IOP Conference Series:
Materials Science and
Engineering

PURPOSE-LED PUBLISHING™

PAPER • OPEN ACCESS

Numerical Investigation of Heat Transfer in Aircraft Engine Blade Using $k-\in$ and SST $k-\omega$ Model

To cite this article: Chethan R Patill *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1013** 012027

View the article online for updates and enhancements.

You may also like

- Influence of fan-shaped holes with different transition surfaces on film cooling performance
Hansong Liu
- Investigation on Shallow Trenched-Hole Film Cooling Effectiveness at Turbine Blade Pressure Side
Jiangjiang Yin, Kenan Huang and Ying Huang
- Measurement and determination of local film cooling performance along a transonic turbine blade tip with viscous dissipation
Phillip M Ligrani, Hallie Collopy and Ward Manneschmidt



This content was downloaded from IP address 103.233.171.39 on 06/01/2025 at 12:27

NUMERICAL INVESTIGATION OF HEAT TRANSFER IN AIRCRAFT ENGINE BLADE USING $k-\epsilon$ AND SST $k-\omega$ MODEL

Chethan R Patil1, Devendra Dandotiya2, Bhaskar Pal3, Nitin Banker4
1,2,3 Department of Mechanical Engineering, Presidency University, Bangalore, 560064, India
4 School of Engineering and Applied Sciences, Ahmedabad University, Gujarat, 380009, India
E-mail: devendradandotiya@presidencyuniversity.in

Abstract - Even the smallest part engineered in gas turbines adds on hugely to its output performance. The blades form a major part which extracts energy from high temperature and high-pressure gases produced from the combustion chamber. This high temperature may cause the blades to undergo creep or fatigue failure eventually. The blade material would not withstand such high temperatures. With an intention to overcome this thermal barrier, various cooling technologies like jet impingement, film cooling, mist assisted film cooling, pin fin cooling, transpiration cooling have been adapted in the gas turbines. Using these cooling technologies, the temperature on the blades can be reduced by 200 to 300 K and higher performance may be achieved without much of a compromise. This study mainly focuses on how much the temperature can be reduced if only convective cavity cooling was used, wherein a hollow blade is used and cold fluid passes through it. Computational Fluid Dynamics (CFD) in ANSYS was used to compute the temperature difference on the blade and high temperature region. The computations were carried out on both CFD and CFX. Two different turbulence models were considered, k-epsilon and k-omega SST (Shear Stress Transport). Analysis were carried out with nearly 3 million elements. Velocity, temperature flows at selected regions are reported.

Keywords - Gas turbines, blades, combustion chamber, high temperature, cooling technology, jet impingement, film cooling, pin fin cooling, convective cooling, CFD, Ansys, CFX, K epsilon, K omega SST (Shear Stress Transport)

1.Introduction

Gas turbines also called combustion turbine, is an internal combustion engine which works on the principle of Brayton cycle. These gas turbines are used in many processing plants and industries for power generation, widely used for aircraft propulsion to provide thrust [1]. Safety and efficiency have to be of prime importance as it finds application in major areas. The air which enters the engine, is first compressed in the compressor, which adds on to its pressure. Later fuel is allowed to combine with this pressurized air and ignited, which adds on to its energy and temperature. This pressurized high temperature air is fed onto the series of blades in turbine which extracts energy and this extracted energy is converted to useful power depending on the application .The energy extracted by the blades is partially used to run the compressor and the remaining is used to do external work .The external work maybe thrust in case of aircrafts ,a propeller in ships or a generator used in industrial areas [2].

In order to survive the harsh environment in turbines like extreme temperature at high rpm, blades are manufactured by superalloys, which have high melting points. One of the earliest materials ever introduced was Nimonic which was used in British Whittle engines. In the modern era, blades are manufactured using Nickel superalloys with some percentage of chromium, cobalt and rhenium. Inconel is another widely used material to manufacture blades .IN-738 was first used by GE specifically for land-based turbine for the second series or stage of turbine blades [5].

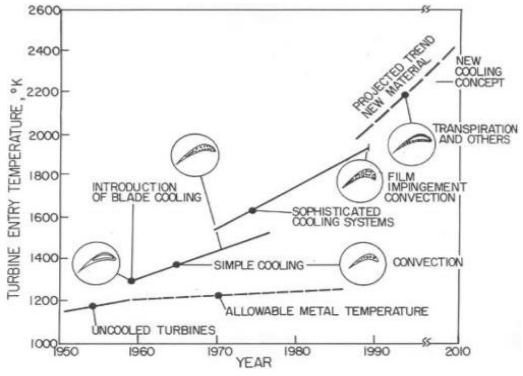


Fig.1 Evolution of Cooling Methods [6]

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

Cooling methods like jet impingement and film cooling use air or water as primary fluid to achieve heat transfer between the blade and the coolant, whereas mist assisted cooling which is a new research uses air along with minute droplets of water which achieves more cooling than using air alone. Employment of water in cooling may lead to corrosion of the parts, leakage, choking and other problems. Using air at high pressure and higher mass flow rates may bring about turbulence in the main stream bringing down efficiency. About 1-3% of main flow is generally used to avoid such problems [7].

There are cooling techniques which use either water or air as cooling medium. Nano fluids with higher heat capacity or any other mixture of fluids can be used as coolant. Such synthesized coolants may possess density higher than air and water, so passing it through holes or multiple passes maybe difficult. In order to reach a higher level of research and interaction of these fluids, a basic research with a simple blade design and traditional method of cooling i.e. convective cooling with air as coolant is employed. The coolant is passed through the hollow blade where heat transfer happens between itself and the blade surface. Heat flows through the blade (conduction) and later this heat conducted heat is lost to the coolant which acts a sink through convection. An improvised model of convection cooling is that the coolant can be allowed to stay for a longer time within the blade by creating multiple passes in the hollow region of the blade. This improved method brings about more heat transfer, hence more cooling can be achieved.

2. Geometric Model and Working Conditions:

The blade profile used is the Rolls Royce Conway blade profile but with a different cooling technique. It is a widely and commonly used blade profile in modern gas turbines. The blade has a cavity in its centre so as to facilitate the flow of coolant through it. The blade geometry was modelled in Solid works. The material used for the blade is nickel and the cooling medium used is Air. The surrounding hot domain is also air, relatively at a higher temperature. The blade material as mentioned above is Nickel (Ni) bearing properties thermal conductivity of 91.74w/m-k, specific heat (C_p) of 460.6 J/kg-K, density of 8900 kg/m^3.The air in the hot domain representing air from the combustion chamber has temperature of 1560 K and air depicting the coolant flowing through the cavity of blade has temperature of 750 K, with density 1.225 kg/m^3 ,thermal conductivity 0.0242 W/m-K and specific heat(Cp)1006.43J/kg-K [8] .

Table 1. Properties of hot domain

Temperature	1560K
Thermal Conductivity(k)	0.0242w/m-K
Specific heat (Cp)	1006.43J/kg-K
Density(ρ)	1.225kg/m^3

Table 2. Properties of cold domain

Temperature	750K
Thermal Conductivity(k)	0.0242w/m-K
Specific heat (Cp)	1006.43J/kg-K
Density(ρ)	1.225kg/m^3

Table 3. Properties of blade material

Thermal Conductivity(k)	91.74w/m-K
Specific heat (Cp)	460.6J/kg-K
Density(ρ)	8900kg/m3

3. Meshing:

Meshing for the model was carried on in Ansys Model-Meshing component systems of Ansys software. The model consists of 2363493 (2.3million) elements and 620843 (0.6million) nodes. An image of the meshing has been shown below in Fig.2. The number of elements was increased to 3.5 million, with an intention to witness any variation in results. But there was no appreciable change, so the model with 2.3 million elements was used for further analysis.

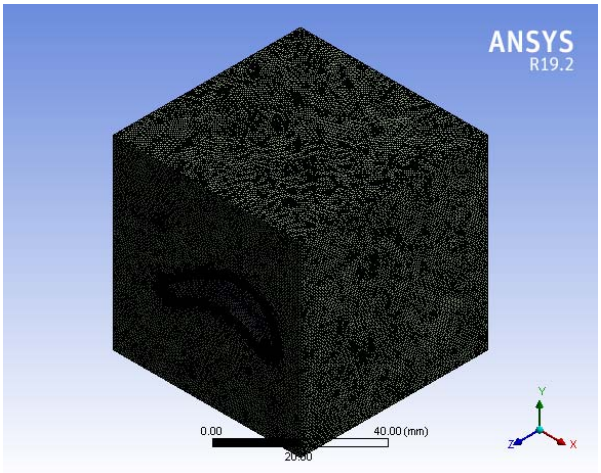


Fig.2 Meshed Component

4. Computational Model and Governing Equations:

As mentioned, the analysis is carried out in CFD and Ansys Fluent. The analysis mainly focuses on comparing the results obtained from K-Epsilon model (CFX) and K-Omega SST turbulence model (Ansys Fluent). Analysis can be carried out theoretically or computationally which abides by certain governing equation for different types of turbulence model. The total energy equation which comprises of the conservation of mass equation, the conservation of momentum equation and the conservation of energy equation is solved internally to yield results in any kind of fluid dynamics problem. Corresponding governing equations for CFX are [8],

$$\frac{D\rho}{Dt} + \rho\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\frac{Du_i}{Dt} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho F_i \tag{2}$$

$$\rho\frac{De}{Dt} = -p\frac{\partial u_i}{\partial x_i} + \emptyset + \frac{\partial}{\partial x_i}(K\frac{\partial T}{\partial x_i}) \tag{3}$$

where

$$\emptyset = \tau_{ij}\frac{\partial u_i}{\partial x_j} \tag{4}$$

$$\tau_{ij} = \mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_r}{\partial x_r}\delta_{ij}) \tag{5}$$

The turbulence model SST (Shear Stress transport) is based on two equations. This model manages calculations of both k-ε and k-ω thus tackling adverse pressure gradients and turbulence properties.

$$\frac{\partial k}{\partial t} + U_j\frac{\partial k}{\partial x_j} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}[v + \sigma_k v_T)\frac{\partial k}{\partial x_j}] \tag{6}$$

$$\frac{\partial \omega}{\partial t} + U_j\frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(v + \sigma_k v_T)\frac{\partial k}{\partial x_j}\right] + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial \omega_i} \tag{7}$$

The transport equation in transitional SST model is governed by the following equation

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \tilde{P}_k - \tilde{D}_k + \frac{\partial y}{\partial x}[(\mu + \sigma_k\mu_t)\frac{\partial k}{\partial x_j}] \tag{8}$$

$$\tilde{P}_k = \gamma_{eff}P_k \tag{9}$$

$$\tilde{D}_k = \min(\max(\gamma_{eff}, 0.1), 1.0)D_k \tag{10}$$

The concept of thermal conductivity plays a major role in the analysis. The high temperature of hot gases from the combustion chamber is absorbed by the solid blade material through thermal convection. The convective heat transfer as per Newton's law of cooling:

$$q = h(T - T_\infty) \tag{11}$$

Thereafter the heat gets conducted from the topmost layer of the blade to the underlying layers through thermal conduction. The interaction of high temperature gas molecules with the blade molecules creates a temperature gradient between the layers of the blade. Heat transfers along the gradient of descending temperature, also sometimes referred to as thermal diffusion. Thermal conduction is best explained by Fourier's equation:

$$q = -\lambda \frac{dT}{dx} \tag{12}$$

A layer of TBC (Thermal barrier coating) on the blade helps to reduce the effect of heat on the blade. The heat from the high temperature gas is transferred to the coating first, later onto the solid blade material. Then the heat gets transferred to the coolant flowing through the cavity. Such TBCs help to increase the life of the blade to a certain extent, but levies high maintenance charges as it undergoes wear and tear very often.

5. Cooling Effectiveness:

In order to know how effective the employed cooling method is, a parameter known as cooling effectiveness is determined. Cooling effectiveness is the ability of the coolant to reduce the blade temperature. The value scales from 0 to 1. The value reaches 1 when the blade temperature reaches the coolant temperature, indicating efficient cooling and is 0 when the blade temperature reaches the main stream temperature. Cooling effectiveness can be calculated using,

$$\varepsilon = \frac{T_g - T_m}{T_g - T_{ci}} \tag{13}$$

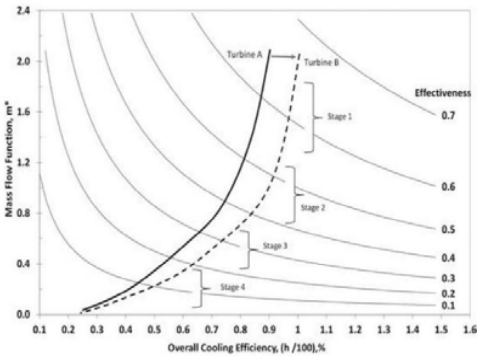


Fig.3 Cooling Efficiency and Effectiveness at Different Stages

6. Results and discussions:

The figure 4 shows comparison of the results generated in Ansys Fluent and CFX wherein the same model with the same number of elements was used. No significant variation was noticed out of these results. The iso-surface generated in CFX gave out relatively more accurate visuals around the blade.

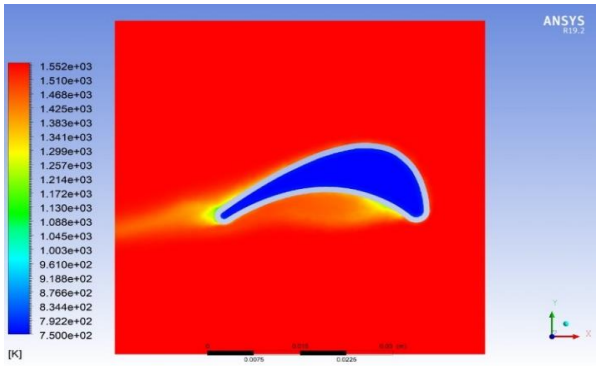


Fig.4(A) Iso- surface generated in Ansys fluent

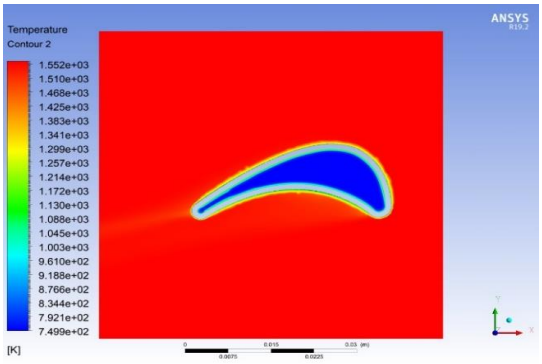


Fig.4(B) Iso- surface generated in Ansys CFX

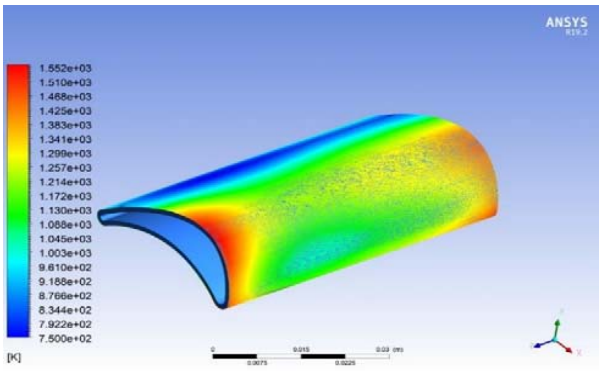


Fig.5(A) Blade Contour Generated in Ansys Fluent

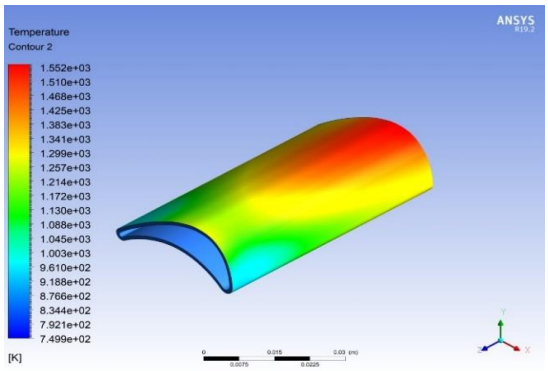


Fig.5(B) Blade contour generated in CFX

The figure 5 show cases the temperature contours of blade, These contours show region of high and low temperatures. Regions of high and low temperatures can be analyzed through these contours and further research can be carried out to increase effectiveness at high temperature region.

Fig.4 shows one of the possible hot spots at the pressure surface near the trailing edge of the blade where the temperature is comparatively higher than other points. It is also known as the stagnation point where the gas flow halts for a moment and thereby this area experiences combined effect of kinetic and static energy that the gas carries. A temperature of 948K was observed at the leading-edge hot spot whereas the other points where lying at a temperature ranging from 850K to 920K. Another most probable point of hot spot is at the trailing edge.

7. Conclusion and Future Research:

The present analysis on gas turbine blade with convective method of cooling generated cooling effectiveness of 0.5. This level of effectiveness is not sufficient to have high efficiency and power output of the gas turbine on the whole. The current model can be made efficient by using different coolant medium with a higher heat capacity. But this may require refabrication of the turbine. So, an upgraded model of convective cooling with multiple passes helps increase the efficiency. An updated model of cooling technology is Film cooling where the coolant gushes out of the blade through small holes creating a layer, thereby reducing the blade temperature.

Gas turbines are majorly used in Airplanes. Commercial flights fly typically at a range of 6 to 8 miles above the Earth surface. The temperature ranges from +15 ºC to -50 ºC. The idea here is to somehow direct this cold atmospheric air onto the blades or through the blades so that the temperature can be reduced. The air has to be directed towards the blade in such a way that the air doesn't come in contact with the main stream air or the combustion chamber. This may yield more efficiency than the existing cooling method technologies.

8. References

[1] Zohuri, B., and Zohuri, B., 2015, "Gas Turbine Working Principles," Combined Cycle Driven Efficiency for Next Generation Nuclear Power Plants, Springer International Publishing, pp. 147–171.
[2] Çengel, Y. A., and Boles., M. A., 2011, 9-8. Thermodynamics: An Engineering Approach, McGraw-Hill, New York.
[3] Dambrine, B., and Mascarell, J. P., 1988, "Designing Turbine Blades for Fatigue and Creep," Def. Sci. J., 38(4), pp. 413–429.
[4] "NPTEL :: Aerospace Engineering - Turbomachinery Aerodynamics" [Online]. Available: https://nptel.ac.in/courses/101101058/. [Accessed: 03-May-2020].
[5] Schilke, P. W., 2004, "Advanced Gas Turbine Materials and Coatings, General Electric Company," GE Energy, p. 30.
[6] Rice, T., 2017, "Numerical Analysis Of The Film Cooling Effectiveness On A Highly Loaded Low Pressure Turbine Blade In Conjunction With Endwall Effects."
[7] Yahya, S. M., 2010, Turbines Compressors and Fans, Tata McGraw-Hill.
[8] ANSYS, 2015, "ANSYS Fluent Theory Guide", ANSYS 16.2