Determination of heat flow rate of turbine blades exposed to products of combustion

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Abstract— **The present work investigates the thermal properties of the turbine blade which is exposed to the products of combustion. Profile of the blade is modelled and analyzed using the computational analysis software ANSYS CFX and the comparative tool DOT NET software. Temperature distributions at various points of the blade are deduced and the overall heat transfer is determined. A detailed study is conducted by considering different materials to obtain optimum material selection.**

Keywords— **Turbine blade, convection parameter, ANSYS CFX, DOT NET, Thermal analysis.**

I. INTRODUCTION

Heat transfer in turbine blades is an extremely critical component in the design of blades. As turbine engine designers try to improve engine efficiency, they try to find ways to increase the operating temperature of the engine [6]. By running the engine at higher temperatures, they are able to produce more work. However, this results in extremely high temperature gases exiting the combustor and entering the turbine stages. These gases can reach temperatures as high as 1350˚C when entering the first stage of a turbine blade, which is higher than the melting temperature of the metal used to manufacture blades. Therefore, if the heat transfer to the turbine blade is high enough, it can cause the blade to quickly deteriorate. Designers need to have a firm grasp on the level of heat transfer they can expect from the air to the blade to determine the life of the blades, ensuring a long component life [7].

Various modes of heat transfer affecting the blade are conduction which is taking place from the base of the blade and distributed over the length along the vertical and horizontal directions [1]. The second type of heat transfer to be examined is convection, where a key problem is determining the boundary conditions at a surface exposed to a flowing fluid. An example is the wall temperature in a turbine blade because turbine temperatures are critical for creep (and thus blade) life.

In the present study heat transfer taking place from the turbine blades is determined. Temperature distribution at various points in the blade surface is determined. Finite element software ANSYS is used for modelling [5]. Meshing of the element is done in order to split into numerous elements. After meshing the boundary conditions are defined to determine various thermal affects. Heat transfer taking place by both conduction and convection are considered. Conventional or theoretical equations which govern the element are used and a code is generated using DOT NET [2]. Various materials are considered and the heat transfer rate and the temperature distribution for the fixed convective coefficient value is calculated. Dot NET software gives flexibility to vary the conductivity and the optimum material selection can be performed.

In the present case a turbine blade of 60 mm long and having the cross-sectional area of 500 mm2 is considered. The temperature of the root of the blade is at 480^0C and it is exposed to the products of combustion which is at a higher temperature of 820^0C. The following element is modelled, meshed and analysed in software ANSYS CFX and the results and compared. Finite element approach provides the solution at every node of consideration [4].

The present problem was structured as a sequence of fundamental problems built on simple models that determine thermal property of the element under study. The models proceed from the simple toward the complex. The objective is to uncover the most fundamental optimization principles (or design trade-offs) that can be put to practical use in real applications. The method of analysis and optimization is the combination of heat transfer, thermodynamics and structures which is used subsequently in many engineering applications [8].

II. RELATED WORK

Robert Kwiatkowski and Roman Doma´nski [1] dealt with heat transfer problems encountered in the cooling of jet engine turbine blades with internal cooling only. For this purpose an exemplary turbine blade was investigated using numerical methods. Sampath et al. [2] investigated the temperature distribution in a bar element which is connected to two different heat reservoirs. Over performance of the connecting element is improved by the selection of appropriate material which dissipates maximum rate of heat. Hari Brahmaiah and Lava Kumar [3] carried out heat transfer analysis of gas turbine with four different models consisting of blade with without holes and blades with varying number of holes were analyzed. The analysis is carried out using commercial CFD software FLUENT has been used. Krishnakanth et al. [4] project specifies how the program makes effective use of the ANSYS pre-processor to analyse the complex turbine blade geometries and apply boundary conditions to examine steady state thermal & structural performance of the blade for N 155, Hastealloy x & Inconel 625 materials. Finally selecting the best suited material among the three from the report generated after analysis.

III. METHODOLOGY

Since the heat transfer takes from different modes that are conduction and convection, governing equations of heat transfer between the elements are applied. Below equation (1) represents the heat transfer which takes place during conduction derived by the Fourier, and equation (2) represents the heat transfer during conduction which is by Newton's law of cooling [2]. The turbine blade which is exposed to the convective film is assumed to be a fin which plays a role of heat dissipation at the tip. The temperature distribution from the blade is given by the equation (3) and the overall heat transfer is given by the equation (4).

Fourier's Law of conduction

$$Q= - K A_c \, dt/dx \qquad \text{...... (1)}$$

Newton's Law of cooling

$$Q=h A_s (t_s-t_a) \qquad \text{...... (2)}$$

Temperature distribution of a blade (fin) loosing heat at the tip

$$\frac{\theta}{\theta_0} = \frac{t-t_a}{t_0-t_a} = \frac{\left[cosh(m(l-x))+\frac{h}{km} sinh(m(l-x))\right]}{\left[cosh(ml)+\frac{h}{km} sinh(ml)\right]} \qquad \text{..... (3)}$$

The rate of heat transfer from the blade

$$Q = kA_c m(t-t_a)\left[\frac{\tanh(ml)+\frac{h}{km}}{1+\frac{h}{km}\tanh(ml)}\right] \qquad \text{..... (4)}$$

Fin Factor

$$m = \sqrt{\frac{hp}{KA_{cs}}} \qquad \text{..... (5)}$$

IV. MODELLING AND ANALYSIS

Present study involves geometric modelling of the turbine blade using ANSYS CFX and its simulation is performed using the same [1]. The material of the element is exposed to the products of combustion on the convective heat transfer coefficient. Since the model set up obeys the second law of thermodynamics the base surface of the blade will be low temperature reservoir and the tip will be high temperature reservoir. The temperature distribution will be observed over the element due to the different modes of heat transfer. Different material can be chosen accordingly by changing the thermal conductivity of the material [3]. The model of the turbine blade is shown in the figure 1.

Fig 1. Model of the Turbine blade & overall system

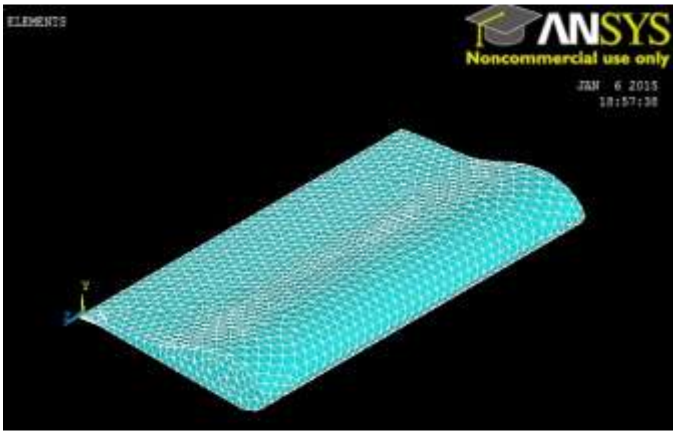


Fig 2. Meshing of the Turbine blade

Heating element is modelled and it is meshed using ANSYS software [1, 2]. Meshing is discretising of an element into finite number of parts and each element is considered and solved separately. Mesh generation is the practice of generating a polygonal or polyhedral mesh that approximates a geometric domain. The term "grid generation" is often used interchangeably. Typical uses are for rendering to a computer screen or for physical simulation such as finite element analysis or computational fluid dynamics [4]. After this step a thermal steady state simulation is performed. By using ANSYS numerical simulation tool, whole analysis of entire assembly is performed. Present simulations adopt realistic boundary conditions by considering various different materials with different thermal conductivities.

Since stainless steel is considered as the material for the blade, thermal conductivity of the element is 29 W/m^{0}C. The second boundary in the simulation was the temperature of the root of blade and of the tip of the blade which is temperature of the combustion gases. Heat transfer coefficient between the blade and the combustion gases is 320 W/m^{20}C. As an important boundary condition is the radiation property of the steel. But due to the high film coefficient, the part of the heat flow caused by radiation is neglected in this work. Modelling and Meshing is done using FEA and the simulation is performed. By means of the numerical solution, a steady state analysis of the entire heating element is achieved [1]. Validation of the results obtained in the FEA is carried out using dot net frame work software.

Dot net provides user interface, data access, database connectivity, cryptography, web application development, numeric algorithms, and network communications. Governing equations are fed and the results are obtained. Classical equations parameters are varied accordingly and the output relating to this are compared with the numerical method.

V. RESULTS AND DISCUSSION

The simulation is carried out with the application of the boundary conditions by defining thermal parameters. Analysis is carried out by providing the thermal conductivity value and heat transfer coefficients. Figure 3 shows the application of temperature at the ends and the film coefficient on the surface.

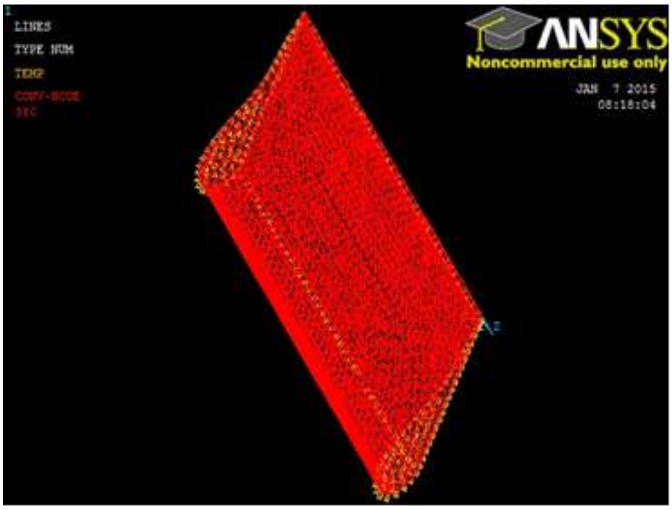


Fig 3. Application of thermal boundary conditions

The above simulation shows the application of thermal parameters on the element defined. Temperature distribution using governing equation of fin is determined using dot net. Heat transfer is steady from the ambient temperature to the element or the net heat transfer which takes place is negative. Figure 4 shows the temperature distribution over the element due the effect of combustion gases. It is noted that temperature is higher at the tip and cross-section of the blade. Figure 6 shows the numerical solution for the calculation of heat transfer rate using dot net software.

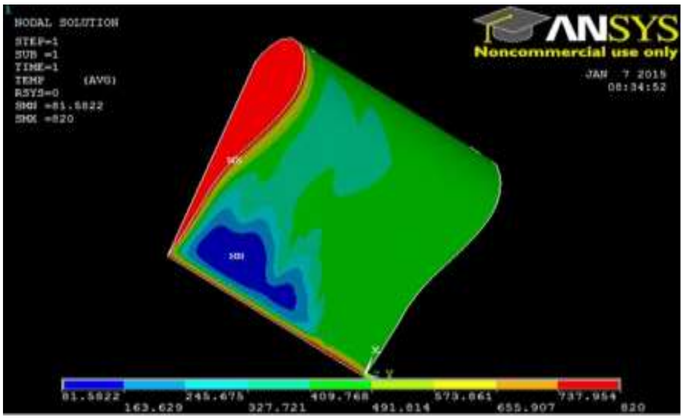


Fig 4. Temperature distribution by considering conduction and convection

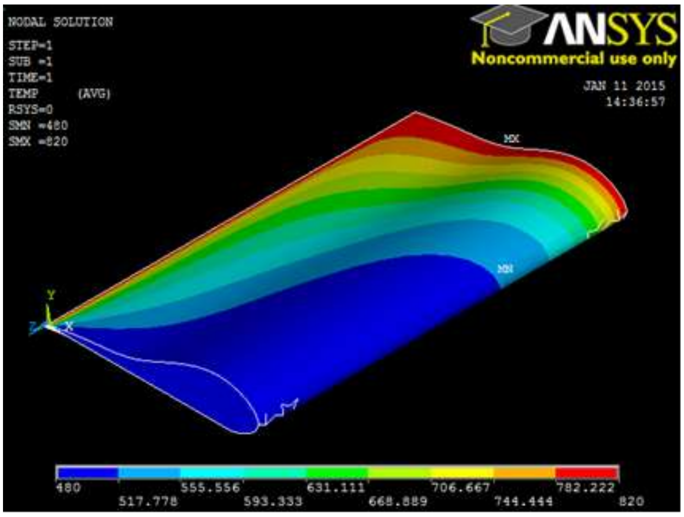
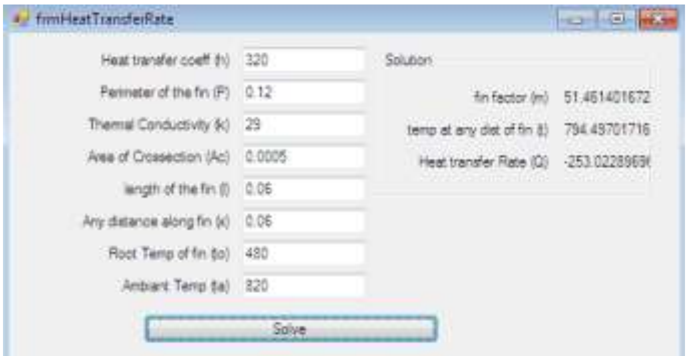


Fig 5. Temperature distribution by considering only conduction


frmHeatTransferRate

Heat transfer coeff (h) 320
Perimeter of the fin (P) 0.12
Thermal Conductivity (k) 29
Area of Crossection (Ac) 0.0005
length of the fin (l) 0.06
Any distance along fin (x) 0.06
Root Temp of fin (to) 480
Ambiant Temp (ta) 820

Solution
fin factor (m) 51.461401672
temp at any dist of fin (t) 794.49701716
Heat transfer Rate (Q) -253.0228969

Fig 6. Numerical solution obtained by dot net software

Table 1. Temperature distribution using FEA and classical methods

Thickness (from inside to outside)	Temperature distribution obtained in Finite element Analysis technique using ANSYS (^{0}C)	Temperature distribution obtained in conventional equations using Dot NET (^{0}C)
5 mm	556.46	556.89
10 mm	618.28	616.28
15 mm	663.18	662.10
20 mm	698.30	697.40
25 mm	727.65	725.55
30 mm	747.39	745.34
35 mm	763.27	761.17
40 mm	775.37	773.07
45 mm	785.66	781.86
50 mm	789.10	788.10
55 mm	794.22	792.22
60 mm	794.67	794.49

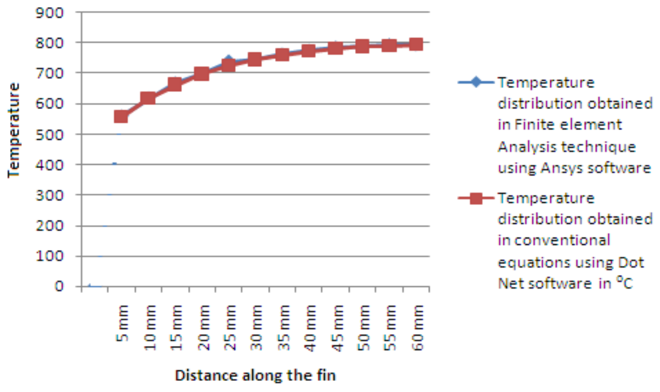


Fig 7. Comparative temperature distribution using FEA and Classical methods

Figure 7 shows the temperature distribution which takes place from the root of the blade to the tip of the blade using both classical and finite element method. Comparison shows the temperature rise and the heat flow is negative. The value of heat transfer rate is - 253 W which is shown in the figure 6.

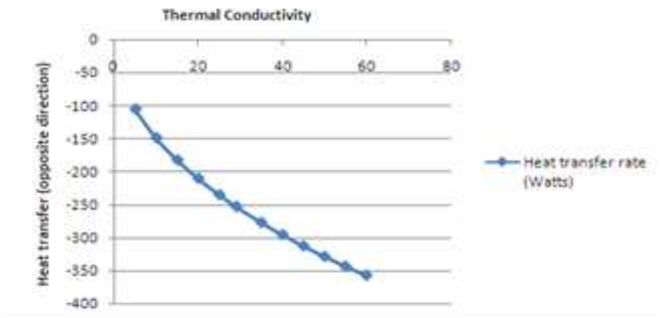


Fig 8. Variation of heat transfer rate with the change in thermal conductivity

Table 2. Variation of heat transfer rate with the change in thermal conductivity

Conductivity (W/m^{0}C)	Heat transfer rate
5	-105.34
10	-148.97
15	-182.42
20	-210.54
25	-235.17
29	-253.02
35	-277.36
40	-295.82
45	-312.91
50	-328.81
55	-343.67
60	-357.61

Table 3. Variation of heat transfer rate with the change in film coefficient

Heat transfer coefficient(W/m^{20}C)	Heat transfer rate
25	-51.57
50	-86.55
75	-113.18
100	-134.93
125	-153.54
150	-169.97
175	-184.80
200	-198.42
250	-222.94
300	-244.83
375	-274.21
400	-283.30

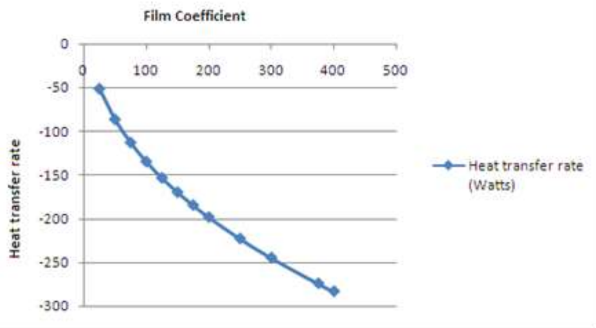


Fig 9. Variation of heat transfer rate with the change in film coefficient

Figure 8 and 9 show the graph which represents the increase in the negative heat flow on increase of thermal conductivity and heat transfer coefficient.

Table 4. Variation of fin factor with the change in thermal conductivity

Thermal Conductivity (W/m^{0}C)	Fin factor (m^{-1})
5	123.93
10	87.63
15	71.55
20	61.96
25	55.42
29	51.46
35	46.84
40	43.81
45	41.31
50	39.19
55	37.36
60	35.77

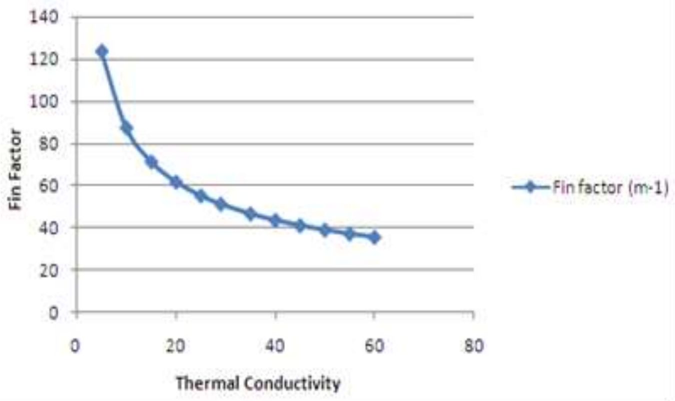


Fig 10. Variation of Fin Factor with the change in thermal conductivity

Table 5. Variation of fin factor with the change in heat transfer coefficient

Film Coefficient (W/m^{20}C)	Fin factor (m-1)
25	14.38
50	20.34
75	24.91
100	28.76
125	32.16
150	35.23
175	38.05
200	40.68
250	45.48
300	49.82
375	55.70
400	57.53

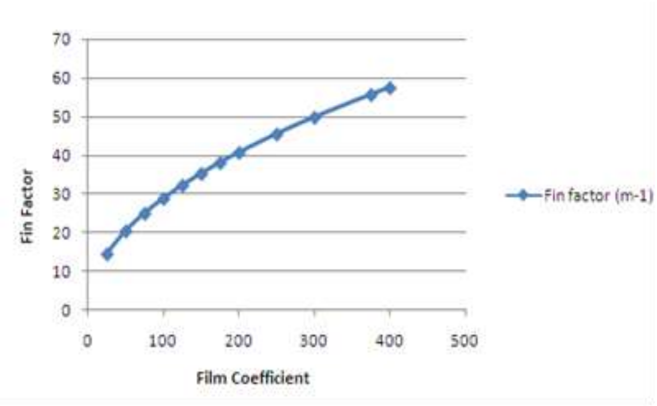


Fig 11. Variation of Fin Factor with the change in film coefficient

From the figure 10 and 11, shows that there is a drop in the fin factor with the rise of thermal conductivity and the rise in the fin factor with the increase in heat transfer coefficient [2].

VI. CONCLUSIONS

In the present analysis, a turbine blade acted with conduction and convection parameters are assessed and the temperature at various points is investigated which enhances the heat dissipation from the entire unit which is exposed to the products of combustion. An attempt is made to demonstrate the improvements to enhance the maximum heat dissipation from the system using FEA technique and the validation of this is carried out by using computer software Dot Net. It is possible to obtain a optimum solution by selecting a material which has better thermal performances. By increasing the value of thermal conductivity and film coefficient it is possible to increase the heat dissipation rate. Shape and size of the fin can also be varied to enhance the change in heat transfer. Concept of forced convection can also be implemented by providing external fan to dissipate the maximum heat transfer; calculations may require various dimensionless numbers like Nusselt, Prandtl, and Reynolds numbers. Due to the forced convection the heat transfer will be transient and the effectiveness will be increased. Fin efficiency and effectiveness can be calculated using the equations and it could be varied in order to obtain an optimum values. Thermal analysis can be carried out by changing the profile of the blade, dimensions which may enhance maximum dissipation of heat to the surroundings which helps in reducing thermal stresses or stress concentration factor.

NOMENCLATURE

Q= Heat Transfer rate, W
A_c= Cross-Sectional Area, m^2
P=Perimeter, m
k= Thermal Conductivity of the material, W/m^{0}C
h= Heat transfer coefficient, W/m^{20}C
t= Temperature, ^{0}C
A_s= Surface Area, m^2

t_s= Surface Temperature, ^{0}C
t_a= Ambient Temperature, ^{0}C
L=Length of the element, m
M=Fin factor, m^{-1}
dt/dx= Temperature gradient, ^{0}C/m
θ= Difference between the temperature at any point on the element and the ambient temperature, ^{0}C
θ_o= Difference between the temperature at root of the element and the ambient temperature, ^{0}C

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