The effect of model material properties on thermal imaging measurements

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Abstract. The temperature distributions arising on the surface of the solid model are investigated. A flow with a shock wave and laminar boundary layer interaction is considered as the main flow. Calculations of the conjugate problem are performed based on RANS approach. The investigated cases correspond to homogeneous material of the solid model and the model consisting of two materials with different thermal conductivity. In this study, the model designs are found to obtain a temperature distribution suitable for thermal imaging measurements. In addition, in the calculations, the effect of forced heating of the model wall on the temperature distribution is investigated.

1. Introduction

The study of the laminar-turbulent transition for transonic flows is not only of great importance from the point of view of fundamental science, but also exhibits great potential of practical application for the development of new generation aircraft. An increase of the laminar flow zone can significantly reduce the aircraft drag, which will increase fuel efficiency and reduce emissions of harmful substances into the atmosphere.

In the experimental study of the problem, panoramic methods, such as thermal imaging measurements, should be used to find the position of the laminar-turbulent transition on complex bodies. Application of the thermal imager has several advantages over other methods estimating the position of the laminar-turbulent transition. Firstly, this method is non-contact and does not introduce any distortions into the measured value; besides, it does not require any change in the design of the model. Secondly, the method is panoramic and allows obtaining information from the entire surface of the model in contrast to heat flux sensors, providing measurements at one point or in a small area.

The problem of interaction of a shock wave with a laminar boundary layer (SWBLI) at a Mach number close to transonic is a good test case to verify this technique. It allows simultaneously considering several phenomena that affect the temperature distribution on the model: laminar-turbulent transition, flow separation, change in the Mach number at the boundary of the boundary layer. The flow structure can also be influenced by the temperature distribution of the model. In numerical simulations, adiabatic conditions on the model wall are often assumed. However, the recovery temperature varies significantly along the flow for the SWBLI problem. This is due to a change in the Mach number at the boundary of the shear layer and heat fluxes in the shear layer. The longitudinal temperature gradient on the surface of the model leads to the appearance of heat fluxes inside the experimental model, which lead to temperature redistribution on its surface. Studies in [1] show that the propagation of heat in the material of the experimental model does not have a significant effect on the flow structure.
It is possible to perform two typical thermal imaging measurements in a wind tunnel test. The first is the visualization of the flow regimes in the boundary layer of the streamlined model. In this case, knowledge of the quantitative characteristics of the model materials and coatings is not required. The only assumptions are made regarding the spatial homogeneity of the surface properties and the acceptability of the level of heat propagation along the surface. The method has sufficient sensitivity. When using modern infrared cameras, it allows obtaining satisfactory results in the presence of temperature difference between the model wall and the flow of several degrees. For example, it is possible to use vertical temperature gradients in the atmosphere in the case of a flight experiment [2]. On the other hand, there is a quantitative method for the processing of unsteady heating of the model surface tacking into account heat propagation in its body. The heat flux distribution is reconstructed by mathematical methods from the recorded history of the surface temperature depending on time.

The temperature distribution in the boundary layer is determined by the Crocco integral [3]. However, it is usually assumed that the recovery coefficient over the entire boundary layer remains constant. In [4] one of the methods of asymptotic solution of the energy equation is presented in order to obtain a modified equation.

Several basic requirements are imposed on the material used to measure heat fluxes in an aerodynamic experiment. The material must have a sufficiently high thermal resistance to prevent lateral heat transfer (i.e., along the surface of the model). The model surface should have a high emissivity, which increases the sensitivity of the method and reduces the level of influence of the radiation reflections on the measurement results. In some cases, the surface is roughened or oxidized for this purpose. For example, in the ONERA experiments, painted metal models or models are made from Vespel (a polymer of the polyimide class), which has a high emissivity. The applied layer during painting should be as thin as possible, and its effect is taken into account in the algorithm for calculating heat fluxes. This complicates the design scheme and increases the number of parameters that must be taken into account [5].

Steel models are often used to ensure the rigidity and stability of the construction when conducting an aerodynamic experiment. However, this type of material has a high coefficient of thermal conductivity, which complicates the analysis of the results obtained by panoramic optical methods. In view of the good thermal conductivity, the temperature front spreads over the entire region of the model, which complicates the diagnosis of the results. Thus, one of the methods to improve the quality of the obtained thermal imaging data is to use a combination of materials with different physical properties or forced heating inside the model.

The influence of these effects may be estimated in a numerical calculation by solving the conjugate problem of heat conduction. The solution of the conjugate problem allows better understanding and studying the redistribution of heat fluxes, formed inside the plate during the interaction of a shock wave and a laminar boundary layer. Thus, the purpose of this study is to investigate the effect of the plate material on the temperature distribution inside the model using the example of the SWBLI problem in a transonic flow.

2. Problem formulation
The computational domain was designed according to the experimental formulation of the problem [6] for the “plate-incident shock wave” configuration, which was investigated in the T-325 wind tunnel (ITAM SB RAS). A flat plate was used as an experimental model. An additional plate (wedge) was installed over the experimental model and used to generate an oblique shock wave incident on the main model.

To reduce the computing resources, the computational domain included only the interaction zone. In this case, a rectangular 10 mm deep region was used as a solid body for solving the conjugate problem. All calculations were performed for the wedge angle $\beta = 4^\circ$ in 2D approach. Steel and polyacetal were considered as the model materials. The problem was simulated numerically with the aid of the software package ANSYS Fluent. The steady Navier–Stokes equations were solved using a density-based solver. An implicit second-order scheme in time and space was applied together with the AUSM method of splitting the convective fluxes. The calculations were performed with help of the Menter transition model $\kappa-\omega-\gamma\text{Re}\omega$ and the turbulent model $\kappa-\omega$ SST. A structured block computational
grid was created based on an experimental setup configuration. The number of cells in the flow area was 140000, and in the solid zone it was 43000.

The boundary conditions at the input boundary were chosen on the basis of experimental data \( P_0 = 70 \text{ kPa}, T_0 = 290 \text{ K}, M = 1.45 \). A flow condition (PressureOutlet) was set at the outlet boundary. The symmetry condition was selected at the upper boundary of the computational domain. A wall condition was set on the wedge with flow attachment and the zero heat flux was taken into account. Heat fluxes inside the solid were calculated only for the plate.

![Figure 1. Flow scheme: design case using a 100% plastic plate.](image)

Figure 1 shows the distribution of the velocity field of the simulated flow. The flow scheme is clearly visible. A wedge at a certain angle of attack generates a shock wave. When a shock wave interacts with a laminar boundary layer, the boundary layer separates, leading to further turbulization of the flow. The formation of a temperature front inside the plate is visible.

3. Calculation results

Calculations of the conjugate problem were performed for a combination of materials, with a steel plate being the main one. The steel plate was coated with polyacetal in various percentages. The obtained ratio of the thicknesses of the plastic and steel layers was sufficient for analyzing the data with the required accuracy. This proves the applicability of this technique in the experiment. Figure 2 shows the temperature distribution inside the plate for the design case using the Mentor transition model for the following material ratios: 75% steel and 25% polyacetal; 90% steel and 10% polyacetal. The temperature is seen to spread in a characteristic manner in the region of the beginning of separation region. This effect is, apparently, more pronounced for the calculation with a thicker section of plastic.

![Figure 2. Distribution of the temperature field inside the plate](image)

a) 75% steel and 25% polyacetal b) 90% steel and 10% polyacetal.
The temperature distributions along the longitudinal coordinate were plotted based on the results obtained. Figure 3 shows that the results for a steel-to-plastic ratio of 75-25 and 90-10 have a structure that is qualitatively similar to the results for an all-steel plate. However, it should be noted that for a solid model with a plastic section, the temperature boundary is more pronounced. Hence, it is possible to more accurately determine the location of the beginning of the separation region.

![Figure 3](image)

**Figure 3.** Distribution of the temperature along the longitudinal coordinate for different thickness of the plastic layer for the design case using the model a) k-w SST and b) Trans SST.

To implement a stationary uniform heat supply, a custom function udf was used. The power was fed along the entire plate in the middle of a 2 mm thick section, which corresponded to an overall increase of about 15K in plate temperature in the main part under investigation.

Figure 4 shows the temperature field for the power supply equal to 200 W for the computational case using the Transition SST model. The distribution of heat in the plate is obviously distributed in such a way that the location of the separation region can be unambiguously determined.

![Figure 4](image)

**Figure 4.** Distribution of the temperature field inside the plate with forced heating.

**Conclusions**

Calculations have shown that, depending on the configuration of the material of the experimental model, the temperature inside the model is redistributed. A steel model with a plastic coating and forced heating of the plate are found to provide better results in thermal imaging studies, which can improve the accuracy of flow analysis in the experiment.
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