Research Article

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The effect of the outlet angle β_2 on the thermomechanical behavior of a centrifugal compressor blade

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Abstract: The objective of this work lies in the three-dimensional study of the thermo mechanical behavior of a blade of a centrifugal compressor. Numerical modeling is performed on the computational code "ABAQUS" based on the finite element method. The aim is to study the impact of the change of types of blades, which are defined as a function of wheel output angle β_2 , on the stress fields and displacements coupled with the variation of the temperature.

This coupling defines in a realistic way the thermo mechanical behavior of the blade where one can note the important concentrations of stresses and displacements in the different zones of its complex form as well as the effects at the edges. It will then be possible to prevent damage and cracks in the blades of the centrifugal compressor leading to its failure which can be caused by the thermal or mechanical fatigue of the material with which the wheel is manufactured.

Keywords: blade, centrifugal compressor, thermo-mechanical, modeling, finite elements, Abaqus

Nomenclature

v_1	The absolute velocity [m/s]
u_1	The training velocity [m/s]
w_1	Relative velocity [m/s]
v_2	The absolute velocity(output) [m/s]
u_2	The velocity (output) [m/s]
w_2	The relative velocity (output) [m/s]
v_{2m}	Projection of v_2 on the radius [m/s]
v_{2u}	Projection of v_2 on the tangent to the wheel [m/s]
α	Angle of the absolute velocity [°]
β	Angle of the relative velocity [°]
T_{ref}	Reference temperature [°C]
S	Area of the surface [m ²]
e	Thickness [m]
$\varnothing$	Heat flux [W/m ²]
λ	Thermal conductivity [W/m°C]
ρ	Density [kg/m ³]
α	Coefficient of thermal expansion [1/K]
σ_{eq}	Equivalent of Von Mises stress [N/mm ²]
E	Young's modulus [N/mm ²]
ν	Poisson's ratio

1 Introduction

The use of renewable energies has been the subject of many research works [1, 2]. Nowadays, the centrifugal compressors are used when looking for a high pressure ratio with a low volume flow. The limitation of the pressure ratio now comes from mechanical stresses, thermal stresses and materials rather than the flow. These causes play a significant role in the problem of increasing the efficiency of centrifugal compressors which has become a major issue for designers. Centrifugal compressors must always be more

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efficient. In such problems the consideration of thermo mechanical coupling is essential for the understanding of the failure mechanisms of the compressor blades. The behavior of the centrifugal compressor is significantly affected by the physical or construction angle β_2 at the outlet of the blades. The interest of this thermo mechanical study on the blade consists in discovering the distribution of the stress fields and displacements as well as the flows of heat while varying the blade outlet angle β_2 . A simulation of three-dimensional thermo mechanical behavior of a centrifugal compressor blade is carried out by means of calculation codes based on the finite element method "Abaqus". The research works that had been undertaken and which have a direct or indirect relation and impact on the purpose of the present work can be summarized as follows:

A numerical analysis of a centrifugal compressor blade subjected to loading under multiple operating conditions with the CFX code [3] was mentioned by Xie *et al.* Jiao *et al.* [4] performed a numerical simulation of the flow in a centrifugal compressor blade based on ANSYS Workbench. Zheng *et al.* [5] tried to analyze the effect of temperature and pressure on the stresses in an axial and centrifugal compressor combined with CFX. Gurloven *et al.* [6] worked on modeling and stress simulation in a centrifugal compressor. Setiya *et al.* [7] performed in their work a structural analysis in a blade under the load of an aircraft compressor using the ANSYS code while changing the material. An experimental investigation was carried out in the framework of the cracking of the wheel of a centrifugal compressor by Li *et al.* [8] in 2013. The study of the blade rupture was evoked by Xiaolong Zhang *et al.* [9] in 2015. In general, most of the works done were focused on the flow studies and the performance of centrifugal compressors. The originality of this work is an analysis of the thermo mechanical behavior with the Abaqus code of a centrifugal compressor blade with shape change by means of the outlet angle β_2 . Finally, it is understood that the prediction of the stress fields have a crucial role in the dimensioning as well as the manufacture and the choice of constituent material in order that the blade retains the required mechanical qualities from the point of view of resistance contributing to a better performance of centrifugal compressor.

2 The theory of compressor

2.1 Velocity triangles

At the compressor inlet and from Figure 1 (a and b), we can define the following parameters:

Figure 1: Velocity triangles (input-output) in a centrifugal compressor

- The absolute velocity V_1 such that: $V_1 = \frac{q_v}{s} = \frac{q_m}{\rho_1 s_1}$
- The training velocity U_1 such that: $U_1 = R_1 \omega$
- The triangle then closes by the relative velocity W_1 which is the speed that would see an observer placed on the wheel with, in general: $\vec{v}_1 = \vec{u}_1 + \vec{w}_1$

For the centrifugal compressor Figure (a):

$$s_1 = 2\pi R_{11}$$

The velocity v_1 is radial.

At the exit of the wheel Figure 1 (a and b), we also have:

1. The absolute velocity V_2 decomposing in velocity V_{2m} (projection of V_2 on the radius) and in tangential velocity V_{2u} (projection of V_2 on the tangent to the wheel);
2. The drive velocity U_2 such that:

$$U_2 = R_2 \omega;$$

3. The relative velocity W_2 with:

$$\vec{v}_2 = \vec{u}_2 + \vec{w}_2$$

2.2 Various blade shapes of a mobile compressor wheel

They are represented as follows according to the outlet angle β_2 as shown in the Figure 2:

Figure 2: Various blade shapes of a mobile compressor wheel

3 Creation of a 3D blade shape in Abaqus

The geometric shape of the centrifugal compressor wheel created in the Abaqus Software Part Module. It is represented by Figure 3 as follows:

Figure 3: Centrifugal compressor wheel: (a) open; (b) closed

Figure 4: The location and position of the blades on the lower part of the wheel

Figure 4 shows the location and position of the blades on the lower part of the wheel.

The geometric shape of the 3D blade of the centrifugal compressor that will be studied is represented by the following configuration:

4 Property of the material

The definition of material properties has been introduced in the "Property" module. The following Table 1 includes the mechanical characteristics of the material of the blade (Aluminum):

Table 1: Mechanical properties of aluminum

General properties	Values
Density ρ en [kg/m ³]	2700
Thermal conductivity λ [W/m.°C]	160
Heat capacity C_p	900
Longitudinal Young's modulus E [MPa]	70000
Poisson's ratio ν	0,33
Elastic limit stress σ_e [MPa]	320
Coefficient of thermal expansion α	$2,3 \cdot 10^{-5}$

(b) The load is a combination of both the centrifugal load and the aerodynamic load that has been applied to the blades of the centrifugal compressor wheel as a static pressure load.

A pressure of 2500 MPa was applied to the intrados of the blade.

Figure 5: Geometry of the blade of the centrifugal compressor under study

Figure 6: Loading and boundary conditions

5 Boundary conditions and loading

(a) The fixing (embedding) was performed at the trailing edge section (Figure 6).

- (c) With an inlet temperature equal to: $T_e = 30^\circ\text{C}$ and an outlet temperature equal to: $T_s = 20^\circ\text{C}$. The blade thickness is equal to 8mm.

6 Model mesh

This module contains all the necessary tools to generate a finite elements mesh on an assembly. The mesh using 4-node volume linear tetrahedral elements has been adopted for the model under study. In this volume element, no simplification hypotheses were assumed on the deformations and the constraints.

Figure 7: Mesh of blade

7 Results and discussions

An attempt has been made to simulate the thermo mechanical behavior of a centrifugal compressor blade. At the blade an inlet temperature and an outlet temperature were imposed which were coupled with a static pressure estimated to be equal to the resultant of the centrifugal and aerodynamic loads. In this simulation the geometry of the blade has been changed by varying its outlet angle β_2 . We have worked with the angles of the following blade: blade lying backward $\beta_2 = 75^\circ$, radial blade $\beta_2 = 90^\circ$ and blade lying forward $\beta_2 = 120^\circ$. Through this simulation we try to find the impact of the change of the outlet angle β_2 on the response of the blade in this case of behavior. The visualization of the displacements, the stresses and the flux distributions for outlet angle $\beta_2 = 75^\circ$, $\beta_2 = 90^\circ$ and $\beta_2 = 120^\circ$ are shown respectively in (Figures 8 to 10) which allow us to deduce the following results:

7.1 The displacement fields

There was a uniform distribution of displacement over the entire surface of the intrados and extrados of the blade for the three cases of angles β_2 studied (Figure 8). The maximum displacements are located at the level of the leading edge of the inlet side of the blade. In this case of thermo mechanical behavior, the values of the displacements are small in the case of the forward lying blade $\beta_2 = 120^\circ$ compared to the two other cases. This may represent an advantage for this form ($\beta_2 = 120^\circ$) for the compressor so that the gap that is likely to generate between rotor and stator can in this case be minimized or even neglected and this to avoid contact and friction between these two elements if the compressor operating temperature increases.

7.2 The Von Mises stress fields

Under pressure and temperature load, the blade is subject to high thermo mechanical stresses. If these constraints exceed the limit resistance of aluminum there will be rupture. For the three cases of the angles studied (Figure 9), the trend of the distributions of the Von Mises' stresses on the intrados and extrados of the blade are identical. We can see which is the location of the Von Mises stress at the leading edge of the outlet side for all the cases. The blade works in the elastic range in complete safety since the maximum Von Mises stresses do not exceed the elastic limit of the aluminum which is equal to 320 MPa. It has been noted that the Von Mises stresses for radial blade $\beta_2 = 90^\circ$ are twice that of backward lying blade $\beta_2 = 75^\circ$. On the other hand, the values of the weakest stresses are found in the case of the forward lying blade $\beta_2 = 120^\circ$. In the case of the radial blade $\beta_2 = 90^\circ$ the maximum Von Mises stress is 305.206 MPa, which is a value that is very close to the elastic limit of the material which is of the order of 320 MPa. Following these observations, it is therefore necessary to think of a cooling system in these weak zones of the compressor blade to avoid any accidental failures that can cause damage. Also, it is necessary to manage and optimize the choice of material and outlet angles β_2 while taking into account the effect of temperature.

7.3 Heat flux fields

The thermo mechanical modeling makes it possible to take into account the energy dissipated during contact in the form of heat. It has been noted that the distribution of heat flux is homogeneous in the three directions as shown in

Figure 8: Displacement fields for: (a) $\beta_2 = 75^\circ$; (b) $\beta_2 = 90^\circ$; (c) $\beta_2 = 120^\circ$

Figure 9: Von Mises stress fields for: (a) $\beta_2 = 75^\circ$; (b) $\beta_2 = 90^\circ$; (c) $\beta_2 = 120^\circ$

Figure 10: Heat flux fields for: (a) $\beta_2 = 75^\circ$; (b) $\beta_2 = 90^\circ$; (c) $\beta_2 = 120^\circ$

(Figure 10). The highest heat flux values are found in the case of the radial blade $\beta_2 = 90^\circ$. The maximum heat flux is concentrated at the outlet of the blade (trailing edge). It is spread over one more area of the upper surface of the

blade in the case of forward lying blade $\beta_2 = 120^\circ$ with a lower value compared to other cases. Temperature variations can lead to thermal expansion. They can have an influence on the behavior insofar as the characteristics of the

material constituting the elastic structures are sensitive to the temperature.

8 Conclusion

In this study the problem has been presented in thermo mechanical coupled form since the geometry is a function of the temperature field which is itself influenced by the pressure forces. The impact of the change of the outlet angle β_2 on the holding of the blade (constraint of Von Mises, displacement) and on the flow of heat was discussed. A comparison with respect to the obtained thermo mechanical results for the three outlet angles, we can conclude that:

- The angle $\beta_2 = 120^\circ$ (the forward lying blade) gives a better result vis-à-vis the thermo mechanical resistance of the blade. Also the displacements are lower compared to the two other cases. This is in good agreement with the result found which deals with the influence of the angle β_2 on the performance of the compressor on the compression ratio. On the other hand, high power consumption with a less flow rate was observed for this same angle. Moreover, the outlet angle $\beta_2 = 75^\circ$ is the most favorable for better performances and at the same time the concentrations of stresses and maximum displacements are acceptable according to the results found. The outlet angle $\beta_2 = 90^\circ$ of the blade gives good performance but there can be a risk of breaking the fact that the Von Mises maximum stresses can exceed the limit of resistance of the material easily.

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