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Research Article

Transient Thermal Analysis of an Aero-Engine Afterburner Liner

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Abstract

In this paper, Finite element thermal analysis has been performed on a gas turbine afterburner jet pipe liner. Burnt air and fuel mixture from the main fuel system and afterburner system flows through the liner before exiting into the atmosphere via nozzle experiences a high variation of temperature across it thorough the engine operation thus susceptible to failure due to thermal stress. Simulations were done considering conduction and convection only. The FE (Finite element) model is first studied under steady-state conditions with constant loading. The analysis is extended to transient boundary conditions which are common in practical afterburner jet pipe liners to investigate the effect of temperature. Each of the parameters had a marked effect on jet pipe liner performance within the range of conditions investigated.

The research work has been carried out at Heat Transfer Group, Gas Turbine Research Establishment, DRDO Bengaluru, Karnataka, India.

Keywords: *Finite element, Afterburner, Steady State, jet pipe liner, Transient*

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Introduction

Gas turbines are a type of internal combustion (IC) engine in which the burning of an air-fuel mixture produces hot gases that spin a turbine to produce power. The combustion process directly affects the operational efficiency of the jet engine system. The chamber is lined with the combustor liner, which is subjected to extremely rapid temperature rise and no pressure drop. Combustor liners operate in high temperature, high stress, and high-pressure conditions which must withstand high rates of burning with little or no pressure drop. An afterburner is an additional component present on some jet engines. Afterburner injects additional fuel into a combustor in the jet pipe behind (i.e., "after") the turbine, "reheating" the exhaust gas. This operation significantly increases thrust as an alternative to using a bigger engine with its attendant weight penalty but at the cost of very high fuel consumption (decreased fuel efficiency) which limits its use to short periods [1] . A jet pipe forms part of the exhaust system of a gas turbine. Burnt air and fuel mixture from the main fuel system and afterburner system flows through the liner before exiting into the atmosphere via the nozzle. It experiences a high variation of temperature across it through the engine operation thus susceptible to failure due to thermal stress. Geometrically it is a cylindrical duct consisting of an outer casing and coating inside. The temperature inside the liner reaches up to approx. 1900K if required. Any severe damage to the liner can turn out to be catastrophic because it can lead to the dysfunction of the nozzle following it. The primary outcome of the project will be to perform Steady-State and Transient Thermal Analysis of jet pipe liner as per the given problem statements and parameters.

Desıgn Procedure

A FE thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. The steps that have been followed for modeling and performing the analysis are as follows:

1. Preparation of the model geometry.
2. Defining and assigning material properties to parts.
3. Meshing the geometry.
4. Creating Entity sets
5. Application of loads and supports.
6. Solving the Model
7. Requesting of results.

This paper has aimed on performing steady-state thermal analysis and transient thermal analysis with varying boundary conditions on an axisymmetric structure. Axisymmetric structure analysis is performed where the geometry, loading, boundary conditions, and materials are symmetric with respect to an axis. Axisymmetric models provide us with a consistent distribution of results. Steady- state thermal analysis can be defined as evaluating the thermal equilibrium of a body in which there is no change in temperature with respect to time. Transient thermal analysis can be defined as how a body reacts to fix as well as to varying boundary conditions with respect to time. Transient analysis is more frequently used as multiple set of inputs such as time and temperature analysis takes place that is more applicable in real time conditions.

Modelıng

The Finite element analysis simulation was performed on ANSYS 2021 software using its tool ANSYS APDL. For the respective simulations material of the model is being considered as PLANE55 as it can be used as an axisymmetric ring element with a 2-D thermal conduction capability. The element is in general applicable for a 2-D, steady-state, or transient thermal analysis. Table 1 shows parameters that have been considered while meshing the 2D model. Material, that has been used for T.B.C i.e. Thermal Barrier Coating, liner, and casing are zirconium alloy, Neo-Nickle alloy, and stainless steel receptively.

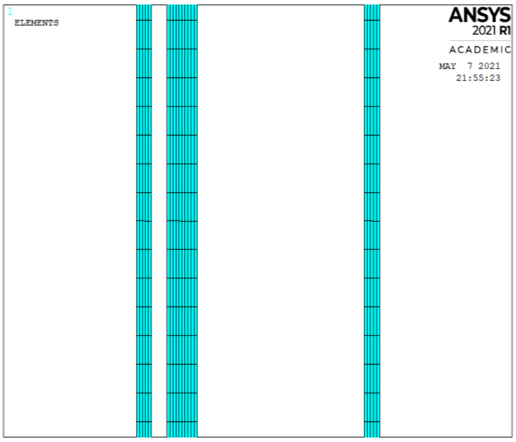


Figure 1: 2D FE Model of Axisymmetric structure

Parameters	Details
Size Function	Adaptive
No. Of element division(Vertical)	480
No. Of element division(Horizontal)	5
No. Of nodes	1610
No. Of elements	1280

Table 1: Modelling parameters

Formula And Calculatıons

1. Dynamic viscosity (μ) = $5.8742 \times 10^{-7} \times (T)^{0.617}$ (Ns/m^2)

   Where T = Temperature (ºK)

2. Specific heat capacity (Cp) = $362.4572 \times (r)^{0.166}$ (kJ/kg/°K)

   Where T = Temperature (ºK)

3. Thermal conductivity (K) = $4.0588 \times 10^{-4} \times (T)^{0.741}$ (W/mK)

   Where T = Temperature (ºK)

4. Reynolds number (Re) = $(\dot{m} \times Lc)/(\mu \times A)$

Where $\dot{m}$ = mass flow rate (kg/s)

Lc = Characteristic length (m)

μ = dynamic viscosity (Ns/m^2)

A = Area (m^2)

5. Prandtl number (Pr) = (μ × Cp)/(K)

   Where μ = dynamic viscosity (Ns/m^2)

   Cp = Specific heat capacity (kJ/kg/°K)

   K = Thermal conductivity (W/mK)

6. Nusselt number (Nu) = $[(f/8) \times (Re - 1000) \times Pr]/[1 + 12.7 \times (f/8)^{0.8} \times (Pr^{2/3} - 1)]$

   Where f = friction factor

   Re = Reynolds number

   Pr = Prandtl number

7. Friction factor (f) = $(0.790 \times \ln(Re) - 1.64)^{-2}$

   Where Re = Reynolds number

8. Heat transfer coefficient (h) = (Nu × K)/ L

   Where Nu = Nusselt number

   K = Thermal conductivity (W/mK)

L = Characteristic length (m)

From the formulas mentioned, the h i.e. heat transfer coefficient was calculated and are shown in Table 2.

Heat transfer coefficient (h)	
h_{g1}	214.5 W/m^{2}K
h_{c1}	364.308 W/m^{2}K
h_{g2}	751.884 W/m^{2}K
h_{c2}	260.8925 W/m^{2}K

Table 2: Calculated (h) value

Sımulatıon And Results

The dimensions and parameters that has been taken in consideration for simulation of steady-state thermal analysis are shown in Table 3, Table 4 and Table 5.

Dimensions	
Length	800 mm
Internal Diameter (Di)	770 mm
External Diameter (Do)	800 mm
Thickness (Liner)	2 mm
Thickness (Casing)	1 mm
Thickness (Coating)	1 mm

Table 3: Dimensions of model

Material Properties	
Density	1.5 kg/m^3
Mass flow rate (Gas Side)	60 kg/s
Mass flow rate (Coolant Side)	6 kg/s
Thermal Conductivity of casing (K)	20 W/mºK
Thermal Conductivity of coating (K)	13.5 W/mºK
Thermal Conductivity of liner (K)	1 W/mºK

Table 4: Material properties of model (Steady state)

Boundary Conditions	
Temperature on gas side (Tg)	1200 ºK
Temperature on coolant side (Tc)	450 ºK
Ambient Temperature	288 ºK

Table 5: Boundary conditions (Steady state)

Application of loads on the model can be seen in Figure 2, where

- Orange arrow signify Gas side load.
- Blue arrow signifies Coolant side load.
- Black arrow signifies natural convection of air.

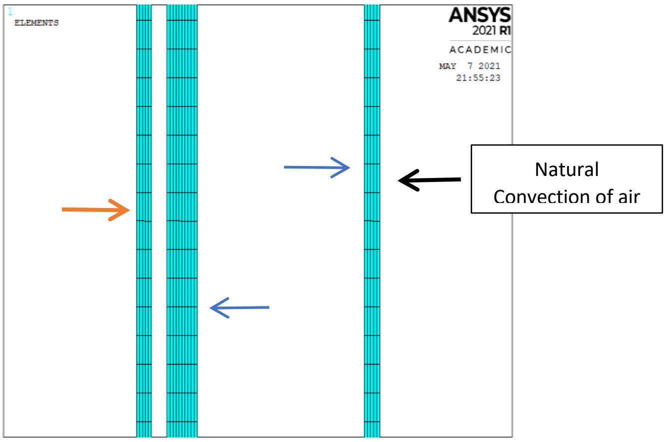


Figure 2: Application of loads

The Temperature contours of the entire model for steady-state thermal analysis are represented in Figure 3. The maximum temperature that was found out after the simulation was 802.567 ºK and the minimum temperature was 288 ºK. The figures shown here are the zoomed-in figures of the model whose analysis was performed.

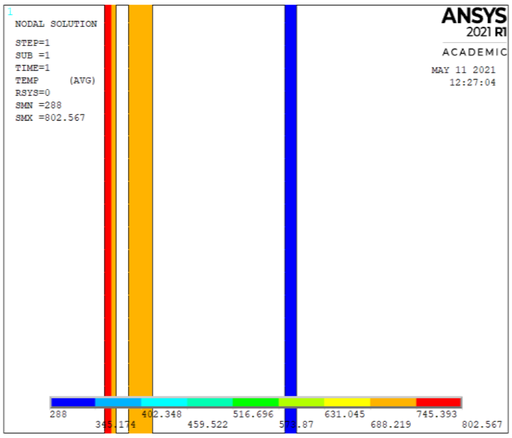


Figure 3: FE analysis temp. Contour

The dimensions for transient thermal analysis remains same and parameters are shown in Table 6 and Table 7.

Material Properties	
Density	1.5 kg/m^3
Mass flow rate (Gas Side) m_{g1}	60 kg/s
Mass flow rate (Coolant Side) m_{c1}	6 kg/s
Mass flow rate (Gas Side) m_{g2}	20 kg/s
Mass flow rate (Coolant Side) m_{c2}	5 kg/s
Thermal Conductivity of casing (K)	20 W/mºK
Thermal Conductivity of coating (K)	13.5 W/mºK
Thermal Conductivity of liner (K)	1 W/mºK

Table 6: Material properties of model (Transient)

Boundary Conditions	
Temperature on gas side (T_{g1})	1200 ºK
Temperature on coolant side (T_{c1})	450 ºK
Temperature on gas side (T_{g2})	700 ºK
Temperature on coolant side (T_{c2})	300 ºK
Ambient Temperature	288 ºK

Table 7: Boundary conditions (Transient)

The Temperature contours of the entire model for transient thermal analysis are represented in Figure 4, 5 and 6. The maximum temperature that was found out after the simulation was 806.302 ºK and minimum temperature was 320 ºK. The figures shown here are the zoomed in figures of the model on which analysis was performed according to time range.

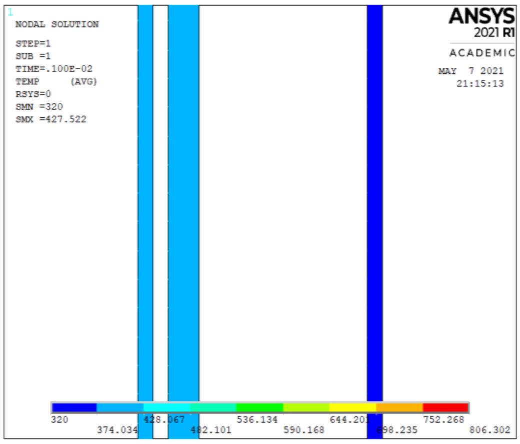


Figure 4 : Temp. Contour of model (t=1s)

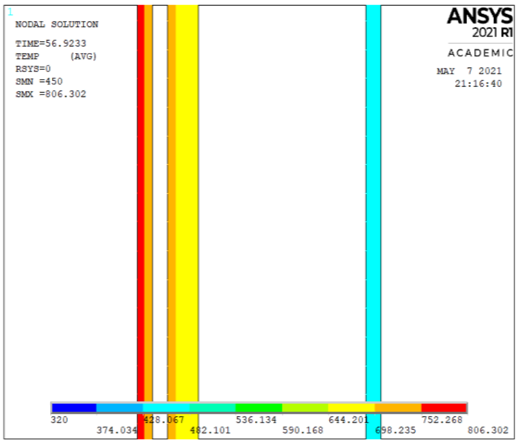


Figure 5: Temp. Contour of model (t=57s approx)

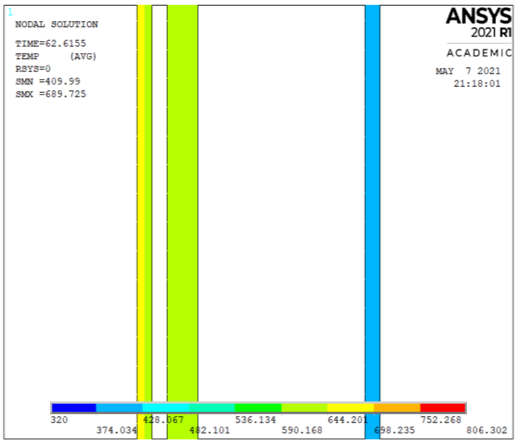


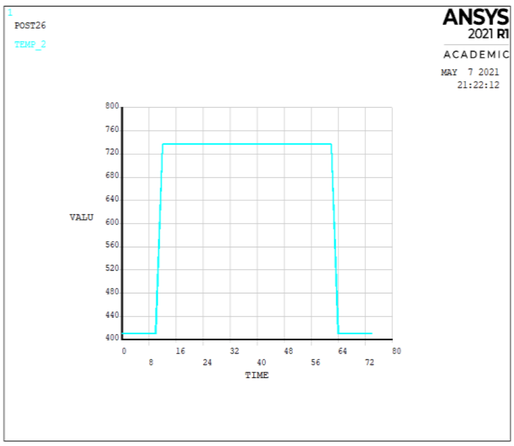
Figure 6: Temp. Contour of model (t=62.62s approx)

Conclusıon

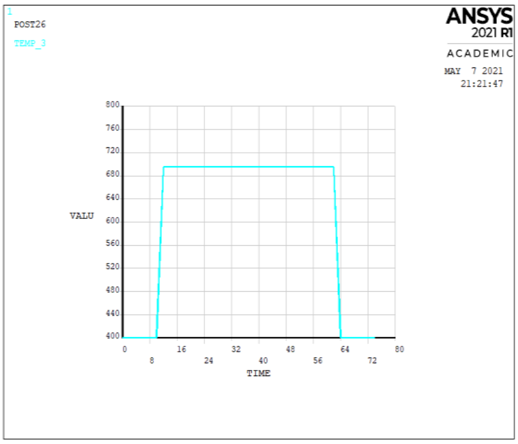
From FE transient thermal analysis, the minimum and maximum temperature that we got from different parts of the axisymmetric structure are shown in table 8. T.B.C plays an important role to decrease the heat transfer from gas side to the casing of the jet pipe liner. From the values shown in table 8, we can clearly see that the maximum temperature of a node on T.B.C was 754.646 ºK whereas the maximum temperature of a node on the liner was 694.184 ºK. Even there is a significant difference in the temperature range of T.B.C and casing, which proposes the effectiveness of T.B.C usage in afterburner jet pipe liner.

Model parts	**Minimum temperature**	**Maximum temperature**
T.B.C (Thermal barrier coating)	414.575 ºK	754.646 ºK
Liner	400.258 ºK	694.184 ºK
Casing	320 ºK	450 ºK

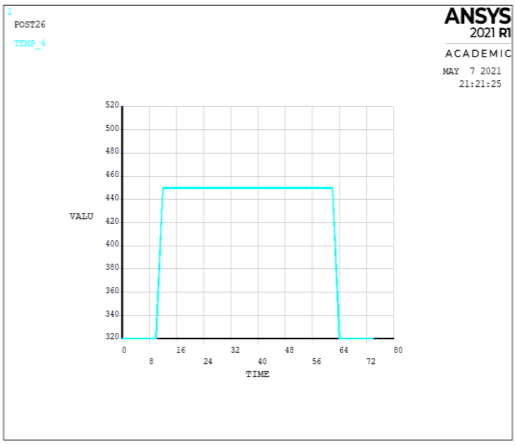
Table 8: Temperature range of different parts of modeled jet pipe liner



Graph 1: Temp variation on T.B.C w.r.t time



Graph 2: Temp variation on liner w.r.t time



Graph 3: Temp variation on casing w.r.t time

By calculations, the percentage reduction in maximum temperature was found out to be 40.37 % (approx.). So we can say the application of T.B.C on jet pipe liner is quite important as it reduces the chances of cracking of liner or failure of adjacent components due to high heat transfer in real-time conditions (i.e. Transient). This will lead to reduce of failure during take-off, and make flights more adaptable for small runways.

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