Calculating the effective thickness of the thermal barrier coating

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Abstract. The paper presents the results of numerical simulation of heat transfer at the interaction of a hot impact nitrogen jet with a ceramic thermal barrier coating 7YSZ based on ZrO₂ with the addition of 7% Y₂O₃. The radiant component of heat transfer is shown to make a significant contribution to the final temperature distribution on the surface of the protected product.

1. Introduction
Currently, the operating temperature of gas turbines is highly dependent on the thermal stability properties of blade materials. For thermal protection, the turbine blades are coated with various types of ceramic coatings, which retain their properties at higher temperatures than the metal on which they are applied. Ceramic thermal barrier coatings can have translucency for radiant heat transfer, which makes an additional contribution to the final heat flux acting on the turbine blade. To calculate the thermal load of radiation-convective heat transfer, it is necessary to take into account coefficients of refraction, reflection and absorption of each layer of the thermal protective coating.

In [1], the dependences of these coefficients on the wavelength were obtained. In [2], a mathematical model of heat transfer inside a thermal barrier coating and a protected product was derived on the basis of integral methods taking into account radiant heat transfer. It was shown that a coating that is translucent for radiant heat transfer increases the temperature on the metal surface, compared to an opaque one. In [3], the heat transfer on the blades of gas turbines was numerically investigated, and the efficiency of the ceramic coating under study was shown, however, the details of the applied mathematical model were not specified in this paper. Multilayer ceramic coatings were studied in [4]. It was shown that such coatings may have a lower thermal conductivity compared to a single-layer coating due to the scattering of phonons at the boundaries of the layers.

In this paper, we evaluate the effective thickness of the thermal barrier coating 7YSZ based on ZrO₂ with the addition of 7% Y₂O₃ at a given thermal load and cooling using CFD.

2. Problem statement
Figure 1 shows the scheme of cooling the flat sample under study: for thermal protection of the product from the “hot” side a thermal barrier layer made of 7YSZ, translucent in the IR radiation range of 3...9 microns, was applied. From above, the product was heated by a hot impact jet, and from below it was cooled by a longitudinal air flow. A two-layer thermal protection coating was also considered.

The total length was 330 mm. The thickness of the heat-protected plate was 12 mm, that of the first buffer layer of the coating was 150 microns, and the top layer of the coating varied in thickness from
100 to 600 microns. In the two-layer case, the thickness of the first layer was 100 microns, the thickness of the second layer varied, and the buffer layer was also 150 microns in thickness. The height of the channel with the cooling gas was 25 mm, the height of the channel with the impact jet was 50 mm, and the width of the impact jet was 30 mm.

Figure 1. Problem statement.

The problem was solved in the Ansys Fluent 2020R2 package (academic license). Mathematically, the problem was described by the following equations: the equations of continuity, motion, and energy in the gas phase and the energy equation in the solid phase. The system of equations was supplemented by the k-ω SST turbulence model and the Discrete Ordinates model of radiant heat transfer. At the interface between the plates and the solid/gaseous phases, the heat fluxes and temperatures from one and the other sides of the interface were equal. The heating impact jet had a temperature of 1500°C, and the cooling gas temperature was 330°C. The gas velocity above the plates was 130-150 m/s, and under the plates it was 30 m/s. The heat-protected plate was made of Inconel: \( \lambda = 11.4 \, \text{W/m K}, \, c_p = 435 \, \text{J/kg K}, \, \rho = 8190 \, \text{kg/m}^3 \), absorption coefficient = 0.5 \(1/\text{m} \), and scattering coefficient = 0.5 \(1/\text{m} \). The thermal barrier coating (top layer) was a transparent medium for radiant heat transfer; and the radiant properties of the material were taken from [1] for a wavelength of 7 microns: absorption coefficient = 0.0014 \(1/\text{m} \), scattering coefficient = 0.011 \(1/\text{m} \), and refractive index =1. The density of the ceramics was assumed to be \( \rho = 5200 \, \text{kg/m}^3 \), \( c_p = 604 \, \text{J/kg K} \), and \( \lambda = 1.2 \, \text{W/m K} \). The intermediate layer of the coating was similar in properties to the heat-protected plate.

The working fluid was nitrogen, the density of which was calculated from the law of the ideal gas.

The solution was obtained using the Coupled method and reduced to \(10^{-5}\) for the density and about \(10^{-7}\) for all other values.

3. Results and discussion

Figure 2 shows the typical velocity and temperature fields, taking into account the radiant heat transfer, for the geometry under study. The velocity of the hot impact jet over the plate at the stagnation point equals null. From the stagnation point, the impact jet spreads to both sides of the plate. The cooling air flows from the bottom of the plate and heats up as it moves along the plate. Since there is no symmetric pattern in the flow dynamics, the heat transfer coefficient is distributed unevenly along the length of the plate, which leads to local maxima and minima of temperature on the ceramic surface (Figure 3). In the gas phase, the maximum temperature is located at the stagnation point of the impact jet. Then the temperature decreases as the jet spreads. In the right part of the plate the temperature is higher than on the left, which is due to the heating of the cooling gas from the
bottom of the plate when it moves from left to right. In the solid phase, a local minimum temperature is observed under the stagnation point of the impact jet, which is probably due to the uneven thermal conductivity inside the solid phases of the geometry under study and the fact that the minimum heat transfer coefficient is observed at the frontal point (Figure 4). The empirical relationship in Figure 4 has the form [5]:

\[ Nu = 0.763 Pr^{0.4} Re^{0.5}. \]

![Figure 2. Velocity field (top) and temperature field (bottom).](image)

![Figure 3. Temperature distribution along the cooled plate: in the gas phase (top), inside the ceramic coating (bottom).](image)
The value of the Nusselt number at the frontal point is determined by the formula:

\[ Nu = 0.935 \frac{Re_0^{0.5}}{(h/d)^{0.77}} Pr^{0.4} . \]

In the formulas, \( Re \) is the Reynolds number calculated from the values of the incoming jet velocity and the plate length, \( Re_0 \) is the Reynolds number calculated from the velocity of the incoming jet and the width of the jet \( (d) \), \( Pr \) is the Prandtl number, and \( h \) is the distance from the jet nozzle to the plate.

**Figure 4.** Theoretical and calculated values of the Nusselt number along the cooled plate.

**Figure 5.** Temperature distribution over the thickness of the thermal barrier coating with and without radiant heat transfer.
Radiant heat transfer significantly affects the temperature of the protected surface (Figure 5). The figure shows the temperature distribution inside the thermal barrier coating, the buffer layer and the protected plate, the profiles being located at the edges of the impact jet (15 mm from the jet axis). The temperature of the incoming gas in this case is 1500 °C, that of the cooling gas is 300 °C, and the velocities are 150 and 30 m/s, respectively. When the temperature of the outer boundaries is less than that of the impact jet (1000 °C), the radiant heat transfer reduces the surface temperature compared to the case with neglect of the radiant heat transfer. Consideration and disregard of the radiant component may lead to a temperature difference of the order of 80 °C on the upper surface of the thermal protection coating.

Table 1 shows the results of estimating the temperature on the metal surface $t_w$ and the surface of the ceramic coating $t_c$ depending on the thickness of the thermal barrier coating under the stagnation point of the impact jet. The maximum temperature at which Inconel retains its properties is 950 °C, and for ceramics it is 1200 °C. Apparently, approximately 1 mm of a single-layer ceramic coating must be applied to maintain $t_w < 950$ °C, and only 250 microns of a two-layer layer is sufficient.

**Table 1.** The temperature of the metal and ceramic coating under the frontal point of the impact jet.

| Number of ceramic layers | $\delta_{\text{intermediate}}$, µm | $\delta_{\text{bottom}}$, µm | $\delta_{\text{top}}$, µm | $t_w$, °C | $t_c$, °C |
|-------------------------|-------------------------------|----------------------|-----------------|--------|--------|
| 1                       | 150                           | -                    | 550             | 989    | 1069   |
|                         | 600                           |                      | 650             | 983    | 1070   |
|                         | 700                           |                      | 800             | 978    | 1071   |
|                         | 900                           |                      | 900             | 973    | 1072   |
|                         | 950                           |                      | 950             | 963    | 1074   |
|                         |                               |                      |                 | 952    | 1076   |
|                         |                               |                      |                 | 948    | 1077   |
| 2                       | 150                           | 100                  | 250             | 939    | 980    |
|                         | 300                           |                      |                 | 934    | 981    |
|                         | 350                           |                      |                 | 930    | 982    |
|                         | 400                           |                      |                 | 925    | 983    |
|                         | 450                           |                      |                 | 921    | 984    |
|                         | 550                           |                      |                 | 911    | 986    |

**Conclusions**

The results of numerical simulation of radiative convective heat transfer at impact jet impingement on a translucent multilayer cooled plate are presented using the Discrete Ordinates model of radiant transfer. The obtained data prove that the convective heat transfer at the outer boundary is satisfactorily described by empirical dependences [5]. The effect of radiant transfer significantly changes the temperature level in the solid wall. Differences in the radiation transfer properties of two layers of ceramics with similar thermophysical properties may reduce the radiation transfer through the wall and provide an additional thermal barrier effect. It should be noted that the properties of the radiant transfer of both GZO and 7YSZ vary significantly depending on the deposition technology [6], and therefore the estimates obtained in this work are of a qualitative nature.

**References**

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