Assessment of the Thermal Improvements Awarded by Horseshoe Vortex Elimination on a Turbine Stator Blade in Computational Fluid Dynamics and Conjugate Heat Transfer

Laurent Lachmann
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ASSESSMENT OF THE THERMAL IMPROVEMENTS AWARDED BY HORSESHOE VORTEX ELIMINATION ON A TURBINE STATOR BLADE IN COMPUTATIONAL FLUID DYNAMICS AND CONJUGATE HEAT TRANSFER

A Thesis
by
LAURENT LACHMANN

Submitted to the Office of Graduate Studies of Embry Riddle Aeronautical University
In partial fulfillment of the requirements for the degree of MASTER OF SCIENCE

November 2007

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LAURENT LACHMANN

This thesis was prepared under the direction of the candidate’s thesis committee chairman, Dr. Magdy Attia, Department of Aerospace Engineering, and has been approved by the members of the thesis committee. It was submitted to the department of Aerospace Engineering and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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Vice President for Research and Institutional Effectiveness

12/13/07
Date
“What makes the desert so beautiful, is that it hides a well somewhere”

Antoine de Saint-Exupéry

(French Aviator and Writer)
ABSTRACT

ASSESSMENT OF THE THERMAL IMPROVEMENTS AWARDED BY HORSESHOE VORTEX ELIMINATION ON A TURBINE STATOR BLADE IN COMPUTATIONAL FLUID DYNAMICS AND CONJUGATE HEAT TRANSFER

by

Laurent Lachmann, M.S.A.E.
Embry-Riddle Aeronautical University, 2007
Chair of Advisory Committee: Dr. Magdy Attia

The present work looks at an advanced turbine stator blade design and evaluates its thermal performance relative to a standard design. A new turbine stator blade is designed to eliminate the horseshoe vortex appearing at the leading edge. The new design is characterized by an extension of the leading edge at the hub and at the tip of about 30% of chord. By comparing this new design to an ordinary one (featuring a straight leading edge), the present thesis verifies the horseshoe vortex elimination, and compares the thermal attributes of the fluid. The fluid is three-dimensional, viscous and turbulent. The analysis looks at the steady-state solution only. The meshing operation and the calculations are made using NASA-developed 3D codes: TCGRID and Swift. The author concludes that the drop in blade surface temperature reaches 109.6 K in a designated region of the tip. Many benefits can be expected from this result, more precisely in the choice of material, the cooling strategy, the mechanical properties, and the cost of the new blade. In addition, a conjugate heat transfer analysis is made on the interior of the blade, to evaluate the heat dissipation through internal cooling. The software tools used in the heat transfer analysis were MS Excel, DS Catia, Gambit, and Fluent. The blade is cooled down internally by cool air flowing spanwise through cooling passages. No additional conclusion can be reached from the conjugate heat transfer analysis, but a path is laid for further work on the unsteady state case and the mechanical performance. Such work will lead to a final design of the blade.
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Thanks above all to Mom and Dad. Also, I'd like

Acknowledgements
Thanks above all to M!

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Thanks above all to my Advisor, Prof. Smith, who

"Piled Higher and Deeper" by Jorge Cham. www.phdcomics.com
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................ IV

ACKNOWLEDGEMENTS .................................................................................. V

TABLE OF CONTENTS .................................................................................. VII

LIST OF TABLES ............................................................................................ X

LIST OF FIGURES ........................................................................................ XI

LIST OF ABBREVIATIONS ............................................................................. XIII

NOMENCLATURE ............................................................................................ 2

I. INTRODUCTION ......................................................................................... 1

1) Problem description .................................................................................. 1
   A) Literature Survey: the Horseshoe Vortex .......................................... 1
   B) Old Design .......................................................................................... 6
      a) Airfoil design ................................................................................. 6
      b) Sections stacking .......................................................................... 7
      c) Cooling passages .......................................................................... 7
   C) New Design ....................................................................................... 8
      a) Airfoil design ............................................................................... 8
      b) Cooling passages ......................................................................... 8

2) Objective .................................................................................................. 9

3) Approach .................................................................................................. 9

II. COMPUTATIONAL FLUID DYNAMICS ANALYSIS .................................. 10

1) Construction of the mesh ....................................................................... 10
   A) Presentation of TCGRID 3D ........................................................... 10
   B) Mesh Properties ............................................................................... 10
      a) Noticeable Parameters ................................................................. 10
      b) Mesh views .................................................................................. 11

2) Flow Analysis .......................................................................................... 14
   A) Presentation of Swift ........................................................................ 14
B) Significant input parameters ............................................. 14
   a) Turbulence model ...................................................... 14
   b) Boundary conditions .................................................. 14
   c) Other parameters ...................................................... 15

3) Results ............................................................................. 15
   A) Elimination of the horseshoe vortex .............................. 15
      a) Velocity vectors ..................................................... 16
      b) Streamlines ............................................................ 17
   B) Temperature Difference .............................................. 19
      a) Temperature Range ................................................. 19
      b) Global comparison ................................................. 21
      c) Local comparison .................................................. 23

III. CONJUGATE HEAT TRANSFER ANALYSIS ............................. 27
  1) Software Coordination Layout ...................................... 27
  2) Assembly of the Geometries ......................................... 28
  3) Construction of the Meshes .......................................... 28
  4) Calculations and Results ............................................. 32

IV. THERMAL IMPROVEMENTS .............................................. 35
  1) Reward in the Choice of Materials ............................... 35
  2) Reward in cooling strategy ......................................... 35
  3) Reward in Endurance to Fatigue Stresses ...................... 35
  4) Reward in mechanical properties ................................ 36
  5) Summary ....................................................................... 37

V. CONCLUSION .................................................................... 38

APPENDIX .............................................................................. 39
  1) Numerical files ............................................................. 39
     A) CFD_Analysis Folder ............................................... 39
     B) Conjugate_heat_transfer_analysis ............................. 39
  2) Convergence History ..................................................... 41
     A) Old Design CFD ...................................................... 41
     B) New Design CFD .................................................... 41
C) Conjugate Heat Transfer Analysis ........................................... 42
3) M-Files .................................................................................... 43
   A) Temperature difference calculator ....................................... 43
   B) Dataset comparer ............................................................... 44
   C) Geometry_preparer.m ......................................................... 47
   D) Fluent Profile Writer ......................................................... 58
4) Fluent Profile Template ........................................................ 59
5) Wöhler Chart ......................................................................... 60
6) Turbine Material Properties ................................................... 61
7) Boundary conditions of the CFD and heat transfer analysis ....... 63
   A) Inlet plane .......................................................................... 63
   B) Exit plane ........................................................................... 63
   C) Coolant Parameters ........................................................... 63

REFERENCES .............................................................................. 64

VITA ............................................................................................ 65
LIST OF TABLES

Table 1 - Old design airfoil parameters ................................................................. 6
Table 2 - Mesh parameters (common to both designs) .............................................. 10
Table 3  Solver Input Parameters .......................................................................... 15
Table 4 - Region with the largest ΔT ....................................................................... 23
Table 5 - Evolution of ΔT with size of the data set ................................................. 24
Table 6 - Mesh properties for CHTA ..................................................................... 29
Table 7 - Convection Heat Transfer Rates ............................................................... 33
Table 8  Turbine material Properties ...................................................................... 61
LIST OF FIGURES

Figure 1: Horseshoe vortex on a protruding object [courtesy of efluids.com] .................. 1
Figure 2: Horseshoe vortex at the symmetry plane ...................................................... 2
Figure 3: Incoming boundary layer and trailing vertices .............................................. 2
Figure 4: Secondary flow in a turbine cascade ............................................................. 2
Figure 5: Endwall Stanton numbers ............................................................................. 4
Figure 6: Stanton number in cascade (NASA – Glenn RC) .......................................... 4
Figure 7: Old design hub and tip airfoil section ............................................................. 6
Figure 8: Section Stacking in CATIA ........................................................................... 7
Figure 9: Cooling passages on the old design ............................................................... 7
Figure 10: Airfoil hub and tip sections comparison ...................................................... 8
Figure 11: Cooling passage of the new design .............................................................. 9
Figure 12: Isometric view of the old (right) and new (left) design mesh ..................... 11
Figure 13: XY-plane views of the old (right) and new (left) design meshes ............... 11
Figure 14: Leading edge views of the old (right) and new (left) design meshes .......... 12
Figure 15: Trailing edge views of the old (right) and new (left) design meshes .......... 12
Figure 16: Boundary layer mesh on the hub wall and the blade leading edge .......... 13
Figure 17: Annulus representations ............................................................................ 13
Figure 18: Boundary conditions for Stagnation pressure and velocity ....................... 14
Figure 19: Velocity vector field on the old design ....................................................... 16
Figure 20: Velocity vectors field on the new design ....................................................... 16
Figure 21: Flow streamlines revealing the vortex on the old design (1) ...................... 17
Figure 22: Vortex-free streamlines on the new design (1) ........................................ 17
Figure 23: Streamlines revealing the vortex on the old design (2) ............................... 18
Figure 24: Vortex-free streamlines on the new design (2) ......................................... 18
Figure 25: Blade temperature on pressure surface (top) and suction surface (bottom) for the old design ......................................................................................... 19
Figure 26: Blade temperature on pressure surface (top) and suction surface (bottom) on the new design ......................................................................................... 20
Figure 27: Static temperature along the chord axis ...................................................... 21
Figure 28: Detail of static temperature along the chord axis ........................................... 21
Figure 29: Static temperature along the span axis .......................................................... 22
Figure 30: Detail of the static temperature along the span axis ...................................... 22
Figure 31: Temperature difference on the pressure surface (right) and the suction surface (left) .............................................................................................................................. 25
Figure 40: Software Arrangement Chart Flow ................................................................. 27
Figure 32: Section of the old design mesh for CHTA ....................................................... 29
Figure 33: Mesh of the old design for CHTA ................................................................. 30
Figure 34: Location of the worst element (skewness) of the old design mesh for CHTA 30
Figure 35: Section of the New Design Mesh for CHTA .................................................. 31
Figure 36: New design mesh for CHTA ................................................................. 31
Figure 37: location of the worst element (skewness) of the new design mesh for CHTA 32
Figure 38: Conjugate Heat Transfer Analysis Results for the Old Design ................. 33
Figure 39: Conjugate Heat Transfer Analysis Results for the New Design .................. 34
Figure 41: Virtuous Chain Diagram ............................................................................ 37
Figure 42: Convergence history of the old design (CFD analysis) ............................... 41
Figure 43: Convergence history of the old design (CFD analysis) ............................... 41
Figure 44: Convergence history of the old design in fluent ........................................ 42
Figure 45: Convergence history of the old design in fluent ........................................ 42
Figure 46: Wölher chart sample .................................................................................... 60
LIST OF ABBREVIATIONS

CAD: Computer Assisted Design
CFD: Computational Fluid Dynamics
CHTA: Conjugate Heat Transfer Analysis
DS: Dassault Systems
ERAU: Embry-Riddle Aeronautical University
MS: Microsoft
ND: new design
OD: old design
NOMENCLATURE

A: area of the cooled surface
$c_p$: specific heat of the fluid
$C_{P,C}$: constant pressure specific heat of the coolant
$D_H$: hydraulic diameter (cooling)
$E$: Young modulus
$h$: convection heat transfer coefficient (cooling)
$K_c$: coolant thermal conductivity
$m_c$: mass flow rate of the coolant
$M_X$: component of velocity in the streamwise direction
$M_Y$: component of velocity in the blade-to-blade direction
$M_Z$: component of velocity in the spanwise direction
$P_o$: stagnation pressure, total pressure
$P_{oR}$: reference stagnation pressure = $P_o$ nominal in the inlet plane
$Re_{nr}$: Reynolds number per unit length
$P_{exit}$: static pressure in the exit plane
$St$: Stanton number
$V$: velocity of the fluid
$T_0$: stagnation temperature, total temperature
$u$: component of velocity in the streamwise direction
$v$: component of velocity in the blade-to-blade direction
$V_S$: Volume of the solid (blade)
$V_C$: coolant velocity
$w$: component of velocity in the spanwise direction
$W_S$: weight of the solid (blade)
$\alpha$: thermal expansion coefficient
$\gamma$: specific heat ratio
$\Delta T$: temperature difference between the old design and the new design, for a given area
$\Delta l$: mechanical strain
$\mu_c$: coolant kinematic viscosity
\( \rho \): density of the fluid
\( \rho_c \): coolant density
\( \rho_s \): density of the solid (blade)
\( \sigma \): mechanical stress
\( \Omega \): blade rotational speed
I. INTRODUCTION

1) Problem description

A) Literature Survey: the Horseshoe Vortex

This chapter helps improve our understanding of published work on flows about stationary leading edges and end-walls. Previous efforts identified a dominant passage flow that migrates from the pressure surface to the suction surface in the endwall boundary-layer fluid driven by the pressure gradient between those two surfaces. The size and strength of this flow, known as the passage secondary flow, are independent of the amount of turning of the mainstream. A second important study of the passage flow looked at three-dimensional separation of the flow at the junction between a protruding body and a wall.

Figure 1: Horseshoe vortex on a protruding object [courtesy of efluids.com]
The flow ahead of the junction has a velocity gradient (and hence a dynamic pressure gradient) normal to the endwall because of the presence of an endwall approach to the boundary layer. When the flow stagnates, the total pressure gradient becomes an endwall-normal pressure gradient. Boundary-layer fluid on the protruding body, driven by this pressure gradient, is forced toward the endwall where it migrates upstream of the leading edge (see fig. 2 below)

Figure 2: Horseshoe vortex at the symmetry plane

Figure 3: Incoming boundary layer and trailing vertices

Figure 4: Secondary flow in a turbine cascade
From figure 2 on the previous page, the inlet end wall boundary layer rolls up in front of the leading edge to form the horseshoe vortex. Measurements showed the evolution of the vortex through the blade row: the pressure surface leg is dragged across the passage, due to its pressure gradient, and merges with the passage vortex.

Previous work also showed that the suction surface leg of the horseshoe vortex lifts up the blade surface where the separation line reaches the blade surface. It then orbits around, and is dissipated by, the passage vortex. This type of interaction is dependent upon the particular cascade geometry and pressure ratio. Any reduction or elimination of the leading edge horseshoe vortex is thought to have little effect on the shape and position of the passage vortex.

Heat transfer rates on the endwall are directly related to the structure of the endwall. The leading-edge region experiences high heat transfer rates because of the horseshoe vortex. Blair’s studies indicate that an increase in heat transfer can be found near the leading edges of the vanes, as a result of the roll up of the horseshoe vortex. Resolution was improved to allow a much more complete picture of endwall heat transfer (see fig. 5). Upstream of the cascade, the boundary is essentially two-dimensional, and Stanton-number contours are parallel to the leading edge plane. The leading edge region experiences high heat transfer rates because of the horseshoe vortex as noted by Blair. The leading edge region shows a distinct wedge - area approximately defined by the leading edge plane, the suction surface leading edge separation line, and the pressure-line of the pressure-side leg of the horseshoe vortex. The heat transfer rates remains approximately equal to those of the incoming boundary. Just downstream of the separation line of the pressure side leg of the horseshoe vortex, a decrease in the heat transfer rate is apparent, and a region of low heat transfer extending all the way to the trailing edge is formed. Because the inlet boundary layer has been swept up into the horseshoe vortex, a new boundary layer, driven by the cross passage pressure gradient, is formed. Heat transfer and secondary flow phenomenon in the throat region are very complex and, apparently, depend on the inlet boundary layer thickness. A spot of high heat transfer rates exists in the wake region behind the trailing edge plane, and Stanton numbers remain essentially uniform downstream of the cascade.
Figure 5 - Endwall Stanton numbers

Figure 6: Stanton number in cascade (NASA – Glenn RC)
The **Stanton number** is a dimensionless number, which measures the ratio of heat transferred into a fluid to the thermal capacity of the fluid. It is used to characterize heat transfer in forced convection flows.

**Equation 1: Stanton number**

\[
St = \frac{h}{c_p \cdot \rho \cdot V}
\]

Where
- \( h \) = convection heat transfer coefficient
- \( \rho \) = density of the fluid
- \( c_p \) = specific heat of the fluid
- \( V \) = velocity of the fluid
B) Old Design

The old design, used for comparison, is a turbine stator 2\textsuperscript{nd} stage. This design consists of a blade intended for a 38-blade annulus, described by 5 sections of 74 points each.

a) Airfoil design

The airfoil was created using TFOIL2, a turbine geometry design code developed by Professor Attia. The following parameters are listed:

![Old design hub and tip airfoil section](image)

\textbf{Figure 7: Old design hub and tip airfoil section}

\textbf{Table 1 - Old design airfoil parameters}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of airfoil design cylinder</td>
<td>40&quot;</td>
</tr>
<tr>
<td>Axial chord</td>
<td>51.05 mm</td>
</tr>
<tr>
<td>Tangential chord</td>
<td>52.17 mm</td>
</tr>
<tr>
<td>Throat</td>
<td>default (0)</td>
</tr>
<tr>
<td>Unguided turning</td>
<td>6°</td>
</tr>
<tr>
<td>Inlet blade angle</td>
<td>24 deg</td>
</tr>
<tr>
<td>Inlet (\frac{1}{2}) wedge angle</td>
<td>19°</td>
</tr>
<tr>
<td>Leading edge radius</td>
<td>6 mm</td>
</tr>
<tr>
<td>Exit blade angle</td>
<td>-62 deg</td>
</tr>
<tr>
<td>Trailing edge radius</td>
<td>1.5 mm</td>
</tr>
</tbody>
</table>
b) Sections stacking

Interpolation between the five sections is made by the software or code that the coordinates are plugged in. For the purpose of the heat transfer analysis, the CATIA Software is used, and more precisely the “multi-section volume” function.

![Figure 8: Section Stacking in CATIA](image)

c) Cooling passages

The internal cooling of the blade is done by 3 cooling passages, the sectioning of which is made to allow for approximately the same volume each. This is not the result of a design endeavor, but the arbitrary setting of a reference used in the conjugate heat transfer analysis. The thickness of the blade wall is 1.5 mm.

![Figure 9: Cooling passages on the old design](image)
The interpolation is guided by “splines” defined arbitrarily between every section. Those splines are parametered in tangency to the vertical plane in order to maintain a constant thickness between the blade outer wall and its cooling passages.

C) New Design

The new design is also a second stage turbine stator, with the same amount of blades per annulus, sections per blade and points per section. The airfoil relies on the same parameters.

a) Airfoil design

The difference stands in the axial chord of the hub and tip sections: it is 30% longer that for the old design. Thus, the leading edge is curved in a bow shape as the following figures show.

Figure 10: Airfoil hub and tip sections comparison

b) Cooling passages

They are identical to those of the old design, and feature the same constant thickness of 1.5 mm.
Figure 11: Cooling passage of the new design

Note: the interpolation between the first and second section, as for the one between the before-last and last section is made to facilitate the later meshing of the blade. Indeed, the construction of a valid mesh in the geometry demands that a substantial angle exists between the end wall and the blade surface at their junction.

2) Objective

The objective of the present thesis is to evaluate the thermal benefits granted by the elimination of the horseshoe vortex by comparing the old design with the new design.

3) Approach

First a computational fluid dynamics (CFD) analysis is run to calculate the blade surface temperatures and verify the disappearance of the horseshoe vortex, and then a conjugate heat transfer analysis is run to assess the temperature distribution inside the blade.
II. COMPUTATIONAL FLUID DYNAMICS ANALYSIS

The CFD analysis uses a series of codes developed by NASA for turbomachinery applications. They are used with permission of Dr. Roderick Chima, NASA Glenn Research center. The input data for the analysis (inlet and exit conditions of the flow) come from previous work done by Hanho Hwang, Masters thesis, ERAU Gas Turbine Lab. The code used to generate the mesh is TCGRID 3D; the one used for the flow analysis is Swift.

1) Construction of the mesh

A) Presentation of TCGRID 3D

TCGRID (Turbomachinery C-GRID) is a three-dimensional grid generation code for turbomachinery blades. In the present work, the code generates multi-block grids of C-type and H-type.

B) Mesh Properties

a) Noticeable Parameters

To ensure an impartial comparison, the same input parameters are used to generate the mesh of the old design as in the new design, exception made of the geometry. A complete list of parameters is available in the appendix.

| Table 2 - Mesh parameters (common to both designs) |
|---------------------------------|-------------------|
| Grid size                       | Size in i- (streamwise direction) | 129 |
|                                 | Size in j- (blade-to-blade direction) | 34 |
|                                 | Size in k- (spanwise direction) | 33 |
| Grid spacing                   | Spacing away from the blade (1st element size) | 0.00004 |
|                                 | Spacing spanwise at the tip | 0.0016 |
|                                 | Spacing spanwise at the hub | 0.0014 |
| Grid type limits               | streamwise length of H-type | 0 – 19% |
|                                 | streamwise length of C-type | 20 – 100% |
b) Mesh views

The following captures are from the old design; since captures on the new design would show similar schemes, they are not presented.

Figure 12: Isometric view of the old (right) and new (left) design mesh

Figure 13: XY-plane views of the old (right) and new (left) design meshes
Figure 14: Leading edge views of the old (right) and new (left) design meshes

Figure 15: Trailing edge views of the old (right) and new (left) design meshes
Figure 16: Boundary layer mesh on the hub wall and the blade leading edge

Figure 17: Annulus representations
2) Flow Analysis

A) Presentation of Swift

Swift is a multiblock code for analysis of three-dimensional viscous flows in turbomachinery. The code solves the Thin Layer Navier-Stokes equations using an explicit finite-difference technique.

B) Significant input parameters

a) Turbulence model

The turbulence model used is Cebeci-Smith (algebraic). This choice was made over Bladwin-Lowmax and Wilcox’s k-ω because of the particular designation of the Cebeci-Smith model to turbine blades.

b) Boundary conditions

A velocity/stagnation pressure profile is applied at the inlet of the mesh. It varies with the span coordinate and simulates the presence of the preceding stage (rotor1). The stagnation temperature $T_0$ is held constant at the inlet. This profile is of type “Cole” and is generated automatically. Note that the largest variation happens between 96% and 100% of the blade span.

![Inlet Profile](image)

Figure 18: Boundary conditions for Stagnation pressure and velocity
c) Other parameters

Table 3 - Solver Input Parameters

<table>
<thead>
<tr>
<th>Algorithm parameters</th>
<th>Number of stage for the Runge-Kutta scheme</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runge-Kutta parameter α₁</td>
<td>.25</td>
</tr>
<tr>
<td></td>
<td>Runge-Kutta parameter α₂</td>
<td>.3333</td>
</tr>
<tr>
<td></td>
<td>Runge-Kutta parameter α₃</td>
<td>.5</td>
</tr>
<tr>
<td></td>
<td>Runge-Kutta parameter α₄</td>
<td>1</td>
</tr>
<tr>
<td>Flow parameters</td>
<td>γ</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>Pₑₓⁱ toolStrip/Pₒᵣ</td>
<td>0.491</td>
</tr>
<tr>
<td></td>
<td>Ω/𝑐ₒ (blade rotational speed)</td>
<td>0</td>
</tr>
<tr>
<td>Viscous parameters</td>
<td>Reynolds number/unit length</td>
<td>1.388E+07</td>
</tr>
<tr>
<td></td>
<td>Prandtl number (laminar/turbulent)</td>
<td>0.719 / 0.9</td>
</tr>
<tr>
<td>Initial conditions</td>
<td>Pₒ (Pa)</td>
<td>1094 / 1086</td>
</tr>
<tr>
<td>(inlet / exit)</td>
<td>Tₒ (°K)</td>
<td>1528 / 1528</td>
</tr>
<tr>
<td></td>
<td>Mₓ</td>
<td>0.45 / 0.20</td>
</tr>
<tr>
<td></td>
<td>Mᵧ</td>
<td>0.50 / -0.95</td>
</tr>
<tr>
<td></td>
<td>Mₗ</td>
<td>0 / 0</td>
</tr>
</tbody>
</table>

3) Results

A) Elimination of the horseshoe vortex

Vortices are conveniently visualized by displaying either the velocity vectors field in a region of the flow, or a selection of streamlines. While the first method is more numerical, but is mostly restricted to 2D visualizations, the second is more graphical and is well suited for 3D. Both methods are applied in the following captures. Note that for every picture, every wall is the one of the tip of the blade.
a) Velocity vectors

Figure 19: Velocity vector field on the old design

The vortex is visible by considering the inversion of the arrows along the wall. This means that the flow is going backward in this region.

Figure 20: Velocity vectors field on the new design

Here all the arrows point in the same direction; there is no backflow, hence no vortex. The next captures show clearly the disappearance of the vortex by the absence of swirl.
b) Streamlines

Figure 21: Flow streamlines revealing the vortex on the old design (1)

Figure 22: Vortex-free streamlines on the new design (1)
Figure 23: Streamlines revealing the vortex on the old design (2)

Figure 24: Vortex-free streamlines on the new design (2)
B) Temperature Difference

a) Temperature Range

The critical measurement is the blade surface temperature because it holds the key to the design of the turbine. Note, the minimum and maximum values are indicated for the whole volume around the blade, not only its surface.

Figure 25: Blade temperature on pressure surface (top) and suction surface (bottom) for the old design
Figure 26: Blade temperature on pressure surface (top) and suction surface (bottom) on the new design

The above figures show that the flow is generally cooler on the surface of the new design, with a more homogeneous temperature distribution. The maximum of 1542K is found in the vicinity of the hub – leading edge intersection.
b) Global comparison

Next are plots of the temperatures along the chord (x) and along the span (z).

Figure 27: Static temperature along the chord axis

Figure 28: Detail of static temperature along the chord axis
The detail plot shows that the new design is tremendously cooler than the old one starting from the leading edge and up to 20% of the axial chord. The temperature difference in this region exceeds 300 °K.

![Graph showing temperature difference between old and new design](image)

**Figure 29: Static temperature along the span axis**

Again a better homogeneity is observed: the green dots are less spread out than the blue ones, except in the hub and tip region.

![Graph showing detail of temperature along span axis](image)

**Figure 30: Detail of the static temperature along the span axis**

In the center of the blade span, a regular shift of static temperatures of approximately 10 °K is observed.
c) Local comparison

Since the new design brings modifications in the blade’s hub and tip sections, the region around those are where the changes are expected to happen. But since some parts of the blade are generally easier to cool down than others, value can be found in knowing by how much the temperature is reduced, and where. For that purpose, a MatLab application is developed (see Appendix). The application calculates the temperature difference (ΔT) within a delimited set of coordinates. This set is defined by: \( x_{\text{min}}, x_{\text{max}}, y_{\text{min}}, y_{\text{max}}, z_{\min}, z_{\text{max}} \). By varying the boundaries of the data set, and calculating the ΔT for every case, the region with the greatest ΔT is identified. Note that to ensure validity of the data set considered, every set has a minimum number of points of comparison: 125. This minimum is equal to 1% of the total number of points on the surface of the blade (12416).

The result of the search is detailed in the next table.

**Table 4 - Region with the largest ΔT**

<table>
<thead>
<tr>
<th></th>
<th>( \Delta T ) (( T_{\text{OLD}} - T_{\text{NEW}} ))</th>
<th>( 109.6 \text{ K} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{\text{min}} ) [% axial chord]</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>( x_{\text{max}} ) [% axial chord]</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>( y_{\text{min}} ) [% tangential chord (*)]</td>
<td>70.9</td>
<td></td>
</tr>
<tr>
<td>( y_{\text{max}} ) [% tangential chord (*)]</td>
<td>78.5</td>
<td></td>
</tr>
<tr>
<td>( z_{\min} ) [% span]</td>
<td>95.5</td>
<td></td>
</tr>
<tr>
<td>( z_{\max} ) [% span]</td>
<td>96.5</td>
<td></td>
</tr>
</tbody>
</table>

(*) The tangential chord is defined as the difference between the two extrema of the Y coordinates.
Since the size of this data set is small in the span direction (2.6 %span), the application was run for different “sizes” of the set. The size is defined as the length in each direction. This length is expressed in percentage of the total length in x, y or z. By increasing the size of the set the following compilation of set size and ΔT can be made:

<table>
<thead>
<tr>
<th>Size</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>25%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔT (°K)</td>
<td>105</td>
<td>89</td>
<td>62</td>
<td>59</td>
<td>32</td>
</tr>
<tr>
<td>$x_{\text{min}}$ (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$x_{\text{max}}$ (%)</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>$y_{\text{min}}$ (%)</td>
<td>50</td>
<td>50</td>
<td>30</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>$y_{\text{max}}$ (%)</td>
<td>55</td>
<td>60</td>
<td>45</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>$z_{\text{min}}$ (%)</td>
<td>95</td>
<td>90</td>
<td>0</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>$z_{\text{max}}$ (%)</td>
<td>100</td>
<td>100</td>
<td>15</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>
Finally, the results can be represented according to the value of $\Delta T$ as a function of their position on the blade.

![Figure 31: Temperature difference on the pressure surface (right) and the suction surface (left)](image)

The preceding figures show that $\Delta T$ reaches $333K$ in a very small area, which is at or near the leading edge – tip region. Most of the pressure surface experiences positive differences of $31K \pm 16.5K$. Negative values of $\Delta T$ are found close to the trailing edge, which indicates that the old design is somewhat cooler than the new design in that region. The reader is advised that the mesh precision is not as high in this region as in the front part of the blade.
"Piled Higher and Deeper" by Jorge Cham. www.phdcomics.com
III. CONJUGATE HEAT TRANSFER ANALYSIS

1) Software Coordination Layout

The above figure shows how the CFD analysis and the CHTA analysis are connected. The general idea is that the CFD results are the boundary conditions for the CHTA analysis. MatLab is used extensively to reformat the files to be exported to other applications.
2) Assembly of the Geometries

The blade surface coordinates were generated prior, using the turbine geometry code TFOIL2. While those points can be run directly into the CFD analysis, the conjugate heat transfer analysis (CHTA) requires cooling passages to be added, hence the need to import them into a CAD software (DS CATIA). This is done by using MS Excel as a medium: the blade surface points are imported into Excel (with the help of a MatLab program) which then exports them into CATIA, by means of a DS developed macro.

Once the surface coordinates are in CATIA, the blade outer shape can be generated in part design, the cooling passages added, and the file then exported as a .step file. Remark: other export formats were tested, but step gave the best result.

3) Construction of the Meshes

The software used for the mesh of the blade is Gambit. It receives the geometry with the .step file created in CATIA. Due to the complexity of the new design geometry (highly curved, some sharp edges), a rudimentary mesh is created using the tetrahedral scheme. The same parameters are used to mesh both designs. It can be noted that the new design retains a few highly skewed elements (aspect ratio between .7 and .99), but their amount is insignificant (7 out of over 900 000). The mesh contains 2 noticeable zones: one for the blade “hot” surface (outside) and one “cool” for the blade cooling passages surface (inside). They are defined as wall-type.
### Table 6 - Mesh properties for CHTA

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Old Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme</td>
<td>Tetrahedral</td>
<td>Tetrahedral</td>
</tr>
<tr>
<td>Size of elements</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of elements</td>
<td>826 144</td>
<td>902 754</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>184 085</td>
<td>200 631</td>
</tr>
<tr>
<td>Number of inverted elements</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(volume &lt; 0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of moderately skewed elements</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>(0.97 &lt; aspect ratio &lt; 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of very highly skewed elements</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(aspect ratio &gt; 1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 33: Section of the old design mesh for CHTA
Figure 34: Mesh of the old design for CHTA

Figure 35: Location of the worst element (skewness) of the old design mesh for CHTA
Figure 36: Section of the New Design Mesh for CHTA

Figure 37: New design mesh for CHTA
4) Calculations and Results

The CHTA solution is calculated in Fluent. The boundary conditions are input using the convection option for the cool zone using the following equation:

**Equation 2_Air Film Heat Transfer Coefficient**

\[
h = 0.023 \times C_{p,c} \times \frac{\dot{m}_c}{A} \times \left( \frac{D_H \times V_C \times \rho_C}{\mu_C} \right)^{-2} \left( \frac{\mu_C \times C_{p,c}}{K_C} \right)^{-2/3}
\]

Where \( h \): heat transfer coefficient of the air film on the cool surface.

\( C_{p,c} \): constant pressure specific heat of the coolant

\( \dot{m}_c \): mass flow rate of the coolant

\( A \): area of the cooled surface

\( D_H \): hydraulic diameter

\( V_C \): coolant velocity

\( \rho_C \): coolant density

\( \mu_C \): coolant kinematic viscosity

\( K_C \): coolant thermal conductivity
Equation 3: Hydraulic Diameter

\[ D_H = \sqrt{\frac{4 \times A}{\pi}} \]

The option selected for the hot zone is a temperature profile (a profile format sample is included in the appendix). Convergence is obtained rapidly, thanks to the roughness of the mesh. And the inner temperature distribution is represented on the next figures.

Table 7 - Convection Heat Transfer Rates

<table>
<thead>
<tr>
<th>Convection heat transfer rate (W/m²)</th>
<th>Cooling passage #1</th>
<th>Cooling passage #2</th>
<th>Cooling passage #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Design</td>
<td>2.16 E+09</td>
<td>8.34 E+08</td>
<td>7.03 E+10</td>
</tr>
<tr>
<td>New Design</td>
<td>2.94 E+10</td>
<td>8.59 E+08</td>
<td>1.06 E+10</td>
</tr>
</tbody>
</table>

Figure 39: Conjugate Heat Transfer Analysis Results for the Old Design
Figure 40: Conjugate Heat Transfer Analysis Results for the New Design

The above figures compare the blade inner temperature distribution. No apparent distinction is noticed, since the CHTA only considers the steady-state solution. Further work on the unsteady-state solution could lead to an interesting comparison.
IV. THERMAL IMPROVEMENTS

1) *Reward in the Choice of Materials*

The very high level of temperature experienced by turbines calls for very sophisticated high-resistance alloys. Often an extra layer made of a different material with boosted performance (TBC – Thermal Barrier coating) is applied on the surface of the blade. Such material is very expensive, and is an important component of the total cost of the engine.

Given that the new design blade will heat less, it can be made of a simpler material, one with a lower temperature resistance. It may allow the designer not to use any blade coating either. The direct consequence will be to lower the cost of the turbine. For reference to material costs and properties, see the turbine materials properties table in appendix 3).

2) *Reward in cooling strategy*

Since the turbine entry temperature is usually above the turbine material melting point, the blades would not resist if it was not for cooling. Hence the importance of designing a cooling strategy that will lower the blade surface temperature below the melting point. Those are generally very complex and tend to significantly complicate the manufacturing of the blade. The new design will allow for a new cooling strategy that will target specific locations of the blade (hub and tip region of the leading edge in particular). Such a change is likely to diminish the level of complexity of the blade, and to simplify its manufacturing.

3) *Reward in Endurance to Fatigue Stresses*

Another consequence in the decrease of blade temperatures is the impact on internal thermal stresses. Those stresses are generated by the thermal expansion naturally occurring in the blade in its very hot environment. Their level is directly proportional to the ratio of the thermal expansion coefficient over the Young modulus.
Equation 4_Mechanical stress

\[ \sigma = E \times \Delta l \]

Equation 5_Thermal expansion

\[ \Delta l = \alpha \times \Delta T \]

According to the above equations, the internal thermal stresses in the new design will be lower.

The appearance and disappearance of those internal stresses as the blade heats up and then cools down with every engine cycle cause fatigue damage. This damage depends on 2 factors: the intensity of the stress, and the number of cycles. The empirical law that governs the amount of damage taken by the blade as a function of those 2 factors is known as the Wöhler chart (see figure 32 in appendix for sample). This law states that if the intensity of the stress is lower, then a material can handle more cycles without increasing the amount of damage. Therefore the new design will allow for more engine cycles before replacing the blade.

4) Reward in mechanical properties

Finally, because of its new shape, the new design blade is also stiffer. This increase in stiffness may yield to a thinner design and hence a decrease in weight. The following equation explains this effect.

Equation 6_Weight_1

\[ W = \rho_s \times V_s \]

Equation 7_Volume

\[ V = f(t) \]

Equation 8_Weight_2

\[ W = \rho \times f(t) \]

[See appendix for sample values of various turbine materials]
5) **Summary**

![Diagram of Virtuous Chain Diagram]

**Surface Temperature**

- Cheaper Materials
- New Cooling Strategy
- Lower Fatigue Stresses

**New Shape**

- Higher Stiffness

**Cause**

**Effect**

**Benefit**

**Figure 41: Virtuous Chain Diagram**
V. CONCLUSION

It is a commonality in turbomachinery to stress the importance of the turbine thermal design. Turbine blade temperature is definitely one of the most critical parameters, and many times a limitation factor. The overall performance of the engine depends heavily on it. For this reason, much effort is made throughout the industry and universities to make progress in this field.

The very high temperatures encountered by turbine blades (especially first stage stator blades) are always set to the limit of material capabilities. The job done by this thesis demonstrates that for the same value of turbine entry temperature, advanced turbine blade design can reduce the level of thermal constrains. This comes from the elimination of a turbulent perturbation of the flow due to a protruding object known as the horseshoe vortex. As a result of eliminating the Horseshoe Vortex, the temperature drops significantly on the blade surface. Much improvement can be expected from this temperature drop, in areas such as weight, manufacturing complexity, lifecycle length and cost.

The perspective is open for further work on this new design. Exact figures regarding mechanical properties such as structural stiffness, load bearing, and fatigue tolerance would greatly improve our comprehension of the benefits of this new blade design.
APPENDIX

1) **Numerical files**

The digital files associated with the present work are gathered in a folder named “Lachmann_Thesis”. It contains the source file of this document and two folders, one for each analysis. The role of every file is given in this section. Note that N/O designates two files with identical purpose, one applies to the old design (its name starts with an “O”), the other applies to the new design (its name starts with an “N”). Also, every m-file has a header with basic information (author, last modification date) and brief instructions when they apply.

A) **CFD Analysis Folder**

- N/ODtcgrid.ing: input file for tcgrid. It contains the geometry of the design.
- N/ODfort.1: CFD mesh file. It must be loaded in Fieldview to visualize the result file.
- N/ODfort.10: “index file”. It contains data that have to be changed manually, especially regarding the rotational velocity of the blade.
- N/ODswift.inp: CFD solver input file. It contains the inlet and exit conditions.
- N/ODfort.3: CFD solution file. It is made of a special format that cannot be edited. It can only be used by Fieldview or similar software.
- N/ODswiftOutput.txt: Output file of swift. It contains the input parameters and a summary of the solution.
- Temp_diff_calculator.m: extracts the coordinates and temperatures from the Fieldview export files, calculates the temperature difference, and stores it in a matrix.
- Dataset_comparer.m: finds the array with the minimum size and a maximum mean temperature difference. The minimum is set by the user with the variable dX. Prints its result in the command window.

B) **Conjugate heat transfer analysis**

- Geometry_preparer.m: extracts the coordinates of the blade from the CFD mesher input file and writes them in a particular Excel spreadsheet. Works on both designs.
• Profile_generator.m: writes the profiles that constitute part of the boundary conditions for fluent in the CHTA.

• N/ODBladecoo.xls: spreadsheet containing a macro that exports the points coordinates into Catia. It requires to run the m-file Geometry_preparer.m beforehand. The file contains instructions on how to run the macro.

• N/OD311007.catpart: CAD model.

• N/ODmodel.stp: CAD model in export format (generated by Catia). It cannot be edited, use the CAD model instead.

• N/ODgambit.dbs: save of the gambit session. It contains the mesh for the CHTA.

• N/ODmesh.msh: mesh file in export export for CHTA, generated by Gambit.

• n/odtprofile.prof: profile file for the ‘hot’ boundary condition (blade surface temperatures). This file is generated in MatLab by the file Profile_generator.m

• N/ODfluent.cas: restart file for Fluent. Once this file is read, all the parameters and the solution are loaded into Fluent

• NDfluent.dat: solution file for Fluent. It is automatically read with the above file.
2) Convergence History

A) Old Design CFD

Figure 42: Convergence history of the old design (CFD analysis)

B) New Design CFD

Figure 43: Convergence history of the old design (CFD analysis)
C) Conjugate Heat Transfer Analysis

Figure 44: Convergence history of the old design in fluent

Figure 45: Convergence history of the old design in fluent
3) M-Files

A) Temperature difference calculator

% Composed by Laurent Lachmann, last updated Nov29th 2007
% produces a [5x12416] matrix named 'DIFF' organized as follows:
% [I X Y Z (Tod-Tnd)]
% INSTRUCTIONS
% The input files required are 'OD231007t.txt' and 'ND231007t.txt',
% in Fieldview export format, must be present in the same directory
% Just hit run.

clear all
clc

% --------------------------------- DATA READER --------------------------------- %
% - reads I,X,Y,Z and S columns of 'ODLLtemp.txt' and 'NDLLtemp.txt'-%
% --------------------------------- Old Design --------------------------------- %
fid1 = fopen('OD311007t.txt', 'r');
Nlod = textscan(fid1, '%d', 1, 'headerlines', 1);
Nod = Nlod{1};
Allod = textscan(fid1, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f', Nod,
'headerlines', 2);
fclose(fid1);
AOD = [Allod{1} Allod{4} Allod{5} Allod{6} Allod{7}];

% --------------------------------- New Design --------------------------------- %
fid2 = fopen('ND311007t.txt', 'r');
Nlnd = textscan(fid2, '%d', 1, 'headerlines', 1);
Nnd = Nlnd{1};
Allnd = textscan(fid2, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f', Nnd,
'headerlines', 2);
fclose(fid2);
AND = [Allod{1} Allnd{4} Allnd{5} Allnd{6} Allnd{7}];

% --------------------------------- SCRUBBER --------------------------------- %
% ------- eliminates wake points by setting I in [17 113]-------- %
sAOD = size(AOD);
k=1;
l=1;
for i = 1:sAOD(1)
    if AOD(i,1)>=17 & AOD(i,1)<=113
        BOD(k,:) = AOD(i,:);
        k=k+1;
    end
    if AND(i,1)>=17 & AND(i,1)<=113
        BND(l,:) = AND(i,:);
        l=l+1;
    end
end
end

% ---------------------------------------------------------------------- %
% -- DIMENSIONALIZER ---------------------------------------------------- %
% ---------------------------------------------------------------------- %
% dimensionize X, Y and Z in % and T by 1528 -------------------------- %

ODXmin=min(BOD(:,2));
ODYmin=min(BOD(:,3));
ODZmin=min(BOD(:,4));

NDXmin=min(BND(:,2));
NDYmin=min(BND(:,3));
NDZmin=min(BND(:,4));

ODX=max(BOD(:,2))-ODXmin;
ODY=max(BOD(:,3))-ODYmin;
ODZ=max(BOD(:,4))-ODZmin;

NDX=max(BND(:,2))-NDXmin;
NDY=max(BND(:,3))-NDYmin;
NDZ=max(BND(:,4))-NDZmin;

for l = 1:length(BOD)
    BOD(l,2)=(BOD(l,2)-ODXmin)/ODX*100;
    BOD(l,3)=(BOD(l,3)-ODYmin)/ODY*100;
    BOD(l,4)=(BOD(l,4)-ODZmin)/ODZ*100;
    BOD(l,5)=1528*BOD(l,5);
end

% ---------------------------------------------------------------------- %
% DIFFERENCE CALCULATOR ------------------------------------------------ %
% ---------------------------------------------------------------------- %

DIFF=BND;
for l = 1:length(BOD)
    DIFF(l,5)=BOD(l,5)-BND(l,5);
end

% ---------------------------------------------------------------------- %
% THE END --------------------------------------------------------------- %
% ---------------------------------------------------------------------- %

B) Dataset comparer

% Composed by Laurent Lachmann, last updated Nov29 2007

% ROLE
% The file 'Temp_Diff_calculator.m' needs to be run before.
% Builds dataset of identical size (in space) based on
% x,y,z coordinates, retains the one with the highest
% temperature difference and displays the result in the command window

% INSTRUCTIONS
% The file 'Temp_Diff_calculator.m' needs to be run before.
% Set the size of the set in the x,y and z direction in percentage
% of the total length of the blade in that direction. Then run.

%---------------------------------------------------------------------------------------------------------------%
% DatasetComparer  
%---------------------------------------------------------------------------------------------------------------%

clc

% Definition of the size of the datasets
dX=4.9;
dY=dX;
dZ=dX;

%---------------------------------------------------------------------------------------------------------------%

DIFFERENCE =0;
success=0;
c=1;
d=1;

for Xmin=0:dX:100
    if (Xmin+dX)<=100
        Xmax=Xmin+dX;
    end
    for Ymin=0:dY:100
        if (Ymin+dY)<=100;
            Ymax=Ymin+dY;
        end
        for Zmin=0:dZ:100
            if (Zmin+dZ)<=100;
                Zmax=Zmin+dZ;
            end
            S=0;
a=0;
for i = 1:length(BOD)
    if DIFF(i,2)>Xmin & DIFF(i,2)<Xmax & DIFF(i,4)>Zmin & DIFF(i,3)>Ymin & DIFF(i,3)<Ymax & DIFF(i,4)<Zmax
        S = S+DIFF(i,5);
a=a+1;
    end
end
if a>125
    DIFFERENCE(c) = S/a;
    Xi(c)=Xmin;
    Xa(c)=Xmax;
    Yi(c)=Ymin;
    Ya(c)=Ymax;
    Zi(c)=Zmin;
    Za(c)=Zmax;
success=1;
c=c+1;
end
end
end

dT=0;
for i=1:(c-1)
  if dT<DIFFERENCE(i)
    dT=DIFFERENCE(i);
    d=i;
  end
end

Tmoy=BND(d,5)+.5*DIFFERENCE(d);
if success==1
  fprintf('dT = %.3f K
Xmin = %.f
Xmax = %.f
Ymin = %.f
Ymax = %.f
Zmin = %.f
Zmax = %.f
dX = %.lf
',dT,Xi(d),Xa(d),Yi(d),Ya(d),Zi(d),Za(d),dx)
else
  fprintf('There is no valid set of this size
Increase the minimum size in one of the directions')
end
C) Geometry_preparer.m

% Composed by Laurent Lachmann, last updated Nov 30 2007

% ROLE
% fills up the spreadsheet that will export the blade coordinates
% into Catia.

% INSTRUCTIONS
% The spreadsheet 'ODBladeCoo.xls', and 'NDBladeCoo.xls' must be
% present in the same directory, if not they will be created but
% will not have the macro to export data into Catia.
% The TCGRID 3D input files 'ODtcgrid.ing' and 'NDtcgrid.ing' must
% be present in the same directory.
% Just hit run.

% clear all
clc

% DATA READER

% Old Design
fid3 = fopen('ODtcgrid.ing', 'r');

% SECTION 01
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 7, 'headerlines', 16);
X2 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 1, 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f', 7, 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f', 1, 'headerlines', 1);
Z1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 1, 'headerlines', 1);

% for j=1:10
x01(:,j)=X1{j};
end

% for j=1:4
x01(8,j)=X2{j};
end

k=1;
for i=1:7
    for j=1:10
        S01(k,1) = x01(i,j);
        k=k+1;
    end
end
for j=1:4
    S01(k,1) = x01(8,j);
    k=k+1;
end

% for j=1:10
y01(:,j)=Y1{j};
for j=1:4
    y01(8,j)=Y2{j};
end

k=1;
for i=1:7
    for j=1:10
        S01(k,2) = y01(i,j);
        k=k+1;
    end
end
for j=1:4
    S01(k,2) = y01(8,j);
    k=k+1;
end

% --------------------------------- Z --------------------------------- %
for i=1:k-1
    S01(i,3)=Z1{l};
end

% --------------------------------- SECTION 02 --------------------------------- %
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7, 'headerlines', 8);
X2 = textscan(fid3, '%f %f %f %f ',1, 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7, 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f ',1, 'headerlines', 1);
Z1 = textscan(fid3, '%f',1, 'headerlines', 1);

% --------------------------------- X02 --------------------------------- %
for j=1:10
    x02(:,j)=X1{j};
end
for j=1:4
    x02(8,j)=X2{j};
end

k=1;
for i=1:7
    for j=1:10
        S02(k,1) = x02(i,j);
        k=k+1;
    end
end
for j=1:4
    S02(k,1) = x02(8,j);
    k=k+1;
end

% --------------------------------- Y02 --------------------------------- %
for j=1:10
    y02(:,j)=Y1{j};
end
for j=1:4
    y02(8,j)=Y2{j};
end

k=1;
for i=1:7
    for j=1:10
        S02(k,2) = y02(i,j);
        k=k+1;
    end
end
for j=1:4
    S02(k,2) = y02(8,j);
    k=k+1;
end
%
%--------------------------------------------------------------- Z02---------------------------------------------------------------%
for i=1:k-1
    S02(i,3)=Zl{l};
end
%
%--------------------------------------------------------------- SECTION 03---------------------------------------------------------------%
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7 , 'headerlines', 8);
X2 = textscan(fid3, '%f %f %f %f ',1 , 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7 , 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f ',1 , 'headerlines', 1);
Z1 = textscan(fid3, '%f',1 , 'headerlines', 1);
%
%--------------------------------------------------------------- X03---------------------------------------------------------------%
for j=1:10
    x03(:,j)=Xl{j};
end
for j=1:4
    x03(8,j)=X2{j};
end
k=1;
for i=1:7
    for j=1:10
        S03(k,1) = x03(i,j);
        k=k+1;
    end
end
for j=1:4
    S03(k,1) = x03(8,j);
    k=k+1;
end
%
%--------------------------------------------------------------- Y03---------------------------------------------------------------%
for j=1:10
    y03(:,j)=Yl{j};
end
for j=1:4
    y03(8,j)=Y2{j};
end
k=1;
for i=1:7
    for j=1:10
        S03(k,2) = y03(i,j);
        k=k+1;
    end
end
for \( j=1:4 \)
    \[ S03(k,2) = y03(8,j); \]
    \[ k = k+1; \]
end

\%
--------------------- Z03 ---------------------

for \( i=1:k-1 \)
    \[ S03(i,3) = Z1(1); \]
end

\%
--------------------- SECTION 04 ---------------------

\[ X1 = \text{textscan}(fid3, '\%f \%f \%f \%f \%f \%f \%f \%f \%f \%f', 7, 'headerlines', 8); \]
\[ X2 = \text{textscan}(fid3, '\%f \%f \%f \%f', 1, 'headerlines', 1); \]
\[ Y1 = \text{textscan}(fid3, '\%f \%f \%f \%f \%f \%f \%f \%f \%f \%f', 7, 'headerlines', 1); \]
\[ Y2 = \text{textscan}(fid3, '\%f \%f \%f \%f', 1, 'headerlines', 1); \]
\[ Z1 = \text{textscan}(fid3, '\%f', 1, 'headerlines', 1); \]

\%
--------------------- X04 ---------------------

for \( j=1:10 \)
    \[ x04(:,j) = X1(j); \]
end

for \( j=1:4 \)
    \[ x04(8,j) = X2(j); \]
end

\[ k = 1; \]

for \( i=1:7 \)
    for \( j=1:10 \)
        \[ S04(k,1) = x04(i,j); \]
        \[ k = k+1; \]
    end
end

for \( j=1:4 \)
    \[ S04(k,1) = x04(8,j); \]
    \[ k = k+1; \]
end

\%
--------------------- Y04 ---------------------

for \( j=1:10 \)
    \[ y04(:,j) = Y1(j); \]
end

for \( j=1:4 \)
    \[ y04(8,j) = Y2(j); \]
end

\[ k = 1; \]

for \( i=1:7 \)
    for \( j=1:10 \)
        \[ S04(k,2) = y04(i,j); \]
        \[ k = k+1; \]
    end
end

for \( j=1:4 \)
    \[ S04(k,2) = y04(8,j); \]
    \[ k = k+1; \]
end

\%
--------------------- Z04 ---------------------

for \( i=1:k-1 \)
S04(1,3)=Zl(1);
end

% 05  %
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7, 'headerlines', 8);
X2 = textscan(fid3, '%f %f %f %f ',1, 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7, 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f ',1, 'headerlines', 1);
Zl = textscan(fid3, '%f',1, 'headerlines', 1);

% 05  %
for j=1:10
x05(:,j)=X1{j};
end
for j=1:4
x05(8,j)=X2{j};
end
k=1;
for i=1:7
for j=1:10
S05(k,1) = x05(i,j);
k=k+1;
end
end
for j=1:4
S05(k,1) = x05(8,j);
k=k+1;
end

% 05  %
for j=1:10
y05(:,j)=Y1{j};
end
for j=1:4
y05(8,j)=Y2{j};
end
k=1;
for i=1:7
for j=1:10
S05(k,2) = y05(i,j);
k=k+1;
end
end
for j=1:4
S05(k,2) = y05(8,j);
k=k+1;
end

% 05  %
for i=1:k-1
S05(i,3)=Zl(1);
end

% Dimensionalization  %
fclose(fid3);
for i=1:74
    s01(i,1)=300*S01(i,1);  
    s01(i,2)=300*S01(i,2);  
    s01(i,3)=300*S01(i,3)-300;

    s02(i,1)=300*S02(i,1);  
    s02(i,2)=300*S02(i,2);  
    s02(i,3)=300*S02(i,3)-300;

    s03(i,1)=300*S03(i,1);  
    s03(i,2)=300*S03(i,2);  
    s03(i,3)=300*S03(i,3)-300;

    s04(i,1)=300*S04(i,1);  
    s04(i,2)=300*S04(i,2);  
    s04(i,3)=300*S04(i,3)-300;

    s05(i,1)=300*S05(i,1);  
    s05(i,2)=300*S05(i,2);  
    s05(i,3)=300*S05(i,3)-300;
end

xlswrite('ODBladeCoo.xls',s01,2);  
xlswrite('ODBladeCoo.xls',s02,3);  
xlswrite('ODBladeCoo.xls',s03,4);  
xlswrite('ODBladeCoo.xls',s04,5);  
xlswrite('ODBladeCoo.xls',s05,6);

X=[s01(:,1); s02(:,1); s03(:,1); s04(:,1); s05(:,1)];  
Y=[s01(:,2); s02(:,2); s03(:,2); s04(:,2); s05(:,2)];  
Z=[s01(:,3); s02(:,3); s03(:,3); s04(:,3); s05(:,3)];

% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %

clear all
fid3 = fopen('NDtcgrid.ing', 'r');  
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 7 , 'headerlines', 16);  
X2 = textscan(fid3, '%f %f %f %f ', 1 , 'headerlines', 1);  
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 7 , 'headerlines', 1);  
Y2 = textscan(fid3, '%f %f %f %f ', 1 , 'headerlines', 1);  
Z1 = textscan(fid3, '%f', 1 , 'headerlines', 1);  
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
for j=1:10  
    x01(:,j)=X1{j};  
end
for j=1:4  
    x01(8,j)=X2{j};  
end

k=1;  
for i=1:7
for j=1:10
S01(k,1) = x01(i,j);
k=k+1;
end
for j=1:4
S01(k,1) = x01(8,j);
k=k+1;
end

% ---------------------------------------- Y ---------------------------------------- %
for j=1:10
y01(:,j)=Y1{j};
end
for j=1:4
y01(8,j)=Y2{j};
end

k=1;
for i=1:7
for j=1:10
S01(k,2) = y01(i,j);
k=k+1;
end
for j=1:4
S01(k,2) = y01(8,j);
k=k+1;
end
% ---------------------------------------- Z ---------------------------------------- %
for i=1:k-1
S01(i,3)=Z1{l};
end

% ------------------------------------------------- SECTION 02 ------------------------------------------------- %
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f',7 , 'headerlines', 8);
X2 = textscan(fid3, '%f %f %f %f ',1 , 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7 , 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f ',1 , 'headerlines', 1);
Z1 = textscan(fid3, '%f',1 , 'headerlines', 1);
% ------------------------------------------------- X02 ------------------------------------------------- %
for j=1:10
x02(:,j)=X1{j};
end
for j=1:4
x02(8,j)=X2{j};
end

k=1;
for i=1:7
for j=1:10
S02(k,1) = x02(i,j);
k=k+1;
end
end
for j=1:4
S02(k,1) = x02(8,j);
k=k+1;
end

% ---------------------------------- Y02 ---------------------------------- %
for j=1:10
  y02(:,j)=Y1{j};
end
for j=1:4
  y02(8,j)=Y2{j};
end

k=1;
for i=1:7
  for j=1:10
    S02(k,2) = y02(i,j);
k=k+1;
  end
end
for j=1:4
  S02(k,2) = y02(8,j);
k=k+1;
end
% ---------------------------------- Z02 ---------------------------------- %
for i=k-1
  S02(i,3)=Z1{l};
end

% ---------------------------------- SECTION 03 ---------------------------------- %
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7 , 'headerlines', 8);
X2 = textscan(fid3, '%f %f %f %f ',1 , 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7 , 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f ',1 , 'headerlines', 1);
Z1 = textscan(fid3, '%f',1 , 'headerlines', 1);
% ---------------------------------- X03 ---------------------------------- %
for j=1:10
  x03(:,j)=X1{j};
end
for j=1:4
  x03(8,j)=X2{j};
end

k=1;
for i=1:7
  for j=1:10
    S03(k,1) = x03(i,j);
k=k+1;
  end
end
for j=1:4
  S03(k,1) = x03(8,j);
k=k+1;
end
% ---------------------------------- Y03 ---------------------------------- %
for j=1:10
  y03(:,j)=Y1{j};
end
for j=1:4
    y03(8,j)=Y2{j};
end
k=1;
for i=1:7
    for j=1:10
        S03(k,2)=y03(i,j);
        k=k+1;
    end
end
for j=1:4
    S03(k,2)=y03(8,j);
    k=k+1;
end
% ------------------------ Z03 ------------------------
for i=1:k-1
    S03(i,3)=Z1{i};
end

% ------------------------ SECTION 04 ------------------------
X1=textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7, 'headerlines', 8);
X2=textscan(fid3, '%f %f %f %f ', 1, 'headerlines', 1);
Y1=textscan(fid3, '%f %f %f %f %f %f %f %f %f %f',7, 'headerlines', 1);
Y2=textscan(fid3, '%f %f %f %f ', 1, 'headerlines', 1);
Z1=textscan(fid3, '%f', 1, 'headerlines', 1);
% ------------------------ X04 ------------------------
for j=1:10
    x04(:,j)=X1{j};
end
for j=1:4
    x04(8,j)=X2{j};
end
k=1;
for i=1:7
    for j=1:10
        S04(k,1)=x04(i,j);
        k=k+1;
    end
end
for j=1:4
    S04(k,1)=x04(8,j);
    k=k+1;
end
% ------------------------ Y04 ------------------------
for j=1:10
    y04(:,j)=Y1{j};
end
for j=1:4
    y04(8,j)=Y2{j};
end
k=1;
for i=1:7
    for j=1:10
        S04(k,2) = y04(i,j);
        k=k+1;
    end
end
for j=1:4
    S04(k,2) = y04(8,j);
    k=k+1;
end
% --------------------------------- Z04 ----------------------------------- %
for i=1:k-1
    S04(i,3)=Z1{1};
end

% --------------------------------- SECTION 05 --------------------------------- %
X1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 7, 'headerlines', 8);
X2 = textscan(fid3, '%f %f %f %f', 1, 'headerlines', 1);
Y1 = textscan(fid3, '%f %f %f %f %f %f %f %f %f %f', 7, 'headerlines', 1);
Y2 = textscan(fid3, '%f %f %f %f', 1, 'headerlines', 1);
Z1 = textscan(fid3, '%f', 1, 'headerlines', 1);
% --------------------------------- X05 --------------------------------- %
for j=1:10
    x05(:,j)=X1{j};
end
for j=1:4
    x05(8,j)=X2{j};
end
k=1;
for i=1:7
    for j=1:10
        S05(k,1) = x05(i,j);
        k=k+1;
    end
end
for j=1:4
    S05(k,1) = x05(8,j);
    k=k+1;
end
% --------------------------------- Y05 --------------------------------- %
for j=1:10
    y05(:,j)=Y1{j};
end
for j=1:4
    y05(8,j)=Y2{j};
end
k=1;
for i=1:7
    for j=1:10
        S05(k,2) = y05(i,j);
        k=k+1;
    end
end
for j=1:4
    S05(k,2) = y05(8,j);
    k=k+1;
end

% ------------------------------------ 205 ------------------------------------ %
for 1=1:k-1
    S05(1,3)=21(1);
end

% -------------------------------- Dimensionalization -------------------------------- %
fclose(fid3);

for 1=1:74
    s01(1,1)=300*S01(1,1);
    s01(1,2)=300*S01(1,2);
    s01(1,3)=300*S01(1,3)-300;
    s02(1,1)=300*S02(1,1);
    s02(1,2)=300*S02(1,2);
    s02(1,3)=300*S02(1,3)-300;
    s03(1,1)=300*S03(1,1);
    s03(1,2)=300*S03(1,2);
    s03(1,3)=300*S03(1,3)-300;
    s04(1,1)=300*S04(1,1);
    s04(1,2)=300*S04(1,2);
    s04(1,3)=300*S04(1,3)-300;
    s05(1,1)=300*S05(1,1);
    s05(1,2)=300*S05(1,2);
    s05(1,3)=300*S05(1,3)-300;
end

xlswrite('NDBladeCoo.xls',s01,2);
xlswrite('NDBladeCoo.xls',s02,3);
xlswrite('NDBladeCoo.xls',s03,4);
xlswrite('NDBladeCoo.xls',s04,5);
xlswrite('NDBladeCoo.xls',s05,6);

X=[s01(:,1); s02(:,1); s03(:,1); s04(:,1); s05(:,1)];
Y=[s01(:,2); s02(:,2); s03(:,2); s04(:,2); s05(:,2)];
Z=[s01(:,3); s02(:,3); s03(:,3); s04(:,3); s05(:,3)];
D) Fluent Profile Writer

% --------------------------------------------------------------- %
% --------------------------------------------------------------- %
% -- writes fluent profiles 'ODtprofile.prof' and 'NDtprofile.prof'-- %
% --------------------------------------------------------------- %
% Requires to run Temp_Diff_Calc.m beforehand                    %
% --------------------------------------------------------------- %

fidO = fopen('odtprofile.prof','w');
fprintf(fidO,'((odtemp point %d)\n(\n',sBOD(1));
fprintf(fidO,'%d\n',BOD(:,1));
fprintf(fidO,')\n(\n');
fprintf(fidO,'%d\n',BOD(:,2));
fprintf(fidO,')\n(\n');
fprintf(fidO,'%d\n',BOD(:,3));
fprintf(fidO,')\n(\n');
fprintf(fidO,'%d\n',BOD(:,4));
fprintf(fidO,')\n)');
fclose('all');
%
% --------------------------------------------------------------- %
% New Design ----------------------------------------------------- %
% --------------------------------------------------------------- %

fidO = fopen('ndtprofile.prof','w');
fprintf(fidO,'((ndtemp point %d)\n(\n',sBND(1));
fprintf(fidO,'%d\n',BND(:,1));
fprintf(fidO,')\n(\n');
fprintf(fidO,'%d\n',BND(:,2));
fprintf(fidO,')\n(\n');
fprintf(fidO,'%d\n',BND(:,3));
fprintf(fidO,')\n(\n');
fprintf(fidO,'%d\n',BND(:,4));
fprintf(fidO,')\n)');
fclose('all');
% --------------------------------------------------------------- %
% THE END -------------------------------------------------------- %
% --------------------------------------------------------------- %
4) Fluent Profile Template

((newdesign point 6)
(x
  .. .. ..
  .. .. ..)
(y
  .. .. ..
  .. .. ..)
(z
  .. .. ..
  .. .. ..)
(t0
  .. .. ..
  .. .. ..)
(p0
  .. .. ..
  .. .. ..)
(rho
  .. .. ..
  .. .. ..))
5) Wöhler Chart

![Sample S-N Diagram](image)

Figure 46: Wöhler chart sample
6) **Turbine Material Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Endurance Limit (ksi)</th>
<th>Young's Modulus (msi)</th>
<th>Max Temp (F)</th>
<th>Density (lb/in$^3$)</th>
<th>Price (USD/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought Nickel-Chromium alloy (Hastelloy x)</td>
<td>40.61-63.09</td>
<td>27.99-28.86</td>
<td>1922-2192</td>
<td>.2944-.2999</td>
<td>5.822-11.64</td>
</tr>
<tr>
<td>Wrought Nickel-Chromium alloy (Hastelloy x, st)</td>
<td>40.61-63.09</td>
<td>29.73-31.26</td>
<td>1890-2100</td>
<td>.2955-.2985</td>
<td>5.822-11.64</td>
</tr>
<tr>
<td>Wrought Nickel-Chromium-iron alloy, Inconel 601, Annealed</td>
<td>39.89-61.64</td>
<td>29.01-31.18</td>
<td>1593-2012</td>
<td>.2872-.2944</td>
<td>5.822-11.64</td>
</tr>
<tr>
<td>Wrought Nickel-Chromium alloy, Inconel 705, Annealed</td>
<td>67.44-105.2</td>
<td>29.73-31.18</td>
<td>1413-1773</td>
<td>.289-.2944</td>
<td>3.327-6.653</td>
</tr>
<tr>
<td>NICHROME V, annealed</td>
<td>35.53-55.11</td>
<td>29.73-31.91</td>
<td>1719-2102</td>
<td>.2999-.3071</td>
<td>3.327-6.653</td>
</tr>
<tr>
<td>Nickel-30%Chromium Resistance Alloy, annealed</td>
<td>50.76-70.34</td>
<td>22.48-25.38</td>
<td>1737-2102</td>
<td>.289-.2962</td>
<td>3.327-6.653</td>
</tr>
<tr>
<td>NICHROME, annealed</td>
<td>36.98-58.02</td>
<td>27.85-30.17</td>
<td>1629-2012</td>
<td>.2944-.3017</td>
<td>3.327-6.653</td>
</tr>
<tr>
<td>NIMONIC 75, annealed</td>
<td>38.44-59.47</td>
<td>31.47-32.63</td>
<td>1665-2066</td>
<td>.2981-.3035</td>
<td>5.822-11.64</td>
</tr>
<tr>
<td>NIMONIC 115, heat treated</td>
<td>63.82-100.1</td>
<td>31.18-33.36</td>
<td>1575-1994</td>
<td>.28-.2872</td>
<td>5.822-11.64</td>
</tr>
<tr>
<td>Alpha-Two Aluminide(24-11) Ti3Al</td>
<td>59.9-60.63</td>
<td>13.05-13.92</td>
<td>986-1292</td>
<td>.1647-.1655</td>
<td>20.79-29.11</td>
</tr>
<tr>
<td>Alpha-Two Aluminide(25-10-3-1) Ti3Al</td>
<td>74.11-74.84</td>
<td>17.26-18.71</td>
<td>1076-1292</td>
<td>.1647-.1655</td>
<td>20.79-29.11</td>
</tr>
<tr>
<td>Titanium Alpha Alloy (Ti5Al2.5Sn.5Fe)</td>
<td>59.47-65.27</td>
<td>15.52-16.31</td>
<td>989.6-1099</td>
<td>.1612-.1628</td>
<td>14.97-23.29</td>
</tr>
<tr>
<td>Titanium near alpha alloy, Ti-6Al-2Sn-4Sn-4Zr-2MO</td>
<td>79.05-82.67</td>
<td>16.39-16.68</td>
<td>989.6-1008</td>
<td>.1637-.1644</td>
<td>13.72-21.62</td>
</tr>
<tr>
<td>Material</td>
<td>Ti-6Al-4Zr-2.5Sn</td>
<td>77.89-82.38</td>
<td>16.39-16.68</td>
<td>896-1076</td>
<td>.1622-.1629</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------</td>
<td>-------------</td>
<td>-------------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>AerMet100 (High Alloy Steel)</td>
<td>112-130.5</td>
<td>27.99-29.43</td>
<td>7120-801</td>
<td>.2836-.2864</td>
<td>2.495-4.158</td>
</tr>
<tr>
<td>High Alloy Steel, AF1410</td>
<td>94.27-108.8</td>
<td>29.44-30.95</td>
<td>7120-801</td>
<td>2.495-4.158</td>
<td>2.495-4.158</td>
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<tr>
<td>Iron-Base alloy, N-155,ST</td>
<td>38-47.28</td>
<td>29.15-30.65</td>
<td>1350-1501</td>
<td>.2985-.3015</td>
<td>2.495-12.47</td>
</tr>
<tr>
<td>Carbon steel, AISI 1080</td>
<td>40.76-47.43</td>
<td>29.01-31.18</td>
<td>546.8-644</td>
<td>.2818-.2854</td>
<td>2.079-.3742</td>
</tr>
<tr>
<td>Low alloy steel, AISI9255</td>
<td>48.01-55.69</td>
<td>29.88-31.33</td>
<td>1099-1197</td>
<td>.2818-.2854</td>
<td>2.079-.3742</td>
</tr>
<tr>
<td>Low Alloy steel, AISI 9310</td>
<td>53.66-62.22</td>
<td>29.88-31.33</td>
<td>1191-1229</td>
<td>.2818-.2854</td>
<td>2.079-.3742</td>
</tr>
<tr>
<td>Wrought Austenitic Stainless Steel, AISI201,3/4 hard</td>
<td>70.92-73.82</td>
<td>27.99-29.15</td>
<td>1463-1553</td>
<td>.2782-.2854</td>
<td>1.247-2.287</td>
</tr>
<tr>
<td>Wrought Austenitic Stainless Steel, AISI 202, 1/2 hard</td>
<td>63.24-70.63</td>
<td>27.56-30.46</td>
<td>1463-1553</td>
<td>.2782-.2854</td>
<td>1.247-2.287</td>
</tr>
<tr>
<td>Wrought Aluminum pure, 1050A</td>
<td>10.34-10.78</td>
<td>10.01-10.44</td>
<td>170.6-356</td>
<td>.0969-.0990</td>
<td>.6277-1.017</td>
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<tr>
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<td>8.514-8.543</td>
<td>10.01-10.44</td>
<td>170.6-356</td>
<td>.0965-.0986</td>
<td>.6277-1.017</td>
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<tr>
<td>Wrought Aluminum pure</td>
<td>3.844-4.163</td>
<td>10.01-10.44</td>
<td>170.6-356</td>
<td>.0965-.0986</td>
<td>.6277-1.017</td>
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<tr>
<td>Wrought aluminum alloy, 8090</td>
<td>20.45-20.89</td>
<td>11.6-12.18</td>
<td>170.6-356</td>
<td>.0910-.0929</td>
<td>.6277-1.017</td>
</tr>
<tr>
<td>Wrought aluminum alloy, 6061</td>
<td>14.07-15.52</td>
<td>9.863-10.37</td>
<td>170.6-356</td>
<td>.0975-.0985</td>
<td>.6237-1.015</td>
</tr>
</tbody>
</table>
7) **Boundary conditions of the CFD and heat transfer analysis**

A) **Inlet plane**

- Total Pressure = 1094 KPa
- Total Temperature = 1528 K
- Mach Number = 0.49
- Vax = 320 m/sec
- Static Temperature = 1470 K
- Static Density = 2.449 Kg/m$^3$
- Alpha 1 = 24 degrees

B) **Exit plane**

- Total Pressure = 1086 KPa
- Total Temperature = 1528 K
- Mach Number = 1.075
- Vax = 340 m/sec
- Static Temperature = 1283 K
- Static Density = 1.61 Kg/m$^3$
- Alpha 1 = -62 degrees (other direction)

C) **Coolant Parameters**

- $\rho_C = 6.8$kg/m$^3$
- $P_S = 1225$KPa
- $m = 4$kg/s (to share between all passages)
- $T_S = 630$K
REFERENCES


VITA

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Author 2 is a graduate student.

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