DEVELOPMENT OF A COMPUTER CODE TO STUDY AND ANALYZE DIFFERENT TECHNIQUES EMPLOYED FOR TURBINE COOLING

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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June 2021

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ABSTRACT

The distribution of temperature for a turbine blade is highly important to be determined so that we can avoid excessive high temperatures of the blade and we can determine its temperature gradients. The temperature distribution was predicted by the use of a unique technique which is known as finite difference technique. This technique involves grid generation and transformation techniques. The two-dimensional steady state conduction equation was used on the internal nodes of the mesh to get the desired temperature distribution. Whereas for all the nodes on the surface (inner and outer), we used the forced convection heat transfer equation. For the determination of convective heat transfer coefficient, we determined its Nusselt Number. We established a computer program for the solution of this problem. MATLAB was used to get the temperature distribution about the turbine blades. In MATLAB, certain different cooling techniques were analyzed and plotted first separately and then comparatively against each other. There are several cases for the thermal analysis of the blade, out of which we devised three cases for the present study of the turbine blades. These three cases require the internal as well as the external boundary conditions. The results of our study indicated that the best cooling method for the turbine blades has been obtained when we use the third case. The third case is when the blades are cooled by the techniques of impingement cooling technique and film cooling technique. We found that when the turbine blade was cooled using film cooling, the temperature drop of 170K was obtained.

ACKNOWLEDGMENTS

We are thankful to ALLAH ALMIGHTY for all his blessings and bestowing us with the strength and skills necessary for the task. We would like to show gratitude to Sir Abdul Naeem Khan for providing us the opportunity to perform this project and guide us in the completion of the project. We would like to thank our Head of Mechanical Department of SMME, Dr. Emad ud din and the Principal of SMME, Dr. Javid Iqbal whose support has been crucial for the completion of our venture. We would like to thank our teachers who helped us with dedication and commitment at NUST. Last but not least we would like to acknowledge the support of the Department of Mechanical Engineering for providing us adequate resources and work space within the premises of university to accomplish our task efficiently. We are grateful to our families who have supported us morally and financially at every step.

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NOMENCLATURE

Symbols:

η Efficiency

f Friction Factor

h Heat transfer coefficient

p density

k Thermal Conductivity

M Mach Number

M Mass flow rate

Nu Nusselt Number

Pr Prandtl Number

P_s Static Pressure

P_o Total Pressure

Re Reynolds Number

T Temperature

T_3 Turbine Inlet Temperature

T_4 Turbine Exhaust Temperature

Ts Turbine blade surface temperature

T_w Temperature of the wall

x Distance in Stream wise direction

Abbreviations:

TIT Turbine inlet temperature

ET Exhaust temperature

CAD computer aided design

CFD Computational Fluid Dynamics

RANS Reynolds Averaged Navier Stokes

TSP Temperature Sensitive Paint

PSP Pressure Sensitive Paint

DNS Direct Numerical Solution

BR Blowing Ratio

MATLAB Matrix laboratory

MBT Maximum blade temperature

CS Computer software

CHAPTER 1: INTRODUCTION

1.1 Motivation

In the modern era turbines are one of the key subjects in the power generation in the industries. In Pakistan, turbines have been in use as one of the most fundamental units. They are the energy production houses of an industry. For both environmental and economic reasons, there is an interest in and a need for power plants with increased efficiency and power output. Power plant cycles that include gas turbines are interesting from these points of view, since the gas turbine combines rapid and easy installation with low cost and low emissions. The requirement of energy has been rapidly increasing over the recent years. The purpose is to minimize the power input while maximizing the output power resulting in increased efficiency. Turbines are termed as powerhouses because of the high efficiency and huge power to mass ratios. The gas turbines have been in use for all the grounds either it be land, air, or sea. Since the introduction of gas turbine, they have been giving important results over time. They have been in use from jet propellers, power plants to the submarines deep under the sea.

1.2 Thermodynamics:

The gas turbines basically work on the principle of Brayton cycle. Following is the T-S diagram of the process. In this cycle the air is basically first compressed and then there is a process of heat addition. This is then converted into work which is extracted at the

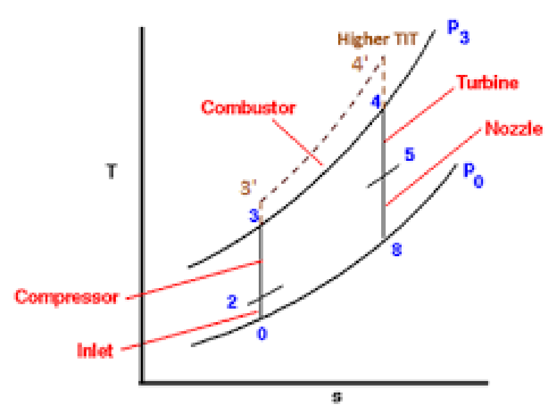


Figure 1 - T-S diagram of Brayton cycle

blades of the turbine. The highest temperature is observed at the turbine inlet. But the temperature is basically limited by the turbine blades' material characteristics.

1.3 Turbine Blade cooling history:

The efficiency if the gas turbines is increased by increasing the inlet temperature of the turbine. Over the previous decades, there have been efforts made to improve the material of the turbine. To increase the turbine inlet temperature, high performance materials with high temperature limitations have been tried. Materials like special steels, alloys of titanium and some super alloys in order to make the turbine blade with high temperature withstanding abilities. But this causes high expenses. Also, when high temperature reaches cooling techniques are necessary to avoid failures. High temperature conditions can be only achieved by special cooling techniques.

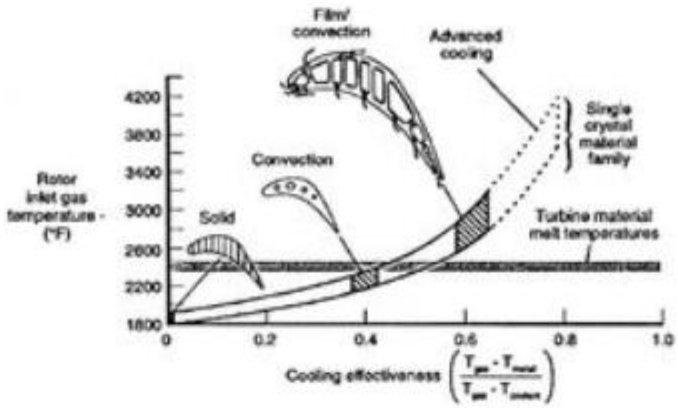


Figure 2 - Turbine blade cooling technology comparison

1.4 Statement of Problem

When high temperature conditions are reached, the efficiency of the turbine depends on the turbine inlet temperature for a fixed pressure ratio. But when the turbine inlet temperature reaches a certain temperature, it undergoes several thermal, vibrational, and centrifugal stresses which may result in warpage and creep at the turbine blade. For this purpose, turbine cooling is necessary. In the power generation industry, the turbines have different objectives to deliver so have difference inlet conditions, so there is a need of an automated software which can provide the user the best cooling technique for the required conditions which can give the maximum performance.

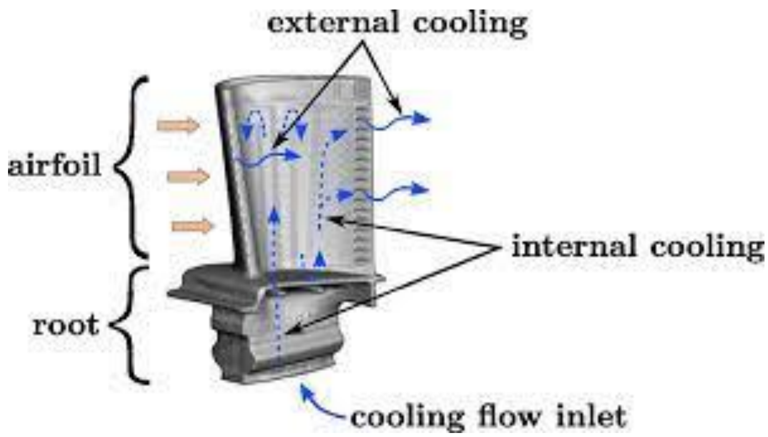


Figure 3 - General turbine blade cooling for a solid blade

Since the thermodynamics and fluid dynamics of the expansion in a cooled turbine are extremely complicated, and thus, time-consuming to calculate, this means that a simplified thermodynamic model that can be incorporated into power plant cycle calculations, is required.

1.5 Purpose of the project

The addition of cooling to the gas turbine means that it will be much more complicated to design and manufacture. From a thermodynamic point of view, it can no longer be treated as a Brayton cycle in the simple, straightforward way that is described in several places in literature. Still, it must be possible to calculate the impact of cooling on gas turbine efficiency and outlet temperature, in order to enable calculations on power plant cycles and concept studies for new power generation solutions. Since the thermodynamics and fluid dynamics of the expansion in a cooled turbine are extremely complicated, and thus, time-consuming to calculate, this means that a simplified thermodynamic model that can be incorporated into power plant cycle calculations, is required.

1.6 Objectives

Several experiments have been conducted for different cooling techniques show which cooling technique has the pros and cons, the analysis is the deciding factor that which cooling technique is desirable under which condition. The CFD analysis for solving and analyzing the fluid flow and heating prints over the turbine blade. It uses the Reynolds and average Napier stokes equations for the generalization of the predicted flow properties. However, it was observed that there was no defining or perfectly accurate method for the turbulence phenomenon. Also, there can be some degree of inaccuracy in numerical methods analysis of CFD.

Following are the objectives for the optimized software with maximum accurate results:

- A complete study and simulative analysis of the turbine cooling techniques currently incorporated in the industry for various power generating conditions.
- A comparative study for the best cooling technique which will give the maximum output efficiency and highest input temperature of the turbine.
- The generation of a computer code for the calculation and comparison of cooling techniques for the user according to his required output conditions.
- The utilization of the computer code into a software/app which an easy-to-use user interface for the user with minimum number of required variables.

CHAPTER 2: LITERATURE REVIEW

2.1 Turbine

Turbines are basically rotating mechanical devices who operate to extract the energy from the flowing fluid and convert it into useful work. This useful work can later be converted to electrical power with the help of a generator. The gas turbines are basically power plants which produce energy greater in amounts for its weight and size. A turbine generally has at least one rotating part called rotor assembly; this is usually blades attached to a shaft. The stationary part is known as a stator. The fluid that is moving acts on the blade causing it to move and impart rotational energy to the rotor.

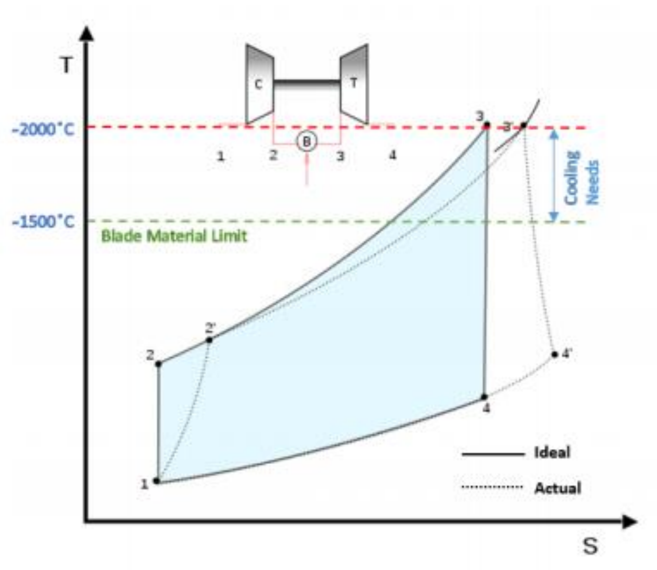


Figure 4 - T-S diagram of Brayton cycle with cooling gain

2.2 Turbine blade

Turbine blades are the most important component of a gas or steam turbine. They are individually responsible for the extraction of energy from the gas produced at high temperature and pressure inside the combustor. At high end conditions, the turbine blades are

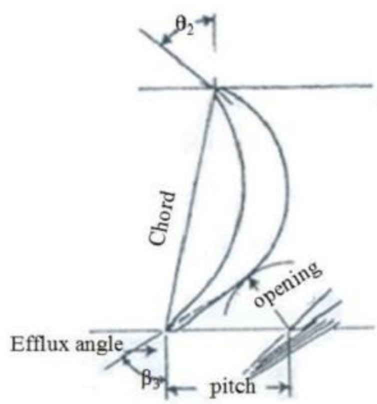


Figure 5 - Turbine blade

usually the limiting components due to their thermal and stress restrictions. Therefore, there needs to be a relevant exotic material to withstand these conditions. The materials are generally super alloys and certain cooling techniques are also utilized for preventing the thermal hostilities. Friction dampers are also used to prevent the high vibrations and stress conditions.

2.3 Cooling

Cooling can be defined as the heat removal which results in lowering the temperature of turbine blade cooling. This cooling can be through any mode either through thermal conduction, convection or radiation. In general, the cooling is achieved through the passing of air through available passages from hub to the tip of the blades. This air usually comes from an air compressor. If we keep the pressure ratio constant, it is observed that with the increase in the turbine inlet temperature, the thermal efficiency of the turbine increases. However, over a certain limit the more increment of temperature can cause warpage to the blades due to thermal and centrifugal stresses at high turbine temperatures. For this reason, turbine blade cooling is very necessary. With the most modern turbines the turbine inlet temperatures are around the 1900K range. Therefore, an active turbine cooling technique is required.

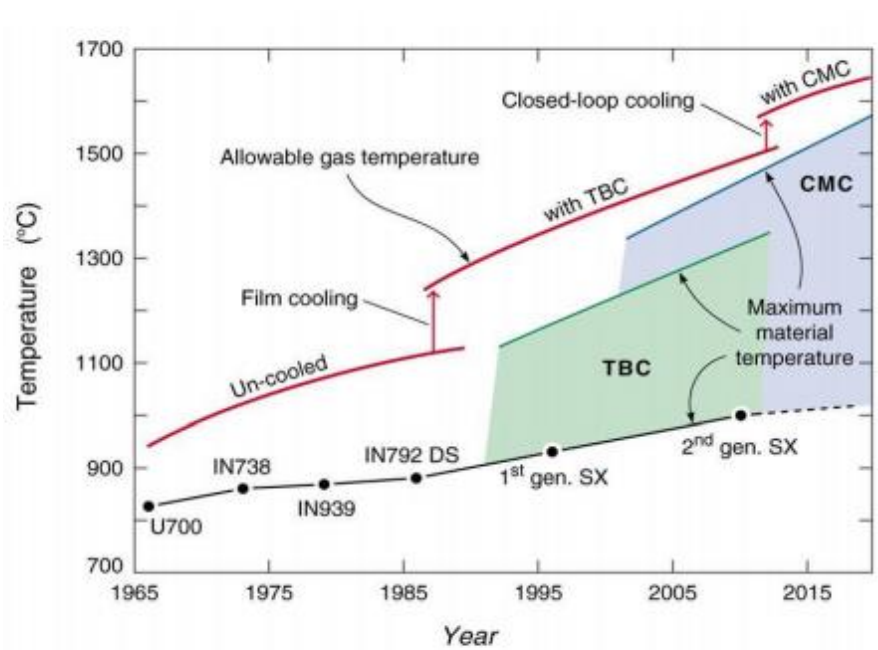


Figure 6 - Turbine inlet temperature over the years

2.3.1 Cooling methods:

The cooling of different parts of the turbine can be done by either air cooling or liquid cooling.

2.3.1.1 Liquid cooling

Following is some of the advantages of liquid cooling:

- The specific heat capacity of liquids is high.
- There are chances that evaporative cooling can also take place

Following is some of the disadvantages of liquid cooling:

- leakage
- corrosion
- choking

Due to these reasons, the disadvantages are more harming than the value brought by the advantages. So, liquid cooling is not preferable.

2.3.1.2 Air Cooling:

In case of air cooling the air being discharged can easily be funneled out of the passage without any leakage or problem. With a very little percentage of air i.e 1-3% of the main flow is required to bring about 200-300 C of decrease in temperature of the blade. There are several air-cooling techniques which can be utilized but they generally all work by using cooler air for the removal of heat from the turbine blades. So, the basic principle is the same.

Types of air cooling:

Following chart summarizes the types of air cooling:

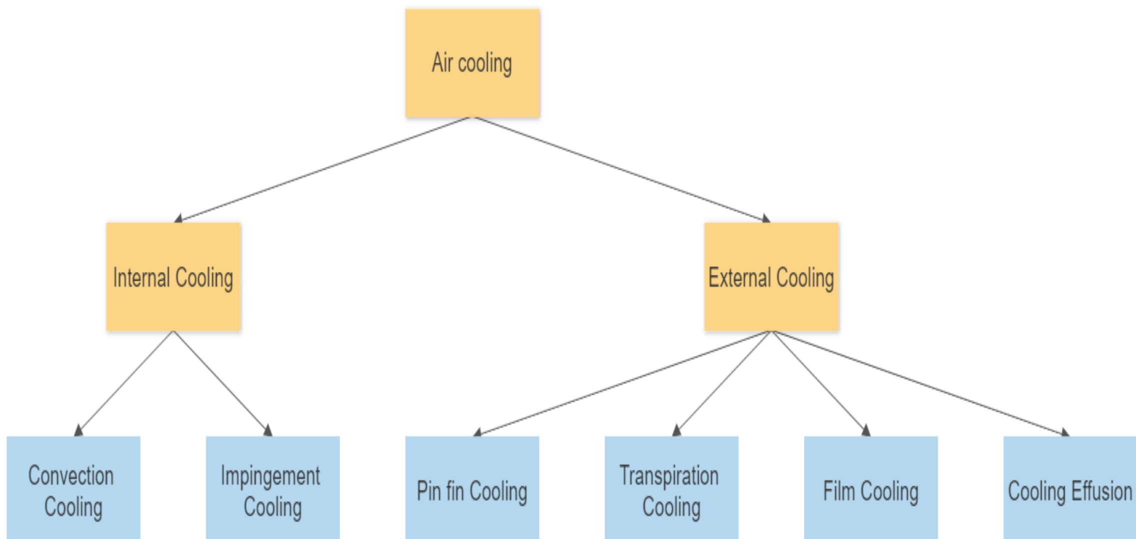


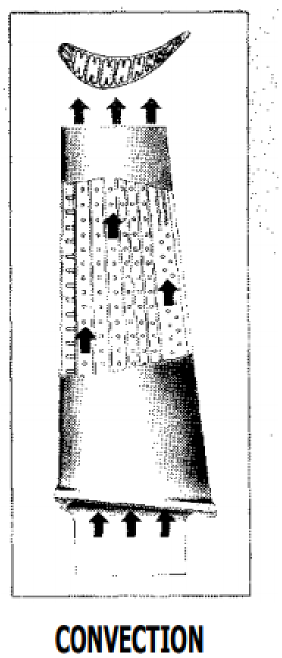
Figure 7 - Types of cooling

2.4 Internal Cooling Techniques

The internal cooling is done by the passage of coolant from the several engraved small passages inside the blade and then followed by extracting the heat from the outer surface of the blade. Convection cooling and Impingement cooling are the types of Internal Cooling.

2.4.1 Convection Cooling

Convection cooling is taken place by passing currents of cooling air internal passages of the turbine blade. The heat transfer takes place first by conduction from the blade and then into air flowing through the blade by convection. This process requires a lot of blade surface area so a lot of small fins can be placed in the blade. The passage for inside can be either circular or elliptically shaped.



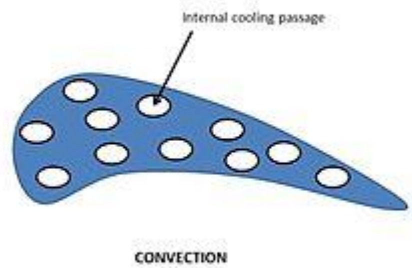


Figure 8 - Convection cooling

For cooling, the air is passed through these passages towards the tip of the blade from the hub. An air compressor is used for the cooling air. In a gas turbine's case, the outside fluid is comparatively hot which, while passing through the cooling pathway, mixes with the major stream at the tip of the blade.

2.4.2 Impingement Cooling:

The impingement cooling has also been in use for the cooling of the turbine internally and this method is widely employed in many of the ongoing industries. This method basically uses the pressure differential method and different nozzle adjustment methods in order to generate jets of high speed directed directly to the internal surfaces of the turbine blade.

This cooling technique is used in all the major hot parts of the engine which include turbine, combustion chamber, turbine vanes and blades, shrouds and as well as rotary discs. The Reynold values of the jets generated are around 10,000 to 500,000. There can be certain complexities with this method as well such as a variety of jet adjustments are required and the combination of geometry of surface of blade also has to be specific. This method can be very advantageous and flexible as well so it can be adjusted for any desired performance such as based on mechanical structure, aerodynamics, low fatigue cycles, vibrations and rupture limits of creep.

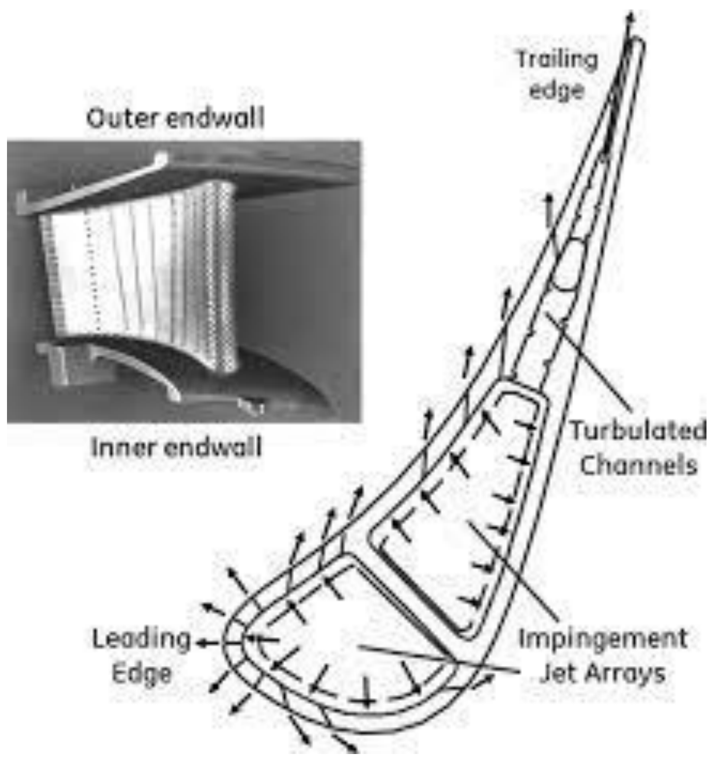


Figure 9 - Impingement cooling

As this cooling method involves the hitting of turbine blades with high velocity jets of air so this allows more heat to be transferred from the blade to the outside by convection than the convection cooling does. Impingement cooling is usually most specific to the hottest parts of the engine where the hot loads are at its peak. The hottest part is turbine blades' leading edge in case of turbine and thus load of heat is maximum there. Impingement cooling technique is generally used at the vane's mid chord. As the blades are hollow with core. For the direction of heat transfer, the cooling enters from the leading edge and then moves towards the other edge, called trailing edge.

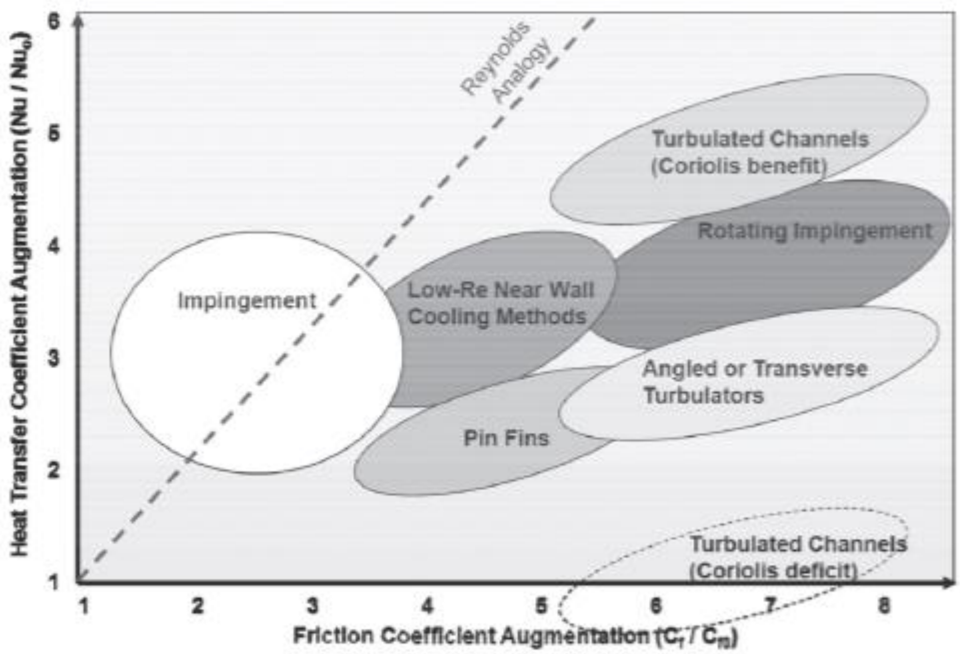


Figure 10 - Heat transfer coefficient augmentation and friction coefficient augmentation of gas turbine cooling techniques

2.5 External Cooling Techniques

<u>2.5.1 Pin fin cooling</u>

The first type of external cooling technique is "Pin fin cooling" in which there are circular pin-fin arrays at the tail of the turbine blade and the flow of air through them is fully developed laminar flow i.e., usually of low Reynolds number. For years, there is a need to reduce the fuel consumption and the pollutant emissions of a gas turbine. So, people have significantly increased the operating temperature of the gas turbine which leads to structural and thermal problems at the turbine blades. We already have some internal cooling techniques but still there is a need to have an efficient cooling system that would necessarily keep the temperature of the turbine blades below the critical values.

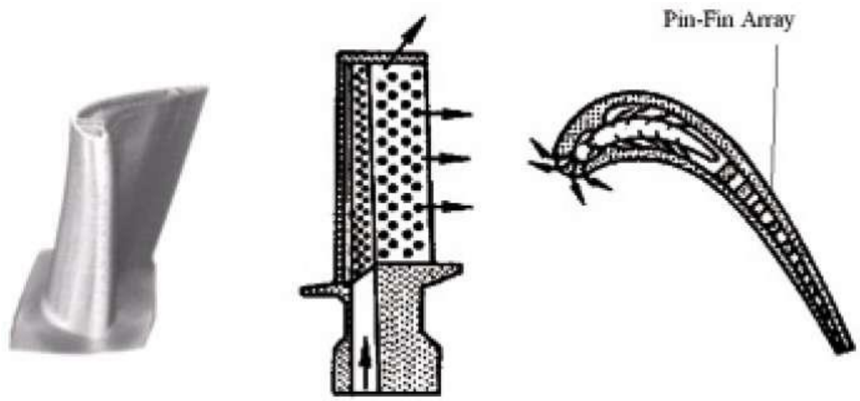


Figure 11 - Pin fin cooling of turbine blade in 3D

The basic arrangement in pin fin cooling technique is the use of cylindrical pin-fins with the circular cross-section attached to the blade in staggered array form. The pin fins not only enhance the heat transfer between the air and the turbine blades, they also provide structural support for the blades. The reason behind using cylindrical pin-fins is that first, it is really easy to manufacture such kind of fins plus circular cross-section fins efficiently promote flow acceleration and turbulence. This flow acceleration and turbulence effectively enhance the heat transfer coefficient. Hence, improving the power output. This whole cooling system setup is placed at the trailing edge of the blade and the air is flowed through the hole blade.

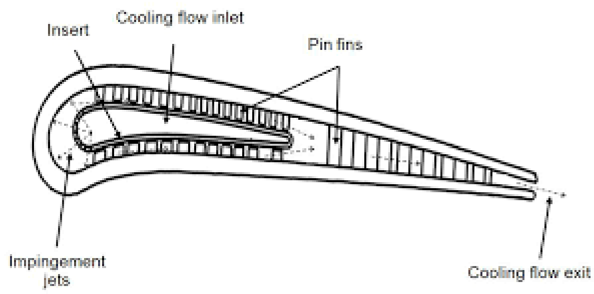


Figure 12 - Pin fin cooling of turbine blade surface view

The way it works is that as the air is allowed to accelerate between the pins, the cross-section decreases significantly. Due to which there is change in Reynolds number and eventually due to change in velocity, the heat transfer occurs between the air and the turbine blade. This heat transfer eventually decreases the temperature of the blades.

The area of interest for the pin fin cooled blade is the leading-edge region and the wake region that is formed in the trailing edge. There is higher heat transfer in these regions due to the cylindrical pins that offer turbulence and flow acceleration. Plus, these pins also break up the boundary layers which are formed on the end walls. This boundary layer breaks due to the formation of a flow commonly known as horseshoe vortex. This vortex later produces wall shear stresses beneath the walls. Hence, resulting in high heat transfer.

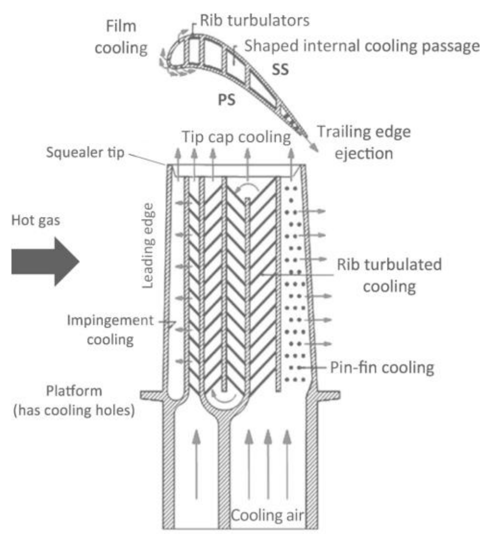


Figure 13 - Detailed view of pin fin cooling

2.5.2 Transpiration cooling

Transpiration cooling is defined as a thermodynamic process in which we move a liquid or a gas through the wall of the blades which absorbs some of the heat energy from the blades causing a cooling effect and decreasing its temperature. Moreover, it also reduces the convective and radiative heat flux of the blade which it gains from the surrounding space.

When the turbine blades are cooled using the technique of Transpiration cooling, the air flows through the tiny pores which are in the airfoil surface. This flow of air exhibits a great potential for allowing a great decrease in the turbine inlet temperature. This type of cooling is very effective as the air flowing cools the blade metal efficiently. The air which significantly has cooled the walls then forms a thin film which insulates the gas-side airfoil surface from the hot gas stream.

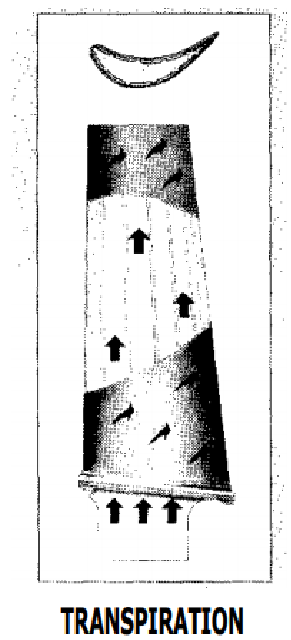


Figure 14 - Transpiration cooling of turbine blade

The airfoil material must be porous as well as it must have good resistance to oxidation as it allows the turbine blades to operate in high temperatures. This ensures that when we use this type of cooled blade design, we ultimately achieve very high cooling effectiveness.

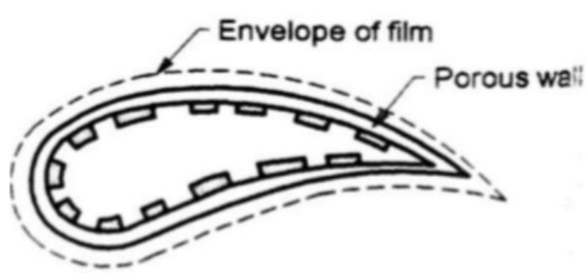


Figure 15 - Surface view of transpiration cooling

The current material industries have made certain alloys which have a great resistance to oxidation and these materials can withstand the temperatures within the limits of 1800 F to 2000 F. This cooling is somewhat comparable to convection cooling but there is a slight difference as in transpiration cooling the concept of achieving low metal temperatures at low cooling airflow rates is evident.

However, there is a limitation to this type of cooling. The limitation is that if the gas turbine is operating at a very high speed and the temperature of the turbine blades is approaching 4000 F or an aircraft requires a flight at very high Mach numbers, the air

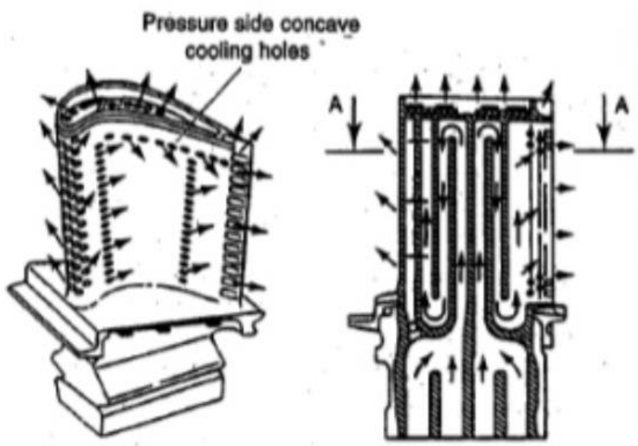


Figure 16 - Transpiration cooling of turbine blade in 3D

which the compressor discharges cannot be used as a coolant for transpiration cooling since it is already at very high temperature. So, it needs to be cooled prior to sending it to turbine blades to achieve effective cooling of the blade components.

<u>2.5.3 Film cooling</u>

There are various types of cooling techniques which are used to achieve a low blade temperature. But among all the cooling techniques, the film cooling technique has relatively more advantages and it is employed in every gas turbine industry. Transpiration cooling as discussed above together with the film cooling promise to be relatively effective methods of cooling the blades of the gas turbine. Analytical and experimental investigations are being conducted to obtain a better understanding of these processes.

The process of the film cooling is illustrated in the figure below:

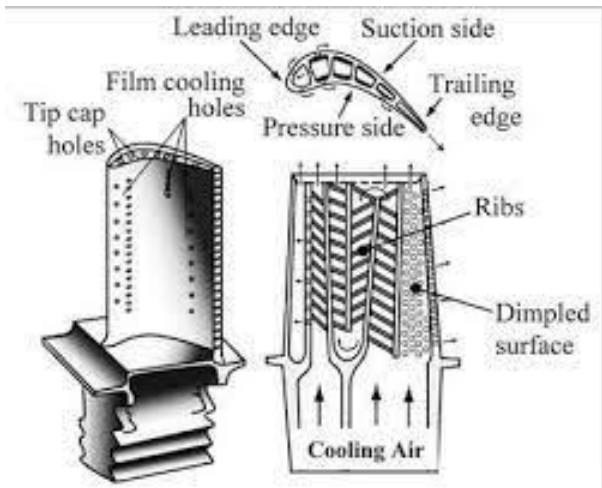


Figure 17 - Film cooling of turbine blade

The cooling air goes from one side of the turbine blade which passes over the dimpled surface into the ribs of the blades. There are tiny holes on the surface of the blades which are called “Film cooling holes”. The air passes through these tiny holes and forms a thin layer on the surface of the blade. This layer then acts as a cooling medium to cool down the temperature of the blade. The flow of air in film cooling is very essential for thermal protection of the gas turbine blades since the material specifications limit the increase of turbine speed. The increase of turbine speed results in very high

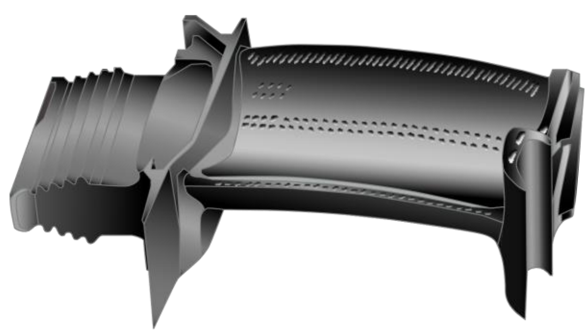


Figure 18 - Solid view of film cooling blade

temperatures which could cause the turbine blades to crack. The difficulty that is faced in employing film cooling is that it is very hard to predict the film cooling flow parameters. The rendered surface that is employed for film cooling is shown.

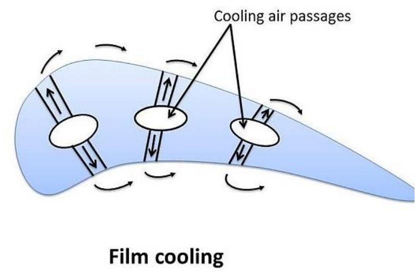


Figure 19 - Surface view of film cooling

It can be seen that the overall effectiveness of the film is highest when the air is downstream of the holes. The overall effectiveness is distributed homogeneously in zones where the holes are near the leading edge of the blade.

<u>2.5.4 Cooling Effusion:</u>

Lastly, the external cooling technique that is used to cool the turbine blade temperature is known as "Cooling Effusion". Gas turbines are operated for long hours at high temperatures due to which there is excessive load on different sections of gas turbines which include nozzle guide vanes, combustion liners and turbine blades. If these parts are not cooled properly, the wall surface may result in local thermal crack which eventually reduces the material strength.

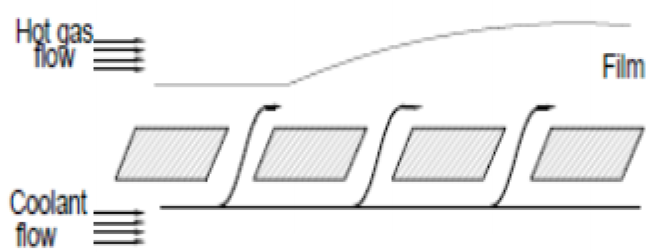


Figure 20 - Cooling effusion of turbine blade

The difference between effusion and film cooling is the size and the number of coolant holes. The size of the coolant holes in effusion cooling is around 0.2 mm. In effusion cooling, the amount of coolant used is less because the coolant passes through small size holes resulting in less impulse on the flow of hot gas. The cooling effectiveness of the cooling effusion technique depends upon hole spacing and hole size/shape. The spaces between the holes affect the adiabatic effectiveness. When there is dense spacing between the holes i.e., the distance between the cooling holes is decreased both in transverse as well as streamwise direction, there is a slight increase in the adiabatic efficiency. The coolant mass flow also increases due to this. The hole size affects the adiabatic efficiency in such a way that as the hole size is increased, the velocity of the coolant is decreased without overshooting into the hot gas flow. This allows the coolant to come in contact with the wall for a longer period of time and eventually more heat transfer takes place. That means by enlarging the diameter and making the holes closer can significantly improve the cooling effectiveness in cooling effusion.

The picture below shows the exact design of the blade that is incorporated with cooling effusion. The surface of the turbine blade is made up of porous material which has a large number of tiny holes in it. The air which aids in cooling is forced through these holes which later forms a boundary layer around the surface of the blade. This effusion of the air over the entire blade surface helps in dropping the temperature of the turbine blade.

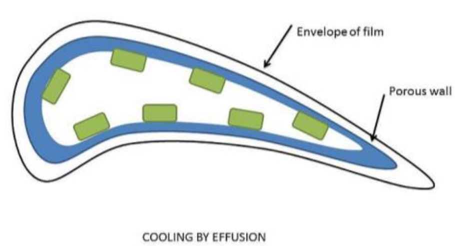


Figure 21 - Surface view of cooling effusion

Sometimes one or more than one cooling techniques are employed together to increase the cooling effectiveness of the turbine blade. Mostly, cooling effusion is employed with impingement cooling as they both have the same basis of cooling idea behind them. As shown in the figure below, on the left-hand side, the blade profile is shown which indicates that the blades are somewhat hollow on the inside that aids in impingement cooling. This impingement cooling being an internal cooling technique delivers approximately a cooling effectiveness of 40%. When this cooling is used side by side with the cooling effusion technique, the overall cooling effectiveness significantly increases to 75%. In this way, internal and external cooling can be used together to get higher heat transfers.

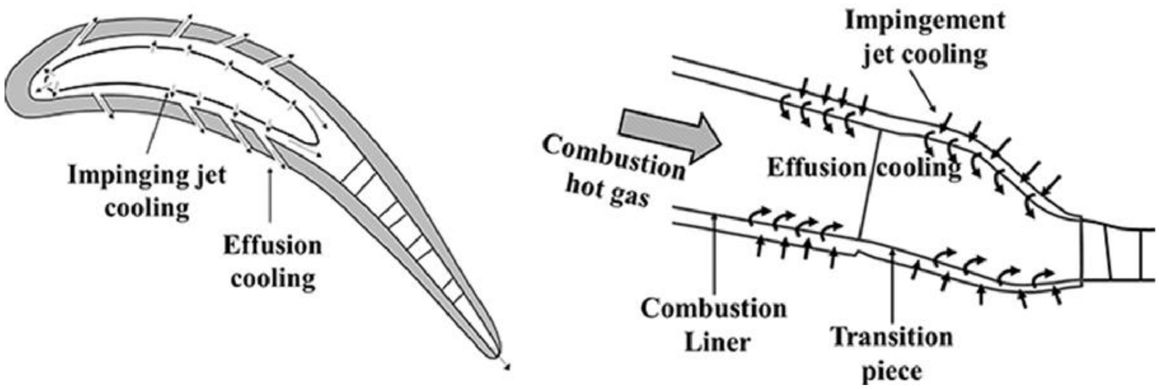


Figure 22 - Labelled cooling effusion of blade

CHAPTER 3: METHODOLOGY

We performed calculations to find the maximum blade surface temperature of the turbines. Determining the maximum blade surface temperature of the turbines will help us compare the effectiveness of the cooling techniques applied for the turbine blading cooling and make a decision based on the comparative result.

The procedure which we will adopt to determine the maximum temperature of the turbine blades will first require us to find the heat flow throughout the turbine blade which will enable us to find the temperature at the outer exposed surface of the turbine blades, which is usually at the maximum temperature.

Usually for the input variables, we will be provided with the exit air temperature and the power production of the turbines. We will be using these two parameters in our calculation. Even if anyone of the parameters is missing, we will perform a suitable assumption and calculate.

For assumptions of the turbine power and exit air temperature, we will use turbine models which are commonly used in power and solar industries.

For simplicity of the mathematical equations obtained, we will be using heat transfer resistance method in which we will be finding heat transfer resistances for different heat transfer modes. Then we combine all those resistances to obtain the inlet air temperature using the equation. After that we will use the inlet air temperature to determine the surface temperature of the turbine blade.

We will follow the steps stated below in order to determine the blade surface temperature:

- First, we will form the heat transfer resistance equation for each of the cooling techniques.
- Then using that equation, we will determine the turbine inlet temperature.

- From the calculated turbine inlet temperature, we will find the blade surface temperature at the leading edge of the turbine blade.
- Using that temperature, we can perform comparisons between the different cooling techniques.

3.1 No Turbine Blade Cooling

First, we will be determining the maximum blade temperature for the turbine blades when no cooling technique is utilized; this will give us a fair idea of temperature of turbine blades.

Although currently turbines are not usually used without a cooling technique but just to provide a solid comparison, we will be performing calculations when no cooling technique is applied which will give us a good overview for our study.

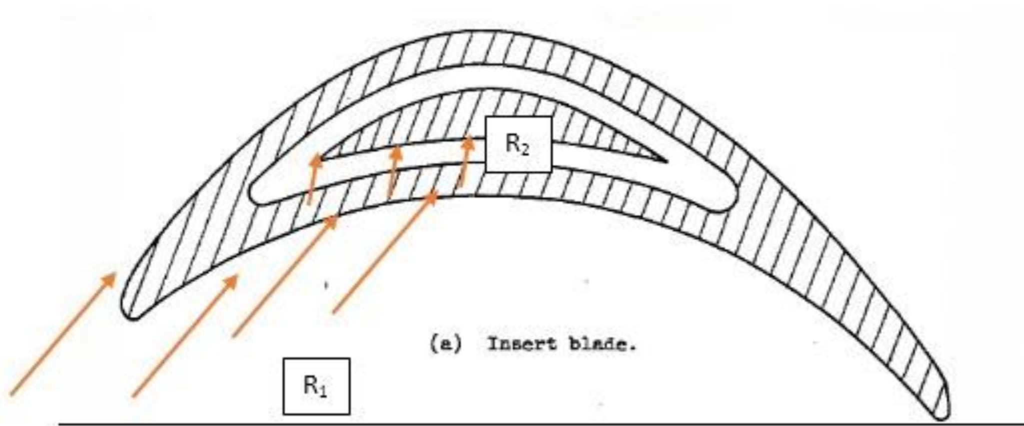


Figure 23 - No Cooling View

3.1.1 Mathematical Analysis

Equations are used for turbulent flows due to high air velocities and multiple contours.

For the mathematical model of the turbine blade heat flow without cooling, we have two types of heat flows.

- First heat transfer is due to the turbine inlet air flow over the turbine blade. For this we will consider the exposed outer surface of the turbine blade which experience convective heat transfer due to the flow of the hot inlet gases.
- Second heat transfer is due to the conduction heat transfer within the turbine blade which in which heat flows throughout the turbine blade for conduction. The conduction will be considered along the thickness of the blade.

3.1.1.1 Convective Heat Transfer Resistance

Convective Heat Transfer through inlet air flow over the turbine blade,

For convective heat transfer coefficient, we use the average Nusselt number over the turbine blade and calculate the convective heat transfer coefficient using that equation. We consider the equation for turbulent flow over a flat plate.

Average Nusselt number can be given as,

$$Nu = \frac{hL}{k} = 0.037Re_L^{0.8}Pr^{1/3}$$

Heat transfer Resistance is given as, $R_1 = \frac{1}{hA_1}$

Where, A_1 is the area of the surface of the turbine blade in contact with the flow of the inlet air. This area is the one which is exposed to the inlet air in turbine and on which the fluid flows along the blade.

Reynolds number is calculated as:

$$Re = \frac{\rho VL}{\mu}$$

Reynolds's number and Prandtl's number are calculated at the inlet air conditions, which will be estimated according to the turbine specifications and use. For better calculations, we will make assumptions for the inlet air temperature and pressure if they are not provided then proceed with the calculations.

3.1.1.2 Conductive Heat Transfer Resistance

Conductive heat transfer is considered along the thickness of the turbine blade and the temperature at the other end of the blade thickness is assumed to be equal to the turbine outlet temperature.

Now for Conduction heat transfer resistance,

$R_2 = \frac{t}{kA_2}$

Where, t is the average blade thickness of the leading edge of the blade, which will be estimated through the model and specifications
k is the conductivity of the blade depending on its material, which will be estimated from the turbine specifications if not provided,

A_2 is the area of the blade through which the heat is conducted till the outlet of the turbine blade.

3.1.1.3 Total Heat Transfer Resistance

Total heat transfer resistance is the sum of both resistances in the turbine blade,

$R_T = R_1 + R_2$

For multiple blades in turbine including stators, we can use the following total resistance:

$R = n*R_T$, where n is the number of blades and stators installed.

Now the total heat transfer rate can be given from the equation, which we will use to calculate the inlet air temperature,

$\dot{Q} = \frac{T_\infty - T_e}{R}$

Where, T_∞ is the temperature of the inlet air

T_e is the exhaust air temperature of the turbine.

Then we will calculate the temperature of the surface of the turbine blades, which is T_s using the following equation,

$\dot{Q} = \frac{T_\infty - T_S}{R_1}$

3.2 Pin Fin Cooling

The first cooling technique we will be analyzing is the pin fin cooling technique, in which a coolant flows over a set of pin fins on the inner surface of the turbine blade for the purpose of cooling the turbine blade.

In pin fin cooling technique, we will adopt the same procedure by determining the heat transfer resistances. The first two resistances will be same as used for the no cooling technique equation, because the heat flow is same as before for the inlet air convection and blade thickness conduction. We will use an extra heat transfer resistance which will be due to the convection heat transfer due to the coolant flow over the pin fins placed on the internal surface of the turbine blades.

3.2.1 Mathematical Analysis

For pin fin cooling, R_1 and R_2 are same,

$R_1 = \frac{1}{hA_1}$

$R_2 = \frac{t}{kA_2}$

Now for the convective heat transfer in the pin fins and the internal surface of the turbine blades on which the coolant air flows,

For this, we will take in-line arrangement of the pin fins for the equation of the Nusselt Number, since it simplifies the calculation and helps us determine the convective heat transfer coefficient easily. Also, we will take the equation of Nusselt Number for turbulent flow since the high-pressure flow is bound to be turbulent.

Convection through pins is determined by considering in-line arrangement of the pins,

Convection through the pin fins,

$Nu = 0.033Re^{0.8}Pr^{0.4}(Pr/Pr_s)^{0.25}$

Here the Reynolds number is calculated by using the temperature and pressure of the cooling air. Pr is calculated at the coolant air conditions and the Pr_s is calculated at the internal surface temperature of turbine blade, on which the coolant is flowing, which will be estimated since we do not currently know the internal blade surface temperature.

Pin fin resistance is,

$R_3 = \frac{1}{h_1 A_{s1}}$

Here, A_{s1} is the total surface area of the pin fins used for cooling. This area is the surface area of the curved part of the pin fins, which will be estimated assuming the number of pins and the size of the pins.

For the internal surface convection,

$Nu = \frac{hL}{k} = 0.037Re_L^{0.8}Pr^{1/3}$

Here the Reynolds number and the Prandtl's number are same as for the pin fins.

Internal Surface convective resistance,

$$R_4 = \frac{1}{h_2 A_{s2}}$$

The area A_{s2} is the turbine blade internal surface area where the pin fins are located.

For total heat transfer resistance, we can see that the resistances R_1 is in series with the parallel combination of resistances R_2, R_3 and R_4. The resultant heat transfer resistance can be given as:

$$R_T = R_1 + \frac{R_2 R_3 R_4}{R_2 R_3 + R_3 R_4 + R_2 R_4}$$

For multiple turbine blades and stators, we can find the total heat transfer resistance as,

$$R = n * R_T$$

Now we calculate the inlet air temperature using the total heat transfer equation,

$$\dot{Q} = \frac{T_\infty - T_e}{R}$$

Surface temperature of turbine blades is then determined using the following equation,

$$\dot{Q} = \frac{T_\infty - T_s}{R_1}$$

3.3 Film Cooling

Second cooling technique we will be analyzing is the film cooling technique. This technique involves forming a coolant film on the leading edge of the turbine blade by bleeding the coolant from small holes in the leading edge of the blade and forming a film of coolant flowing on the leading edge of the blade. We shall consider the layer of the coolant in between the inlet fluid and the blade surface, hence facilitating the heat transfer between the inlet hot air and the coolant while keeping the temperature of the blade surface minimum.

3.3.1 Mathematical Analysis:

For film cooling, R_1 is same as the previous.

$R_1 = \frac{1}{hA_1}$

Now the heat transfer through the coolant forming a film on the external turbine blade surface is determined as,

Nusselt Number for Convective heat transfer of coolant film is,

$Nu = \frac{h_1 L}{k} = 0.037 Re_L^{0.8} Pr^{1/3}$

Here the Reynolds number is calculated for the temperature and pressure parameters of the coolant and the Prandtl number is also calculated at the coolant air conditions.

Convective Heat transfer resistance for the coolant film is then given by,

$R_2 = \frac{1}{h_1 A_1}$

Here the surface area is same as for the surface area used for the inlet hot air since the film cooling essentially covers the same surface area which is exposed to the inlet hot air for turbines.

Conduction heat transfer which is same as the previous,

$R_3 = \frac{t}{kA_2}$

Since the heat transfer resistance R_3 is in series with the parallel combination of the resistances R_1 and R_2, the total heat transfer resistance is,

$$R_T = \frac{R_1 R_2}{R_1 + R_2} + R_3$$

For multiple turbine blades and stators, we can find the total heat transfer resistance as,

$$R = n*R_T$$

The inlet air temperature can be determined by the total heat transfer equation,

$$\dot{Q} = \frac{T_\infty - T_e}{R}$$

Surface temperature of turbine blades can be found using the equation,

$$\dot{Q} = \frac{T_\infty - T_S}{R_2}$$

Here we use heat transfer resistance R_2 since we the surface is essentially in constant with the coolant.

3.4 Impingement Cooling

Blade impingement cooling is one of most commonly used cooling technique for industry grade turbines. In impingement cooling, multiple jets of coolant are impinged on the inner side of the leading edge of the turbine blade. These jets cool down the turbine blade by transferring heat from the blades to the coolant.

In the mathematical analysis of this cooling technique, we shall be using the similar procedure as we used for the previous two techniques. The heat transfer resistances R_1 and R_2 are same as for the previous cooling techniques. The additional heat transfer resistance R_3 is due to the convective heat transfer through the flow of the coolant jet over the internal surface of the leading edge of the turbine blade.

3.4.1 Mathematical Analysis

For impingement cooling, R_1 and R_2 are same,

$R_1 = \frac{1}{hA_1}$

$R_2 = \frac{t}{kA_2}$

Here the variables in the equation have the same meaning as in the previous equations developed.

Now for R_3, we shall consider the flow of the coolant over the internal surface of the leading edge. The coolant flows on the internal side of the leading edge of the blade. We consider turbulent flow for the heat transfer coefficient value.

Average Nusselt's number for the convective heat transfer due to the coolant jets:

$Nu = \frac{h_1 L}{k} = 0.037 Re_L^{0.8} Pr^{1/3}$

$R_3 = \frac{1}{hA_2}$

Here the Reynold's number is calculated for the coolant air and the Prandtl number is calculated at the coolant air conditions with film temperature considered. Here we will estimate the film temperature since we currently won't know the internal surface temperature. The area is of the internal surface on which the jets are impinged and the coolant flows on it.

Since the heat transfer resistance is in series with the parallel combination of the resistances R_2 and R_3, the total heat transfer resistance is,

$R_T = R_1 + \frac{R_3 R_2}{R_3 + R_2}$

For multiple turbine blades and stators, we can find the total heat transfer resistance as,

$R = n*R_T$

The inlet air temperature can be determined by the total heat transfer equation,

$$\dot{Q} = \frac{T_\infty - T_e}{R}$$

Surface temperature of turbine blades can be found using the equation,

$$\dot{Q} = \frac{T_\infty - T_S}{R_1}$$

3.5 Other Cooling Techniques

Some other cooling techniques which were considered but not analyzed in our computer program are described as follows:

3.5.1 Transpiration Cooling

This cooling technique involves flow of a coolant through small pores on the outer edge of the turbine blade and is similar to film cooling, having similar heat transfer equations, involving convection heat transfer from inlet air and from the coolant flowing through the pores over the blade outer edge, and conduction heat transfer through the turbine blade.

3.5.2 Cooling Effusion

Cooling effusion is also same to the film cooling and transpiration cooling having difference in the size of the pores on the turbine blade used to bleed the coolant onto the leading edge of the turbine blade.

3.5.3 Combination Cooling Techniques

In industrial applications, multiple cooling techniques are used in combination to perform efficient cooling and reducing the blade surface temperature to a maximum limit.

Commonly used techniques are impingement and film cooling with any type of convection cooling. Sometimes film cooling is replaced by transpiration or effusion cooling. Also, for small turbine blades which do not have enough internal space to accommodate for the insert, they do not use impingement cooling but rather use internal convection cooling techniques, such as pin fin cooling. All the heat transfer mechanisms assist each other, therefore reducing the total heat transfer resistance and also reducing the turbine blade temperature.

3.6 Industrially Used Turbines and Techniques

A thorough study of turbine specifications was needed so that we can range out the parameters for the inlet and outlet conditions. For this purpose, we targeted the solar industry. We came across a variety of designs with various input and output conditions.

3.6.1 Saturn 20

This gas turbine has been in 4800 successful installations. It was first introduced in 1960 and they have clocked 620 million working hours. They can operate with a single shaft and with a constant speed for the driving of generators.

Given table shows most of the general output conditions of the Saturn 20 solar gas turbine as per company specifications.

Parameter	Power Generation	Mechanical Drive
Power Output	1.21 MW	1.185 MW
Efficiency	24.3%	24.5%
Heat Rate	14,795 kJ/kWh	14,670 kJ/kWh
Pressure Ratio	6.7	6.7
Exhaust Mass Flow	5.8 kg/s	5.8 kg/s
Exhaust Temperature	505 Â°C	520 Â°C
Turbine Speed	22,300 rpm	22,300 rpm

Table 1 - General output conditions of the Saturn 20 as per industry standard

3.6.2 Centaur 40, 50

Centaur turbines are also in wide use in the solar industry at both land and offshore regions with more than over thousand installations which range from arctic to tropical zones. Following table shows most of the general output conditions of the Centaur 50 solar gas turbine as per company specifications.

Parameter	Power Generation	Mechanical Drive
Power Output	1.21 MW	1.185 MW
Efficiency	24.3%	24.5%
Heat Rate	14,795 kJ/kWh	14,670 kJ/kWh
Pressure Ratio	6.7	6.7
Exhaust Mass Flow	5.8 kg/s	5.8 kg/s
Exhaust Temperature	505 Â°C	520 Â°C
Turbine Speed	22,300 rpm	22,300 rpm

Table 2 - General output conditions of the Centaur 50 as per industry standard

3.6.3 Taurus 60, 65, 70:

The Taurus family of gas turbines are also in use in the solar industry and they have been a state-of-the-art engineering and manufacturing group of solar turbines and there are several advanced features in it too. Following table shows most of the general output conditions of the Taurus 70 solar gas turbine as per company specifications:

Parameter	Power Generation	Mechanical Drive
Power Output	7.965 MW	8.140 MW
Efficiency	34.0%	35.2%
Heat Rate	10,505 kJ/kWh	10,195 kJ/kWh
Pressure Ratio	17.6	16.5
Exhaust Mass Flow	26.6 kg/s	26.2 kg/s
Exhaust Temperature	510 Â°C	510 Â°C
Turbine Speed	15,200 rpm	15,200 rpm

Table 3 - General output conditions of the Centaur 50 as per industry standard

3.6.4 Titan 130, 250:

This is currently the most powerful turbine in the solar industry of the US as compared to the other models. Titan 250 produces about 50% more power than its previous model Titan 130. The shaft efficiency produced is 40% and emissions are reduced by 30%. Following table shows most of the general output conditions of the Titan 250 solar gas turbine as per company specifications

Parameter	Power Generation	Mechanical Drive
Power Output	21.745 MW	22.370 MW
Efficiency	38.9%	40.0%
Heat Rate	9,260 kJ/kWh	9,000 kJ/kWh
Pressure Ratio	24.0	24.0
Exhaust Mass Flow	67.3 kg/s	67.3 kg/s
Exhaust Temperature	465 Â°C	465 Â°C
Turbine Speed	10,500 rpm	10,500 rpm

Table 4 - General output conditions of the Titan 250 as per industry standard

CHAPTER 4: RESULTS AND DISCUSSIONS

The main objective of development of a computer program has been accomplished through MATLAB and its GUI through the app designer. The background computer code for both design and mathematical analysis has been successfully developed. (See Appendix)

4.1 Program Outputs:

The interface of the program is simple and easy to understand.

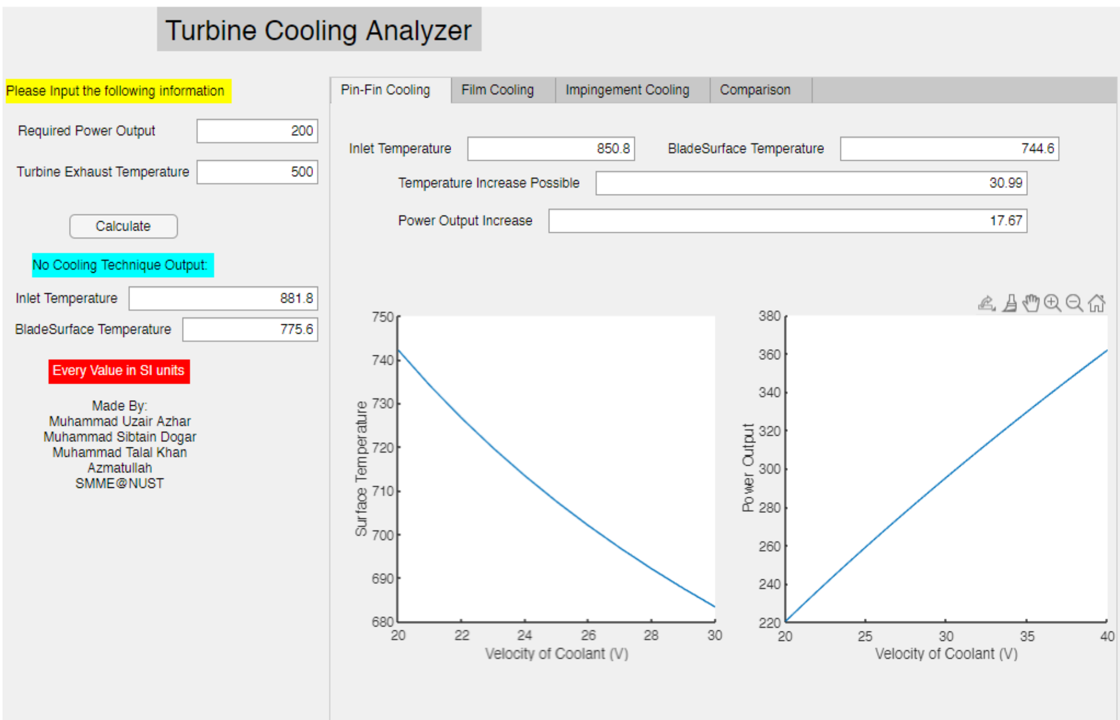


Figure 24 - App Interface

The input values are to be entered in the boxes on the left side. After pressing the calculate button, we first get the no colling technique outputs below and then the other cooling technique outputs with the graphs. The first three tabs produce the values of Pin-fin cooling, film cooling and impingement cooling in the shown order and then the comparison tab gives the plot of comparison of techniques.

The provided picture shows the working of the program when values are provided. The plots show the variation in the inlet temperature and power output with the velocity of coolant variation.

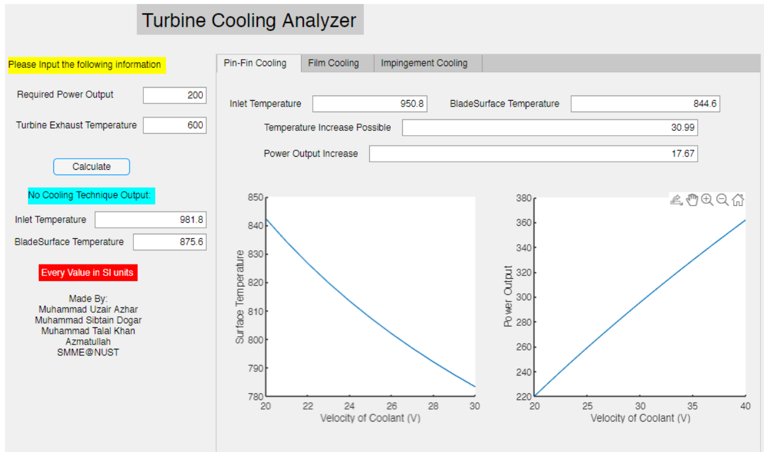


Figure 25 – Cooling Outputs

We can change alternate between the tabs to see more results and plots of different techniques.

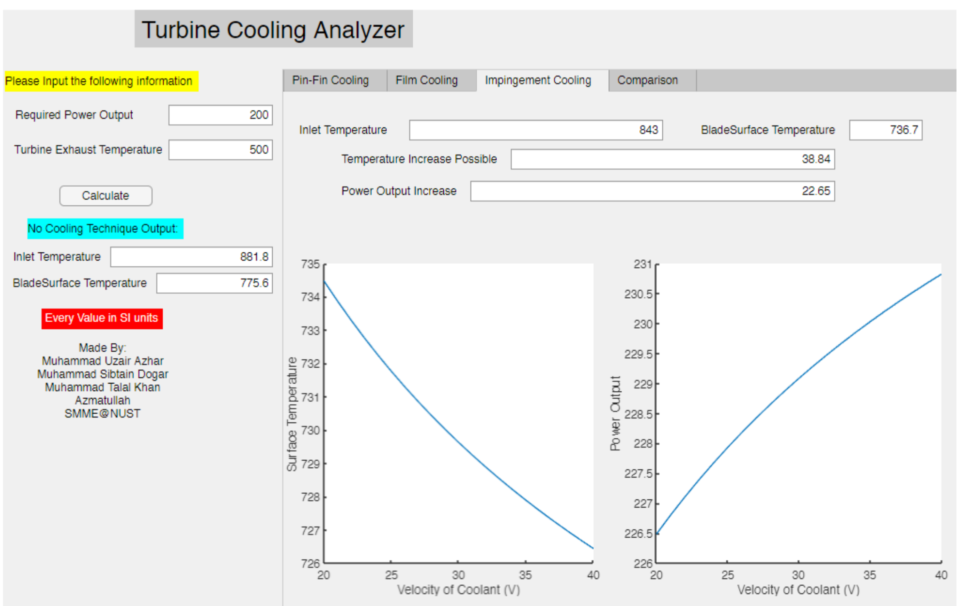


Figure 26 - Impingement cooling output

In the last tab, the comparison of all techniques with respect to the varying coolant velocity can be observed in the form of a plot.

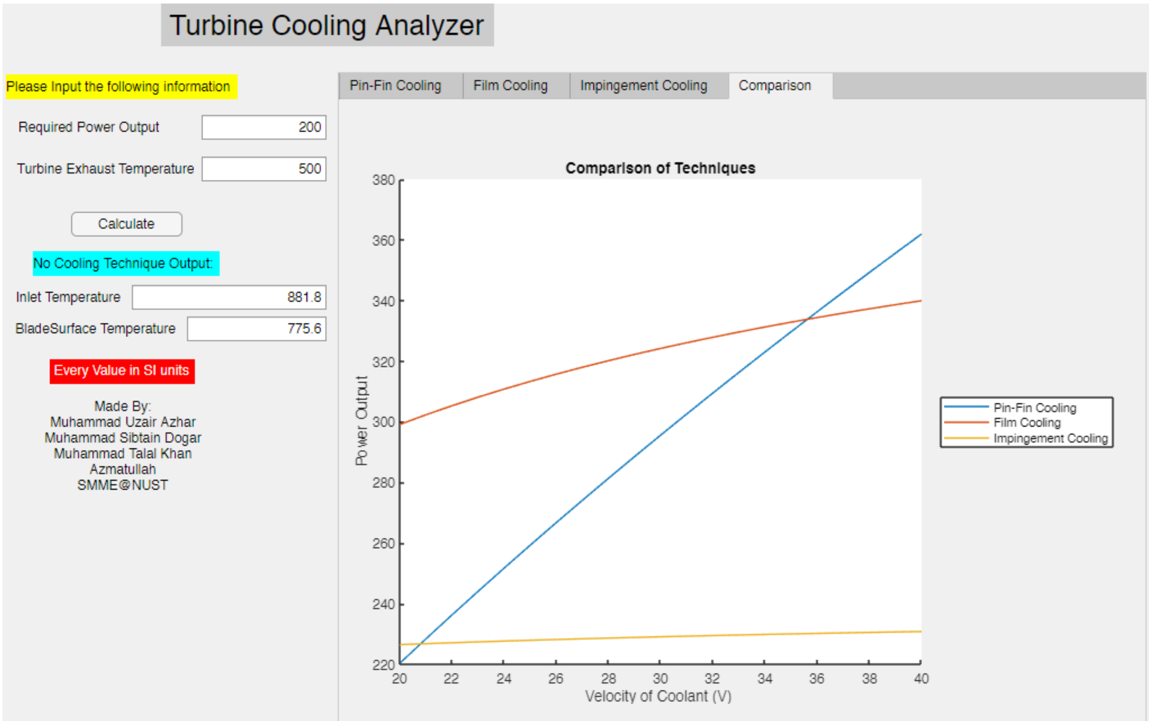


Figure 27 - Comparison of Techniques Graphically

The lines of plot represent the variation in the power output for the type of cooling described. We can see that the film cooling can be observed to give the optimized best result while the pin-fin cooling gives better and better results with increasing values of velocity and number of pins.

CHAPTER 5: CONCLUSION

Conclusively, the thermal efficiency of the gas turbines depends on the inlet temperature of the gas that means as the temperature of the inlet gas is increased, the efficiency also increases. We analyzed various cooling techniques and did a comparative study on it too. Our comparative study showed that impingement and film cooling are the most effective cooling techniques for the cooling of turbine blades. Almost 170K - 200K temperature drop is achieved when we use these two cooling techniques. If we use these cooling techniques together, we can achieve a temperature drop of up to 350K.

When we increase the inlet temperature of the gas, thermal stresses are developed on the turbine blades which is why a cooling media is often required so that we can avoid failures of turbine blades due to high temperature. As discussed above, the two-cooling media used are highly effective and thereby provide the necessary cooling effect. In external cooling techniques, we have holes on the surface of the blades. These drilled holes aid in the decrease of the temperature of the blades as these holes have high heat dissipation. When we increase the number of holes of the surface of the blades, we eventually increase the heat transfer rate. For highly effective cooling, we need inlet fogging which helps in decreasing the temperature of the turbine blade. The specific work output and the thermal efficiency can be improved by the injection of steam of air in the combustion chamber of the turbine. The principle of the film cooling is convection in which there is a film formed by the coolant on the outer periphery of the turbine blade. This film then absorbs the heat and a highly effective cooling effect is achieved. It is concluded that by decreasing the temperature of the turbine blades, we can increase the inlet temperature of gas significantly. The life of the engine is extended.

By the comparative study of the different cooling techniques, we can clearly see on the graph that on different conditions of inlet, different cooling techniques perform differently. In this way, we can choose the best cooling technique by plotting them and selecting them on the basis of what we are required.

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APPENDIX: PROGRAM CODE

```
classdef app1 < matlab.apps.AppBase

    % Properties that correspond to app components
    properties (Access = public)
        UIFigure                        matlab.ui.Figure
        TurbineCoolingAnalyzerLabel     matlab.ui.control.Label
        PleaseInputthefollowinginformationLabel  matlab.ui.control.Label
        RequiredPowerOutputEditFieldLabel  matlab.ui.control.Label
        RequiredPowerOutputEditField    matlab.ui.control.NumericEditField
        TurbineExhaustTemperatureEditFieldLabel  matlab.ui.control.Label
        TurbineExhaustTemperatureEditField  matlab.ui.control.NumericEditField
        CalculateButton                 matlab.ui.control.Button
        TabGroup                        matlab.ui.container.TabGroup
        PinFinCoolingTab                matlab.ui.container.Tab
        InletTemperatureEditField_2Label  matlab.ui.control.Label
        InletTemperatureEditField_2     matlab.ui.control.NumericEditField
        BladeSurfaceTemperatureEditField_2Label  matlab.ui.control.Label
        BladeSurfaceTemperatureEditField_2  matlab.ui.control.NumericEditField
        TemperatureIncreasePossibleEditFieldLabel  matlab.ui.control.Label
        TemperatureIncreasePossibleEditField  matlab.ui.control.NumericEditField
        PowerOutputIncreaseEditFieldLabel  matlab.ui.control.Label
        PowerOutputIncreaseEditField    matlab.ui.control.NumericEditField
        UIAxes                          matlab.ui.control.UIAxes
        UIAxes2                         matlab.ui.control.UIAxes
        FilmCoolingTab                  matlab.ui.container.Tab
        InletTemperatureEditField_3Label  matlab.ui.control.Label
        InletTemperatureEditField_3     matlab.ui.control.NumericEditField
        BladeSurfaceTemperatureEditField_3Label  matlab.ui.control.Label
        BladeSurfaceTemperatureEditField_3  matlab.ui.control.NumericEditField
        TemperatureIncreasePossibleEditField_2Label  matlab.ui.control.Label
        TemperatureIncreasePossibleEditField_2  matlab.ui.control.NumericEditField
        PowerOutputIncreaseEditField_2Label  matlab.ui.control.Label
        PowerOutputIncreaseEditField_2  matlab.ui.control.NumericEditField
        UIAxes3                         matlab.ui.control.UIAxes
        UIAxes4                         matlab.ui.control.UIAxes
        ImpingementCoolingTab           matlab.ui.container.Tab
        InletTemperatureEditField_4Label  matlab.ui.control.Label
        InletTemperatureEditField_4     matlab.ui.control.NumericEditField
        BladeSurfaceTemperatureEditField_4Label  matlab.ui.control.Label
        BladeSurfaceTemperatureEditField_4  matlab.ui.control.NumericEditField
        TemperatureIncreasePossibleEditField_3Label  matlab.ui.control.Label
        TemperatureIncreasePossibleEditField_3  matlab.ui.control.NumericEditField
        PowerOutputIncreaseEditField_3Label  matlab.ui.control.Label
        PowerOutputIncreaseEditField_3  matlab.ui.control.NumericEditField
        UIAxes5                         matlab.ui.control.UIAxes
        UIAxes6                         matlab.ui.control.UIAxes
        ComparisonTab                   matlab.ui.container.Tab
        UIAxes7                         matlab.ui.control.UIAxes
```

```
    InletTemperatureEditFieldLabel  matlab.ui.control.Label
    InletTemperatureEditField       matlab.ui.control.NumericEditField
    BladeSurfaceTemperatureEditFieldLabel  matlab.ui.control.Label
    BladeSurfaceTemperatureEditField  matlab.ui.control.NumericEditField
    NoCoolingTechniqueOutputLabel   matlab.ui.control.Label
    EveryValueinSIunitsLabel        matlab.ui.control.Label
    MadeByLabel                     matlab.ui.control.Label
end

% Callbacks that handle component events
methods (Access = private)

    % Button pushed function: CalculateButton
    function CalculateButtonPushed(app, event)
        % No cooling
        Q=app.RequiredPowerOutputEditField.Value;
        Te=app.TurbineExhaustTemperatureEditField.Value;
        V=20;
        L=0.015;
        k=12;
        mu=52.06*(10^-6);
        p=0.24;
        A1=0.000792;
        Pr=0.74;
        t=0.002;
        A2=0.001584;
        n=3;
        Rel=(p*V*L)/mu;
        h=(0.037*k*(Rel^0.8)*(Pr*(1/3)))/(L);
        R1=1/(h*A1);
        R2=t/(k*A2);
        R=R1+R2;
        Rt=n*R;
        Tin0=(Rt*Q)+Te;

        app.InletTemperatureEditField.Value=Tin0;

        Ts0= Tin0-(Q*R1);

        app.BladeSurfaceTemperatureEditField.Value=Ts0;

        %Pin Fin Cooling

        V1=10;
        p=0.71;
        L=0.008;
        mu=25*(10^-6);
        Prs=0.722;
        Re=(p*V1*L)/mu;
        As1=0.000025;
        As2=0.000528;
```

```
h1=(k*0.033*(Re^0.8)*(Pr^0.4)*((Pr/Prs)^0.25))/L;
h2=(k*0.037*(Rel^0.8)*(Pr^(1/3)))/L;

R3=1/(h1*As1);
R4=1/(h2*As2);
Rt=R1+((R2*R3*R4)/(R2*R3+R3*R4+R4*R2));
R=n*Rt;

Tin1=(R*Q)+Te;

app.InletTemperatureEditField_2.Value=Tin1;

Ts1= Tin1-(Q*R1);

app.BladeSurfaceTemperatureEditField_2.Value=Ts1;

app.TemperatureIncreasePossibleEditField.Value= Tin0-Tin1;
P=((Tin0-Te)/R)-Q;
app.PowerOutputIncreaseEditField.Value=P;



%Film Cool
L=0.01;
A1=0.000528;
p=0.71;

R3=R2;
Re=(p*V1*L)/mu;
h1=(k*0.037*(Re^0.8)*(Pr^(1/3)))/L;
R2=1/(h1*A1);

R=n*(R3+((R1*R2)/(R1+R2)));
Tin2=(R*Q)+Te;

app.InletTemperatureEditField_3.Value=Tin2;

Ts2= Tin2-(Q*R1);

app.BladeSurfaceTemperatureEditField_3.Value=Ts2;

app.TemperatureIncreasePossibleEditField_2.Value= Tin0-Tin2;
P=((Tin0-Te)/R)-Q;
app.PowerOutputIncreaseEditField_2.Value=P;

%Impingement Cooling

R2=R3;
L=0.0528;
V1=20;
Pr=0.722;
Re=(p*V1*L)/mu;
```

```
h1=(k*0.037*(Re^0.8)*(Pr^(1/3)))/L;
R3=1/(h1*A1);
R=n*(R1+((R3*R2)/(R3+R2)));
Tin3=(R*Q)+Te;

app.InletTemperatureEditField_4.Value=Tin3;

Ts3= Tin3-(Q*R1);

app.BladeSurfaceTemperatureEditField_4.Value=Ts3;

app.TemperatureIncreasePossibleEditField_3.Value= Tin0-Tin3;
P=((Tin0-Te)/R)-Q;
app.PowerOutputIncreaseEditField_3.Value=P;

function Ts1 = A(V)
L=0.015;
N=50;

k=12;
mu=52.06*(10^-6);
r=0.24;
A1=0.000792;
Pr=0.74;
t=0.002;
A2=0.001584;

Rel=(r*V*L)/mu;
h=(0.037*k*(Rel.^0.8)*(Pr*(1/3)))/(L);
R1=1./(h*A1);
R2=t/(k*A2);
R=R1+R2;
Rt=3*R;
V1=10;
r=0.71;
L=0.008;
mu=25*(10^-6);
Prs=0.722;
Re=(r*V1*L)/mu;
As1=0.001*0.0005*N;
As2=0.000528;

h1=(k*0.033*(Re^0.8)*(Pr^0.4)*((Pr/Prs)^0.25))/L;
h2=(k*0.037*(Rel.^0.8)*(Pr^(1/3)))/L;

R3=1./(h1*As1);
R4=1./(h2*As2);
Rt=R1+((R2*R3*R4)/(R2*R3+R3*R4+R4*R2));
R=3*Rt;

Tin1=(R*Q)+Te;
```

```
        Ts1= Tin1-(Q*R1);


end

        B=[20:30];
 plot(app.UIAxes,B,A(B));

 function C = D(V)
        L=0.015;
        N=50;


        k=12;
        mu=52.06*(10^-6);
        r=0.24;
        A1=0.000792;
        Pr=0.74;
        t=0.002;
        A2=0.001584;

        Rel=(r*V.*L)/mu;
        h=(0.037*k*(Rel.^0.8)*(Pr*(1/3)))/(L);
        R1=1./(h*A1);
        R2=t/(k*A2);
        R=R1+R2;
        Rt=3*R;
        V1=10;
        r=0.71;
        L=0.008;
        mu=25*(10^-6);
        Prs=0.722;
        Re=(r*V1*L)/mu;
        As1=0.001*0.0005*N;
        As2=0.000528;

        h1=(k*0.033*(Re^0.8)*(Pr^0.4)*((Pr/Prs)^0.25))/L;
        h2=(k*0.037*(Rel.^0.8)*(Pr^(1/3)))/L;

        R3=1./(h1*As1);
        R4=1./(h2*As2);
        Rt=R1+((R2*R3*R4)/(R2*R3+R3*R4+R4*R2));
        R=3*Rt;

        Tin1=(R*Q)+Te;


        Ts1= Tin1-(Q*R1);

        C=((Tin0-Te)./R);
```

```
end
C=[20:40];
plot(app.UIAxes2,C,D(C));

function Ts2 = E(V)
        L=0.015;
        N=50;

        k=12;
        mu=52.06*(10^-6);
        r=0.24;
        A1=0.000792;
        Pr=0.74;
        t=0.002;
        A2=0.001584;
        V1=15;
        Rel=(r*V1*L)/mu;
        h=(0.037*k*(Rel^0.8)*(Pr*(1/3)))/(L);
        R1=1/(h*A1);
        R2=t/(k*A2);
        R=R1+R2;
        Rt=3*R;
        V1=10;
        r=0.71;
        L=0.008;
        mu=25*(10^-6);
        Prs=0.722;
        Re=(r*V1*L)/mu;
        As1=0.001*0.0005*N;
        As2=0.000528;


        L=0.01;
        A1=0.000528;
        p=0.71;

        R3=R2;
        Re=(p*V.*L)/mu;
        h1=(k*0.037*(Re.^0.8)*(Pr^(1/3)))/L;
        R2=1./(h1*A1);

        R=3*(R3+((R1.*R2)./(R1+R2)));
        Tin2=(R*Q)+Te;


        Ts2= Tin2-(Q*R1);


end

F=[20:40];
```

```
plot(app.UIAxes3,F,E(F)+145);

function P2 = Y(V)
        L=0.015;
        N=50;

        k=12;
        mu=52.06*(10^-6);
        r=0.24;
        A1=0.000792;
        Pr=0.74;
        t=0.002;
        A2=0.001584;
        V1=15;
        Rel=(r*V1*L)/mu;
        h=(0.037*k*(Rel^0.8)*(Pr*(1/3)))/(L);
        R1=1/(h*A1);
        R2=t/(k*A2);
        R=R1+R2;
        Rt=3*R;
        V1=10;
        r=0.71;
        L=0.008;
        mu=25*(10^-6);
        Prs=0.722;
        Re=(r*V1*L)/mu;
        As1=0.001*0.0005*N;
        As2=0.000528;


        L=0.01;
        A1=0.000528;
        p=0.71;

        R3=R2;
        Re=(p*V.*L)/mu;
        h1=(k*0.037*(Re.^0.8)*(Pr^(1/3)))/L;
        R2=1./(h1*A1);

        R=3*(R3+((R1.*R2)./(R1+R2)));
        Tin2=(R*Q)+Te;


        Ts2= Tin2-(Q*R1);

        P2= 0.35*((Tin0-Te)./R);


end
Z=[20:40];
plot(app.UIAxes4,Z,Y(Z));
```

```
 function Ts3 = W(V)
          L=0.015;

          p=0.71;

          k=12;
          mu=52.06*(10^-6);
          r=0.24;
          A1=0.000792;
          Pr=0.74;
          t=0.002;
          A2=0.001584;
          V1=15;
          Rel=(r*V1*L)/mu;
          h=(0.037*k*(Rel^0.8)*(Pr*(1/3)))/(L);
          R1=1/(h*A1);
          R2=t/(k*A2);
          R=R1+R2;
          Rt=3*R;
          V1=10;



          L=0.0528;
          Pr=0.722;
          Re=(p*V.*L)/mu;
          h1=(k*0.037*(Re.^0.8)*(Pr^(1/3)))/L;
          R3=1./(h1*A1);
          R=3*(R1+((R3.*R2)./(R3+R2)));
          Tin3=(R*Q)+Te;

          Ts3= (Tin3-(Q*R1))-60;


end
X=[20:40];
 plot(app.UIAxes5,X,W(X));

 function T = U(V)
          L=0.015;
          p=0.71;

          k=12;
          mu=52.06*(10^-6);
          r=0.24;
          A1=0.000792;
          Pr=0.74;
          t=0.002;
          A2=0.001584;
          V1=15
          Rel=(r*V1*L)/mu;
          h=(0.037*k*(Rel^0.8)*(Pr*(1/3)))/(L);
```

```
        R1=1/(h*A1);
        R2=t/(k*A2);
        R=R1+R2;
        Rt=3*R;
        V1=10;
        p=0.71;


        L=0.0528;
        Pr=0.722;
        Re=(p*V.*L)/mu;
        h1=(k*0.037*(Re.^0.8)*(Pr^(1/3)))/L;
        R3=1./(h1*A1);
        R=3*(R1+((R3.*R2)./(R3+R2)));
        Tin3=(R*Q)+Te;

        Ts3= (Tin3-(Q*R1))-60;

        T=1.27*((Tin0-Te)./R);
end
T=[20:40];
 plot(app.UIAxes6,T,U(T));

 plot(app.UIAxes7,C,D(C),C,Y(C),C,U(C));

leg1 = legend(app.UIAxes7,{'Pin-Fin Cooling','Film Cooling','Impingement
Cooling'},'Location','EastOutside');
        end
    end

    % Component initialization
    methods (Access = private)

        % Create UIFigure and components
        function createComponents(app)

            % Create UIFigure and hide until all components are created
            app.UIFigure = uifigure('Visible', 'off');
            app.UIFigure.Position = [100 100 640 480];
            app.UIFigure.Name = 'MATLAB App';

            % Create TurbineCoolingAnalyzerLabel
            app.TurbineCoolingAnalyzerLabel = uilabel(app.UIFigure);
            app.TurbineCoolingAnalyzerLabel.BackgroundColor = [0.8 0.8 0.8];
            app.TurbineCoolingAnalyzerLabel.FontSize = 25;
            app.TurbineCoolingAnalyzerLabel.Position = [173 441 296 40];
            app.TurbineCoolingAnalyzerLabel.Text = ' Turbine Cooling Analyzer';

            % Create PleaseInputthefollowinginformationLabel
            app.PleaseInputthefollowinginformationLabel = uilabel(app.UIFigure);
            app.PleaseInputthefollowinginformationLabel.BackgroundColor = [1 1 0];
            app.PleaseInputthefollowinginformationLabel.Position = [5 389 206 22];
```

```
app.PleaseInputthefollowinginformationLabel.Text = 'Please Input the following information';

% Create RequiredPowerOutputEditFieldLabel
app.RequiredPowerOutputEditFieldLabel = uilabel(app.UIFigure);
app.RequiredPowerOutputEditFieldLabel.HorizontalAlignment = 'right';
app.RequiredPowerOutputEditFieldLabel.Position = [11 349 131 22];
app.RequiredPowerOutputEditFieldLabel.Text = 'Required Power Output';

% Create RequiredPowerOutputEditField
app.RequiredPowerOutputEditField = uieditfield(app.UIFigure, 'numeric');
app.RequiredPowerOutputEditField.Position = [181 349 23 22];

% Create TurbineExhaustTemperatureEditFieldLabel
app.TurbineExhaustTemperatureEditFieldLabel = uilabel(app.UIFigure);
app.TurbineExhaustTemperatureEditFieldLabel.HorizontalAlignment = 'right';
app.TurbineExhaustTemperatureEditFieldLabel.Position = [10 308 163 22];
app.TurbineExhaustTemperatureEditFieldLabel.Text = 'Turbine Exhaust Temperature';

% Create TurbineExhaustTemperatureEditField
app.TurbineExhaustTemperatureEditField = uieditfield(app.UIFigure, 'numeric');
app.TurbineExhaustTemperatureEditField.Position = [181 308 23 22];

% Create CalculateButton
app.CalculateButton = uibutton(app.UIFigure, 'push');
app.CalculateButton.ButtonPushedFcn = createCallbackFcn(app, @CalculateButtonPushed, true);
app.CalculateButton.Position = [64 253 100 22];
app.CalculateButton.Text = 'Calculate';

% Create TabGroup
app.TabGroup = uitabgroup(app.UIFigure);
app.TabGroup.Position = [216 1 425 414];

% Create PinFinCoolingTab
app.PinFinCoolingTab = uitab(app.TabGroup);
app.PinFinCoolingTab.Title = 'Pin-Fin Cooling';

% Create InletTemperatureEditField_2Label
app.InletTemperatureEditField_2Label = uilabel(app.PinFinCoolingTab);
app.InletTemperatureEditField_2Label.HorizontalAlignment = 'right';
app.InletTemperatureEditField_2Label.Position = [12 338 99 22];
app.InletTemperatureEditField_2Label.Text = 'Inlet Temperature';

% Create InletTemperatureEditField_2
app.InletTemperatureEditField_2 = uieditfield(app.PinFinCoolingTab, 'numeric');
app.InletTemperatureEditField_2.Position = [126 338 34 22];

% Create BladeSurfaceTemperatureEditField_2Label
app.BladeSurfaceTemperatureEditField_2Label = uilabel(app.PinFinCoolingTab);
app.BladeSurfaceTemperatureEditField_2Label.HorizontalAlignment = 'right';
app.BladeSurfaceTemperatureEditField_2Label.Position = [184 338 148 22];
app.BladeSurfaceTemperatureEditField_2Label.Text = 'BladeSurface Temperature';
```

```
% Create BladeSurfaceTemperatureEditField_2
app.BladeSurfaceTemperatureEditField_2 = uieditfield(app.PinFinCoolingTab, 'numeric');
app.BladeSurfaceTemperatureEditField_2.Position = [347 338 25 22];

% Create TemperatureIncreasePossibleEditFieldLabel
app.TemperatureIncreasePossibleEditFieldLabel = uilabel(app.PinFinCoolingTab);
app.TemperatureIncreasePossibleEditFieldLabel.HorizontalAlignment = 'right';
app.TemperatureIncreasePossibleEditFieldLabel.Position = [57 307 171 22];
app.TemperatureIncreasePossibleEditFieldLabel.Text = 'Temperature Increase Possible';

% Create TemperatureIncreasePossibleEditField
app.TemperatureIncreasePossibleEditField = uieditfield(app.PinFinCoolingTab, 'numeric');
app.TemperatureIncreasePossibleEditField.Position = [243 307 100 22];

% Create PowerOutputIncreaseEditFieldLabel
app.PowerOutputIncreaseEditFieldLabel = uilabel(app.PinFinCoolingTab);
app.PowerOutputIncreaseEditFieldLabel.HorizontalAlignment = 'right';
app.PowerOutputIncreaseEditFieldLabel.Position = [57 273 128 22];
app.PowerOutputIncreaseEditFieldLabel.Text = 'Power Output Increase';

% Create PowerOutputIncreaseEditField
app.PowerOutputIncreaseEditField = uieditfield(app.PinFinCoolingTab, 'numeric');
app.PowerOutputIncreaseEditField.Position = [200 273 143 22];

% Create UIAxes
app.UIAxes = uiaxes(app.PinFinCoolingTab);
title(app.UIAxes, '')
xlabel(app.UIAxes, 'Velocity of Coolant (V)')
ylabel(app.UIAxes, 'Surface Temperature')
app.UIAxes.PlotBoxAspectRatio = [1.04929577464789 1 1];
app.UIAxes.Position = [20 50 193 185];

% Create UIAxes2
app.UIAxes2 = uiaxes(app.PinFinCoolingTab);
title(app.UIAxes2, '')
xlabel(app.UIAxes2, 'Velocity of Coolant (V)')
ylabel(app.UIAxes2, 'Power Output')
app.UIAxes2.PlotBoxAspectRatio = [1.06293706293706 1 1];
app.UIAxes2.Position = [227 50 196 185];

% Create FilmCoolingTab
app.FilmCoolingTab = uitab(app.TabGroup);
app.FilmCoolingTab.Title = 'Film Cooling';

% Create InletTemperatureEditField_3Label
app.InletTemperatureEditField_3Label = uilabel(app.FilmCoolingTab);
app.InletTemperatureEditField_3Label.HorizontalAlignment = 'right';
app.InletTemperatureEditField_3Label.Position = [12 338 99 22];
app.InletTemperatureEditField_3Label.Text = 'Inlet Temperature';

% Create InletTemperatureEditField_3
app.InletTemperatureEditField_3 = uieditfield(app.FilmCoolingTab, 'numeric');
```

```
app.InletTemperatureEditField_3.Position = [126 338 23 22];

% Create BladeSurfaceTemperatureEditField_3Label
app.BladeSurfaceTemperatureEditField_3Label = uilabel(app.FilmCoolingTab);
app.BladeSurfaceTemperatureEditField_3Label.HorizontalAlignment = 'right';
app.BladeSurfaceTemperatureEditField_3Label.Position = [195 338 148 22];
app.BladeSurfaceTemperatureEditField_3Label.Text = 'BladeSurface Temperature';

% Create BladeSurfaceTemperatureEditField_3
app.BladeSurfaceTemperatureEditField_3 = uieditfield(app.FilmCoolingTab, 'numeric');
app.BladeSurfaceTemperatureEditField_3.Position = [358 338 29 22];

% Create TemperatureIncreasePossibleEditField_2Label
app.TemperatureIncreasePossibleEditField_2Label = uilabel(app.FilmCoolingTab);
app.TemperatureIncreasePossibleEditField_2Label.HorizontalAlignment = 'right';
app.TemperatureIncreasePossibleEditField_2Label.Position = [57 307 171 22];
app.TemperatureIncreasePossibleEditField_2Label.Text = 'Temperature Increase Possible';

% Create TemperatureIncreasePossibleEditField_2
app.TemperatureIncreasePossibleEditField_2 = uieditfield(app.FilmCoolingTab, 'numeric');
app.TemperatureIncreasePossibleEditField_2.Position = [243 307 100 22];

% Create PowerOutputIncreaseEditField_2Label
app.PowerOutputIncreaseEditField_2Label = uilabel(app.FilmCoolingTab);
app.PowerOutputIncreaseEditField_2Label.HorizontalAlignment = 'right';
app.PowerOutputIncreaseEditField_2Label.Position = [57 273 128 22];
app.PowerOutputIncreaseEditField_2Label.Text = 'Power Output Increase';

% Create PowerOutputIncreaseEditField_2
app.PowerOutputIncreaseEditField_2 = uieditfield(app.FilmCoolingTab, 'numeric');
app.PowerOutputIncreaseEditField_2.Position = [200 273 143 22];

% Create UIAxes3
app.UIAxes3 = uiaxes(app.FilmCoolingTab);
title(app.UIAxes3, '')
xlabel(app.UIAxes3, 'Velocity of Coolant (V)')
ylabel(app.UIAxes3, 'Surface Temperature')
app.UIAxes3.Position = [12 29 184 185];

% Create UIAxes4
app.UIAxes4 = uiaxes(app.FilmCoolingTab);
title(app.UIAxes4, '')
xlabel(app.UIAxes4, 'Velocity of Coolant (V)')
ylabel(app.UIAxes4, 'Power Output')
app.UIAxes4.Position = [212 29 194 185];

% Create ImpingementCoolingTab
app.ImpingementCoolingTab = uitab(app.TabGroup);
app.ImpingementCoolingTab.Title = 'Impingement Cooling';

% Create InletTemperatureEditField_4Label
app.InletTemperatureEditField_4Label = uilabel(app.ImpingementCoolingTab);
```

```
        app.InletTemperatureEditField_4Label.HorizontalAlignment = 'right';
        app.InletTemperatureEditField_4Label.Position = [12 338 99 22];
        app.InletTemperatureEditField_4Label.Text = 'Inlet Temperature';

        % Create InletTemperatureEditField_4
        app.InletTemperatureEditField_4 = uieditfield(app.ImpingementCoolingTab, 'numeric');
        app.InletTemperatureEditField_4.Position = [135 338 25 22];

        % Create BladeSurfaceTemperatureEditField_4Label
        app.BladeSurfaceTemperatureEditField_4Label = uilabel(app.ImpingementCoolingTab);
        app.BladeSurfaceTemperatureEditField_4Label.HorizontalAlignment = 'right';
        app.BladeSurfaceTemperatureEditField_4Label.Position = [195 338 148 22];
        app.BladeSurfaceTemperatureEditField_4Label.Text = 'BladeSurface Temperature';

        % Create BladeSurfaceTemperatureEditField_4
        app.BladeSurfaceTemperatureEditField_4 = uieditfield(app.ImpingementCoolingTab, 'numeric');
        app.BladeSurfaceTemperatureEditField_4.Position = [358 338 29 22];

        % Create TemperatureIncreasePossibleEditField_3Label
        app.TemperatureIncreasePossibleEditField_3Label = uilabel(app.ImpingementCoolingTab);
        app.TemperatureIncreasePossibleEditField_3Label.HorizontalAlignment = 'right';
        app.TemperatureIncreasePossibleEditField_3Label.Position = [57 307 171 22];
        app.TemperatureIncreasePossibleEditField_3Label.Text = 'Temperature Increase Possible';

        % Create TemperatureIncreasePossibleEditField_3
        app.TemperatureIncreasePossibleEditField_3 = uieditfield(app.ImpingementCoolingTab,
'numeric');
        app.TemperatureIncreasePossibleEditField_3.Position = [243 307 100 22];

        % Create PowerOutputIncreaseEditField_3Label
        app.PowerOutputIncreaseEditField_3Label = uilabel(app.ImpingementCoolingTab);
        app.PowerOutputIncreaseEditField_3Label.HorizontalAlignment = 'right';
        app.PowerOutputIncreaseEditField_3Label.Position = [57 273 128 22];
        app.PowerOutputIncreaseEditField_3Label.Text = 'Power Output Increase';

        % Create PowerOutputIncreaseEditField_3
        app.PowerOutputIncreaseEditField_3 = uieditfield(app.ImpingementCoolingTab, 'numeric');
        app.PowerOutputIncreaseEditField_3.Position = [200 273 143 22];

        % Create UIAxes5
        app.UIAxes5 = uiaxes(app.ImpingementCoolingTab);
        title(app.UIAxes5, '')
        xlabel(app.UIAxes5, 'Velocity of Coolant (V)')
        ylabel(app.UIAxes5, 'Surface Temperature')
        app.UIAxes5.Position = [1 29 195 185];

        % Create UIAxes6
        app.UIAxes6 = uiaxes(app.ImpingementCoolingTab);
        title(app.UIAxes6, '')
        xlabel(app.UIAxes6, 'Velocity of Coolant (V)')
        ylabel(app.UIAxes6, 'Power Output')
        app.UIAxes6.Position = [203 29 211 185];
```

```
% Create ComparisonTab
app.ComparisonTab = uitab(app.TabGroup);
app.ComparisonTab.Title = 'Comparison';

% Create UIAxes7
app.UIAxes7 = uiaxes(app.ComparisonTab);
title(app.UIAxes7, 'Comparison of Techniques')
xlabel(app.UIAxes7, 'Velocity of Coolant (V) ')
ylabel(app.UIAxes7, 'Power Output')
app.UIAxes7.Position = [12 29 391 310];

% Create InletTemperatureEditFieldLabel
app.InletTemperatureEditFieldLabel = uilabel(app.UIFigure);
app.InletTemperatureEditFieldLabel.HorizontalAlignment = 'right';
app.InletTemperatureEditFieldLabel.Position = [8 182 99 22];
app.InletTemperatureEditFieldLabel.Text = 'Inlet Temperature';

% Create InletTemperatureEditField
app.InletTemperatureEditField = uieditfield(app.UIFigure, 'numeric');
app.InletTemperatureEditField.Position = [118 182 86 22];

% Create BladeSurfaceTemperatureEditFieldLabel
app.BladeSurfaceTemperatureEditFieldLabel = uilabel(app.UIFigure);
app.BladeSurfaceTemperatureEditFieldLabel.HorizontalAlignment = 'right';
app.BladeSurfaceTemperatureEditFieldLabel.Position = [8 152 148 22];
app.BladeSurfaceTemperatureEditFieldLabel.Text = 'BladeSurface Temperature';

% Create BladeSurfaceTemperatureEditField
app.BladeSurfaceTemperatureEditField = uieditfield(app.UIFigure, 'numeric');
app.BladeSurfaceTemperatureEditField.Position = [168 152 36 22];

% Create NoCoolingTechniqueOutputLabel
app.NoCoolingTechniqueOutputLabel = uilabel(app.UIFigure);
app.NoCoolingTechniqueOutputLabel.BackgroundColor = [0 1 1];
app.NoCoolingTechniqueOutputLabel.Position = [31 214 166 22];
app.NoCoolingTechniqueOutputLabel.Text = 'No Cooling Technique Output:';

% Create EveryValueinSIunitsLabel
app.EveryValueinSIunitsLabel = uilabel(app.UIFigure);
app.EveryValueinSIunitsLabel.BackgroundColor = [1 0 0];
app.EveryValueinSIunitsLabel.FontColor = [1 1 1];
app.EveryValueinSIunitsLabel.Position = [45 111 129 22];
app.EveryValueinSIunitsLabel.Text = ' Every Value in SI units';

% Create MadeByLabel
app.MadeByLabel = uilabel(app.UIFigure);
app.MadeByLabel.HorizontalAlignment = 'center';
app.MadeByLabel.Position = [37 10 145 84];
app.MadeByLabel.Text = {'Made By:'; 'Muhammad Uzair Azhar'; 'Muhammad Sibtain Dogar';
'Muhammad Talal Khan'; 'Azmatullah'; 'SMME@NUST'};
```

```
            % Show the figure after all components are created
            app.UIFigure.Visible = 'on';
        end
    end

    % App creation and deletion
    methods (Access = public)

        % Construct app
        function app = app1

            % Create UIFigure and components
            createComponents(app)

            % Register the app with App Designer
            registerApp(app, app.UIFigure)

            if nargout == 0
                clear app
            end
        end

        % Code that executes before app deletion
        function delete(app)

            % Delete UIFigure when app is deleted
            delete(app.UIFigure)
        end
    end
end
```