer 1 mm, t = 1 h	800	800 / 0	577	<577
	*Thin layer 1 mm, t = 0.001 s	519	519 / 0	580	<500
Semitransparent heat insulating coating from translucent porous ceramics (the model of the sample on the basis of chemically clean powder of stabilized oxide zirconium), semitransparent near and in the visual ranges of the waves lengths.	Thick layer with out heat reject t = 1 час	819	1307 / 0.05	500.	500
	*Thin layer 1 mm, t = 1 h	602	602 / 0	381	<500
	*Thin layer 1 mm, t = 0.001 s	511	511 / 0	492	<500

* Heat rejection in the external surface η_{out} - 30 % from the full thermal flux in the combustion chamber.

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