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Design Study of HTR Power Turbine Blades

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1. PURPOSE AND SCOPE

1.1 PURPOSE

The purpose of this document is to analyse the feasibility of the projected blades for the HTR Power Turbine, as well as the thermal and stress fields through its components.

This document is the contribution from Empresarios Agrupados (EA) to Deliverable 7a of WP1.

1.2 SCOPE

The analysis of the aerodynamic behaviour of the power turbine has been performed based on the information available on the design of the HTR Power Turbine (Deliverable 2 of WP 1, Ref. [1]). A proposal from an aerodynamic point of view has been presented for the preliminary geometries of the blades for the first stage of the power turbine (Von Karman Institute - VKI). Their thermo-mechanical behaviour has been analysed for these geometries (EA).

These preliminary results are the input data for the future work on the development of the turbine of the HTR (Deliverables 8 and 9 of WP 1).

2. INTRODUCTION

Deliverable 2 of WP1 set the foundations for the design of the ‘turbomachinery’ of the HTR Power Conversion Unit.

Based on this information, the VKI has carried out the preliminary aerodynamic analysis of the power turbine and the compressors. This study is set out in a different document ([2]) and has allowed the preliminary geometry of the blades of the stator and rotor of the first stage of the power turbine and compressor to be obtained.

Based on the geometries proposed by the VKI for the blades as a basis, EA has performed the thermo-mechanical analysis of the blades, taking into consideration the stresses caused by the pressure gradient in the helium, its temperature and the stresses caused by the rotation speed of the rotor.

This document details the results obtained from the thermo-mechanical analysis and defines the future work to be performed for the development of the power turbine.

3. INPUT GEOMETRY

The CAD of figure 3.1 shows the preliminary configuration of the HTR-E rotor and stator blades proposed by VKI [2].

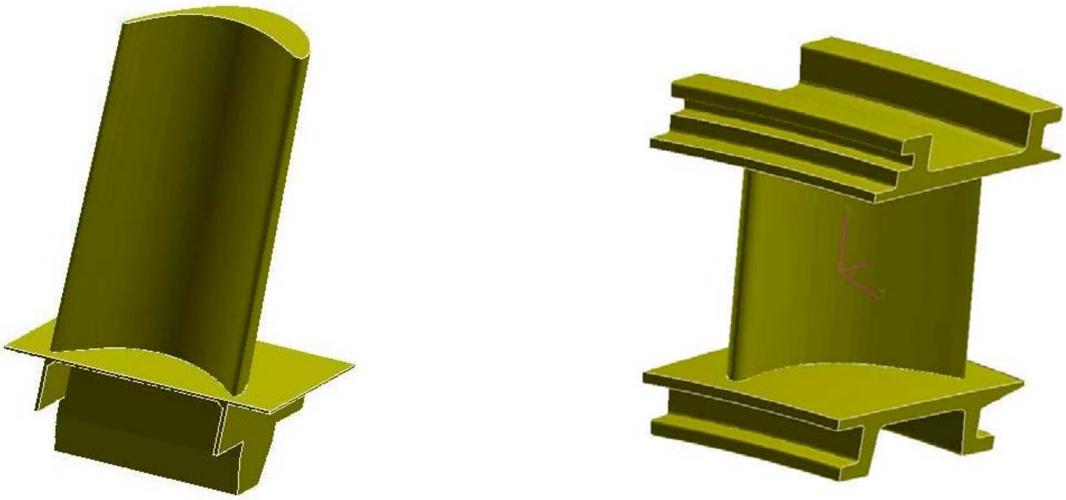

Figure 3.1.- HTR-E Turbine blades (Rotor and Stator)

This configuration and the conditions presented below have been used to perform a preliminary thermo-mechanical evaluation to analyse the aspects that need to be addressed in the detail design. The configuration studied corresponds to the first stage of the HTR-E Turbine.

4. THERMO-MECHANICAL ANALYSIS

4.1 FINITE ELEMENTS MODELS (FEM)

The preliminary thermo-mechanical evaluation has been carried out using the finite elements models presented in this section, developed by EA from the CAD in [3].

The FEM and corresponding analyses (Thermal and Thermo-mechanic) have been developed with the PATRAN program and the general purpose finite element program SAMCEF v.9.1, and, more specifically, the pre- and post-processing BACON module, the MECANO thermal module for the thermal analysis and the ASEF module for the thermomechanical analysis.

The rotor blade has been analysed by means of the three-dimensional finite elements model in figure 4.1. The model is formed by ~8798 3D elements of grade 1 and ~11654 nodes.

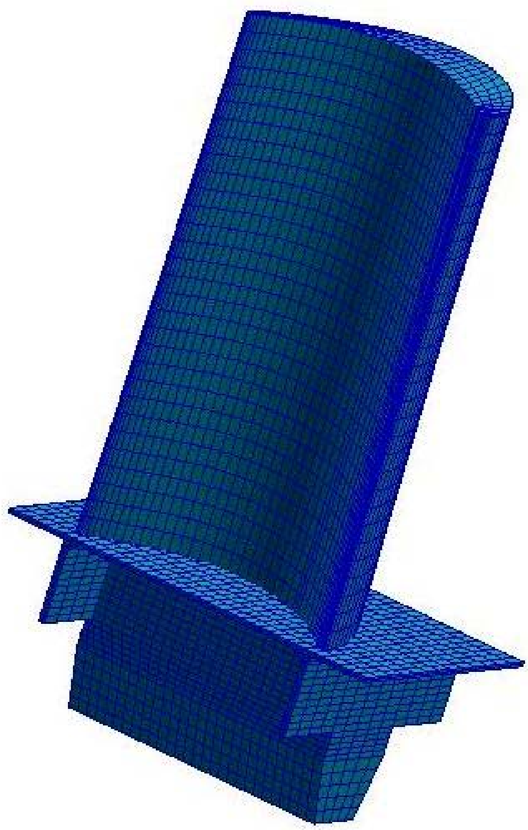

Figure 4.1.- Rotor-blade FEM

The stator blade has been analysed by means of the three-dimensional finite elements model in figure 4.2. The model is formed by ~10048 3D elements of grade 1 and ~12920 nodes.

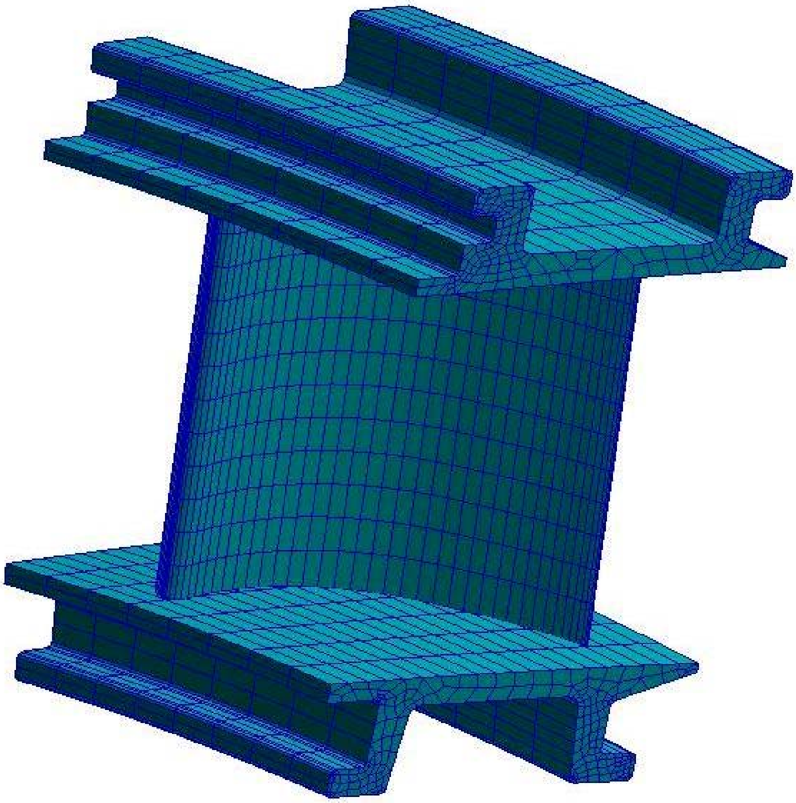

Figure 4.2.- Stator-blade FEM

4.2 MATERIAL PROPERTIES CONSIDERED

The material considered for the analyses of both models has been *Inconel 792 (Ni-based Alloy),* and the thermo-mechanical characteristics considered are indicated in the following table.

E (GPa)	ν	α	ρ **(Kg/m^3)**	**k (W/mK)**
164.78	0.29	8.6×10^{-06}	8250	15

Table 4.1.- Characteristics of Inconel 792 [5] at 850ºC

4.3 BOUNDARY CONDITIONS

The calculations performed in this document were performed by applying slightly conservative boundary conditions to the mechanical behaviour of the components analysed. The boundary conditions applied to each FEM are the following:

- *Rotor-blade*: The FEM of this component has been analysed attaching the lower part of the blade support in the three directions (axial, radial and circumferential). This attachment is represented in figure 4.3

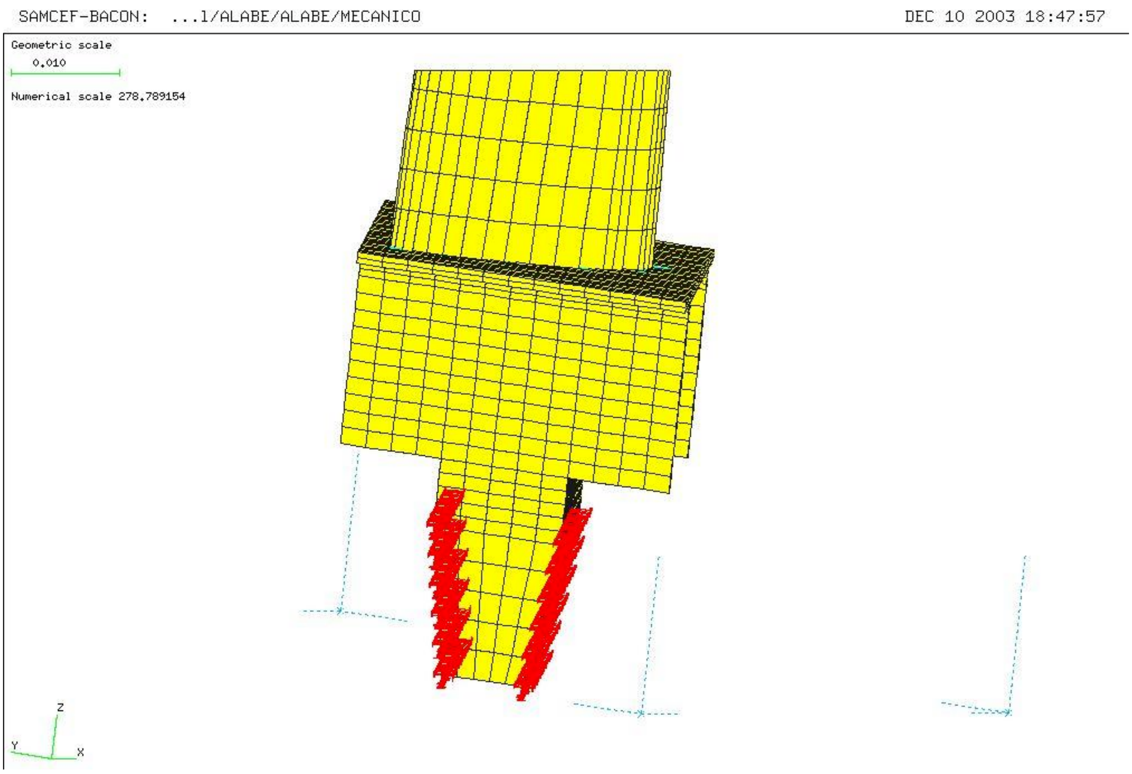

Figure 4.3.- Rotor-blade attachment

- *Stator-blade*: The FEM of this component has been analysed by attaching the cyclic symmetry planes of the upper and lower attachments of the blade to the axial and circumferential components, and the lower part of the lower blade support to the radial component. This condition is represented in figure 4.4.

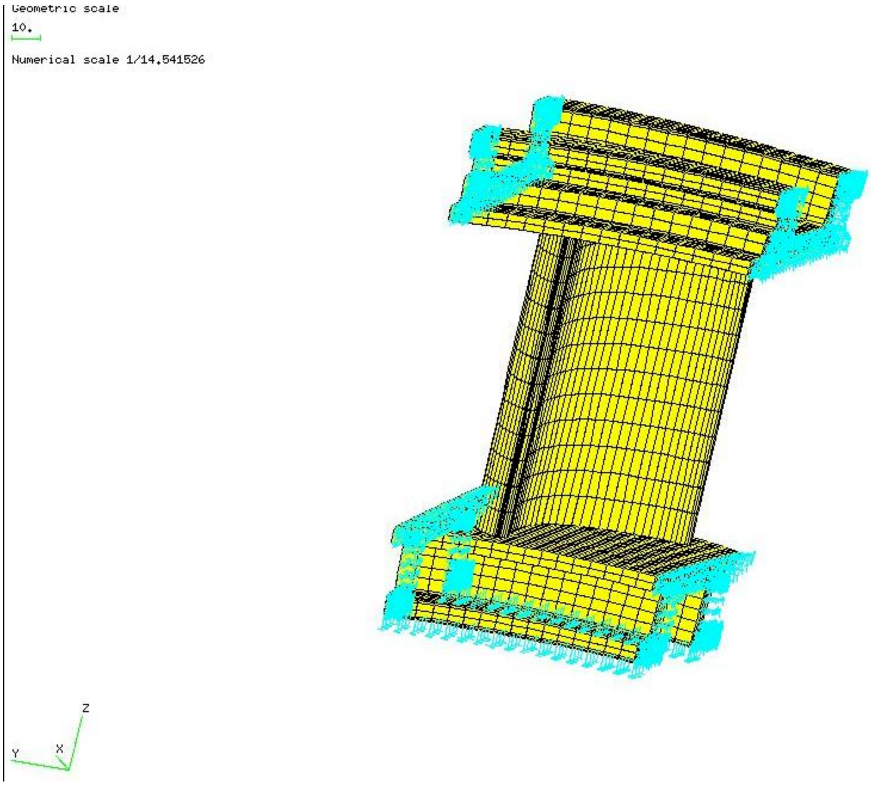

Figure 4.4.- Stator-blade attachment

4.4 ANALYSES PERFORMED

A steady state thermal analysis has been performed to obtain the temperature distribution, and a linear stress analysis has been carried out to determine the stress state of the components with the load state during normal operation.

The stresses and strains of each component are determined by applying to the FEM of said component (Figures 4.1 and 4.2) the temperature and the mechanical loads applied on the component distribution corresponding to the normal operation conditions.

Stress state of the component under : Temp $_{Normal\ operation} \oplus$ Pressure $|_{Normal\ operation} \oplus$ Rotation speed $|_{Normal\ operation}$.

The calculations performed in this document only contemplate the loads mentioned, detailed below.

4.5 LOADS

4.5.1 Temperature

The He pressure and temperature conditions for the first stage of the power turbine were provided by VKI [4]. A steady state calculation was performed with these conditions to determine the temperature distribution in the component.

The temperature distribution depends mainly on the heat transmission phenomenon in the component, so the boundary conditions of the component must be known to obtain a correct temperature distribution.

In a first approach, with a pessimistic point of view, the temperature of the blade walls has been considered to coincide with that of the helium at that point. This means that a perfect thermal coupling between the helium and the blade has been considered.

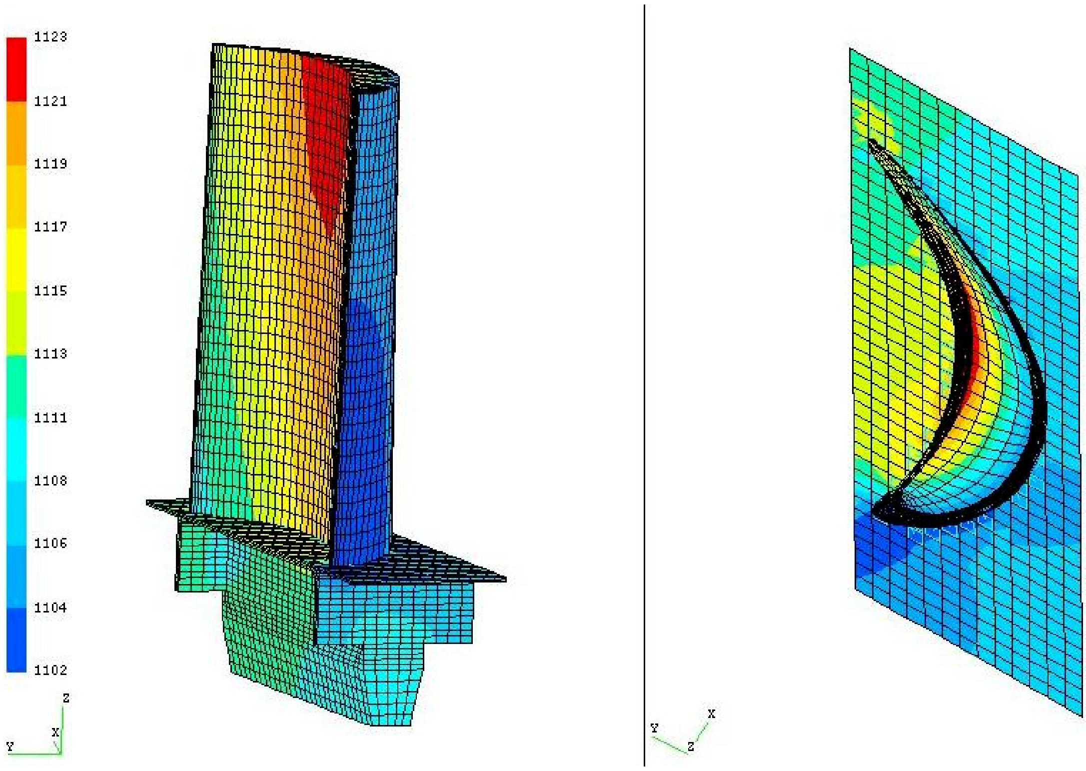

Figure 4.5.- Temperature Distribution in the rotor blade

The first approach has also taken into consideration that there is no cooling in the blade, the disc or the stator, supposing that there is no heat transfer from the blade to the disc or the stator.

Figure 4.5 shows the temperature distribution obtained in the case of the rotor blade. As expected, the temperature gradient in the component is low, and the maximum temperature in the component was the temperature used to evaluate the mechanical stresses.

The stress evaluation temperature in each component was of 1123 K (850ºC) for the rotor blade and 1130 K (857ºC) for the stator blade.

4.5.2 Rotation Speed

The rotation speed applied in the rotor blade was of 3000 rpm, while there was no rotation speed in the case of the stator blade (0 rpm).

4.5.3 Pressure

Figures 4.6 and 4.7 show, respectively, the pressure distribution applied to the rotor blade and the stator blade. These distributions were obtained in accordance with the conditions supplied in Ref. [4].

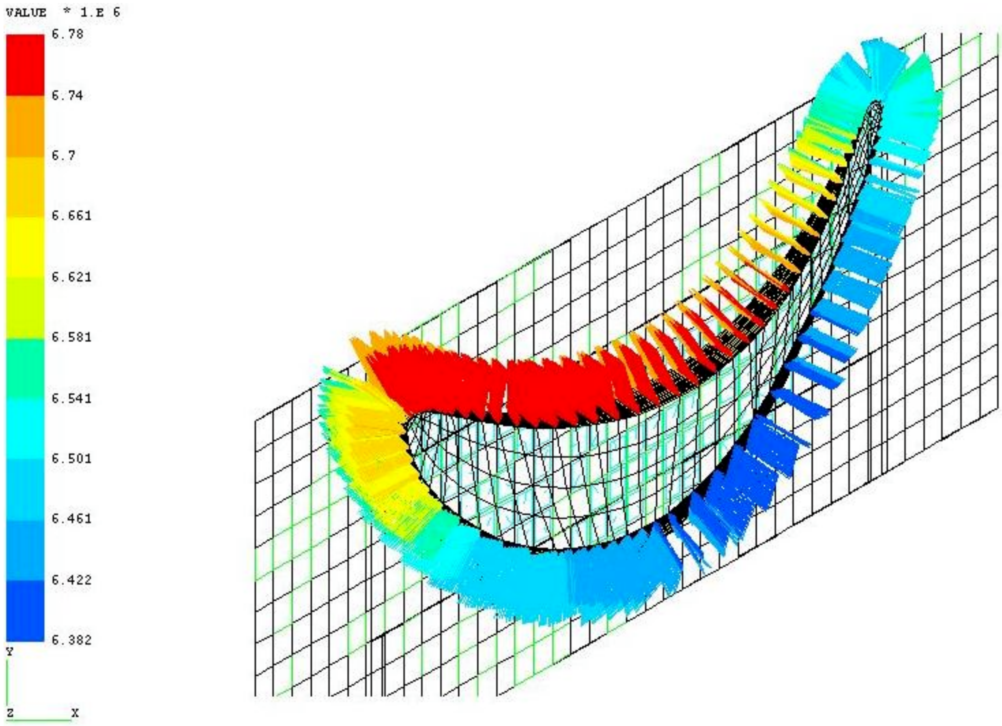

Figure 4.6.- Pressure Distribution in the Rotor-blade

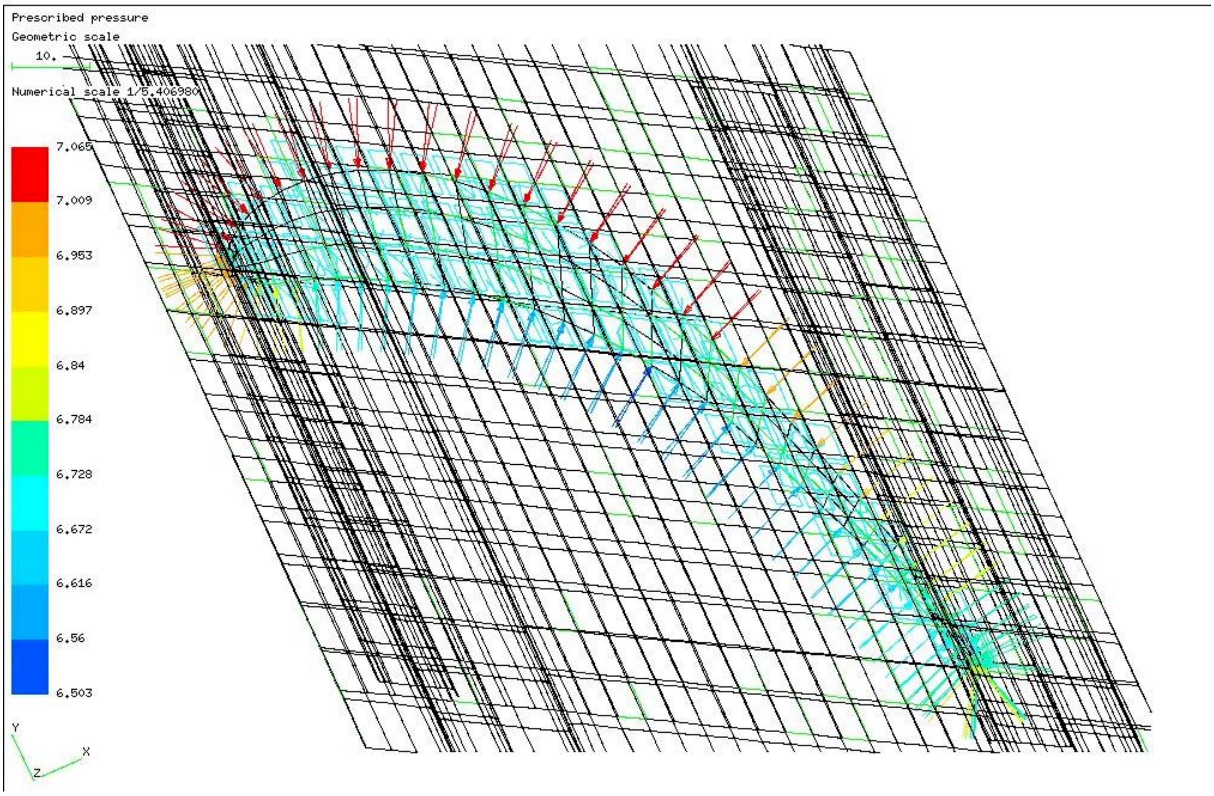

Figure 4.7.- Pressure Distribution in the Stator-blade

5. RESULTS OBTAINED

Once performed the stress analysis corresponding to the load state Pressure⊕Speed|$T^{a}_{\text{normal operation}}$, the following results were obtained:

	Displacements (mm)			σ (MPa)
	r	θ	z	Von Mises
Rotor blade (*850 ºC*)	1.12	-0.4	-0.53	269
	Figure A.1	*Figure A.2*	*Figure A.3*	*Figure A.4*
Stator blade (*857 ºC*)	0.007	0.036	0.087	34
	Figure A.5			*Figure A.6*

Table 5.1.- Displacements and stresses

According to the hypotheses (FEM and boundary conditions) considered in the calculation herein performed, the stress and displacement values given in Table 5.1 should be considered estimates. Moreover, the stresses given for the blades of the stator and rotor correspond to maximum values.

The maximum Von Mises stress in the stator blade occurs in the blade itself. In the rotor blade it occurs in the blade/blade foot joint area according to the hypotheses considered.

The maximum displacement generated in the stator blade is very small and occurs in the blade itself. In the rotor blade, it is produced in the radial direction, primarily in the blade tip, as a result of the rotation speed.

The first results seem to indicate that the stator blade presents low stress levels, which means it should not be difficult to achieve certain operating levels with the preliminary geometry analysed. For the point of view of mechanical strength, the rotor blade also presents no problems. From the thermal point of view, however, and if we take into account the lifetime operating hours, there are problems due to the high temperature level. Blade cooling is highly recommended.

A detailed analysis of the blades of the stator and rotor requires good knowledge of the stress state of the component and the real geometry (stiffness, thermal inertia, etc) to be used to represent the component correctly.

6. CONCLUSIONS

The analyses performed are a good starting point for the future detail analysis, once progress has been made on the design of the Power Turbine.

In view of the results obtained throughout the preliminary analysis performed, it may be said that:

- The assessment of both components requires the detailed geometric definition of the components and the more precise definition of the heat transfer phenomenon that takes place in each component
- A study must be performed on the heat transfer from the helium to the blade and from the rotor blade to the disc and the stator blade to the stator
- A reduction of the maximum temperature levels in the rotor blade would allow the operating time to be increased. Blade cooling is highly recommended
- An evaluation must be performed of the fixation of the rotor blade to the disc
- A detailed evaluation of all the loads that occur in the various operating modes must be performed
- A precise definition of the evaluation of the characteristics of materials with temperature

7. FUTURE WORK

As a conclusion to this preliminary report, a proposal is made for continuity in the design of the rotor and stator blades with the following tasks:

- Thermomechanical analysis of the turbine assembly: development of an axisymmetric model of the whole power-generating turbine, with a preliminary model of blades and discs but considering all the stages. This model would allow the evaluation of the global thermal behaviour of the turbine and the study of whether or not the turbine discs need to be cooled

- Detail analysis of the first stage of the turbine: development of a 3D model of the disc and blade that allows, for the normal operating conditions, the following:

  - Adaptation of the final configuration

  - Selection of the materials to be used

  - Design of the cooling system (if required)

  - Detailed evaluation of the temperature distribution in the components

  - Design of the attachment system of the base of the blade to the disc

  - Assessment of the operating lifetime of the disc and blade

8. REFERENCES

[1] Design Use, System Review, Integration and In-Service Inspection and Repair. FRAMATOME ANP, HTR-E-02/12-D-1-1-1-2, 2002

[2] Aerodynamic Analysis of HTR Turbomachinery. VKI, 2003

[3] IGS Files: e-mail from VKI to EA, dated 21st October 2003

[4] Pressure and temperature files: e-mail from VKI to EA, dated 21st October 2003

[5] The Superalloys. Chester T. Sims, William C. Itagel, John Wiley & Sons, 1972.

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APPENDIX A

FEM RESULTS

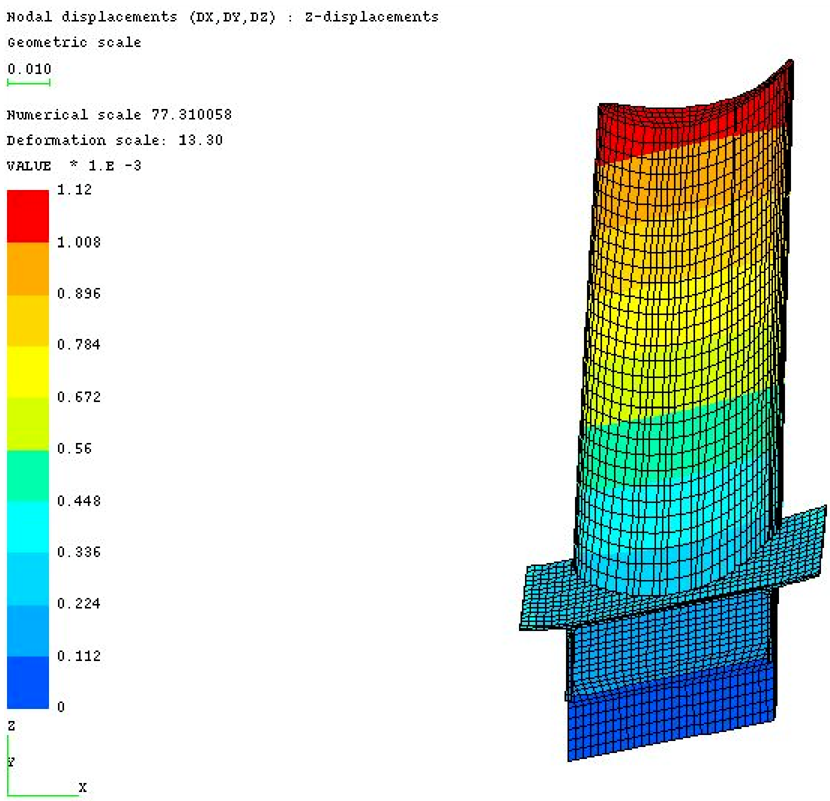

Figure A.1.- *Rotor blade radial displacements*

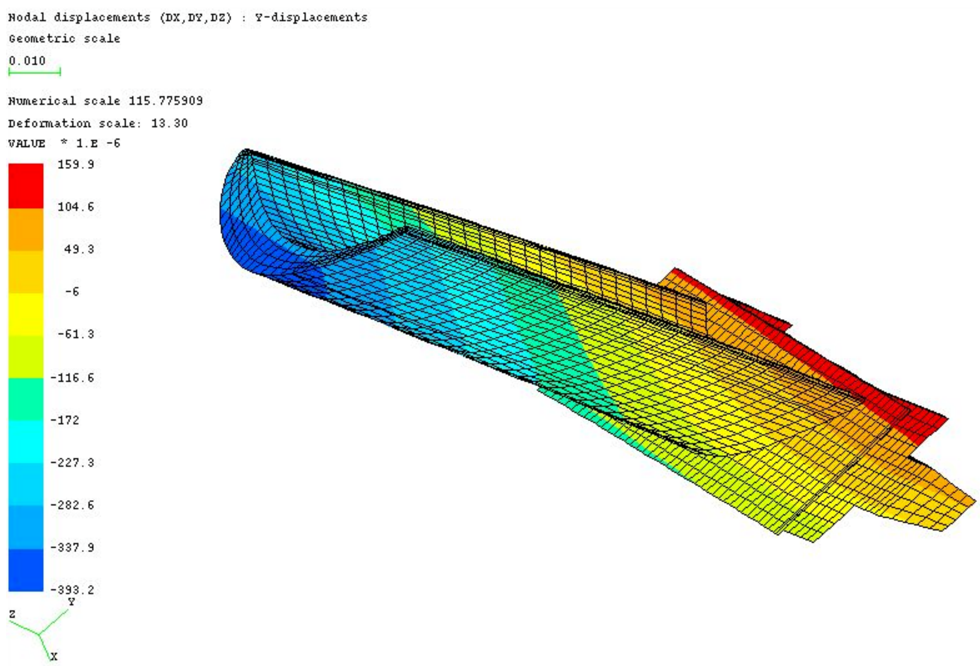

Figure A.2.- *Rotor blade circumferential displacements*

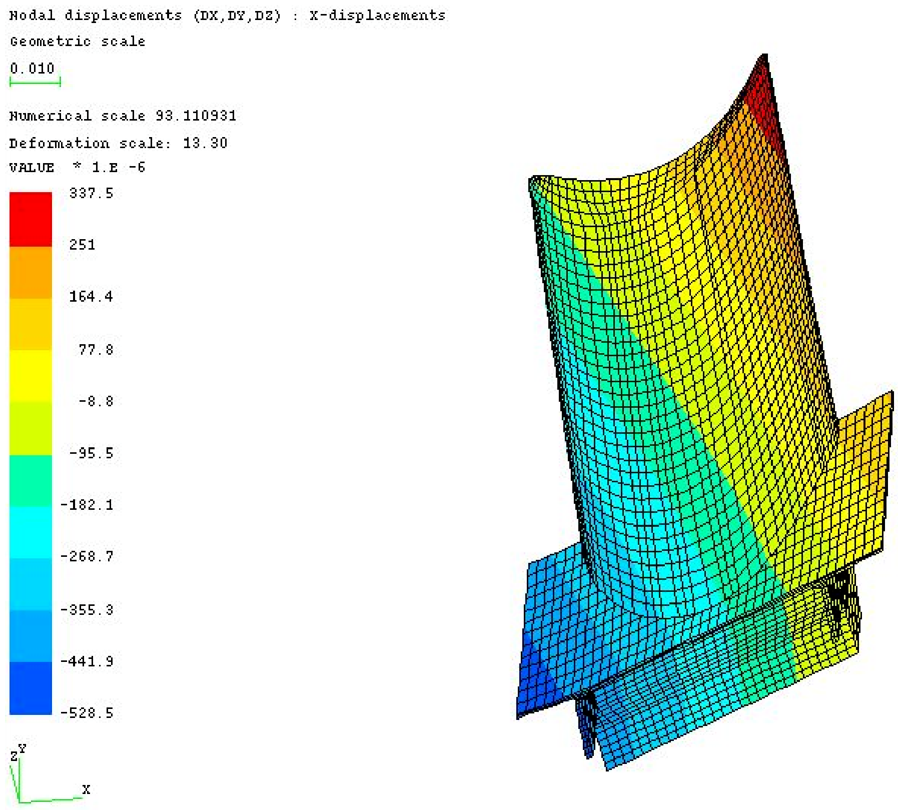

Figure A.3.- *Rotor blade axial displacements*

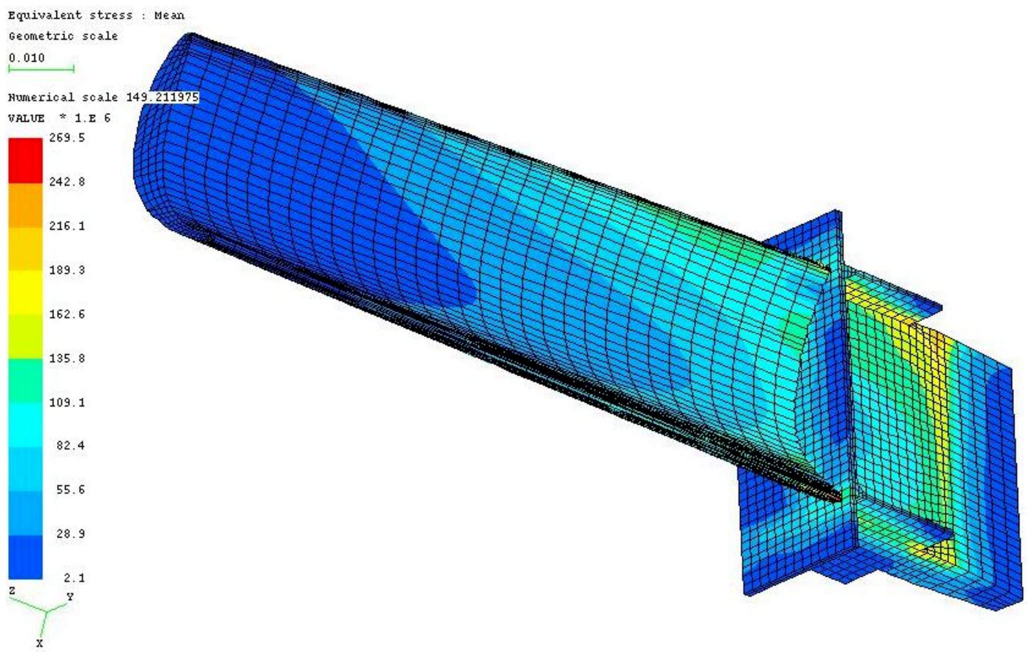

Figura A.4.- Rotor blade Von Mises stresses

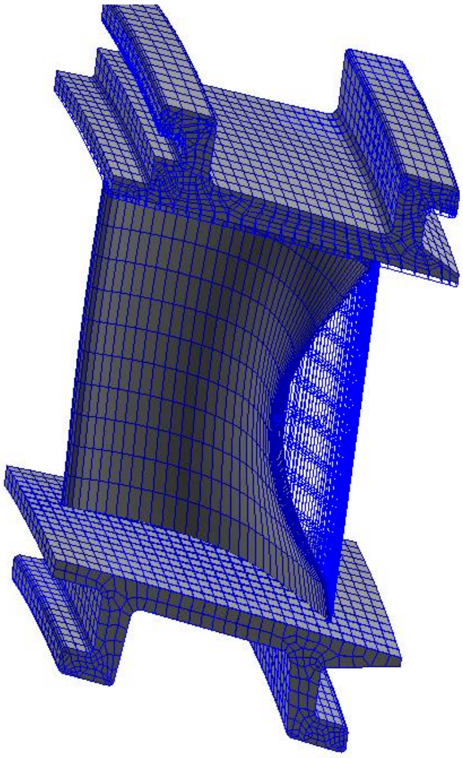

Figure A.5.- Stator blade displacements

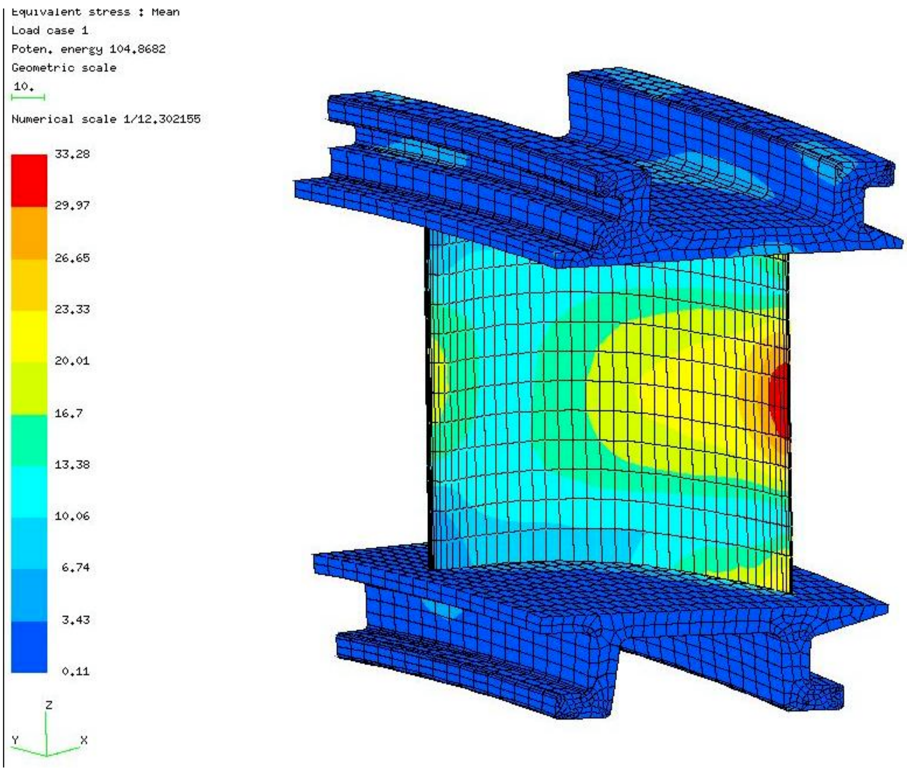

Figure A.6.- Stator blade Von Mises stresses