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Non Linear Transient Thermal Analysis of Turbine Blade Cooling

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Abstract— The main objective of this paper is to reduce the turbine blade high temperature gases from combustion chamber. Because of this temperature the life of the blade is going to get decrease significantly. It is necessary to design a cooling system for the turbine blade will be provided with coolant holes. Current objective of the project is to understand the physics behind the cooling phenomenon and rise in temperature coolant fluid. Ansysis and it is family of element will be used for the purpose. An initial analysis will be carried out with traditional bulk temperature approach and transient temperature behaviour of blade will be observed. Traditional approach of thermal analysis of commercial finite element software, ANSYS. Using this, non-linear transient thermal analysis can be studied in a time effective manner. Moeckel has studied the blade temperatures using ANSYS. But this study was majorly a 2D analysis with plane-35 elements. But, for the current project, only blade geometry in 3D is considered to model the cooling holes & to study the temperature distribution across the blade. It becomes computationally expensive if turbine and other structure is included and consumes lot of time & effort. By using these results, we can identify whether this methodology of using 5th stage bleed air is good or not.

Keywords— finite Element Analysis, ANSYS, Geometry of Blade, Flow temperature And Pressure Vs Time for Secondary flow air, Flow temperature And Pressure Vs Time for Gas path air

I. INTRODUCTION

The gas turbine is an internal combustion engine that uses air as the working fluid. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine and propeller, which, in turn, propel the airplane

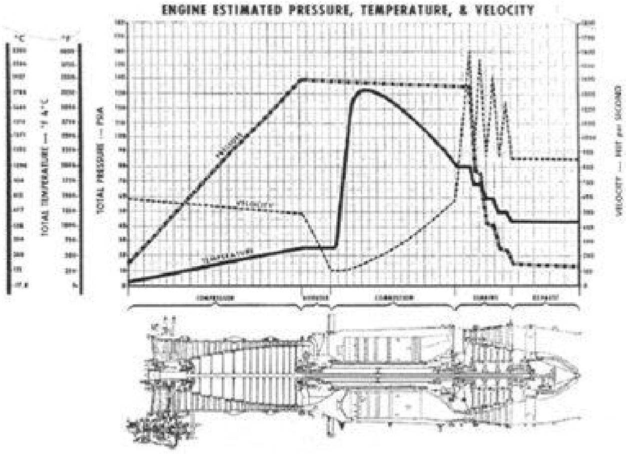


Figure 1: sample pressure, temperature and velocity

The turbine has engine 4 sections.
The inlet section
The compressor section
The combustion section (the combustor)
The turbine (and exhaust) section.

In turbine section power will get generated to drive propeller, compressor and all engine accessories. It does this by expanding the high temperature, pressure, and velocity gas and converting the gaseous energy to mechanical energy in the form of shaft power. The sample pressure, temperature and velocity graphs are shown in figure 1. This job is done by blades of the aero engine. So, the blades in the turbine will see high temp and it is necessary to cool these blades to get higher life.

II. . LITERATURE SURVEY

Thermal modeling of cooled turbine blades can range in fidelity from simple one-dimensional resistance-network models to complex conjugate heat transfer models. In a probabilistic analysis, the fidelity of the models are limited by the computational expense of running a sufficient number of cases. It is noted that a single one dimensional model cannot accurately predict all features simultaneously. There is an extensive work using conjugate heat transfer method by Savas Yavuzkurt1, Mangesh Kane, carelas, Freskos etc. But conjugate heat transfer requires lot of computational resources and it is very difficult to perform transient CFD analysis. The CFD analyses mentioned above are carried out for one or two major time points only. So, this option is omitted because of the current requirements

III.THERMAL ANALYSIS IN ANSYS INTRODUCTION

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are:

The temperature distributions
The amount of heat lost or gained
Thermal gradients
Thermal fluxes.

Thermal simulations play an important role in the design of many engineering applications including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components. In many cases, engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (that is, stresses caused by thermal expansions or contractions).

A. Types Of Thermal Analysis

We have two types of thermal analysis:

A steady-state thermal analysis determines the temperature distribution and other thermal quantities under steady-state loading conditions. A steady-state loading condition is a situation where heat storage effects varying over a period of time can be ignored.

A transient thermal analysis determines the temperature distribution and other thermal quantities under conditions that vary over a period of time.

1) Steady-State Thermal Analysis: A steady-state thermal analysis calculates the effects of steady thermal loads on a system or component. Engineer/analysts often perform a steady-state analysis before performing a transient thermal analysis, to help establish initial conditions. A steady-state analysis also can be the last step of a transient thermal analysis, performed after all transient effects have diminished. You can use steady-state thermal analysis to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that do not vary over time. Such loads include the following:

Convections
Radiation
Heat flow rates
Heat fluxes (heat flow per unit area)
Heat generation rates (heat flow per unit volume)
Constant temperature boundaries

A steady-state thermal analysis may be either linear, with constant material properties; or nonlinear, with material properties that depend on temperature. The thermal properties of most material do vary with temperature, so the analysis usually is nonlinear. Including radiation effects also makes the analysis nonlinear.

2) Transient Thermal Analysis: Transient thermal analysis determines temperatures and other thermal quantities that vary over time. Engineers commonly use temperatures that a transient thermal analysis calculates as input to structural analyses for thermal stress evaluations. Many heat transfer applications - heat treatment problems, nozzles, engine blocks, piping systems, pressure vessels, etc. - involve transient thermal analyses. A transient thermal analysis follows basically the same procedures as a steady-state thermal analysis. The main difference is that most applied loads in a transient analysis are functions of time. To specify time-dependent loads, you can either use the Function Tool to define an equation or function describing the curve. Then apply the function as a boundary condition, or you can divide the load-versus-time curve into load steps. As shown in the following figure 2.

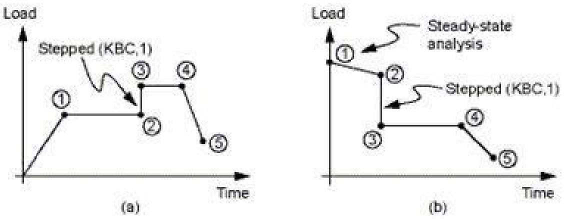


Fig. 2 Examples of Load vs. Time Curves

For each load step, you need to specify both load values and time values, along with other load step options such as stepped or ramped loads automatic time stepping, etc. You then write each load step to a file and solve all load steps together. To get a better understanding of how load and time stepping work, see the example casting analysis scenario in this chapter.

B. Elements Used In The Analysis

1) SOLID70 Element: TSOLID70 has a 3-D thermal conduction capability. The element has eight nodes with a single degree of freedom, temperature, at each node. The element is applicable to a 3-D, steady-state or transient thermal analysis. The element also can compensate for mass transport heat flow from a constant velocity field

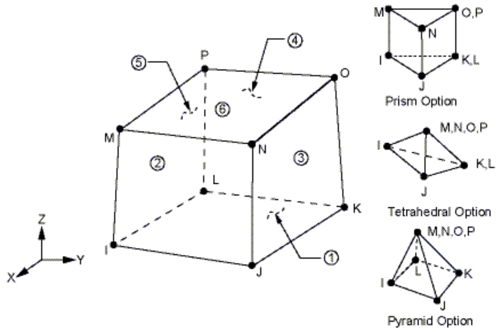


Fig. 2 Element SOLID70 Geometry

SOLID70 Input Summary
Nodes are I, J, K, L, M, N, O, P
Degrees of Freedom is TEMP

SOLID70 Assumptions and Restrictions
The element must not have a zero volume. This occurs most frequently when the element is not numbered properly.
A prism or tetrahedron shaped element may be formed by defining duplicate node numbers as described in Triangle, Prism and Tetrahedral Elements.
SOLID90 Element Description
SOLID90 is a higher order version of the 3-D eight node thermal element (SOLID70). The element has 20 nodes with a single degree of freedom, temperature, at each node. The 20-node elements have compatible temperature shapes and are well suited to model curved boundaries.
The 20-node thermal element is applicable to a 3-D, steady-state or transient thermal analysis.

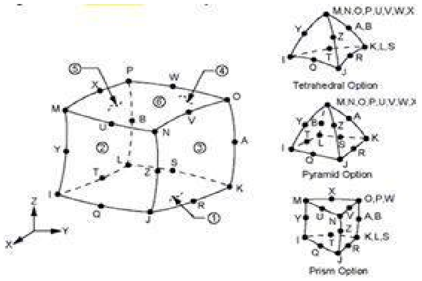


Figure 3 Element SOLID90 Geometry

SOLID90 Input Summary

Nodes: I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, A, B

Degrees of Freedom: TEMP

Material Properties: KXX, KYY, KZZ, DENS, C, ENTH

Surface Loads

Convection or Heat Flux (but not both) and Radiation (using Lab = RDSF) --

face 1 (J-I-L-K), face 2 (I-J-N-M), face 3 (J-K-O-N),

face 4 (K-L-P-O), face 5 (L-I-M-P), face 6 (M-N-O-P)

Body Loads

Heat Generations --

HG(I), HG(J), HG(K), HG(L), HG(M), HG(N), HG(O), HG(P), HG(Q), HG(R),

HG(S), HG(T), HG(U), HG(V), HG(W), HG(X), HG(Y), HG(Z), HG(A), HG(B)

Special Features

[1] Birth and death

KEYOPT (1)

[2] Specific heat matrix:

0 -- Consistent specific heat matrix

1 -- Diagonalized specific heat matrix

SURF152 Element description

SURF152 may be used for various load and surface effect applications. It may be overlaid onto an area face of any 3-D thermal element. The element is applicable to 3-D thermal analyses. Various loads and surface effects may exist simultaneously.

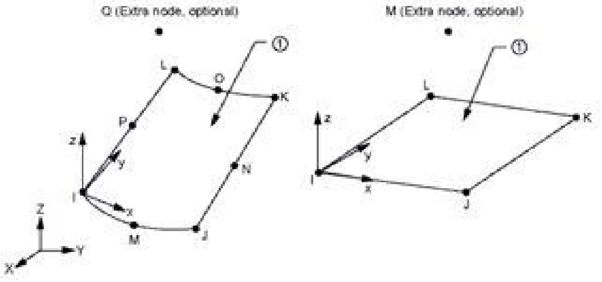


Figure 4 surf152 geometry

Surf152 Input Summary

Nodes: I, J, K, L

I, J, K, L, M (with additional settings)

Degrees of Freedom

PRES, TEMP if KEYOPT(1) = 0

TEMP if KEYOPT(1) = 1

PRES if KEYOPT(1) = 2

SURF152 Assumptions and Restrictions

The element must not have a zero area.

If KEYOPT(9) > 0 (radiation is used):

element is nonlinear and requires an iterative solution

Extra node must be present.

If KEYOPT (4) = 0, midside nodes may not be dropped

IV. THERMAL TRANSIENT ANALYSIS

A. Problem Description

Out of many engine parameters, temperature, pressure, mass flow rate at the outlet of each component & three shaft speeds (N1, N2 & N3) are considered as primary variables and below are the corresponding variables w.r.t time as per mission cycle.

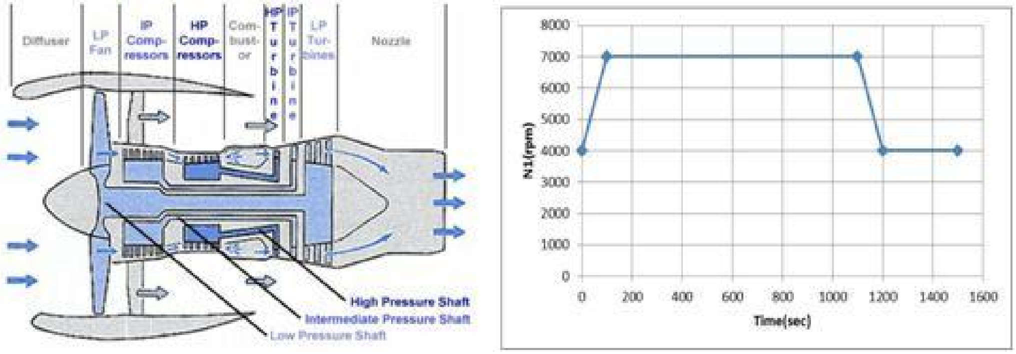


Figure 5 2Acceleration and deceleration mission cycle

It is customary to use HPC bleed to cool turbine. This was performed to prevent higher thermal gradient across rotor bore to dead rim of turbine, which in turn reduces thermal stress in the component & increases fatigue life. As HPC is a multistage axial compressor, any stage bleed can be used. By performing system level overall performance analysis (carried out by another department), it was decided to use 7th stage bleed air. Necessary control systems & valves were provided to obtain bleed from the gas path.

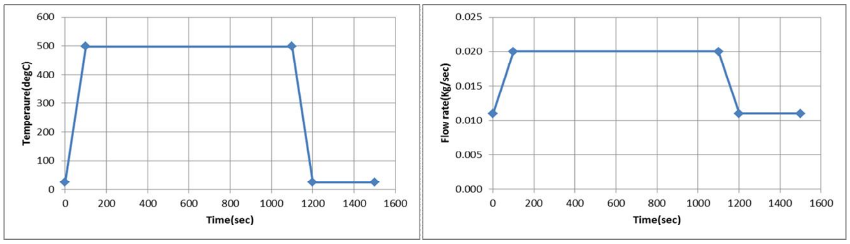


Figure 6 Temperature vs. time and flow rate vs. time diagrams

B. Geometry Description And meshing

All the fillets of blade are removed as part of the simplification of geometry and imported in to ANSYS. The geometry details are shown in figure 7. Ten number of cooling holes can be observed for convection cooling of blade.

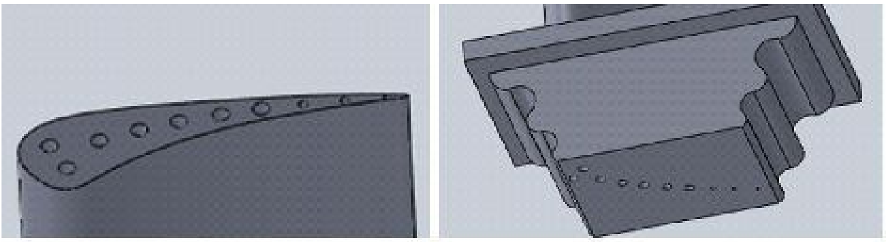


Figure 7 Blade geometry

The FE-modeling is carried out in ANSYS and the blade is modeled with Hex elements and tetrahedron elements. The FE-modeling details of the blade is shown in figure . Solid element type 70 is used for hex meshing and solid 90 is used for 2nd order tetrahedron meshing. Surf 152 elements are used to create the thermal zones and fluid element 116 is used to simulate the flow in the analysis.

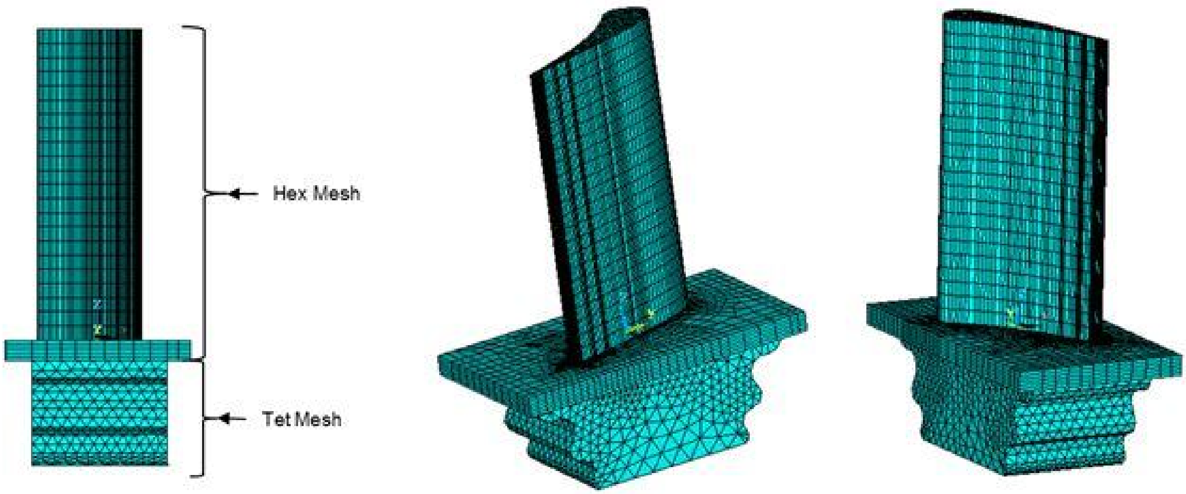


Figure 8 FE-Modeling details

C. Boundary Conditions And Thermal Zones

Calculation of heat transfer coefficients is straight forward task as described in standard text book.

The geometry is divided into several thermal zones based on geometry, flow variation. The right top picture in figure 15 is showing the zones in the leading edge side and right bottom picture is showing the zones in the tailing edge side.

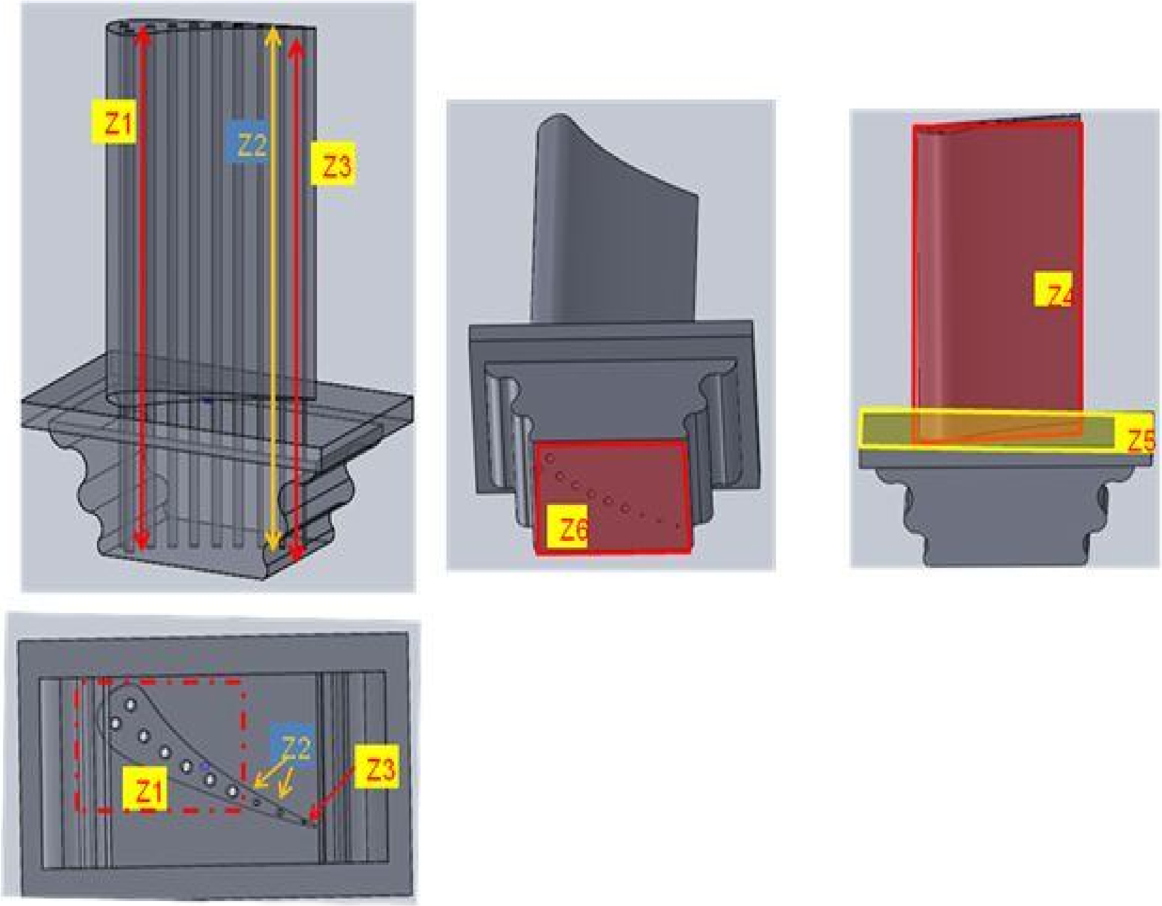


Figure 9 zones of the blade

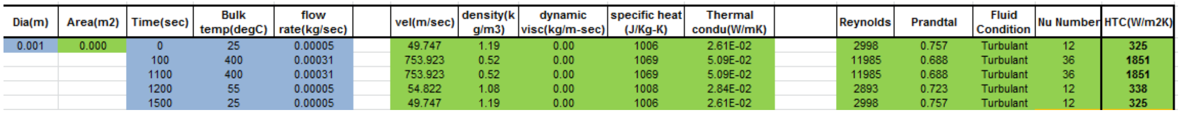
The thermal zone details are shown in the table

[3] **Zone**	[4] **Correlation**	[5] **Description**
[6] 1	[7] Pipe	[8] Cooling holes of one set of diameter
[9] 2	[10] Pipe	[11] Cooling holes of 2nd set of diameter
[12] 3	[13] Pipe	[14] Cooling holes of third set of diameter
[15] 4	[16] General	[17] HTC & Bulk temperatures for the entire height of blade are given
[18] 5	[19] General	[20] HTC & Bulk temperatures for blade platform are given
[21] 6	[22] Pipe	[23] Entry region of flow(ID of blade)

Table 1 Thermal zones details

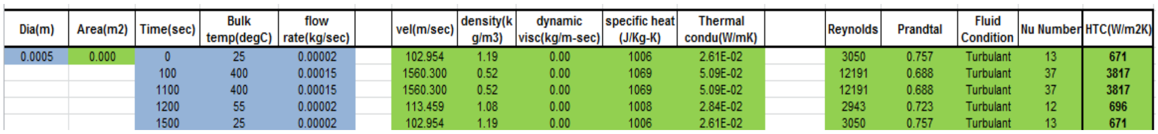
D. Discussion Of HTC Calculations For Several Correlations

Heat transfer coefficients are calculated based on pipe correlation. Below are the snaps of heat transfer coefficient calculation for zone-1.



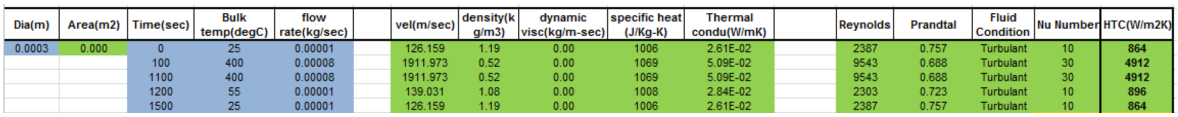
Dia(m)	Area(m2)	Time(sec)	Bulk temp(degC)	flow rate(kg/sec)		vel(m/sec)	density(kg/m3)	dynamic visc(kg/m-sec)	specific heat (J/Kg-K)	Thermal condu(W/mK)		Reynolds	Prandtal	Fluid Condition	Nu Number	HTC(W/m2K)
0.001	0.000	0	25	0.00005		49.747	1.19	0.00	1006	2.61E-02		2998	0.757	Turbulant	12	**325**
		100	400	0.00031		753.923	0.52	0.00	1069	5.09E-02		11985	0.688	Turbulant	36	**1851**
		1100	400	0.00031		753.923	0.52	0.00	1069	5.09E-02		11985	0.688	Turbulant	36	**1851**
		1200	55	0.00005		54.822	1.08	0.00	1008	2.84E-02		2893	0.723	Turbulant	12	**338**
		1500	25	0.00005		49.747	1.19	0.00	1006	2.61E-02		2998	0.757	Turbulant	12	**325**

Table 2 HTC & Bulk temperature calculation of Zone 1



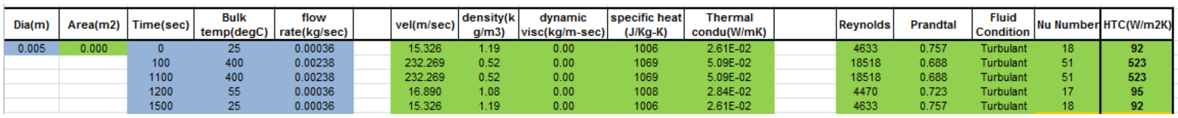
Dia(m)	Area(m2)	Time(sec)	Bulk temp(degC)	flow rate(kg/sec)		vel(m/sec)	density(kg/m3)	dynamic visc(kg/m-sec)	specific heat (J/Kg-K)	Thermal condu(W/mK)		Reynolds	Prandtal	Fluid Condition	Nu Number	HTC(W/m2K)
0.0005	0.000	0	25	0.00002		102.954	1.19	0.00	1006	2.61E-02		3050	0.757	Turbulant	13	**671**
		100	400	0.00015		1560.300	0.52	0.00	1069	5.09E-02		12191	0.688	Turbulant	37	**3817**
		1100	400	0.00015		1560.300	0.52	0.00	1069	5.09E-02		12191	0.688	Turbulant	37	**3817**
		1200	55	0.00002		113.459	1.08	0.00	1008	2.84E-02		2943	0.723	Turbulant	12	**696**
		1500	25	0.00002		102.954	1.19	0.00	1006	2.61E-02		3050	0.757	Turbulant	13	**671**

Table 3 HTC & Bulk temperature calculation of Zone 2



Dia(m)	Area(m2)	Time(sec)	Bulk temp(degC)	flow rate(kg/sec)		vel(m/sec)	density(kg/m3)	dynamic visc(kg/m-sec)	specific heat (J/Kg-K)	Thermal condu(W/mK)		Reynolds	Prandtal	Fluid Condition	Nu Number	HTC(W/m2K)
0.0003	0.000	0	25	0.00001		126.159	1.19	0.00	1006	2.61E-02		2387	0.757	Turbulant	10	**864**
		100	400	0.00008		1911.973	0.52	0.00	1069	5.09E-02		9543	0.688	Turbulant	30	**4912**
		1100	400	0.00008		1911.973	0.52	0.00	1069	5.09E-02		9543	0.688	Turbulant	30	**4912**
		1200	55	0.00001		139.031	1.08	0.00	1008	2.84E-02		2303	0.723	Turbulant	10	**896**
		1500	25	0.00001		126.159	1.19	0.00	1006	2.61E-02		2387	0.757	Turbulant	10	**864**

Table 4 HTC & Bulk temperature calculation of Zone 3



Dia(m)	Area(m2)	Time(sec)	Bulk temp(degC)	flow rate(kg/sec)		vel(m/sec)	density(kg/m3)	dynamic visc(kg/m-sec)	specific heat (J/Kg-K)	Thermal condu(W/mK)		Reynolds	Prandtal	Fluid Condition	Nu Number	HTC(W/m2K)
0.005	0.000	0	25	0.00036		15.326	1.19	0.00	1006	2.61E-02		4633	0.757	Turbulant	18	**92**
		100	400	0.00238		232.269	0.52	0.00	1069	5.09E-02		18518	0.688	Turbulant	51	**523**
		1100	400	0.00238		232.269	0.52	0.00	1069	5.09E-02		18518	0.688	Turbulant	51	**523**
		1200	55	0.00036		16.890	1.08	0.00	1008	2.84E-02		4470	0.723	Turbulant	17	**95**
		1500	25	0.00036		15.326	1.19	0.00	1006	2.61E-02		4633	0.757	Turbulant	18	**92**

Table 2 HTC & Bulk temperature calculation of Zone 6

E. Modeling Of Heat Transfer Phenomenon In FE Model

As discussed in previous sections, surf152 elements with necessary key option settings are used to simulate convectional effects in the thermal model. Based on the zone map shown in fig#, surf152 elements are created/generated on existing solid70 elements. For easy modeling purposes, a macro was written to perform this task. While creating surf elements, to distinguish each zone, zone number was added with numerical "100" to get corresponding mat id. So, as an example, zone1 in zone map of fig# refers to mat101. This process will simplify the selection & modification of corresponding element set

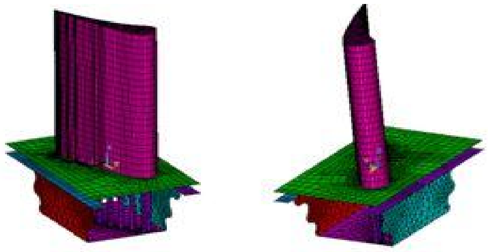
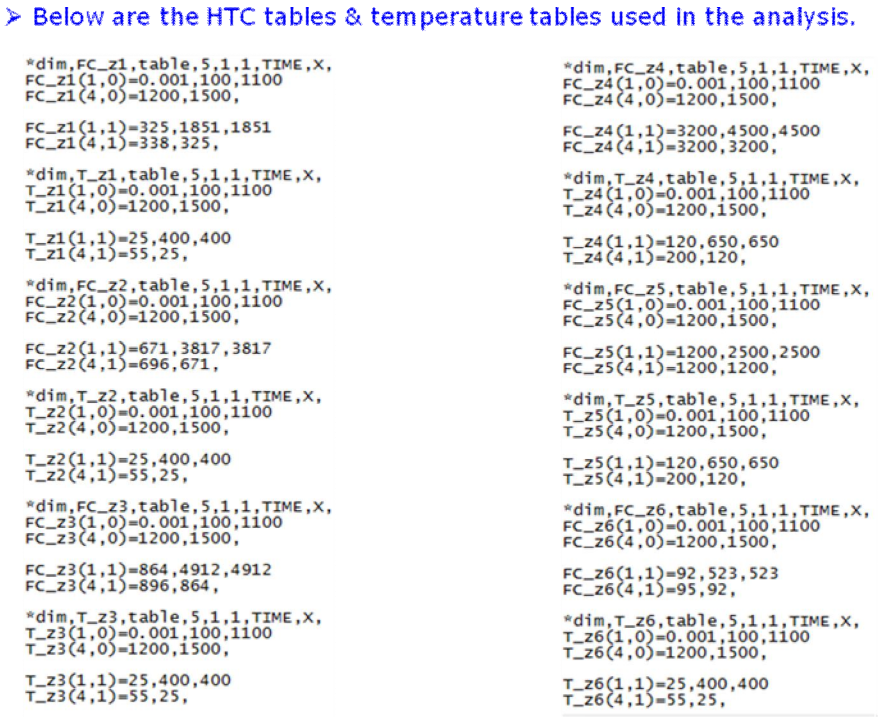


Figure 10 Surf152 elements for modeling convection effects

F. Table Creation In ANSYS

Transient convectional boundary conditions are calculated based on section . These HTC & bulk temperatures are input to ANSYS for running non-linear thermal analysis. ANSYS supports creation of HTC & bulk temperature tables w.r.t time. To perform this activity, a sequential commands has to be used. Figure 11 shows the snap shot of zone1. In figure FC_z01 refers to film coefficient of zone1 & T_Z01 refer to bulk temperature of zone-1. Similar snap shots were provided for zone number7&8 in figure .



➢ Below are the HTC tables & temperature tables used in the analysis.

```
*dim,FC_z1,table,5,1,1,TIME,X,
FC_z1(1,0)=0.001,100,1100
FC_z1(4,0)=1200,1500,

FC_z1(1,1)=325,1851,1851
FC_z1(4,1)=338,325,

*dim,T_z1,table,5,1,1,TIME,X,
T_z1(1,0)=0.001,100,1100
T_z1(4,0)=1200,1500,

T_z1(1,1)=25,400,400
T_z1(4,1)=55,25,

*dim,FC_z2,table,5,1,1,TIME,X,
FC_z2(1,0)=0.001,100,1100
FC_z2(4,0)=1200,1500,

FC_z2(1,1)=671,3817,3817
FC_z2(4,1)=696,671,

*dim,T_z2,table,5,1,1,TIME,X,
T_z2(1,0)=0.001,100,1100
T_z2(4,0)=1200,1500,

T_z2(1,1)=25,400,400
T_z2(4,1)=55,25,

*dim,FC_z3,table,5,1,1,TIME,X,
FC_z3(1,0)=0.001,100,1100
FC_z3(4,0)=1200,1500,

FC_z3(1,1)=864,4912,4912
FC_z3(4,1)=896,864,

*dim,T_z3,table,5,1,1,TIME,X,
T_z3(1,0)=0.001,100,1100
T_z3(4,0)=1200,1500,

T_z3(1,1)=25,400,400
T_z3(4,1)=55,25,
```

```
*dim,FC_z4,table,5,1,1,TIME,X,
FC_z4(1,0)=0.001,100,1100
FC_z4(4,0)=1200,1500,

FC_z4(1,1)=3200,4500,4500
FC_z4(4,1)=3200,3200,

*dim,T_z4,table,5,1,1,TIME,X,
T_z4(1,0)=0.001,100,1100
T_z4(4,0)=1200,1500,

T_z4(1,1)=120,650,650
T_z4(4,1)=200,120,

*dim,FC_z5,table,5,1,1,TIME,X,
FC_z5(1,0)=0.001,100,1100
FC_z5(4,0)=1200,1500,

FC_z5(1,1)=1200,2500,2500
FC_z5(4,1)=1200,1200,

*dim,T_z5,table,5,1,1,TIME,X,
T_z5(1,0)=0.001,100,1100
T_z5(4,0)=1200,1500,

T_z5(1,1)=120,650,650
T_z5(4,1)=200,120,

*dim,FC_z6,table,5,1,1,TIME,X,
FC_z6(1,0)=0.001,100,1100
FC_z6(4,0)=1200,1500,

FC_z6(1,1)=92,523,523
FC_z6(4,1)=95,92,

*dim,T_z6,table,5,1,1,TIME,X,
T_z6(1,0)=0.001,100,1100
T_z6(4,0)=1200,1500,

T_z6(1,1)=25,400,400
T_z6(4,1)=55,25,
```

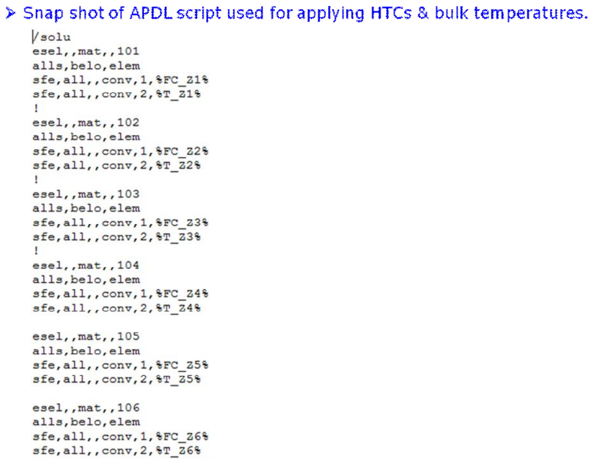
Figure 3 Table creation in ANSYS

G. *Material Properties*

Blades are going to see high temperature flue gases from combustor. So, typical turbine blades are be made of Ni-Cr alloy, which has more temperature resistant properties. As this is a non-linear transient thermal analysis, Thermal conductivity, specific heat w.r.t temperature has to be defined. Density is one more material property to ANSYS. Because of export control issues, curves of these properties are not given in this thesis

H. ANSYS BC File To Apply Loads

After creation of necessary tabular boundary conditions for all zones, it is required to apply these tables on the corresponding surf152 elements. Figure gives the snap shot of command snippet used for this activity. It can be observed that elements of mat101 is applied with film coefficients & bulk temperature of zone1



➢ Snap shot of APDL script used for applying HTCs & bulk temperatures.

```
/solu
esel,,mat,,101
alls,belo,elem
sfe,all,,conv,1,%FC_Z1%
sfe,all,,conv,2,%T_Z1%
!
esel,,mat,,102
alls,belo,elem
sfe,all,,conv,1,%FC_Z2%
sfe,all,,conv,2,%T_Z2%
!
esel,,mat,,103
alls,belo,elem
sfe,all,,conv,1,%FC_Z3%
sfe,all,,conv,2,%T_Z3%
!
esel,,mat,,104
alls,belo,elem
sfe,all,,conv,1,%FC_Z4%
sfe,all,,conv,2,%T_Z4%

esel,,mat,,105
alls,belo,elem
sfe,all,,conv,1,%FC_Z5%
sfe,all,,conv,2,%T_Z5%

esel,,mat,,106
alls,belo,elem
sfe,all,,conv,1,%FC_Z6%
sfe,all,,conv,2,%T_Z6%
```

Figure12 Input files to Apply Loads

Advantages of writing command snippets are

Human errors & repetitive tasks can be eliminated by writing all the activities in command snippet format

This method is useful for a task which needs multiple iterations.

All the information about boundary conditions, material properties are easy to understand & knowledge base has been retained.

The below mac is file used to run non-linear transient simulation.

```
resume,blade_thermal,db
alls
/prep7
/input,therm_Ni_Cr_alloy,mac,bc,      !Ni-Cr alloy
/input,tables_HTCs_temp,txt,BC   !tables of HTCs & Bulk
temperatures
/input,tables_gas_path,txt,bc    !Tables of gas path BCs
/input,bc,mac,BC                 !Applying of loads and running
                                 !the transient analysis
```

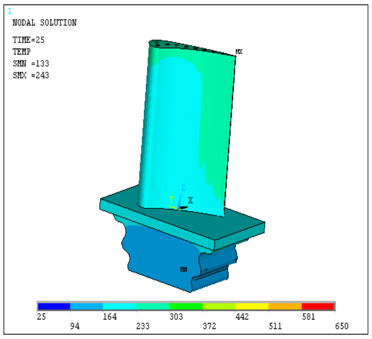
Figure 13 Input file to submit the run

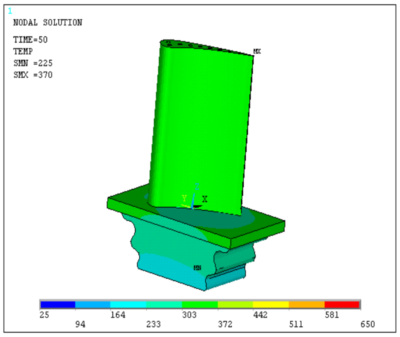
V. SIMMULATION RESULTS

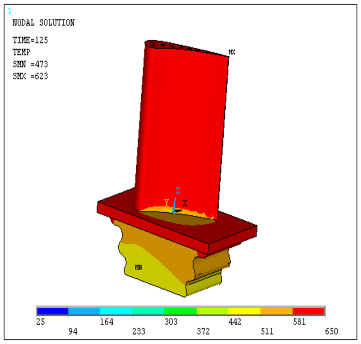
A. Thermal Analysis Results (Iteration #1)

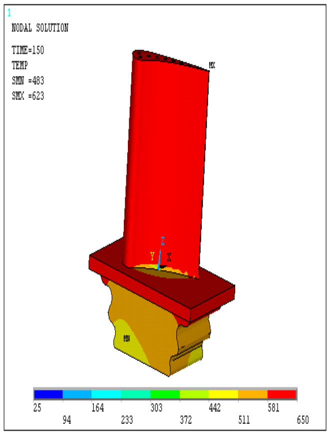
With boundary conditions discussed above, a non-linear transient thermal analysis was performed with necessary steady state & transient analysis settings. Temperatures at different points of mission cycle are observed. Below are the temperature plots at different points. Till the acceleration time of 100sec, heating phenomenon of blade can be observed. After 100sec, in no time, component came to steady state. Similarly, influence of decal of can be observed b/w 1100sec-1200sec.

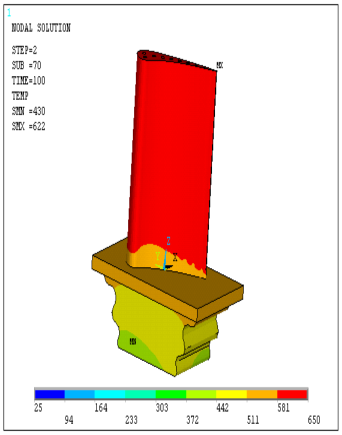
The following pictures are showing the temperature profiles of HPT blade at various time points.

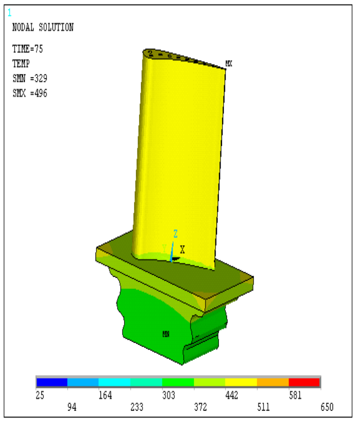


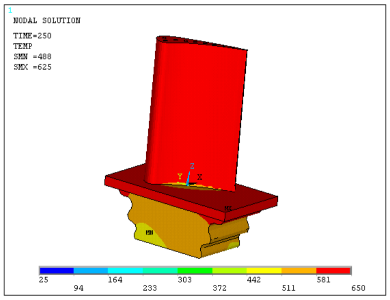


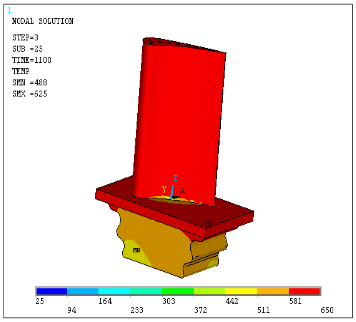


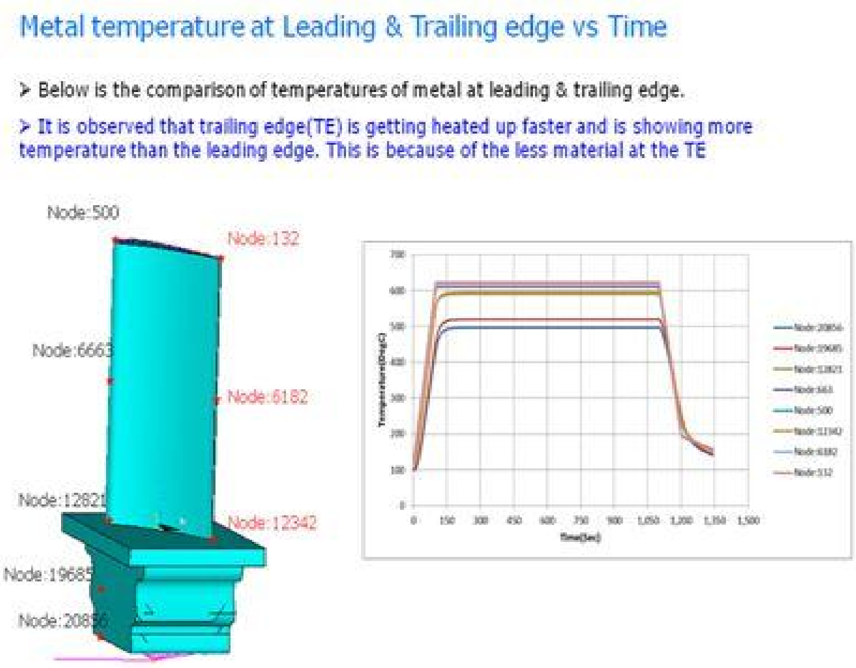












Metal temperature at Leading & Trailing edge vs Time

- Below is the comparison of temperatures of metal at leading & trailing edge.
- It is observed that trailing edge(TE) is getting heated up faster and is showing more temperature than the leading edge. This is because of the less material at the TE

VI. CONCLUSIONS

Meshing of the given blade is performed in good quality criterion.
Heat transfer coefficient are estimated for the transient mission cycle using standard correlations.
From the results, because of lower thickness & higher HTC in smaller channels, TE of the blade is heating up faster compared to LE
Due to heavier mass, blade platform is shows sluggish behaviour in heating/cooling.
Blade is attaining maximum temperature in 1100sec which is in sync with shaft speed ramp up.
This analysis is good start to compare ANSYS temperatures with engine thermocouple data.

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