Modeling the conjugate problem of heat transfer at hot jet impingement onto a cooled surface

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Abstract. The paper solves the problem of thermal conductivity inside a flat plate under the impact of a hot jet of nitrogen impinging from one side and cooled by a gas flow from the other side. In this formulation of the problem, there may be local maxima and minima of the temperature inside the plate, caused by an uneven distribution of heat fluxes along the plate.

1. Introduction
A large number of works are devoted to the heat transfer and dynamics of the interaction of the impact jets with an obstacle. Generalized data on heat transfer may be found, for example, in [1, 2]. In general, heat transfer in such problems is considered only in the gas phase, while thermal conductivity inside the plate with the jet impingement is not considered. However, in several problems, for example, when assessing the thickness of the thermal barrier coating of turbine blades, it is necessary to consider the temperature field inside the heat-protected element. Depending on the heating and cooling conditions, the temperature distribution in the product may contain local minima and maxima of temperatures. This can significantly affect the strength properties of a thermal barrier coating operating at limiting temperatures.

2. Problem statement
In this paper, the problem of conjugate heat transfer is modeled when a hot nitrogen jet with a temperature of 1500°C flows onto a rectangular plate cooled on the other side by a nitrogen stream with a temperature of 330°C (Fig. 1). The total length of the plate was 330 mm. The thickness was 12 mm, the height of the channel with 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 h = 30 mm. The plate was made of Inconel: λ = 11.4 W/m K.

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 Reynolds stress model and k-ω SST turbulence model. At the interface between the plates and the solid/gaseous phases, the heat fluxes and temperatures from both sides of the interface were equal. The gas velocity above the plates was 130 m/s, and under the plates, it was 30 m/s. The working fluid was nitrogen, whose density was calculated from the law of the ideal gas,
thermal conductivity was calculated based on molecular kinetic theory and varied within the range of 0.042-0.091 W/m K.

The solution was obtained using the coupled method and reduced to $10^{-8}$-$10^{-13}$ for various values.

The computational grid consisted of rectangles, and the number of grid elements was ~8.4 million. The step along the OX axis was $4 \times 10^{-5}$ m, along the OY axis the step in each calculated area was set separately and was equal to values of the order of $10^{-5}$ m.

![Figure 1. Problem statement](image)

3. Simulation results

The turbulent flow characteristics were calculated using the $k-\omega$ SST model [3] and the Reynolds stress model. Both models gave similar distributions of velocity and temperature in the entire calculation domain, however, radically different distributions of wall temperature were observed locally at the frontal point. Figure 2 shows a temperature field in the gas and solid phases typical for this problem. In the region of a hot impact jet, the highest temperature is observed at the frontal point, then, the flow spreads in both directions along the plate and cools as it moves away from the jet axis. The temperature at the stagnation point is slightly higher than the temperature at the inlet. This is because at the stagnation point the temperature is equal to the stagnation temperature: $T^* = T + \frac{U^3}{2e_n}$.

The deceleration of the nitrogen flow at a velocity of 130 m/s contributes to the temperature of about 10 degrees. At the outlet, in the area of the impact jet near the upper wall, the temperature is reduced, which is associated with reverse flows in this area. The temperature of the gas flow entering the computational domain is assumed to be equal to 1000°C. The area of reverse flows has a small extent compared to the entire simulation area, so its influence on the final distribution of the wall temperature, in this case, is negligible.

In the region of the cooling gas, the temperature in the boundary layer on the upper wall increases. Due to the increase in the thickness of the boundary layer, the heat flux entrained by the cooling gas decreases along the length. This leads to the fact that in the solid phase and the region of the impact jet, the temperature of the gas and the wall is higher in the right part of the simulated region relative to the axis of the jet.

In the solid phase, the temperature increases from the left to the right (the cooling gas is supplied from the left). The temperature also decreases from the boundary in contact with the impact jet to the boundary in contact with the cooling gas. Since the heat flux from above and below the plate is distributed unevenly along the length, minima and maxima of temperature are observed inside the
plate (Figures 3 and 4). The shape and magnitude of the minimum depend on the turbulence model used and on the radiant component of heat transfer, taken into account. Thus, when using the Reynolds stress turbulence model in the solid phase, a maximum temperature is observed under the axis of the impact jet, a sharp decrease in temperature occurs near the boundaries of the impact jet, and then the temperature increases again as moving away from the axis of the jet (Fig. 3 on the left). At that, no local minimum temperature is observed in the gas phase.

In such problems, the temperature distribution can be significantly affected by radiant heat transfer [4]. In this case, the consideration of the radiant component according to the DO model (Fig. 3 on the right) has led to a general decrease in the wall temperature, since the upper boundary has a temperature lower than the temperature of the impact jet, and to a decrease in the temperature difference on the axis of the impact jet and its boundary. In this case, no temperature extremes were observed in the gas phase either.

When using the $k-\omega$ SST model of turbulence, a local minimum temperature was observed in the wall, located under the impact jet. The minimum temperature in this case reached about 60°C.

Such a different distribution of the wall temperature when using different turbulence models indicates the need for correct modeling of the interaction of the impact jet with the barrier, especially in the area of the frontal point. However, the choice of the turbulence model affects only the shape and magnitude of the temperature at the extreme point. The main reason for the occurrence of the minimum temperature in the solid phase in this formulation of the problem is the uneven distribution of heat fluxes from above and below over the plate (Fig. 4 on the right). Temperature extremes were also observed when simulating the problem of thermal conductivity in a plate with an uneven distribution of heat fluxes along the boundaries, without taking into account the dynamics of flows streamlining the plate.

![Figure 2. The temperature field in the gas and solid phases](image-url)
Figure 3. Temperature distribution in the gas and solid phases along the length of the cooled plate above and below the gas-solid contact boundary using the Reynolds stress model without taking into account (left) and taking into account (right) the radiant component of heat transfer.

Figure 4. Temperature distribution in the gas and solid phases along the length of the cooled plate above and below the gas-solid contact boundary without taking into account the radiant heat transfer using the $k-\omega$ SST turbulence model (left) and the local Nusselt number constructed along the upper boundary (right).

4. Conclusion
The conjugate problem of heat transfer with a hot impact nitrogen jet impingement onto a cooled metal plate has been simulated. It is shown that due to the uneven heat fluxes above and below the plate, local extremes in the temperature distribution are observed. The magnitude, shape of the temperature extremes, and their position along the plate length also depend on the chosen turbulence model, i.e., on how accurately it describes the dynamics of the impact jet flow. Taking into account the radiant component of the heat flux leads, under the considered conditions, to a decrease in the wall temperature, compared with the case of neglecting the radiant component, and to a decrease in the temperature values at extremes.
References

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