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Numerical analyses of heat transfer in high-temperature loaded turbine blades

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Abstract

This article deals with heat transfer problems encountered in the cooling of jet engine turbine blades with internal cooling only. For this purpose an exemplary turbine blade was investigated using numerical methods. The results and conclusions are presented.

Keywords: heat transfer, turbine blade, numerical methods, jet engines, ANSYS FLUENT

1. Introduction

Turbines are parts of jet engines which work in the most extreme environmental conditions demanded of any machine. High temperature and pressure with highly oxidant substrates cause rapid material degradation. However, the high firing temperatures are favorable because they increase the efficiency of the entire engine, which in consequence lowers fuel consumption. This is profitable for all jet engine users, e.g. commercial airlines.

For engineers the biggest problem is to design an effective cooling system to protect turbine materials from degradation. For this purpose many modern numerical programs are commonly used. However, these tools require good solver configurations, well-prepared geometries with meshes and proper boundary conditions. In many cases like for, example, turbine blade cooling, it is hard to model an entire machine because of the limited computational power of commonly used computers. We need accurate methods with reasonable system requirements. To this end engineers analyze only parts of machines, especially when the geometry is periodic (such as in a turbine). Calculations for an entire row of blades may be very time consuming, whereas modeling a single blade with proper boundary conditions and solver settings should still deliver accurate results.

The aim of this work is to determine the temperature distribution in the exemplary turbine blade with internal cooling only. Regions of additional cooling requirements in such case will be defined.

The geometry of the turbine blade was prepared in Unigraphics NX 5.0 using an airfoil contour extracted from the sketch of US patent no. 6893210 (Fig. 1). The obtained airfoil was different from the original one due to the low quality of the sketch and the approximation done in the digitizer used to obtain coordinates of points on the airfoil. These points were used to create a sketch in NX which, after extruding, gave the outer surfaces of the blade.

The internal cooling passages were subsequently created. A drawing of a sophisticated cooling system was not necessary to obtain general data about the

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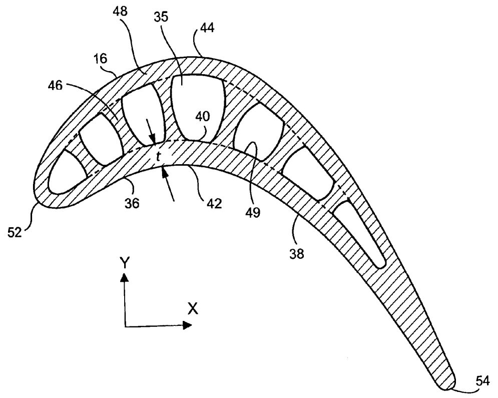

Figure 1: Geometry of the turbine blade

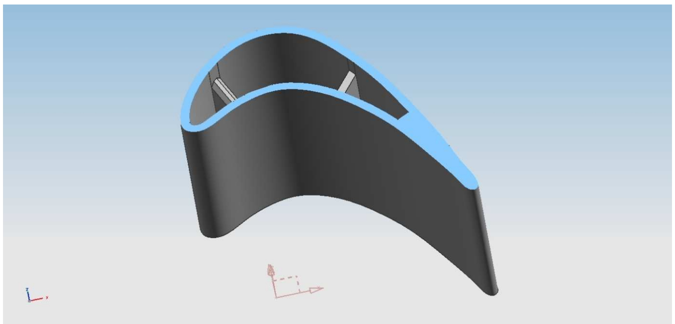

Figure 2: Meshing and boundary conditions

cooling of turbine blades. Thus, the modeled system consisted only of internal cooling without film cooling, impingement cooling or dimple cooling. There was only one central inlet and two lateral outlets. A cross-section of this blade is shown on Fig. 2. The height of the blade is 50 mm and the upper common air chamber is 10 mm high.

The geometry was exported as a Parasolid file and imported to Gambit. The blade was placed in a flat canal whose geometry is shown in Fig. **??**. The angle of attack of gases was 45 degrees (parallel to the walls). A velocity inlet was placed at the entrance to the canal. The upper and lower front boundary conditions are walls. They are parallel to the direction of flow. The aft boundary condition is the pressure outlet. The interior and exterior faces of the blade are walls. The inlet to the cooling passage is a velocity inlet and outlets are pressure outlets. The upper and lower surfaces were modeled as walls. It was assumed that there is no gap between the tip of the blade and the casing. Meshing was installed using structured elements.

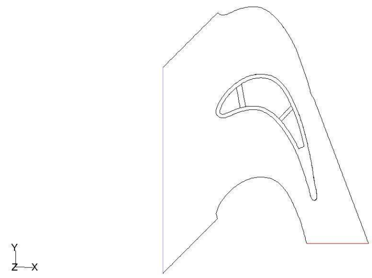

Figure 3: Shape of canal and boundary conditions

Table 1: Properties of hot gases

Hot gases			
Temperature, K	300	600	1,500
Density, kg/m^3	3.74	2.5	1.6
Thermal conductivity, W/mK	0.02	0.045	0.06

2. Inputs and solver configuration

To avoid convergence problems a Pressure Based solver was used instead of Density Based Self-Configuration. Due to the lack of available computers in a distributed system, a second simplification was made: analysis in a steady state. Velocity formulation is absolute and the gradient option is Green-Gauss Cell Based.

Table 2: Properties of cooling air

Cooling air			
Temperature, K	300	600	1500
Density, kg/m^3	3.5	2.32	1.4
Thermal conductivity, W/mK	0.022	0.04	0.07

Table 3: Inconel X750 physical data

Inconel X-750	
Density, kg/m^3	8,303
Melting Range, K	1,666/1,700
Temperature, K	Thermal Conductivity, W/mK
422	16.9
589	20.5
811	26.5
922	28.7

Table 4: Basic data about the model

Number of elements	996,244
Number of nodes	869,705
Turbulence model	k-e
Hot gases velocity, m/s	80
Hot gases temperature, K	1,500
Velocity of cooling air, m/s	10
Temperature of cooling air, K	360

Properties of hot gases and cooling air were modeled as piecewise linear in the temperature range of 300–1,500 K. They are shown in Tables 1 and 2. These data were obtained from the Institute of Heat Engineering at Warsaw Technical University.

A nickel-based superalloy Inconel X750 was selected as blade material. It is an alloy with high corrosion and oxidation resistance. X750 is used in turbines for rotor blades, wheels, bolts and other structural parts. Its physical data are summarized in Table 3, which are culled from the manufacturer's sheet data.

The inlet temperature of hot gases was 1,500 K and their speed was 80 m/s. The inlet temperature of cooling air was 360 K (temperature estimated at the 4th stage of the axial compressor) with a velocity of 10 m/s. Owing to the lack of turbulence intensity data, turbulence values are set at default from the program. Viscosity is modeled using Sutherland's model. The most basic information about the model is summarized in Table 4.

Results

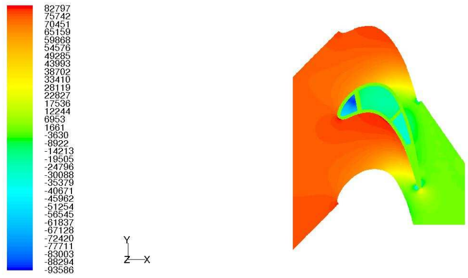

Figure 4: Distribution of static pressure inside and around the blade

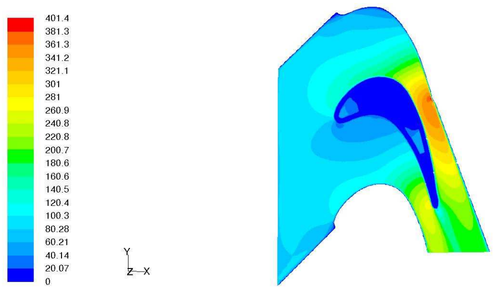

Figure 5: Distribution of velocity

Fig. 4 shows static pressure distribution in a cross-section of the calculation area. This section is done halfway up the blade and will be used as the standard view for the presentation of results. This picture shows there is identical pressure distribution in both inter-blade canals. The highest pressure is on the leading edge of the turbine blade. This is a stagnation point at which velocity is equal to zero and the entire dynamic pressure is converted into static pressure. The concave side of the blade is another zone with high static pressure and it suggests that there is a reduction in hot gases velocity.

Fig. 5 shows the distribution of a velocity magnitude. It can be seen that there is a boundary layer in close vicinity to the walls. The maximum speed of

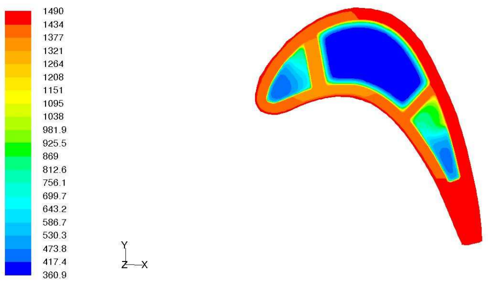

Figure 6: Distribution of a temperature inside the blade

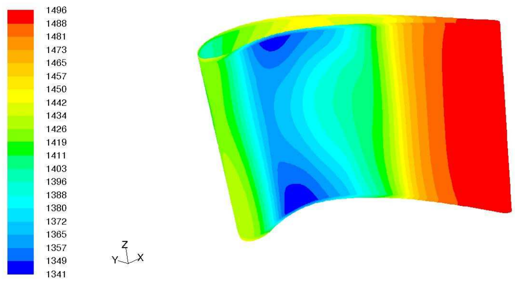

Figure 7: Distribution of temperature on the concave face of the blade

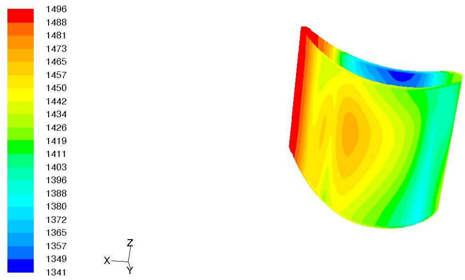

Figure 8: Distribution of temperature on the convex face of the blade

the gases is 401 m/s, which at this temperature and pressure is below the speed of sound.

Temperature distribution in a cross-section halfway up the turbine blade is shown in Fig. 6. To better present the results, the scale was narrowed from 360 to 1,490 K. It can be seen that the highest temperature is in the aft part of the blade where the outer surfaces are in close proximity to each other; there is no special cooling system in this area. It can be assumed that the material will degrade rapidly in this area, because Inconel X750 loses its great physical strength above 1,300 K. The second area with a high material temperature is the leading edge. High pressure with a high temperature gradient in that area may cause faster material degradation.

Fig. 7 shows the distribution of temperature on the concave face of the blade. It can be seen that the distribution is highly heterogeneous along the height especially in the aft part of the blade face. There is a high temperature gradient along the central cooling passage. The lowest temperature is at the height corresponding to the place where the inlet cooling canal divides into two outlet passages (high turbulence level) as well as at the entrance to the channel.

Fig. 8 depicts the distribution of temperature on the convex face of the blade. It can be seen that the best cooling is near the forward cooling passage. There is also a high temperature region near the central part of this surface.

Fig. 9 shows the distribution of the surface heat transfer coefficient on the convex and sides of the turbine blade. It can be seen that this value varies from around 0 in the aft part of the blade (where material temperature is almost equal to gas temperature) to around 157 in the central part. Fig. 10 shows the distribution of this coefficient on the concave side of the blade. On this side the highest value is on the leading edge: 156.9 W/m^{2}K.

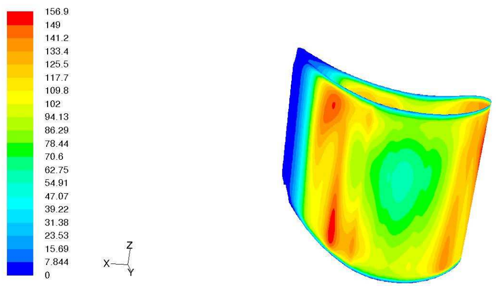

Figure 9: Distribution of Surface Transfer Coefficient—convex side

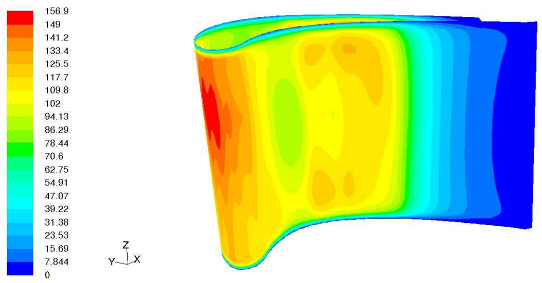

Figure 10: Distribution of Surface Transfer Coefficient – concave side

3. Conclusions

From the conducted computer analysis of heat transfer in the exemplary turbine blade, the following conclusions can be drawn.

Using numerical simulation for complex geometries, including material properties dependent upon temperature, gives good and relatively quick results.

The turbine blade material has to be very reliable at high temperatures due to the high oxidation rate. Since the highest temperatures were observed in the aft part of the blade, additional cooling techniques should be implemented there. The biggest difficulty there is the small distance between two external surfaces, resulting in there being little space for the cooling passage, which will be very narrow with a high aspect ratio.

Additional film cooling would be preferable from the reliability point of view–turbine materials have better oxidation and strength characteristics at lower temperatures.

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